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FINAL PROJECT REPORT

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Duration of Project : April 1992 to March 1993

DMEA Division : Energy Branch

Project Reference No : NE 14/3/1/14

CERTIFIED AN OFFICIAL FINAL REPORT

for DEPT OF MINERAL & ENERGY AFFAIRS DATE

This report was prepared as a result of work sponsored by the Department of Mineral and Energy Affairs (DMEA). The report has been submitted to, reviewed and accepted by the DMEA. However, the view or opinions of authors expressed herein do not necessarily confirm or reflect those of the DMEA. Material in this report may be quoted provided the necessary acknowledgement is made.

TITLE : RAPS component characterisation: Phase II

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DATE : 3 March 1993

EXECUTIVE SUMMARY

Aims and objectives

The aims of this project are to test and evaluate components used in Remote Area Power Supply systems. Storage batteries, regulators, controllers and inverters centrally affect performance, reliability and energy costs in typical RAPS systems.

The data and findings are to be made available to two parallel research projects at EDRC.

- The data and understanding in component performance contributes to the accuracy of PV system simulation methods developed at EDRC. Simulation tools offer an attractive way of evaluating design options. Battery behaviour is the most problematic component. Regulator and inverter models are in need of validation.

- The RAPS information and dissemination project, incorporating the RAPS Design Manual, will present the performance and economic data, together with design guidelines and recommendations in a format for PV system designers. Battery performance and lifetimes are major determinants of PV systems costs. Battery lifetimes and economics are determined by system design, battery cycling regimes, and effective charge and discharge regulation. Charge regulator algorithm and set-points are critical.

The component data derived from EDRC tests can be used to provide design feedback to manufacturers and suppliers of locally available components. Engaging suppliers, and encouraging them to participate are a primary aim. Future large-scale PV projects with large institutional funding will rely on the industry to provide documentation for components and systems to an acceptable international standard.

Further objectives are to link the component data experience with PV systems performance testing methodologies. PV testing methods offer a system performance specification which could greatly assist in management of and tender awards for large PV projects. Simulation already offers one way of assessing system design. Experimental PV testing methods are in reality complex to analyze and are of presently unknown accuracy. Experience in experimental techniques gained during component testing could provide valuable feedback.

Experimental design

Major objectives during the phases of the project were to design and develop test facilities for component characterisation. Versatile and accurate hardware was purchased, in-house electronics designs undertaken where required and custom control software written. Test methods were investigated and developed.

At the end of phase II of the component project, a range of testing facilities and test methods exist at EDRC.

Battery testing facilities and methods

A micro-computer controlled battery cycling unit was developed. The unit consists of a 3kW power supply and a 1.8kW load

The control software supports conventional constant current battery discharge testing, and constant current / constant voltage recharging. Software also supports a variety of charge/discharge cycling profiles, with time constraints, voltage constraints, current limits, charge accumulation limits etc... A graphical output of any logged parameters is available at any time.

A primary limitation of the facility is the ability to test only one battery bank at any time. The software could be easily be modified to cater for more tests at one time, but the main expense would be the need for additional power supplies and loads.

In the interests of testing efficiency, a detailed review of testing literature was undertaken and innovative methods developed.

A short method of determining charge curves was developed. This method entails periodically and incrementally varying the charge current over a suitable range and maintaining the current till the voltage stabilises. The stabilised voltage is taken as one point on the charge curve, and points of constant current can be joined to form the charge curve. This approach was particularly useful for determining low rate charge curves typical of PV systems, which would otherwise be impractically time consuming.

Instantaneous charging efficiencies were determined by monitoring battery gassing rates, and charge curves were corrected for the charging inefficiencies indicated by the gassing curves.

For longer term performance testing and evaluation, a range of battery cycling tests were used. Temporary and reversible capacity losses caused by stratification and undercharging, and permanent losses leading to battery failure, were also monitored through the cycling tests. Variation in charge and discharge curves during cycling was noted, and runaway effects or implications for system design recorded.

Regulator testing

Regulator tests can be divided into two groups: i) characterisation, and ii) performance testing.

Regulator characterisation involves determination of setpoints for top-of-charge and for loadshed, including any time delays and temperature compensation of the setpoints. Voltage losses through the regulator, and regulator energy consumption under various switch conditions are also important data.

A micro-computer controlled test and measurement unit consisting of an array-simulator power supply, battery simulator and controlled loads was set up for characterisation tests. The system ramps the battery simulator voltage while monitoring array and load currents to automatically detect whether charge regulation or loadshedding has occurred. The unit can also measure parasitic power consumption and voltage losses.

For performance testing, the battery simulator is replaced by a real battery, and the regulator and battery pair monitored under controlled cycling conditions. An array model is used to ensure that the array simulator outputs true IV characteristics under the control solar day used. Tests are conducted for overcharge, recharge efficiency and steady-state operation for different battery types.

Inverter testing

Inverter performance characterisation is simpler than for other system components, primarily because the only PV system variable to consider is the battery voltage. In most cases a snap-shot performance assessment is sufficient.

A computer controlled waveform analyzer was designed using off-the-shelf hardware and customised software. A high frequency oscilloscope captures isolated DC and AC voltage and current waveforms, and communicates these to a host computer. In the computer the waveforms are processed; true RMS values, true efficiencies, waveform distortion and power factor are calculated. For accurate measurements a systems multimeter is also used. Data is stored for later recall or analysis. Sophisticated software allows for high volume throughput during repetitive testing. DC input voltage is controlled by programmable DC power supplies. New AC electronic loads coming onto the market could allow for fully automated tests with variable AC output power and capacitance or inductance.

Performance was monitored at various AC resistive loads, DC input voltages and real loads. Overload, shortcircuit, reverse polarity, and battery protection features were checked. Electromagnetic interference tests were conducted at a specially equipped private laboratory.

Module testing under natural light

PV module testing is conventionally a snapshot electrical output test done under controlled indoor conditions. A facility was set up for simple IV curve scanning under natural light conditions. Although spectral composition of the light cannot at this stage be monitored, other important variables are, and the robust equipment allows for easy, accurate IV scans throughout the day.

The data capture facility automatically scans and records IV curves for up to four modules at a time. Accurate instrumentation and electronic loads were used to generate data over a range of irradiance and temperature conditions throughout the day. Sufficiently accurate data can be generated in quantities for statistical curve or model validation.

Previous attempts by other institutions had resulted in poor data quality and accuracy, and insufficient quantity to justify detailed analysis. Methods had mostly required intimate operator involvement.

PV systems performance testing

PV systems performance testing following the EDRC recommended procedure is a simple process, but local institutions attempting the procedure have failed over and again to deliver reproducible results or any results at all. As part of an investigation into the method, facilities were set up for automatic testing.

Facilities were set-up for PV systems monitoring. All the major insolation, temperature and energy flows were recorded using accurate multimeters that required no input signal amplification.

The crux of the system, however, is customised software for automatic test control and error detection. Array and load relays are opened and closed under software control (and array IV scans are actually taken during the test as well). The software ensures that errors do not result in catastrophic failure of any system, and that operator involvement is limited. Failure can mean restarting the whole test sequence, which takes a minimum of thirty days, but usually up to sixty days. PV systems testing, as with IV testing, could be a full-time time commitment for at least one person unless automated. For accurate results, the test should be repeated several times.

Ad-hoc and future testing

Facilities also exist for ad-hoc testing of non-PV system components. A petrol generator/alternator system has been evaluated. In future the inverter test software will be modified to enable battery charger testing, water pump characterisation is planned, and hybrid system controllers will be evaluated where necessary.

Test results (Phase II)

Genset-plus-battery

Genset systems that charge batteries offer the opportunity of increasing system availability, while optimising running costs by limiting generator runtimes and maximising generator outputs.

Operating costs of generator plus battery systems are largely determined by runtimes and fuel consumption. In the longer term, however, generator maintenance and battery replacement costs could be more significant.

Energy costs, initially assumed to be relatively independent of load demand within the capabilities of the generator, are now considered fairly dependent on operating conditions

A difficult trade-off in design and operation arises from the conflict between optimal battery operating regimes and optimal diesel engine operating regimes. Empirical solutions are complicated by the uncertainties involved in generator and battery life-cycle curves, as well as the range of failure modes commonly encountered under different operating conditions.

Battery charger efficiency and mode of operation are fundamental to any design and optimisation. Some battery chargers interact unfavourably with the electrical alternator, resulting in systems that cannot recharge the battery.

Battery research and testing

The performance of seven generic battery types has been characterised using the methods developed in a prior EDRC battery testing project.

Battery operating regimes in renewable energy systems play the most significant role in determining how the battery will perform in the longer term.

Emphasis in battery testing has now shifted from short term characterisation tests to longer term cycling tests under the PV regime, and to ways of estimating battery lifetime.

Battery economics has been linked in this project to battery operating regimes and charge protection. Instead of encouraging the design of technically sound and reliably configured systems, economics shows the punitive costs of not taking relevant design precautions.

The technical and economic aspects of battery behaviour and selection have been included in the battery section of the RAPS Design Manual, as well as some step by step procedures for regulator set-point determination.

Using batteries that are not designed for the PV cycling regime is economically risky. The size and value the PV battery market in South Africa has been estimated, with a view to a locally developed specialist PV battery with stipulated cycle life guarantees.

The total market for PV batteries is about R15M/annum (compared with module sales of about R14M/annum). The market comprises one for new PV systems, and one for replacement batteries for older systems. By 1996, batteries in PV systems will be costing R22M/annum, of which 65% will be for replacement batteries. Within that battery market there are two main battery groups: i) heavy duty batteries, and ii) modified SLI batteries used in PV systems. Heavy duty batteries presently account for about R5M/annum in PV systems, while the balance of R10M is spent on lower cost modified SLI typically used in household lighting kits.

Regulator testing

Regulator behaviour and setpoints critically affect battery lifetimes. It is rarely possible for PV systems to operate for sustained periods without charge and discharge regulation.

Over-discharge protection is based most often on battery voltage. For effective battery protection the approximate discharge current must be known if load-shedding is to occur anywhere above 50% depth-of-discharge, since the cut-off voltage is a strong function of discharge current. Locally available load-shed units which respond only to battery voltage are ineffective in maintaining the desired battery maximum depth-of-discharge in shallow cycling regimes encountered in domestic PV systems.

A broad range of charge control philosophies are used. Some locally available regulators are not able to completely recharge batteries in PV systems. This is primarily due to a combination of high parasitic power consumption, charge algorithm and inappropriate charge set points.

No conclusions can at this stage be drawn about charge algorithms themselves, other than that linear charge algorithms would, logically, be more capable of reversing battery decay once it began to set in, while on-off regulators might exacerbate the problem. A great deal depends on the system configuration. Regulators that prevent overcharge most effectively do not necessarily recharge batteries more slowly than others.

Data from regulator testing is in the form of setpoint, power consumption and efficiency data published in the RAPS Design Manual.

Less precise and more subtle performance data from regulator recharge tests could substantiate literature data and provide the required confidence to use the data.

PV Module testing under natural conditions

PV module characteristics are the single largest determinant of PV system behaviour, for systems in which the load demand is known and well defined.

PV modules are specified within loose tolerances by suppliers, often ±10%. Modules are usually over-specified rather than under specified.

For three identical polycrystalline modules tested, output power ratings showed a 16% variability from module to module ($25W_p$ to $30W_p$ at $1000Wm^{-2}$ and NOCT). Open circuit voltage also varied significantly.

The characteristic IV scans taken hourly over the day for one of the modules were fitted to a mathematical model. The Rauschenbach model corresponded closely with other IV scans at different irradiances and panel temperatures taken during the day for that module.

The model highlights specific module characteristics, particularly the unusually strong positive effect of temperature on short circuit current.

PV systems performance testing

EDRC PV system performance test

Three identical PV systems were tested using the recommended EDRC PV System Performance Testing method. Four test runs were completed to gather statistical data on the accuracy of the method, yielding six sets of results for each system. The test procedure ran smoothly, without the catestophies that have plagued other institutions attempting the method, and the experimental outputs conceivably represent a best case set of data. Eighteen identical results were therefore expected.

The method yielded a very broad range of results, some of which were impossible as they implied higher module output power than the PV panels could possibly deliver. Other results were unbelievably low.

The standard deviation of the mean (for the array-to-load peak power) was 21% of the mean, suggesting poor accuracy. This level of accuracy is insufficient to distinguish between dissimilar PV systems under test.

A detailed error investigation was unable to pinpoint the source of the error, highlighting the practicality and complexity of the method. It seems probable, however, that cumulative inaccuracies in irradiance measurements are mainly to blame. It is unlikely that more accurate irradiance measurements could be taken without more sophisticated real-time integrating equipment.

In the existing procedure, irradiance inaccuracies in the depletion stage of the procedure are combined with variations in battery autonomy results to yield unstable output parameters.

One feature of the tests which were conducted was that the irradiation doses were significantly lower than the test method recommends, increasing these causes of inaccuracy.

Hardware based PV test

A hardware based PV systems test was developed, using an array IV model and programmable electronics to supply the array power to the system. This procedure provided excellent and very consistent results. The accuracy, but not consistency, of the results depends on being able to measure the array IV characteristics accurately.

The good results obtained by eliminating the array and irradiance measurements from the performance experiment itself implicated the irradiance measurements in the original depletion system test as a source of extreme uncertainty.

Paper-based evaluation method

A paper based method was also used to determine the array-to-load peak power, and was consistent with the hardware based test. This test was easy to perform. Other system configuration options using previously characterised components were easily investigated.

Recommendations

PV systems testing

EDRC PV system performance test

The EDRC PV systems test method does not easily provide reliable results. Certainly, if only one experimental run is performed due to time or cost constraints, the results will not be able to distinguish between similar but different systems.

Analysis of the data from the test is difficult.

The test procedure should be upgraded or modified, primarily to yield more reliable results.

Hardware based PV test

The hardware based system testing method is more reliable, and could be a practical alternative. The main weakness is a dependence on the array IV model, and accurate module IV data.

Using the hardware method introduces some errors, and this seems to be a trade-off, but in practice there are few advantages to using the EDRC method as it stands since it does not yield believable results in the tests performed.

Paper-based evaluation method

The paper-based method is most simple.

PV designers and suppliers should submit paper-based estimates of their system performance predictions when tendering systems for evaluation.

An on-site PV evaluation method should be developed and tested in the field for accuracy and reproducibility.

PV module testing under natural conditions

Further types of module should be evaluated on the test bench, and the array model should be validated with these different types of module.

More data is needed on variability between modules of the same make and model, because of the potential effect on system design.

More accurate irradiance measuring equipment may be required for module testing. Accurate IV data would also greatly assist PV systems testing.

Regulator testing

Accurate regulator characterisation is necessary, but regulator performance depends primarily on battery behaviour, which is variable from battery to battery and with age.

An open analytical approach to regulator selection should be tabled, which allows logical use of background knowledge and available regulator and battery data to determine suitability of particular combinations, because it is uneconomical to test every regulator / battery pair.

Battery research and testing

New battery cycling tests could provide immediately useful design data on battery loss of capacity. Battery testing could provide for variations in battery behaviour caused by different regulator designs.

Battery cycling data could be used directly in paper-based PV systems tests or design to indicate the sensitivity of system design and performance to battery aging and wear.

Local development of a specialist PV cycling battery with cycle-life guarantees should be considered. A successful battery could capture a large share of the R15M/annum presently spent on PV batteries, easily covering R&D costs.

Genset plus battery

Battery chargers should be tested and evaluated in terms of the generic designs and input/output characteristics.

Charger conversion efficiencies should be investigated. The interaction between limited power source alternators and certain battery chargers should be investigated.

Outputs

Main outputs from this project were:

- RAPS Manual Chapters Volume 1
  - Batteries
  - Regulators
  - Power conditioners

- RAPS Manual Resource Data, Volume 2
  - Battery data
  - Regulator data
  - Inverter data

List of all components tested

BATTERIES
(charge/discharge curves and cycling tests, and some costing estimates in PV applications)

Chloride FCP	(flat plate, standby)
Chloride 4DCLA	(heavy tubular)
Delco 2000	(similar to Delco 1250)
GNB Mini Absolyte	12V5000
GNB Power Breed	(similar to Delco 2000)
Raylite RR2	(leisure pack)
Raylite RMT 108	(tubular)
Varta Solar	(small)
Willard 774	
Willard LS90	(UPS type)

REGULATORS
(mainly 12V, less than 20A.)

BP Solar	BPRS
	BPR1
Helios	MX2
	NG15
KG Electric	BCC12S160
	and temperature compensated vesion
National Luna	Universal
PDI	boost/float
	float
Shekida	
Siemens	SR11
Technipower	TP1
	SS3

INVERTERS
(Inverters are mainly 12Vdc, and under 400VA. Tests include efficiency under various conditions, wave forms, distortion and some EMI tests.)

Compu-power	sine wave
Electrobat	quasi-square
Elfa-Tronic	quasi-square
KG Electric	quasi-square (old model)
	quasi-square (new model)
Lit-Tronics	square
MLT Drives	sine wave
Power-Star	quasi-square
Technipower	quasi-square

PETROL GENERATOR

Maxlite	petrol engine with car alternator charging car battery.

ACKNOWLEDGEMENTS

This phase of the EDRC RAPS research programme would not have been possible without the long-term support and funding provided by the Energy for Development Division of the Energy Branch, Department of Mineral and Energy Affairs (formerly the National Energy Council).

The following companies provided equipment and feedback and are thanked for their participation:

Compupower

Helios

Messina

MLT

Technipower

KG Electric

BP Solar

National Luna

Siemens

Shekida

PDI

BP Solar

KG Electric

Technipower

Willard

FNB

Chloride/Raylite

Optitron, Battery Division

Varta

Delco

Sabat

Dan Price of Compupower is thanked for providing facilities for EMI testing of inverters and for generously giving his time when needed.

Stephen Schrire gave invaluable electronic design advice, while staff of the Department of Electrical Engineering, University of Cape Town, gave their time and provided loans of test equipment when required.

Many thanks to Bill Cowan, our project leader, for his contributions and support. Thanks too, to Mark Borchers and Glynn Morris, my colleagues in the RAPS team, and to all at EDRC for their ongoing cooperation and help.

PROJECT LEADER'S NOTE:

The text of this draft report, and the conclusions, have not been materially altered by the project leader, although there are certain areas of dispute about the presentation and interpretation of experimental results. In scientific research, there is value in open assessment of disagreements and critical enquiry. Attention is drawn, in particular, to the experimental results and conclusions provided in Chapter 5 of this report ("PV System Testing"). Some reservations about the validity of the experimental procedures are outlined in Appendix A.

CHAPTER 1
INTRODUCTION

Solar photovoltaic (PV) electric systems are a feasible energy supply option for areas remote from the grid, where they are increasingly being used for electrification of community facilities such as clinics and schools, rural telecommunications, trading stores and for domestic use. As this technology matures, PV systems are displacing the more conventional diesel generator technologies as institutions and users realise that it is in many cases simpler, more reliable and more economic.

Recently ESKOM, the sole licensed electricity generation agency in South Africa, acknowledged the place of PV in the generation market by introducing its 'R-tariff' structure, specifically aimed at users for whom grid extension is not an option, but whose needs could be met by PV or PV-hybrid systems. ESKOM's realisation that their slogan 'Electricity for All' cannot be realised by grid extension alone, has opened the way for large institutional involvement in PV systems.

The Independent Development Trust (IDT) has recently embarked on a major programme to upgrade rural health services. One aspect will be the installation or upgrading of the electricity supply at up to 400 clinics by using PV systems for vaccine refrigeration, lighting and clinic staff needs.

PV systems will also play an important role in meeting basic electrical energy needs in urban formal and informal areas in Southern Africa where demand for electricity is low, or where the rate of electrification is slow or unlikely to occur. PV systems offer users access to basic electricity within days of acquiring the necessary equipment. In this sense PV generation can be described as an 'off-the-shelf' technology, and an abundance of small distributors are marketing pre-designed 'household lighting kits' to this sector.

EDRC staff have been at the forefront of research into PV systems in South Africa since 1986 when they began monitoring existing PV systems and documenting problem areas.

This research expanded into a three-year programme with three researchers addressing the outstanding technical questions limiting the widespread use of PV technology.

User perception has played an important role. PV systems have frequently failed to meet expected load demand at the advertised cost. System reliability has been disappointing due to systems being undersized, or to components decaying and losing capacity over time so that they no longer deliver the design power output. Suspect design philosophies have led to the installation of systems with ill-advised battery operating/cycling regimes. Battery life has been shorter than expected, resulting in increased operating costs to the user. Poor quality of installation, and the use of inappropriate components has also lead to failure of key components.

EDRC's research work has addressed these issues by examining in detail:

- system sizing, simulation and life cycle costing;
- component choice, component life;
- system specification and testing,

and disseminating this information to institutions, users and designers.

This report is primarily concerned with the component characterisation and testing programme.

1.1 Component testing project

The main components in a PV system are the PV array, storage battery, voltage regulator for battery charge/discharge protection, and optional DC/AC inverter.

The aims of component testing were:

- to provide design data in a format useful for PV system designers;
- to provide data and technical in-house support for parallel EDRC research projects concerned with PV systems;
- to test locally available components, and to provide feedback to the industry

Batteries

The first task was to address the complex and little understood problems of battery performance in PV systems. A comprehensive literature review was conducted, a laboratory test facility was set up, testing methods were developed and locally available batteries tested and characterised. The initial work was invaluable and provided essential feedback and data to subsequent research projects. The battery testing project is summarised in chapter 2, and the most recent work is described in detail.

Work has focused on charge and discharge curves, charging efficiency, capacity loss, suitability of generic battery types for use in PV operating regimes, battery lifetime expectancy and battery economics. Battery decay, and the design implications of this for component selection have been the subject of the most recent work.

Regulators

Regulators define the operating regimes in which batteries operate, and the regulator testing project was informed by previous experience in battery testing.

Locally available regulators were tested, electrically characterised, and charge set-points and loadshed set-points were recorded. Temperature compensation was also noted. Regulator power consumption was also tested under various operationing conditions, and the mode of regulation or control algorithm noted, so that regulators could be generically grouped.

Test methods and a test-facility were established for cycling the regulators under simulated PV regimes to check performance implications.

Most recent regulator testing work is documented in chapter 3.

Inverters and power conditioners.

Many users of small PV systems have some requirement for AC power use, and need DC/AC inverters to generate that power from the DC battery bank.

An accurate inverter test facility was set up for capturing inverter waveforms and determining the true efficiency, harmonic distortion and power factor under a range of load power and battery input voltages. Real loads were also tested. Inverter standby consumption and battery protection cut-off voltages were measured.

In this project cycle, electromagnetic interference tests were conducted. These are attached in appendix 1.

Module testing

PV module output specifications are often supplied by manufacturers with a 10% tolerance, and outputs are usually optimistic. Uncritical acceptance of these specifications by designers can result in undersized systems.

A facility for testing modules under natural conditions has been set up at EDRC. This facility enables automatic scanning of the module IV characteristics at regular intervals throughout the day, and subsequent processing of the data to provide performance prediction under any conditions. Spectral composition of the light is not analyzed at this stage.

PV module testing is documented in chapter 4.

1.2 PV systems testing

Component testing is very useful for understanding detailed behaviour of subsystems of the PV system, and data generated is therefore useful at a detailed design level and for drawing up PV system tender specifications. It is also a convenient way of assessing PV system design.

Institutions involved in funding large scale PV projects, or bodies involved in tender adjudication have a requirement for some guarantee of performance to specification, but do not have the resources for detailed data analysis.

PV systems qualification or performance tests can potentially specify the performance of tested systems. EDRC has conceptualised a PV System Performance Test for use by these institutions.

Performing these tests, however, involves considerable expertise in experimentation and analysis, and is a challenging practical problem.

The full EDRC test method has been performed, analyzed and discussed to isolate possible problem areas, and to gather data on the statistical validity of results (Chapter 5).

Two shorter, abridged methods have also been developed with the intention of achieving the same results in a more practical way with greater experimental certainty. Both draw on experience in component testing. The first method requires testing of the PV module, and then a cycling test of the regulator and battery using laboratory equipment. The second method is purely paper based, and draws heavily on component test data. These methods and results are discussed in Chapters 6 and 7.

Component testing has been used to inform PV systems testing, and the accumulated experience in testing and experimentation has resulted in a set of best-case system testing results.

1.3 Other technical information and backup

A final objective of component testing was to provide support at a technical level for future explorative work into hybrid system design and sizing.

Diesel generators have been used for many years to provide power on farms. A genset plus storage battery system is potentially a much more efficient system, reducing both generator runtimes and fuel efficiency, so that the additional cost of storage batteries can be justified.

Chapter 9 discusses some technical considerations of genset-plus-battery systems, drawing particularly on experience in battery operation and charge regimes. This chapter is an example of cross pollination of ideas and transfer of the knowledge gained by analysis and testing at the detailed component level to the testing and analysis of systems.

Future work is likely to focus on hybrid system components, hybrid system control philosophies and some testing of subsystems. Batteries will remain an important area of focus.

1.4 Outputs

Component research work has often been inaccessible to system designers, even though suppliers have found component data useful.

The primary objective for this project cycle has been to make this data and research knowledge more accessible. The EDRC RAPS Design Manual has provided an effective medium for communicating this information, along with other design information from parallel EDRC research projects.

The RAPS Design Manual presents significant background information on the individual components, as well as design data and step-by-step procedures on how to use component data.

Future research work will be styled into the RAPS Design Manual format, which will make it immediately accessible and useful.

CHAPTER 2
BATTERY RESEARCH AND TESTING

Batteries are the heart of almost all renewable energy systems, which are characterised by inconsistent or unpredictable resource availability making energy storage a necessity rather than an option. Batteries are also used for load levelling in more conventional energy systems, yet they remain the least understood of the components commonly used. In fact, batteries are often cited as the weakest link in remote energy generation systems. EDRC's multi-year battery research project has debunked some of the myths about batteries, and has constructively suggested ways to improve battery performance and life expectancies in renewable energy systems.

2.1 Introduction

The research project began in 1986, in parallel with concerted work on PV system sizing, to investigate battery performance in stand-alone PV systems.

Literature review

A very substantial literature review on lead acid batteries in general was completed, as well as a detailed scan of information regarding PV system failure and battery failure in PV systems. Very little detailed work on battery performance in PV systems was found. However, it was clear that international research resources were beginning to focus on problems related to batteries in PV systems.

The literature review served as the foundation for understanding the complex electrochemistry of lead-acid batteries, and also provided a foundation for the formulation of the research project. Since literature on PV battery performance was not widely available, detailed research work was justified.

Planning

The initial phase identified <u>batteries and battery regulators</u> as the primary areas in need of attention in PV systems. Problems associated with batteries in PV systems were identified as:

- battery life in PV systems is far shorter than expected;
- selection of inappropriate battery types;
- use of inappropriate charge and discharge regulators, or settings are chosen that do not correspond with the selected battery type;
- battery temperature regimes in operation are substantially different from specifications, leading to sharply reduced battery life;
- battery failure is often caused by regulator failure, and regulator failure can lead to battery failure (depending on regulator design).

Most of the problems above were due to insufficient battery data being available, insufficient understanding of battery data or insufficient understanding of battery behaviour in general and in PV systems in particular.

This project set out to collect relevant data on locally available batteries likely to be used in PV systems.

Some published data was available, but in most cases battery testing was required.

Test-rig

A computer controlled battery test-rig was designed, built and commissioned in-house to automatically control and record battery bank behaviour while cycling through relevant charge/discharge regimes.

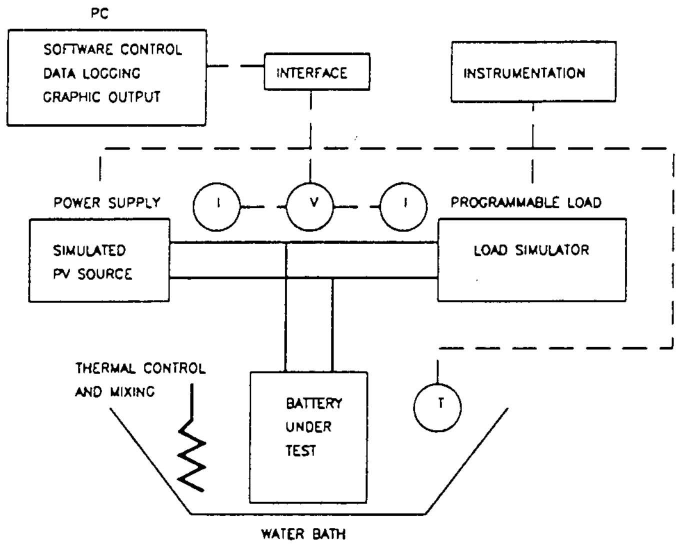


Figure 2.1 Battery test-rig

Suite of test methods

Standard test methods were reviewed, some discarded as unsuitable for the type of outputs required, though standard capacity and discharge tests were retained. Some cycling test methods were adopted from recent research literature. Innovative methods were also developed for rapidly obtaining battery charge curves for low rates typical of PV charge regimes. Electrical, electrochemical and physical methods were used to assess instantaneous battery charge efficiency, as opposed to average charge efficiency over a full charge cycle.

Testing of seven generic types

Seven generic lead-acid battery types were identified and tested using the standard suite of methods. This data was used for understanding the differing requirements during PV operation of the generic battery types. Some designs were identified as totally unsuitable for PV usage, and the weaknesses and strengths of the different types were recorded. Testing was backed up by research literature where available.

Data on local batteries

Data for locally available batteries tested at EDRC was published in a form considered suitable for PV system designers. This data filled an important resource gap, and local suppliers supported the project by providing batteries for analysis.

PV battery operating regimes

The literature review data, testing of generic battery types and data for locally available batteries was combined with accumulated technical expertise on electrical behaviour of PV systems and charge regulators to establish a set of typical battery operating regimes for several categories of PV systems. These operating regimes were mated (matched) with operating requirements for generic battery types to establish best choice batteries for the specific PV categories.

Conclusions of Phase I

The first phase of the project resulted in considerable accumulated expertise, knowledge and data, but of a research standard rather than a format suitable for PV designers or users without years of technical training.

The second phase of the project was to continue with the important research work, but primarily to make this data accessible. The channel for this was the EDRC/NEC Remote Area Power Supply Design Manual.

This work is detailed below.

2.2 Ongoing research work

Battery research in the second phase of the project has changed direction from a narrower battery technology perspective to a broader and more practical perspective suitable for PV system evaluation and design method support. Work has focused on ways to use the battery data generated, rather than on generating more data itself or researching in more detail. (Larger international research bodies have now fully taken up the challenge of detailed battery research for PV systems and are more suited to doing that work.) However, a background in battery behaviour is a strong base for developing iterative engineering type methods for checking PV system designs.

A simplified iterative procedure for PV system design might be as follows:

(suggested design process after load assessment)

1. Rough system sizing, yielding array and battery size (with assumed array-to-load path efficiency,Kp).
2. Component choice (use RAPS design procedures).
3. System evaluation / design assessment (determination of Kp to check practicalities of component choice and component matching)
4. check Kp against assumption in step 1. If Kp is lower, then redo step 1.
5. Check effect of decayed components on system performance, and on the load that can be supported, using system evaluation/design assessment method.

Use of battery data

Battery data has been identified as the most uncertain of all component data, as well as the most likely to vary considerably over the component life. (Other major components are the regulator, array and inverter.)

Battery choice

A good understanding of battery literature and operating regimes enables designers to make reasonable battery choices. Comparative data on the economics of different battery types facilitates cost-effective decisions. Considerable time and effort has gone toward generating decision tables for battery choice.

(Tables 2.1 'Battery economics' and Table 2.2 'Summary of battery selection and operating criteria' in Batteries, p53-65, RAPS Design Manual)

Design

During the PV system design phase, experimental data should and can readily be used to:

- facilitate component matching
- establish regulator charge and loadshed settings.

Procedures for checking these and other critical values have been established and are explicitly documented ('Battery design steps' in Batteries, p64-69, RAPS Design Manual).

Assessment and system testing

In assessing PV system designs, battery data is required to determine energy efficiencies and array operating points.

As part of the process of integrating the component and systems evaluation approaches, a paper-based system evaluation or design assessment method has been proposed that uses published component data to produce a result similar to experimental system evaluation methods. The paper-based method is covered by an example in detail in chapter 7. PV system evaluation methods are the subject of discussion in chapters 5, 6, and 7 of this report.

The proposed iterative technical procedure for system design mentioned earlier as an example should preferably use the quick paper-based PV evaluation method. Full scale testing would preferably use the monitoring or laboratory type testing approach.

Performance data for batteries that have been in PV systems for prolonged periods is now becoming available. This forms a useful database for assessing potential loss in system availability, which is possible where battery characteristics have changed as the battery 'settles' into the system. Data such as this can be used easily in conjunction with the paper-based PV evaluation methods.

New experimental methods

Some new experimental methods have been proposed for analysis of batteries after PV cycling.

Batteries in PV systems tend to lose capacity if not fully charged, particularly during the first few months, but the usable capacity may settle to a stable value for some time thereafter. To cater for the effect of battery decay, one design approach is simply to increase the battery in the system, but this can exacerbate the undercharging problem.

Designers need battery decay data for trouble-shooting, for design analysis and for checking system availability under these conditions. Designers need to know how much and how fast batteries settle into the system.

There are three main sources of this data:

- Field data
- Monitoring data
- Laboratory data

Field data

Field data is difficult to evaluate since the history of the battery is never well known.

In one evaluation a nominally 100Ah Sonnenschein 12V battery remarkably produced only 17Ah (to 11.5V at 10A) immediately after being removed from the PV system. The battery was supposedly at full charge according the boost/float indicator on the battery charge regulator. (The battery charge regulator was subsequently tested in the laboratory and found to be in perfect order!) Subsequent cycling (recharging at 10A, 14.4V and discharging as before) showed that the capacity was recoverable to 75Ah. PV systems seem to be very non-ideal battery environments unless <u>all the necessary design precautions</u> are taken!

Table 2.3 Batteries in PV systems can reversibly degrade to such an extent that only boost charging by an external charger can reverse the decay. The number of Ah that can be returned to the battery are adversely affected by the onset of degradation, and recharge rates are slowly improved by equalisation charging.

CYCLE	DISCHARGE CAPACITY (AH REMOVED AT 10A TO 11.5V)	AH RETURNED (10A LIMIT, 14.2V LIMIT, 17HOUR LIMIT)
1	17	49
2	48	60
3	60	68
4	68	76
5	78	86
6	76	88
7	75	87
after 4 day float charge	75	

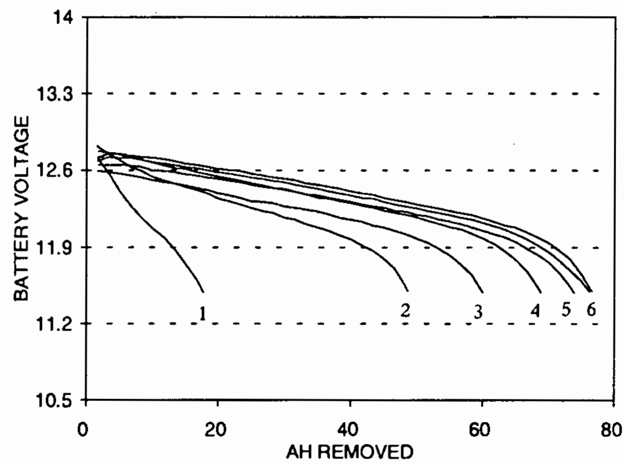


FIGURE 2.2 Discharge curves for consecutive cycles during prolonged overcharge cycling of the batteries after removal from PV system. The numbers illustrating the recoverable battery capacity after each cycle.

Other batteries removed from PV systems for evaluation showed 30% loss of usable capacity, which was completely recoverable. Some batteries (lead-calcium types mainly) are not recoverable by more than 5%, implying irreversible damage.

Monitoring of systems

Monitoring of systems is very expensive and notoriously unreliable, but can under some circumstances yield useful results.

The PV system performance test in chapter 7 is probably of too short duration and too few charge/discharge cycles to provide battery cycle data of immediate use.

Laboratory testing

A laboratory based simple charge/discharge procedure has been added to the suite of battery test methods developed in phase I. This cycling test, unlike tests developed internationally, includes the battery charge regulator effect to allow the battery to settle realistically and quickly, yet under laboratory conditions. In the charge regulator chapter, the ability of the regulator to maintain the battery in good condition by equalise charging is discussed in more detail. This seems to be related to regulator algorithm and to the setpoints.

In the new test the battery is discharged till a loadshed voltage, then recharged at a low current until a cut-out voltage. The cycle is repeated and the load capacity monitored. Loss in capacity is due to electrolyte stratification, lack of equalisation charge and inadequate overcharge: all characteristics of real PV systems.

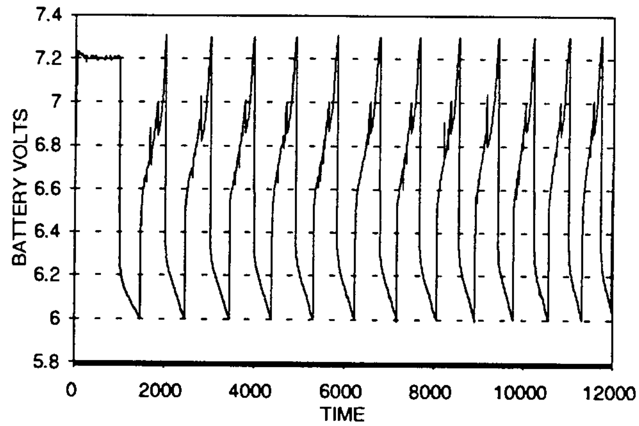


Figure 2.3 New cycle test

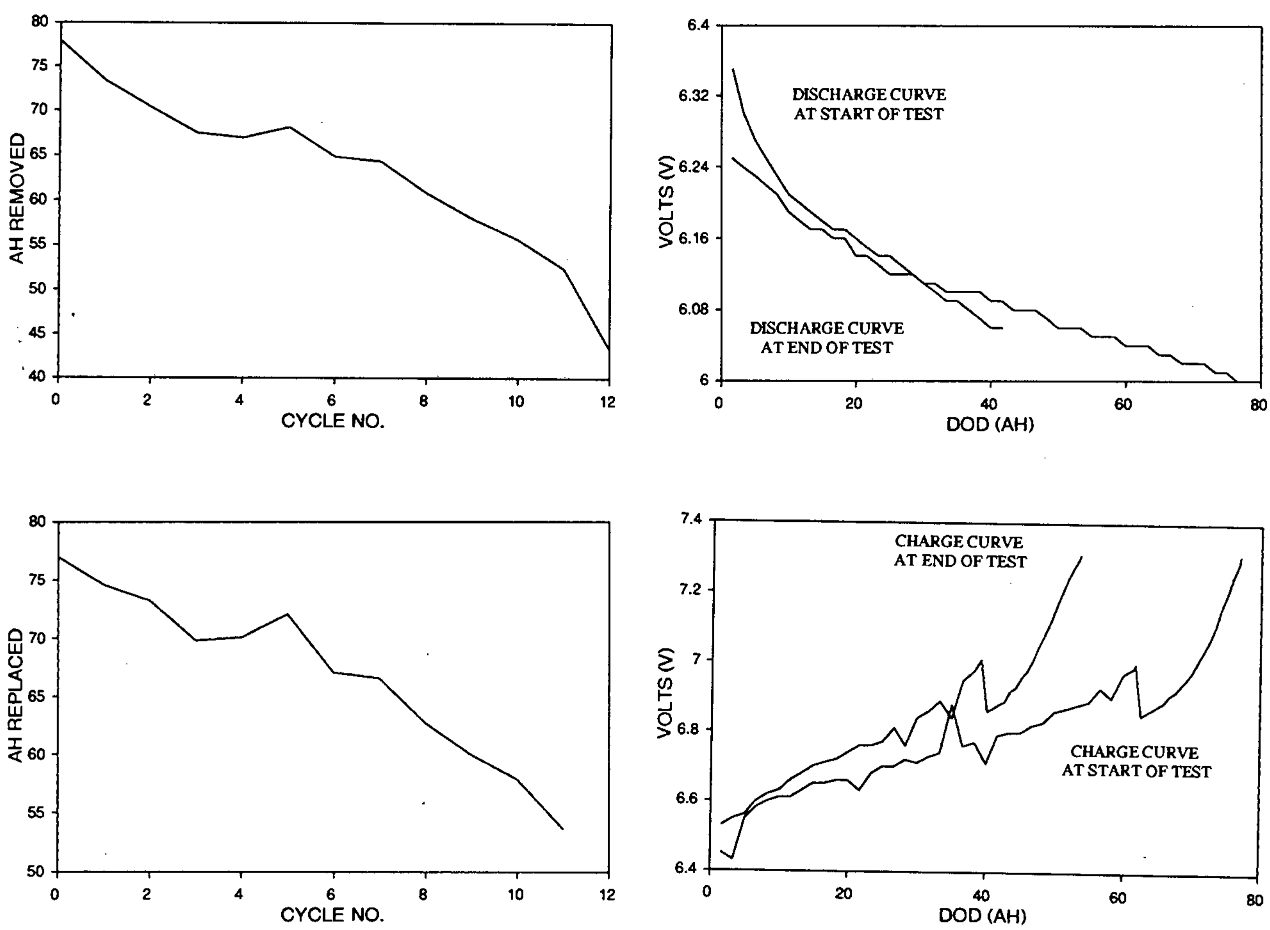


Figure 2.4 FCP cycle test results

This charge/discharge degradation trend can be used directly in the paper-based PV evaluation method in chapter 7.

Hybrid systems

Hybrid energy systems are the logical extension to PV system work, and EDRC has committed itself to addressing some of the key issues.

Typical hybrid system configurations would probably include either a wind or PV renewable generator backed up by diesel generators. Obviously analysis of these systems can become complex, and research has addressed the simpler issues first. The most basic configuration is a diesel generator with load levelling battery storage, and this is the fundamental building block for hybrid system design.

Practical considerations for genset-plus battery-systems are discussed in chapter 9, which explores the central role that batteries play in design and operating decisions. The experience gained informs trade-off decisions involving genset motor or battery life optimisation.

Battery research is likely to be central to future hybrid system design work, as it involves system sizing, component choice, operating characteristics as well as various subtle performance trade-off or compromise decisions.

2.3 Outputs

RAPS Design Manual battery chapter

The comprehensive research work on battery performance accomplished in phase one of the project was considered inaccessible to users interested in solving practical problems themselves. The decision by EDRC to publish a RAPS Design Manual offered an ideal opportunity to disseminate the results of the battery work in a form that was more palatable, and also to emphasise to system designers the critical importance of carefully considering all aspects of battery behaviour when selecting a battery and designing the operating regime and battery protection in a stand-alone PV system.

Careful economic analysis of performance of battery types was conducted. Economic performance depends mainly on initial battery cost and reasonably expected battery life under PV operating regimes. Simple technical procedures were developed to ensure that the expected battery performance could be attained; by providing adequate charge and discharge protection, avoiding certain operating regimes for particular generic battery types and compensating for these effects.

The battery chapter is a small, but not insignificant, part of this comprehensive and well written document. The RAPS Manual will be periodically updated with the latest research work, including hybrid design sections. The Manual incorporates a Resource File containing test results for locally available batteries and PV related components.

2.4 THE FUTURE, THE PV BATTERY MARKET AND LOCALLY PRODUCED SPECIALIST BATTERIES.

The problems with batteries are well known. As they are a recurring source of uncertainty and a problem area in PV system design, would it be appropriate to design a new battery suited to PV operating regimes?

Lead-acid battery technology is sufficiently mature and developed for suitable batteries to be designed. International manufacturers are already marketing specialist PV batteries, but these are imported and expensive, and are best suited to larger installations only.

There are some key questions to be answered. Is there a market for affordable locally produced batteries tolerant of PV operating regimes? Can the market support the research and tooling requirements for a new battery design?

A possible market scenario is outlined below.

BACKGROUND

Photovoltaics offer an elegant, environmentally clean and cost-effective solution for meeting basic electrical energy requirements for areas remote from the main electrical grid. In developing regions photovoltaics compete with other generation technologies to provide energy for:

- telecommunications and repeater stations;
- remote clinics, mainly for cold chain refrigeration, task lighting and radio communication, but increasingly for staff use as well;
- remote schools, chiefly for educational television and lighting, but also for staff use;
- remote farms, for complete domestic electrical needs, often in conjunction with diesel generators;
- domestic use, mainly for essential lights and television. Often these users may not be located in areas remote from the grid, but their demand for high quality energy is low;
- water pumping, where PV is increasingly maturing as a reliable option.

PV can meet specific development energy needs in remote areas. Initially, most PV installations in South and southern Africa were telecommunications applications, but with increasing developmental concerns, the main growth areas have shifted to domestic users, and institutional programmes aimed at upgrading community facilities such as schools, clinics and access to potable water.

Battery problems

Almost all PV systems require some form of energy storage, usually in the form of chemical batteries, to ensure reliable system operation during inclement weather or to meet high energy demand. (The exception is for water pumping, although current trends incorporate some battery storage.)

Batteries have long been identified as a problem area in PV systems, together with the battery charge controller. Lead-acid batteries are currently the only viable technology. Battery selection is difficult:

- as it requires an intimate understanding of battery behaviour;

- there are many generic types of lead-acid battery, many of which are unsuitable for PV operation as they have been designed primarily for other applications. Many batteries will fail catastrophically in certain PV operating conditions; and
- batteries that fail prematurely require replacement and this drives up the cost of PV energy.

Battery costs in systems, including battery replacements

Batteries comprise a significant portion of PV system costs. Typically, they may make up 35% of capital costs, while routine or planned battery replacements may contribute over 80% of running costs of the system, as illustrated in the pie charts below. Unplanned battery replacements can reduce the feasibility of PV technology.

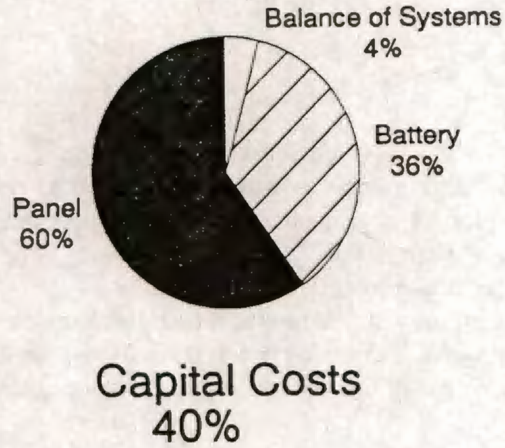


Figure 2.5 Capital costs

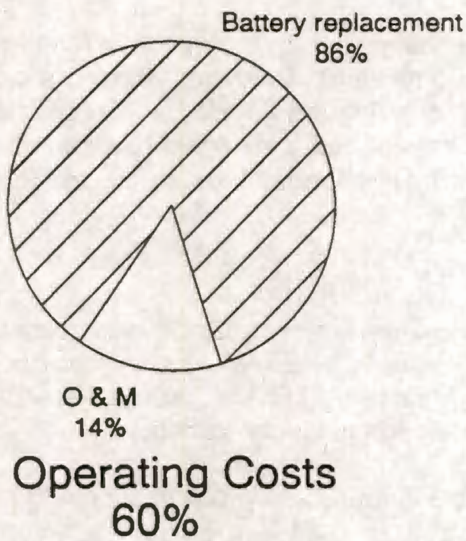


Figure 2.6 Operating costs

Specialist batteries for PV systems have been developed. Most of these are imported, high cost but long life batteries offering good value for money over the life of the PV system. Generally these are considered only for larger installations such as telecommunication or large domestic users. Smaller energy users tend to select batteries based on lowest cost, often choosing multi-purpose or modified car batteries which are not always a cost-effective choice when amortised over the life of the PV system.

This review aims to assess the potential demand for locally manufactured batteries suitable for small PV systems. This is a response to enquiries from manufacturers, as well as to an established need for suitable low cost batteries.

MARKET POTENTIAL FOR PV

The assessment of the PV battery market is based on current PV installations and a projected growth in number of installations. Replacement batteries are also considered.

Existing

According to present South African customs and excise statistics for the importation of PV modules, the present installed capacity in South Africa may be about 2.7MWp. Informed industry sources estimate annual sales at about 0.7MWp per annum.

Growth points

In 1980 approximately 80% of installed PV capacity was servicing telecommunications and military or police applications. This amounted to about 0.5MWp, although most of this capacity was in large installations. Although the market for large installations is probably saturated, current growth centres around a network of PV powered radio phones covering most rural areas. The installed capacity for telecom will be about 1.14MWp by 1996.

1980 also a developing demand for PV energy systems suitable for farms, and several systems were installed in the 1kWp size range as the technology become commercially viable. The market for farm systems is limited by the number of farms remote from the electricity grid, and after a consistent growth period it is estimated that this market is nearly saturated at about 150kWp.

By 1990, about 150 clinics in South Africa used PV for lighting and refrigeration, and a present initiative could see a further three or four hundred rural clinics supplied with PV power over the next few years. These systems will probably be larger than the original installations in order to cater for staff as well as clinic energy needs. The total market will foreseeably grow to about 150kWp.

More than 300 secondary schools in South Africa use PV systems to power educational television and video. Depending on the success of the clinics upgrading project, it is possible that a national initiative could see several hundred more schools connected to PV supply. Once again staff needs are likely to be emphasised.

PV water pumping is a relatively new and developing field showing excellent promise and reliability over current technologies. The sudden demand for these systems indicates that by 1996 about 750kWp could be installed for pumping. This figure could well be an under-estimate.

The small domestic PV market opened between 1980 and 1985, and in terms of volume this market has the greatest growth potential and could have the most significant effect on any total projections. Current estimates produced by surveys vary from 30 000 to 60 000 domestic systems already installed. Probably 30 000 systems of 50Wp size is a fair estimate that corresponds to data from other sources, giving a present installed domestic capacity of 1.25MWp. The probable growth in this market is about 0.5MWp per annum.

Figure 2.7 shows the estimates of the growth in installed capacity by user type, and Figure 2.8 shows the change in type of user as the technology matures.

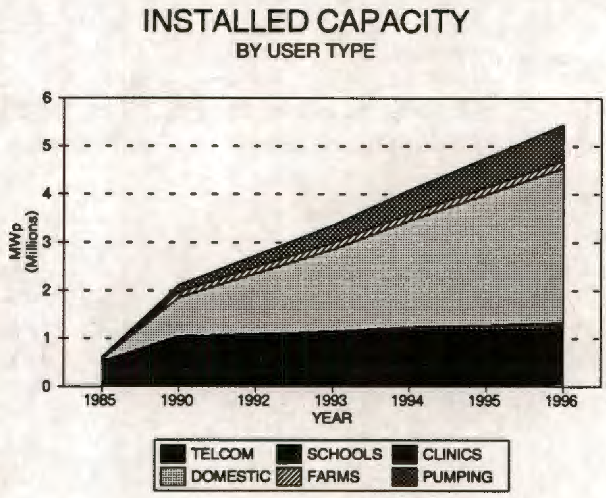


Figure 2.7 Total MWp installed.

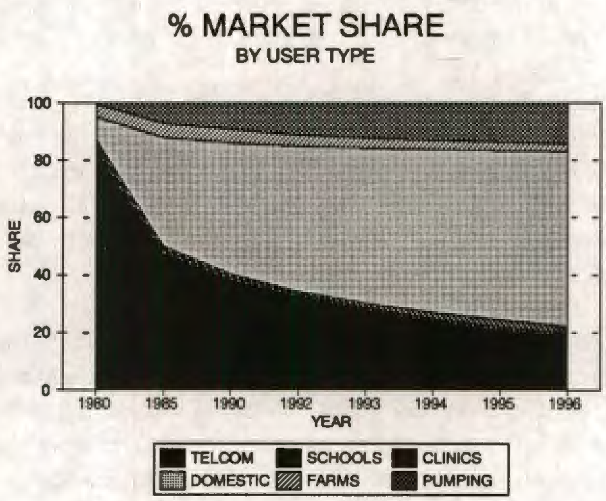


Figure 2.8 Market share.

BATTERY MARKET

The main aim of this exercise is to estimate the potential value of the market for batteries for PV systems.

Crude estimates based on installation costs

For estimated annual module sales of 7kWp per annum, the value of the modules (at R20/Wp) is R14M. Figure 2.5 suggests that this R14M is 60% of the total capital cost, and the battery market, which is 35% of the capital cost, would work out at about R8M per annum. The PV system market (including balance of system components, but excluding installation costs) is about R23M.

The R8M refers only to batteries for newly installed systems, and does not reflect the substantial market for replacement batteries. This crude calculation also does not allow for differentiation between specialist PV batteries, which can last for eight years, and modified car type batteries which last for only a few years.

Two different battery markets

Two essentially different PV battery markets exist side by side. A market for large, heavy-duty, long-life but high capital cost batteries is limited to PV installations of over 300Wp. This market is well catered for by existing battery designs, both by locally manufactured tubular and flat plate designs and imported exotic types. The main growth market is for small PV systems for domestic use, for small telecom/radio transmitters, and small clinics. Most of these would conceivably use small less expensive batteries with considerably reduced life expectancy. Although indications are that these lower cost batteries are not necessarily cost-effective over the life of the PV system, the trend has been for these batteries to be selected in the design stage.

By making assumptions about the sizes of systems likely to be installed in future for the different types of end users, it is possible to get a better handle of the two battery markets. Figure 2.9 shows aggregated estimates for system sizes in the future. Most new systems will be less than 200Wp in size.

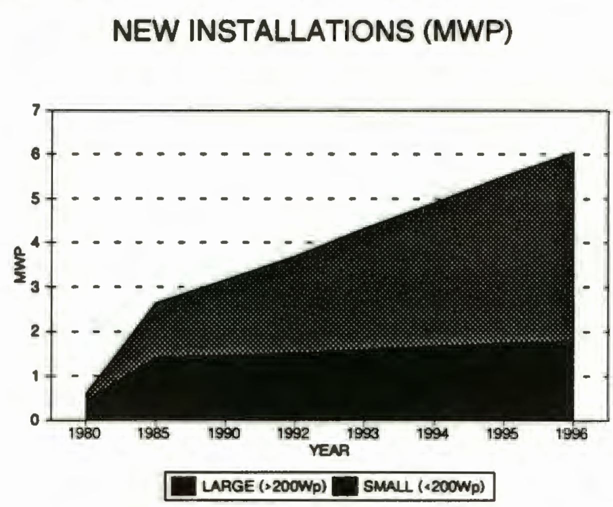


Figure 2.9 Size of PV systems

The total value of the battery market can be estimated by assuming that large batteries will last up to six years, and that the modified car batteries will optimistically last three years in PV systems. Using a 100Ah 12V battery as a unit size, the estimated market for heavy duty batteries is about 7500 units in 1992, stabilising at about 9000 units by 1996. The market for small batteries is about 42 000 units, rising to about 65 000 units per annum in 1996. The replacement market will be about 50 000 units per anum in 1996.

The split between new and replacement batteries is shown in figures 2.10 and 2.11.

SPECIAL PV BATTERIES DEMAND

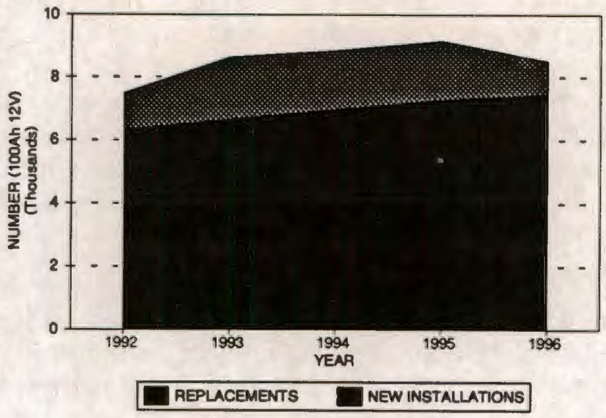


Figure 2.10 Number of 100Ah 12V units

CHEAP CAR/PV BATTERIES DEMAND

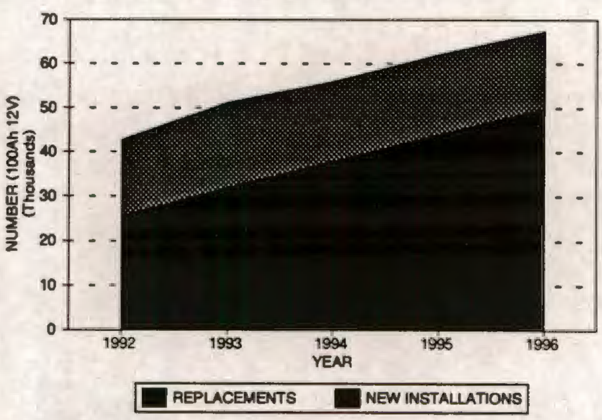


Figure 2.11 Number of 100Ah 12V modified car battery units

The total value of the PV battery market is about R15M in 1992, rising to R22M in 1996. The major growth will be about R17M/annum for the small batteries.

PV BATTERY MARKET VALUE

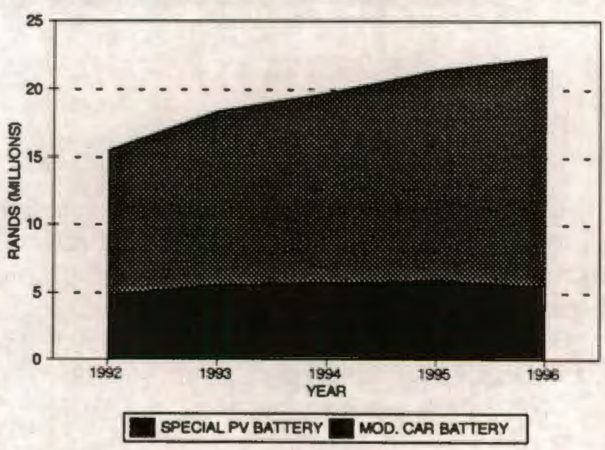


Figure 2.12 Value of the South African PV battery market. (Estimates are based on the following costs: modified SLI battery @ R250/100Ah 12V block, tubular design @ R640/100Ah 12V block)

CONCLUSIONS

Substantial opportunities exist for supplying batteries to the PV industry. The value of this battery component presently equals the value of the module sales themselves (around R14M per annum).

The market is probably also ripe for a locally designed, manufactured (and exported?) modified SLI battery better suited to PV operating regimes than those currently available. There are several obvious modifications that could improve battery performance and ensure more predictable battery life.

Manufacturers would have to consider the design and tooling costs, as well as ensuring that good distribution networks are in place to enable (particularly domestic) users to have access to these batteries for new systems and for replacement needs.

The logistics and gains from developing and marketing the new battery would have to be considered against the competition from the existing, established multiple-use batteries (Raylite RR2 and Willard 774, for instance).

Finally, suppliers should consider the effect on the PV battery market if a new battery were introduced (at comparable cost to existing modified SLI designs but offering a guaranteed longer life). This initial assessment indicates that by introducing longer life batteries, suppliers would be decreasing the size and value of the important battery replacement market.

However, it could be strongly argued that any improvements in battery design (without substantial cost increases) will appropriately address the main problem areas in PV systems. This is likely to improve perceptions about PV system reliability, probably expanding the PV market (and certainly making it a more attractive investment option to large-scale funding bodies). The previous graphs and discussion have already clearly shown that the demand for replacement batteries is very significant in value (65% by value of the total battery market). Any increase in the total PV market increases the demand for battery replacement, which remains a recurring cost and a recurring source of profit for the battery industry; but only if the products are suitable. This is a critical stage for the local battery industry.

CHAPTER 3

REGULATOR TESTING (PHASE II)

3.1 Background

In RAPS systems, the battery regulator provides the electrical interface between the battery and the rest of the system.

The regulator and battery are widely acknowledged to be the main causes of failure of PV systems. Regulator failure is likely to cause battery failure.

The regulator settings define boundaries to the battery operating and cycling regimes, which have a deterministic effect on battery life expectancies. Different generic battery types have different requirements for operating regimes, so incorrect regulator settings for top-of-charge and loadshed may well cause battery failure.

In PV systems operation, regulator losses can play a very significant role in reducing system efficiency, which can lead to unnecessarily high energy costs. Regulator losses, particularly voltage losses, can result in poor component matching between array and battery if not properly accounted for, resulting in systems that underperform radically.

Regulator data can play a significant role towards reversing some of these catastrophic effects caused by design errors.

More importantly, certain types of regulator do not always allow the battery to reach full charge, and certainly do not boost-charge or equalise the battery. This can be a real problem when the batteries are beginning to degrade and accept charge less readily under regulated charging conditions. The recharge and battery conditioning problem is related to regulator setpoints and algorithms. This raises more philosophical questions about methods of control and battery optimisation in hybrid RAPS systems.

EDRC has set up facilities for regulator characterisation. The facilities and testing requirements have been informed by the battery testing project.

3.2 Testing

Regulator testing in phase I focused on PV system regulator characterisation, namely the determination of power consumption or current losses, voltage drops, charge voltage setpoints, setpoint temperature compensation, loadshed protection setpoints and state-of-charge indicators on the regulator. (This data has been published in the RAPS Design Manual Resource File.) Work during phase II has attempted to address operational aspects of regulator performance, in particular, choice of charge and loadshed setpoints and overall regulator effectiveness.

Performance tests have examined regulator behaviour and its effect on system performance using hardware simulation. A suite of four operational charging tests have been developed, which rely on preliminary characterisation tests.

Table 3.1 Regulators selected for performance testing.

Brand name	Type	Charge voltage settings	Power consumption
Helios NG	Relay switch with low series losses	14.45 V (off) 13.49 V (on)	60 mA 18 mA
Luna	Relay switch with higher losses	14.29 V (off) 12.80 V (on)	218 mA 118 mA
Shekida	Solid state float with higher series losses	14.20 V (float)	43 mA

Data sheets generated during phase I for the regulators are in appendix 2.

Test-rig

The regulator performance tests have been accomplished using a PC controlled PV array and load simulator incorporating off-the-shelf power supplies with fast, custom written software. The electronics tracks the actual PV array operating points accurately, and enables the examination of the array/regulator/battery interaction within the constraints of the array models used, but with the added benefit of a laboratory controlled environment.

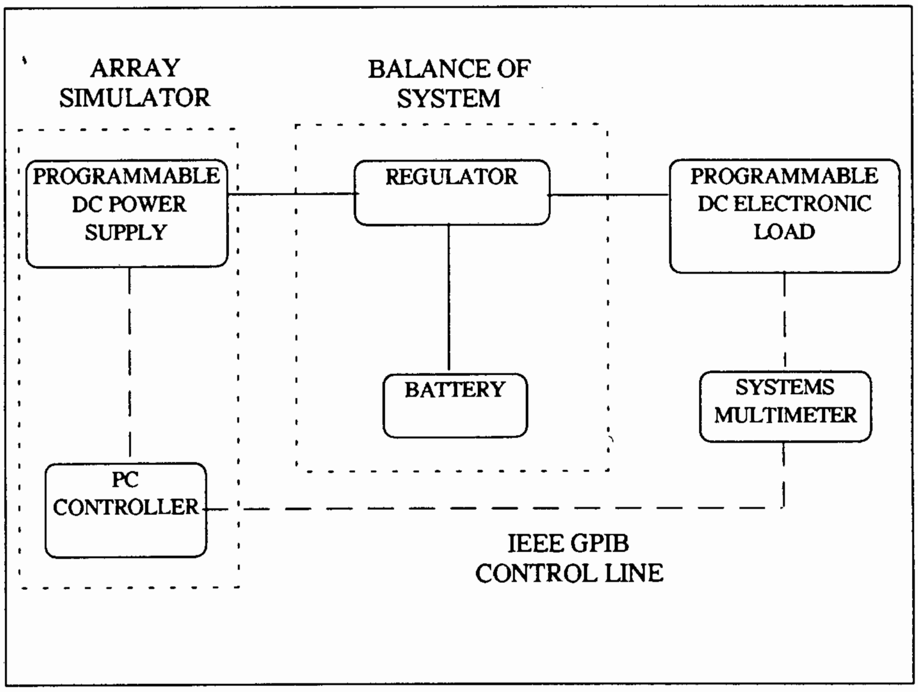


Figure 3.1 Regulator test-rig

For all charge performance tests a controlled solar profile of 6500Wh/day was used with solar array models.

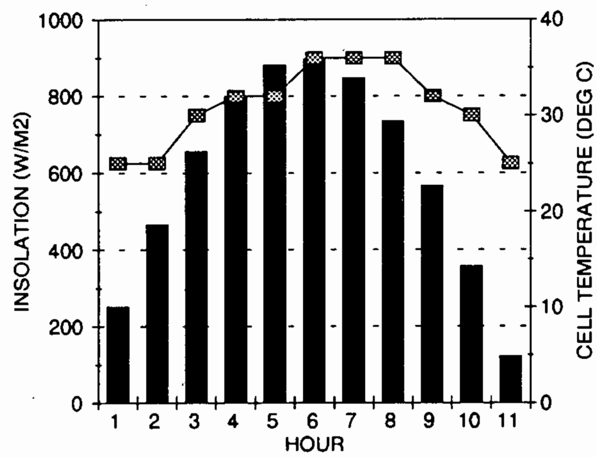


Figure 3.2 Controlled solar insolation and temperature profile. The total daily insolation amounts to 6500Wh/day.

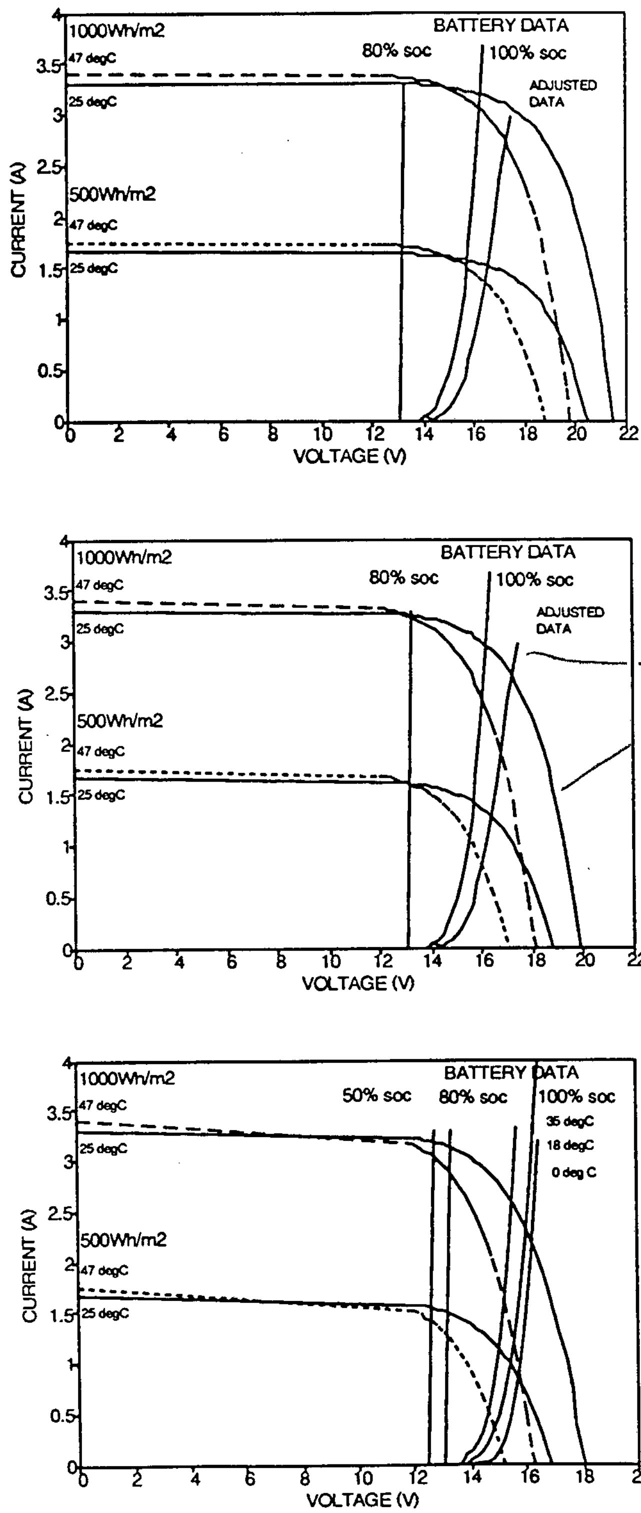
Test method and results

Charging tests using different panels

System performance can be strongly affected by whether 36, 33 or 30 cell PV modules are used. 36 cell modules generally have higher operating voltages, while 30 cell modules are sometimes called "self-regulating panels". They operate at lower voltages and tend to self-limit the rate of charge into the battery as it approaches full charge. If a regulator with a high series voltage drop is used, or if line losses are significant, then even a conventional 33 cell module can limit the rate of charge input.

This suite of tests was used to check the operation of the Shekida charge controller with the popular 90 Ah Raylite RR2 battery when charged by an electric model of each of the well known M55, M75 or M65 modules supplied by Siemens. The results were used to check the accuracy and ability of the experimental equipment to perform, and to check the sensitivity of PV system performance to different arrays.

The typical operating points for the battery/array, as well as instantaneous battery current, voltage and cumulative charge inflow for the day are shown in Figure 3.3 for a 90 Ah battery recharged after 15 Ah had been removed.



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IV

Figure 3.3 Array IV curve operating point interaction with battery regulator curves for 36, 33 and 30 cell modules.

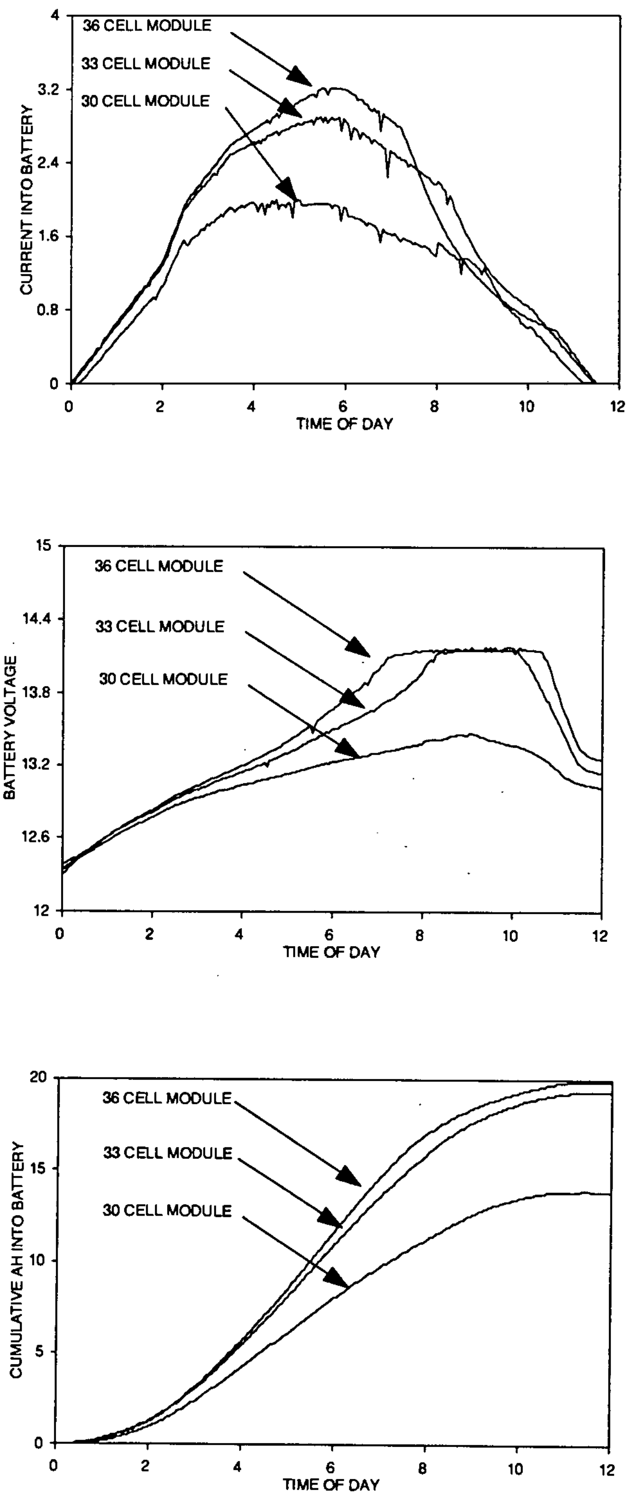


Figure 3.4 After 15 Ah had been removed from the 90 Ah battery, it was recharged using the three different modules. The graphs show (a) instantaneous charge current, (b) battery voltage indicating when charge regulation occurred, (c) actual ampere-hours delivered to the battery after one day of charging.

The experimental equipment was judged to be performing satisfactorily and sufficiently accurately. The actual regulator performance tests were thereafter conducted using the M75 panel only. Under the standard solar day (6500Wh/day) used, the M75 panel can deliver a maximum output of 21.4 Ah if it operates at its optimum power point throughout the day.

The actual array output power over the day was compared with the maximum array output power if the array operated consistently at its maximum power point. The results tabulated below show that the M75 module is well matched to the battery, while the M55 module is less well matched and could possibly benefit from a maximum power point tracking regulator, provided that the MPPT efficiency was greater than about 95% to make it economically feasible. The M65 module is not well matched and underperforms quite seriously with this regulator / battery pair. A voltage boosting MPPT could improve the situation radically, but would again have to be economically justified.

Table 3.2 Actual array output power compared with maximum output power over the day.

	M75 Module		M65 Module		M55 Module	
	Max. Power Wh	Actual Wh	Max. Power Wh	Actual Wh	Max. Power Wh	Actual Wh
Wh	295	280	257	196	331	301
Module Optimum Power Tracking	94.9%		75.0%		90.5%	

Charging using different batteries

Battery choice is also a major determinant of system performance. In performance tests the main difference is caused by the variation between different battery charge curves. These can be simplistically divided into two groups: lead-antimony batteries and lead-calcium or antimony free batteries. Antimony free batteries generally require higher charge voltages. Tests were conducted using low antimony 90 Ah Raylite RR2 batteries and 100 Ah Delco lead-calcium batteries.

In the longer term the rate of battery degradation will be the main performance factor, and the regulator should limit the rate of battery decay. The rate at which the battery accepts charge and overcharge becomes the main problem (see Chapter 2), and once decay has become established the regulator cannot easily reverse the process. Long term systems tests with studies of battery decay are unfortunately very expensive and beyond the scope of this more targeted research effort. An engineering appreciation of battery characteristics and behaviour is recommended to guide and facilitate system design and assessment.

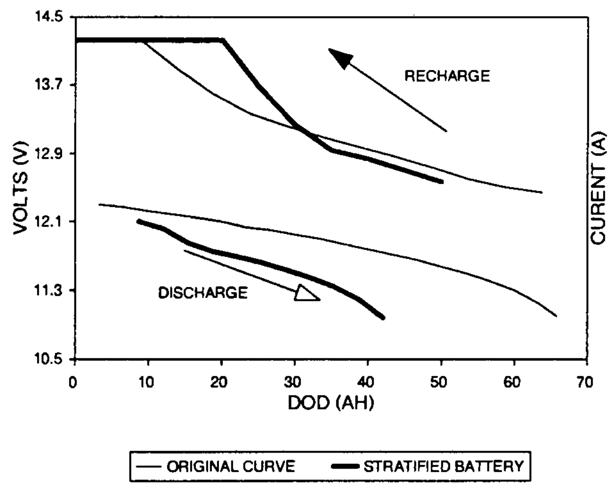


Figure 3.5 Charge and discharge curves for a degraded battery, showing higher charge voltage before the battery if fully charged. This reduces the rate of charge input.

Overcharge test

The regulator overcharge test examines top-of-charge regulation. The array/regulator is connected to a full battery for two solar days to determine the average amount of overcharge the regulator allows into the battery under no-load conditions; a situation that could occur if a site were left under-used or unused for a period.

There are two considerations:

- the array operating point, or the charge from the array to the regulator/battery
- the actual charge into the battery after regulation and regulator consumption

Table 3.3 Ah received from the panel during overcharge tests.

	Helios/ RR2/ M75	Shekida/ RR2/ M75	Helios/ Delco/ M75	Shekida/ Delco/ M75	Luna/ Delco/ M75
	Ah delivered				
day 1	2.8	4.3	not tested	2.0	1.5
day 2	1.8	2.4		1.6	2.3
day 3				1.5	

Table 3.4 Ah delivered to the battery during overcharge tests.

	Helios/ RR2/ M75	Shekida/ RR2/ M75	Helios/ Delco/ M75	Shekida/ Delco/ M75	Luna/ Delco/ M75
	Ah delivered				
day 1	2.1	3.7	not tested	1.5	-0.9
day 2	1.1	1.9		1.1	-0.2
day 3				1.0	

Under top-of-charge conditions surplus energy is available from the panel, so that the panel operating point is not too critical, but the charge delivered to the battery is important.

It seems that the Luna regulator will not allow sufficient charge to equalise the battery under no-load conditions, and top-of-charge may settle around 98% maximum.

Steady state charge test

The steady-state overcharge test checks performance under standard design load conditions, to determine daily top-of-charge. The charge into the battery was measured over five control solar days when subjected to a simultaneous load of about 15 Ah/day based on the control load profile shown in Figure 3.5. The battery was initially at full charge in an equalised state. The same regulators were compared, with the intention of measuring the steady-state charge into the battery.

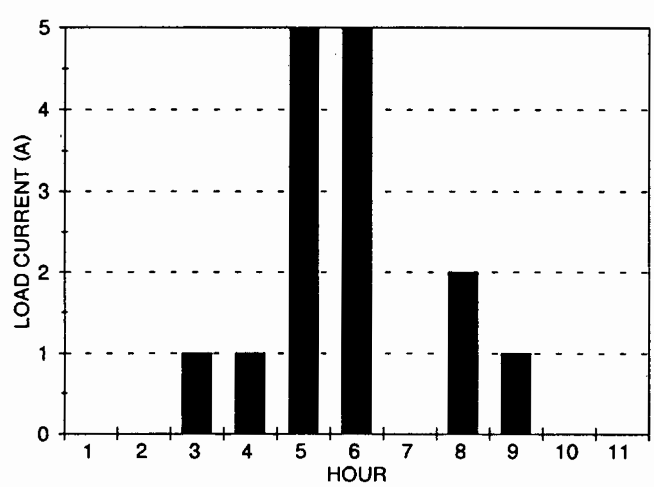


Figure 3.6 Control load profile used to remove 15 Ah/day from the batteries under test.

As before, array operating point and battery charge are important.

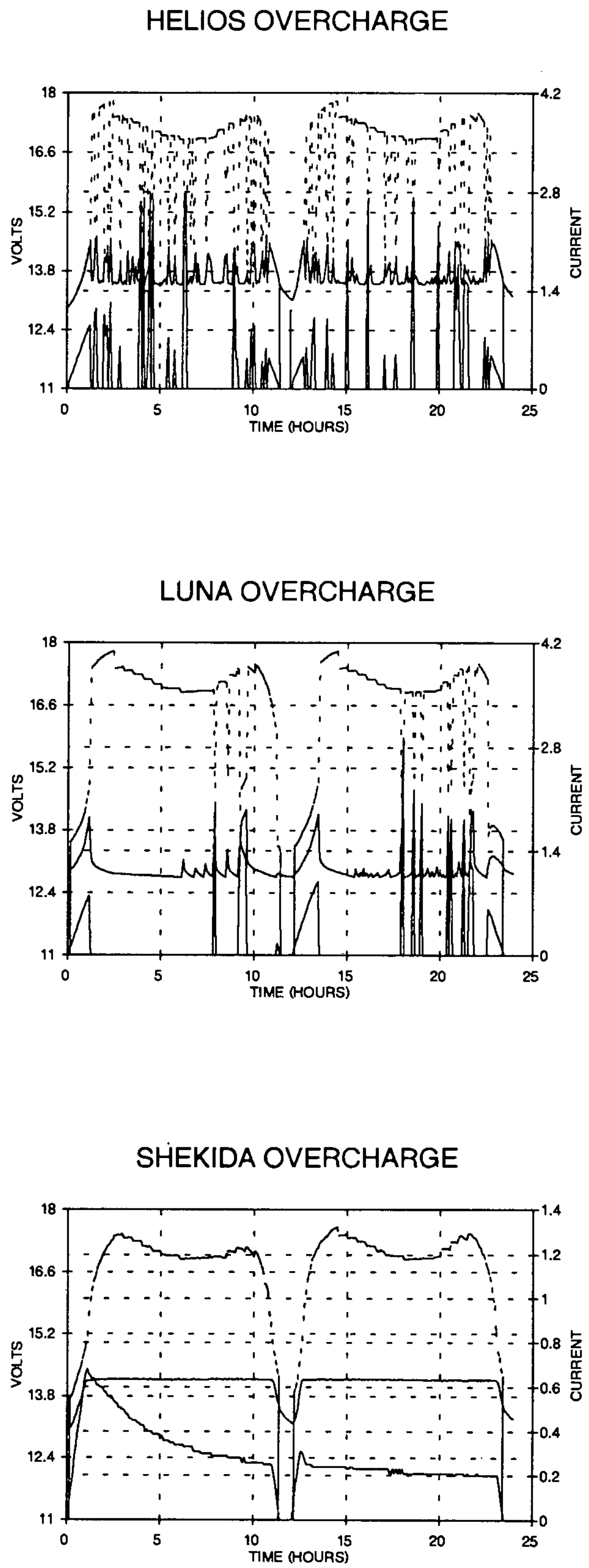


Figure 3.7 Plot of array and battery voltage, and array current during the overcharge test.

Table 3.5 Ah delivered during steady-state tests.

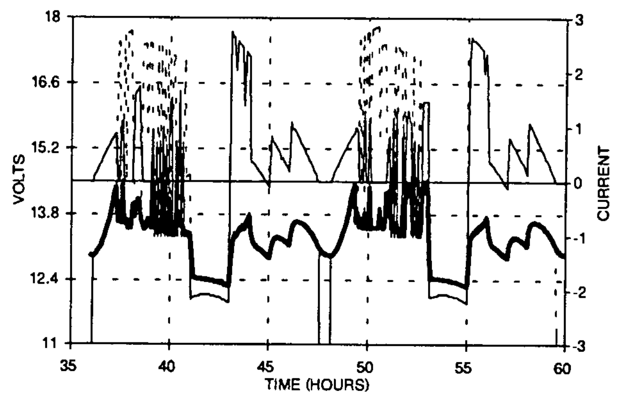
	Helios/ RR2/ M75	Shekida/ RR2/ M75	Helios/ Delco/ M75	Shekida/ Delco/ M75	Luna/ Delco/ M75	All Systems
	Ah in	Ah in	Ah in	Ah in	Ah in	Ah out
day 1	15.9	15.0	20.2	14.4	15.5	14.9
day 2	16.2	15.9	17.4	15.6	16.1	14.9
day 3	16.3	16.0	16.5	15.7	16.1	14.9
day 4	16.3	16.0	16.1	15.7	16.2	14.9
day 5	16.3	16.1	15.9	15.7	16.1	14.9
total	86.1	81.0	79.0	77.1	80.0	74.5
Net Ah in 3 days only	4.2	3.4	3.8	2.4	3.7	

Table 3.6 Ah delivered to battery during steady-state tests.

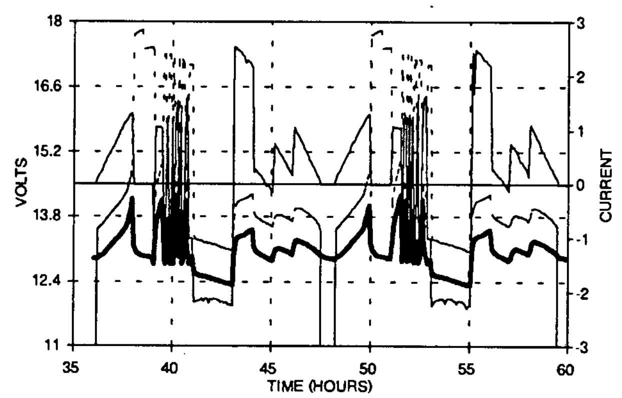
	Helios/ RR2/ M75	Shekida/ RR2/ M75	Helios/ Delco/ M75	Shekida/ Delco/ M75	Luna/ Delco/ M75	Load
	Ah in	Ah in	Ah in	Ah in	Ah in	Ah out
day 1	15.6	14.5	19.9	13.9	13.8	14.9
day 2	15.9	15.4	17.1	15.1	14.4	14.9
day 3	16.0	15.5	16.2	15.2	14.4	14.9
day 4	16.0	15.5	15.7	15.2	14.5	14.9
day 5	16.0	15.6	15.6	15.2	14.4	14.9
total	79.5	76.5	84.6	74.6	71.4	74.5
Net Ah in last 3 days only	3.3	1.9	2.8	0.9	-1.5	

Only days 3,4 and 5 were used to determine the average daily overcharge under load conditions, since this was when all systems seemed to have reached some form of equilibrium. It is interesting how much of the 'overcharge' is consumed by the regulator, and that a very small proportion reaches the battery. The Luna regulator, once again, seems unable to fully charge the battery.

HELIOS STEADY-STATE



LUNA STEADY-STATE



SHEKIDA STEADY-STATE

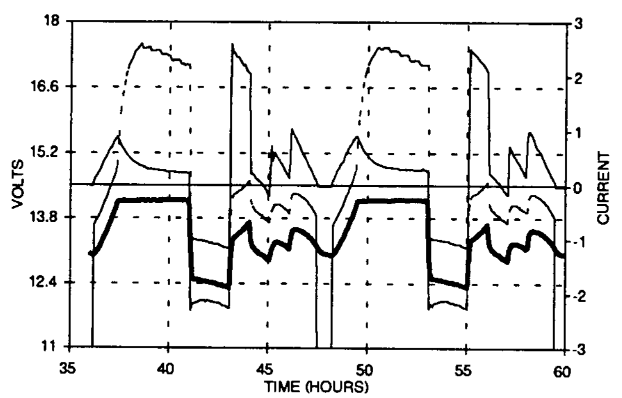


Figure 3.8 Plot of array and battery voltage, and array current during the final two days of the steady-state charge test.

Recharge test

The recharge test is a non-steady state test to recharge the battery from 15 Ah DOD under conditions of 15 Ah daily load using the discharge profile of the steady-state charge test. A five day recharge time is allowed. Under optimum power conditions, the array can output 21.5 Ah, so that the battery could be completely charged after 2.5 days if the regulator were 100% efficient. Under conditions of no regulation, the net Ah charge to the battery after 5 days would be just over 15 Ah. Under real conditions the charge acceptance rate should taper as the battery approaches full charge. The time to recharge the battery, as well as the maximum charge input to the battery was measured for the different regulators.

Table 3.7 Ah received from panel during recharge tests.

	Helios/ RR2/ M75	Shekida/ RR2/ M75	Helios/ Delco/ M75	Shekida/ Delco/ M75	Luna/ Delco/ M75	All Systems
	Ah in	Ah in	Ah in	Ah in	Ah in	Ah out
						15.0
day 1	21.0	20.3	21.1	20.3	20.5	14.9
day 2	20.8	20.0	20.9	20.0	20.3	14.9
day 3	18.9	19.4	20.1	19.3	20.2	14.9
day 4	17.5	17.1	16.5	16.8	18.0	14.9
day 5	16.5	16.4	16.0	16.4	16.8	14.9
total	95.0	92.7	94.6	92.8	95.8	89.5
Net Ah in	5.5	3.2	5.1	3.3	6.3	

After five days, only the Luna regulator had not fully charged the battery. The other regulators had begun to equalise charge the battery.

As the batteries become fuller (about day 4) the charge into the battery converges with the steady-state test result. If the systems were to enter steady state, the Luna regulator would still not allow overcharge into the battery. The Luna regulator had not yet reached the steady-state condition by the end of the recharge test.

Table 3.8 Ah delivered to battery during recharge tests.

	Helios/ RR2/ M75	Shekida/ RR2/ M75	Helios/ Delco/ M75	Shekida/ Delco/ M75	Luna/ Delco/ M75	All Systems
	Ah in	Ah in	Ah in	Ah in	Ah in	Ah out
						15.0
day 1	20.7	19.8	20.7	19.7	19.1	14.9
day 2	20.6	19.5	20.6	19.5	19.0	14.9
day 3	18.6	18.9	19.9	18.8	18.7	14.9
day 4	17.2	16.6	16.2	16.3	16.4	14.9
day 5	16.2	15.9	15.7	15.9	15.1	14.9
total	93.3	90.7	93.1	90.2	88.3	89.5
Net Ah in	3.8	1.2	3.6	0.7	-1.2	

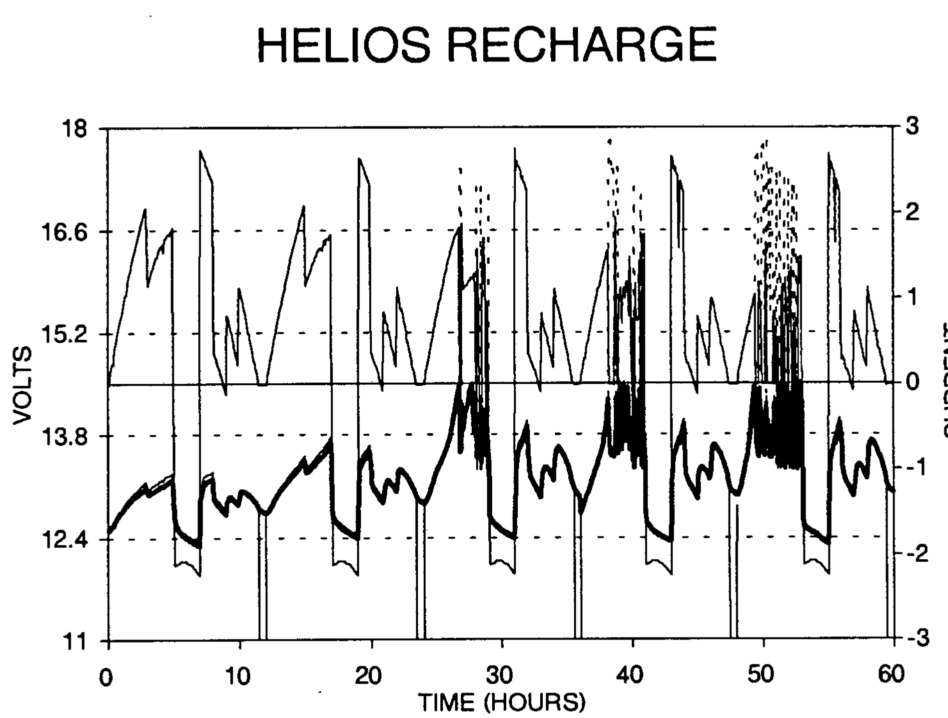


Figure 3.9 Plot of array and battery voltages, and array current during the recharge test for the Helios regulator.

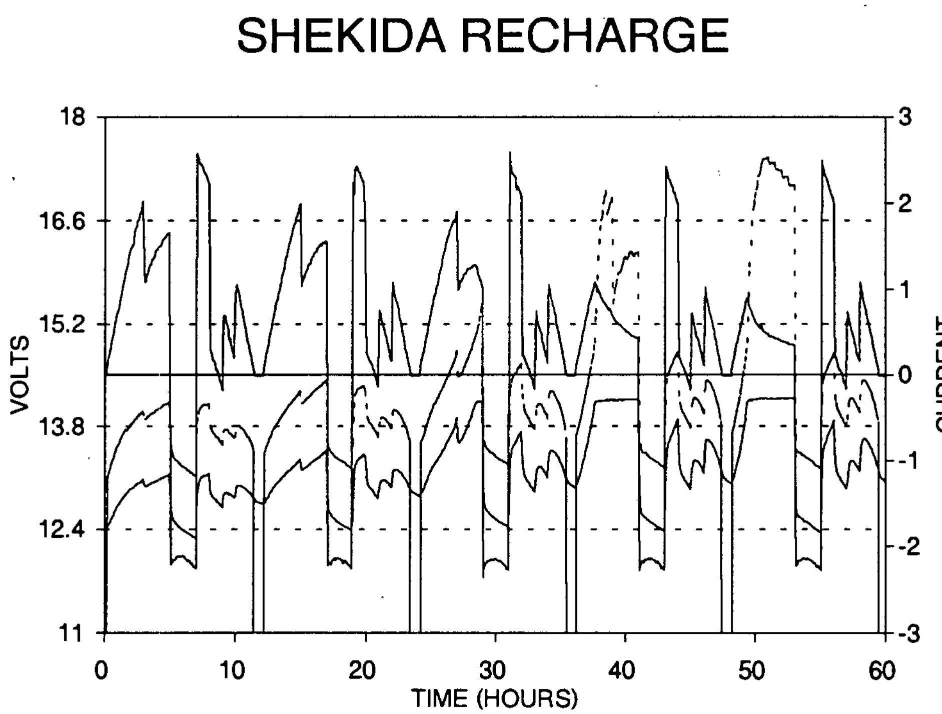


Figure 3.10 Plot of array and battery voltages, and array current during the recharge test for the Shekida regulator.

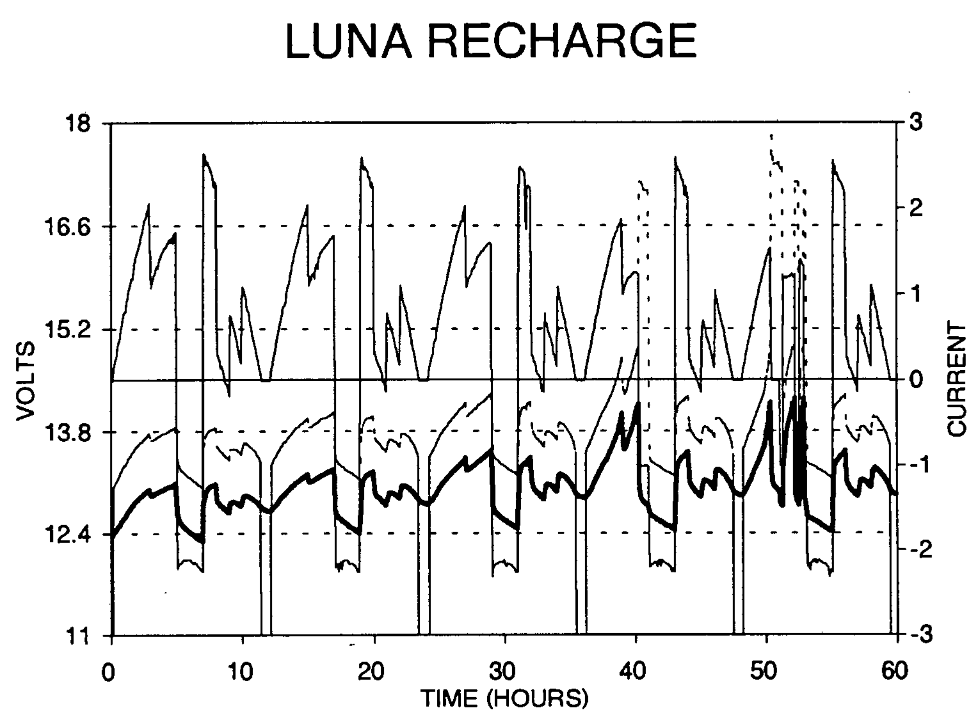


Figure 3.11 Plot of array and battery voltages, and array current during the recharge test for the Luna regulator.

Discussion of results

The set of tests seems to yield consistent results for the sample of regulators and batteries selected.

The regulators that provided the most overcharge in the overcharge test did not necessarily do so in the steady-state test or recharge test, because the presence of a load affects performance in some instances. Here the dependence of the switch type regulator algorithm on the presence of a load is quite clear, and they deliver almost as much charge as the floating type regulator.

Although regulator voltage losses can be critical, for the small PV systems considered in the tests, power consumption by the regulator is of overriding concern. Regulators with low power consumption perform far better than those with high consumption. Indications are that high consumption regulators may not be able to fully charge the battery. (The regulators all drew approximately the same energy from the panels in the same tests, but differed significantly in the amount of energy finally delivered to the battery.)

In the tests conducted, the single most significant factor determining the rate of recharge of the battery was the type of module used, 36, 33 or 30 cells. This is not at all unexpected.

The regulator tests were conducted under very specific conditions, but the results provide insight as to whether the regulators are suited to the conditions, whether they should be used only in larger systems or what their effects on other systems might be.

The tests provide useful comparative performance indicators.

What the tests cannot do is determine whether the regulator will be able to maintain the battery in the required condition for optimal battery life. There are too many external factors, both involving other components selected in the system design, and load usage and weather patterns. In the design stage, however, good judgement and suitable data should facilitate the right regulator choice decisions.

With the exception of high power consumption devices, regulator voltage settings can be adjusted to allow the desired amount of overcharge into the battery. Once this has been done, regulator reliability is probably far more important. Reliability testing is not feasible, and would have to be informed by field experience and judgement decisions based on regulator designs. (Simple regulators would always take precedence, but more complex designs could be considered if they had been very well tested).

3.3 Regulator data

The regulator testing program at EDRC has provided three types of data:

- Hard data on regulator characteristics, of the type described above and also obtained in phase I. This is useful for design, regulator selection, paper-based PV evaluation (see Chapter 7) and design assessment.
- Regulator performance indicators, which can be used in conjunction with the regulator characteristics.
- Soft data of a more philosophical nature. This data is more literature-based, less precise and would consider effects of regulator design on different batteries under varying conditions by using broader rules and guidelines. Soft data would be useful for trouble shooting. Soft data can be used in conjunction with similar data for other components, for instance battery performance and insights into battery behaviour.

One question cannot easily be answered but is intimately dependant on the regulator: can the regulator boost-charge the battery and maintain it in a good condition?

- Battery testing and overcharge requirements together with data on the effects of undercharge on the battery could be used to determine whether the PV system would work and last. Battery degradation, recovery and regulation is discussed in chapter 2, together with a new battery/regulator testing method.

- Of course, longer term battery cycling tests or PV systems type testing could be attempted, regularly checking whether the battery is adequately recharged. But this is difficult because the outputs depend on the system configuration and the load use patterns. Ultimately it is more economical to develop a good understanding of behaviour than to retest every time the configuration changes.

3.4 Outputs

The primary outputs from the regulator testing program have been published in the RAPS Design Manual

- A chapter on voltage regulators in PV systems, describing the various categories, electronic designs and control algorithms of regulators, when to use particular designs and when to avoid others. This section is particularly important since it is these guidelines that are ultimately most useful.

- Design data and characterisation information for the individual regulators tested, in the Resource file (Volume 2) of the Design Manual.

- A method for determining loadshed and charge setpoints for different batteries, in the Battery chapter of the Design Manual.

3.5 Proposals

Methods should be developed for deciding whether the regulator is suitable for charging and optimising battery utilisation in the system. Present methods may not be conclusive enough:

- Clearly,the most conclusive method is to cycle the battery to loadshed, and recharge it on the PV system over a recovery period. Regularly cycling would show any capacity loss, but obviously this process is very time-consuming.

- Results of innovative battery cycling tests obtained in the laboratory could be used in conjunction with laboratory test data of regulators, and with background knowledge of regulator control philosophies in PV systems. Possibly some further experience in system monitoring or performance testing, together with suitable data analysis would give the required confidence.

Far more detailed electronic analysis would be required to ascertain regulator reliability. Some regulator designs and control algorithms are more reliable than others, and therefore less likely to cause catastrophic damage to the PV system or battery. But reliability testing is impractical and engineering judgement based on experience is far more economical.

Hybrid system control and regulation are more complex and far more variable than that for PV systems. An open, philosophical method of appraisal should be encouraged and adopted by both researchers and the industry for future work in this field.

CHAPTER 4

PV MODULE TESTING

Most module manufacturers provide performance specifications for their PV modules, but it is not possible to check these exactly because of difficulties in accurate measurement of:

- solar irradiance and its spectral composition[1]
- the operating temperature of the PV cells in the modules[2]

These variables affect the output characteristics of the modules quite considerably.

Manufacturers' specifications usually stipulate module output characteristics with such high tolerances (±10%), that this latitude combined with measurement uncertainties is likely to cause inconclusive results.

(Module ratings are usually in the form of IV curves at standard test conditions (STC) of 1000W/m^2 at cell temperatures of 25°C and under very specific spectral conditions.

The maximum power output and IV curves are usually presented at two irradiances and three temperatures:

1) irradiance of 1000W/m^2 at a cell temperatures of 25°C and also at a more realistic cell operating temperature, about 40°C.
2) irradiance of 500W/m^2 and a cell temperature of 25°C.)

However, since manufacturers' production batches may vary significantly from specifications it is desirable to know the output power relative to specifications. Some motivations for module testing are listed.

- It is useful to be able to check module performance as part of the procedure of PV system performance testing, so that if the module is under-performing the effect on overall PV system performance can at least be quantified.

- The output at normal and realistic cell operating conditions and temperature under particular conditions may not be covered by the specifications.

- In the case of a very broad range of operating conditions being encountered in the field, it may be desirable to check panel performance under a range of conditions, and also check the applicability of mathematical models to predict performance.

---

1 The various irradiance measuring instruments respond differently to the solar spectrum. Different makes of PV modules can additionally have different spectral responses.

2 The actual operating temperature of the semiconductor p-n junction is the relevant measurement, not the module skin temperature.

4.1 Recommended procedure for testing under natural conditions

If different modules are to be compared, they should be tested in quick succession under stable atmospheric conditions, preferably cloudless days.

IV curves

For each module, the current and voltage should be rapidly sampled while a variable impedence load attached to the module output is ramped from zero impedance to infinite impedance. Plotting of the sampled voltage/current pairs will produce the module IV curve under those environmental conditions.

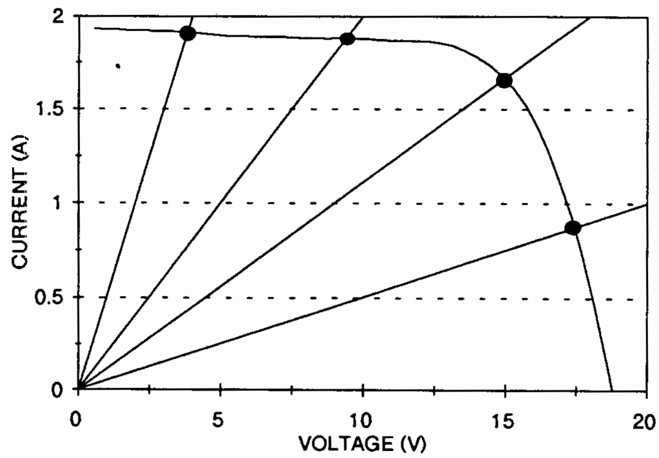


Figure 4.1 Varying the load resistance from zero to infinite impedance will cover the full range required to obtain an IV scan

The plane of array irradiance measured by the pyranometer should be recorded at the beginning and end of each module test sequence. (Experience has shown that a variance of more than 3% in this recorded value will yield IV curves of suspect shape, and that the test should be repeated. For a less than 3% variance the irradiance values can be averaged.) If only one set of module readings are to be taken, these should occur when the irradiance is about 750W/m^2 and the ambient temperature in the shade is about 25°C. The module should have reached stable operating conditions.

Temperature effect

PV cell temperature has a marked effect on cell outputs and the effect of temperature may be well worth knowing, but measurement of the cell internal operating temperature is extremely difficult. While IV curve measurement at the approximate Normal Cell Operating Temperature (NOCT) at about 750W/m^2 will be useful, the non-linear change in performance at other temperatures and insolations may be critical. An ideal way of estimating cell operating temperature is with a reference cell of the same material as the module under test, which has a temperature-sensitive resistor internally mounted.

IV curves at 750-850W/m^2 and at NOCT can be compared with the manufacturer's data; in particular, the short circuit current (I_{sc}), open circuit voltage (V_{oc}), and maximum power (P_{max}), as well as the current and voltage at the maximum power point (I_{opt} and V_{opt}).

4.2 Test equipment

Experimental test equipment was set up at the EDRC laboratory to record IV data for modules under natural conditions.

The recommended method specifies the bare minimum testing requirements and is not ideally suited for laboratory-based testing where greater precision is required. Automatic testing equipment was set up in the EDRC test laboratory to periodically scan the IV curves of several modules in quick succession with the intention of comparing modules and providing data for fitting mathematical models (which obviously cannot be done with only one curve per module). The IV scans are done in system, that is the modules are periodically switched out of PV system operation and scanned for a few seconds, and then switched back into the PV system.

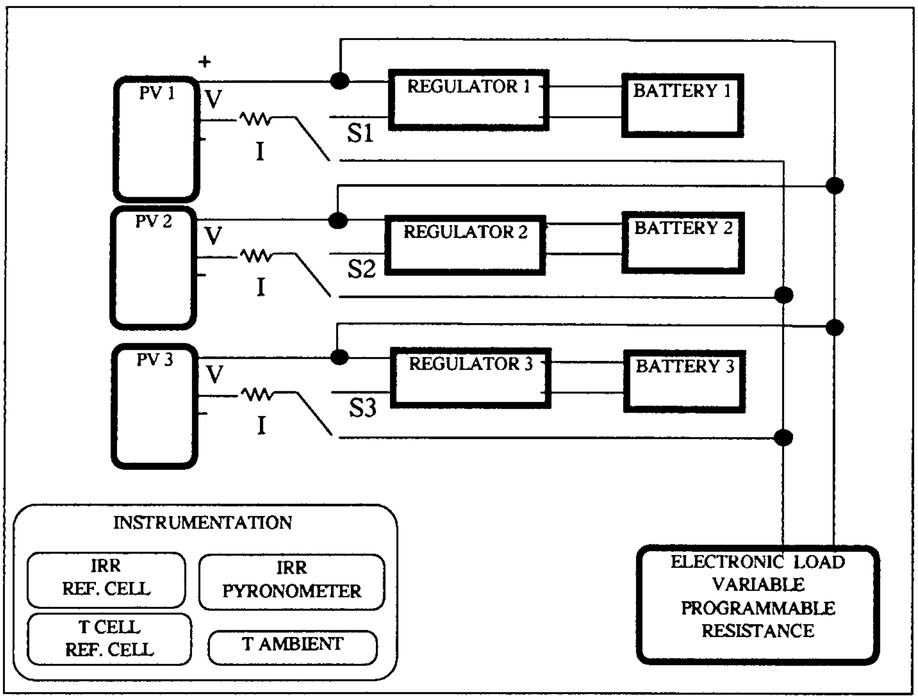


Figure 4.2 Experimental layout of monitoring set-up.

The modules are all mounted in the same plane on a mounting that can be pivoted in both the horizontal and vertical directions.
The solar irradiance instruments are mounted in exactly the same plane as the modules. A class 1 pyranometer and a calibrated reference cell are used to provide a more accurate indication of irradiance. The polycrystalline reference cell was used; this is expected to show the same spectral response as the modules (the pyronometer almost certainly will not), reducing experimental error considerably. The reference cell, with a current source onto its internal temperature-sensitive resistor, provides a voltage output indicating the cell temperature. Ambient temperature recorders are also located nearby.

Module voltages are sensed at the module terminals, and module currents sensed at current shunts located in the laboratory.

All readings are multiplexed into a 5 digit systems multimeter and automatically stored onto computer disk.

The computer also controls a programmable, variable electronic load which is used to ramp the module load resistance. The computer sequentially switches several two-pole relays which allow several modules to be scanned within a few seconds.

4.3 Results for one polycrystalline module

Figure 4.3 shows selected curves obtained during one day of module monitoring till midday using the experimental monitoring equipment.

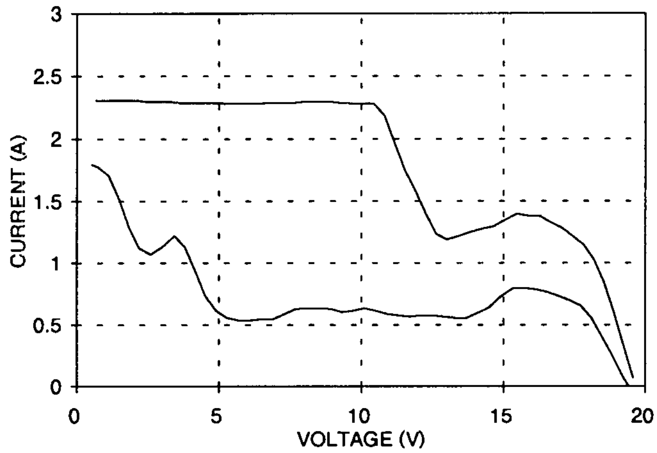


Figure 4.3 IV curves scanned every half-hour till midday on a clear day.

Figure 4.4 shows the effect of intermittent cloud during a scan on an IV curve, even though start and finish irradiance measurements were the same. A critical practical consideration is to ensure that the pyranometer is in exactly the same plane as the modules. Several days of inaccurate (useless) data were recorded when the pyranometer was dislodged by only a few degrees. (Parallel tests conducted by ESKOM at their TR&I test site on the Witwatersrand showed curves that were too round, suggesting interference of their measurement equipment with results.) Obtaining credible and reliable readings is no trivial task.

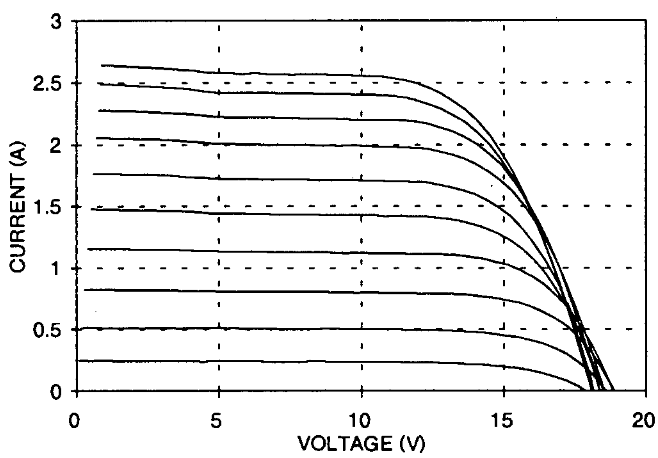


Figure 4.4 IV curves showing the effect of cloud shadow during the scan.

In figure 4.5, four stable, representative IV scans have been selected for further analysis. The curves shown are:

- 1000W/m^2 (38°C)
- 1022W/m^2 (50°C),
- 886W/m^2 (35°C),
- 446W/m^2 (27°C),

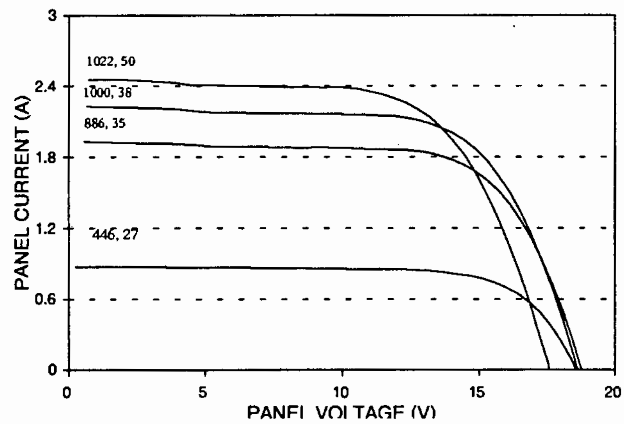


Figure 4.5 IV scan of four representative curves selected for analysis.

Table 4.2 Measured output characteristics of the representative curves.

Test condition	**1022W/m^2 50°C**	**1000W/m^2 38°C**	**886W/m^2 35°C**	**446W/m^2 27°C**
V_{oc} (V)	17.60	18.64	18.74	18.60
I_{sc} (A)	2.40	2.23	1.93	0.87
P_{max} (W)	28.3	28.2	25.1	11.6
V_{opt} (V)	13.22	14.05	14.44	15.11
I_{opt} (A)	2.14	2.01	1.74	.77
I_{sc}/Irr *1000	2.41	2.23	2.18	1.96

Some initial observations can immediately be made from these results:

- V_{oc} decreases markedly with temperature
- I_{sc} increases with irradiance
- P_{max} increases with irradiance
- V_{opt} deceases with irradiance and temperature
- I_{opt} increases with irradiance
- The relationship between I_{sc} and irradiance is non-linear, or else depends also on temperature, which may vary considerably from the NOCT.

These observations, particularly the last, considerably strengthen the argument for including cell temperature as an important variable, even in rudimentary testing. It is very unlikely that experimental IV curves based only on irradiance can be compared with specifications and yield conclusive results. The temperature effect on I_{sc} can be theoretically explained, and is quantified in a mathematical model.

A description of a proven model follows, with a curve fit correlation to determine how well model terms can explain observed IV curve behaviour.

4.4 Mathematical model of IV characteristics

Model description

The model (Rauschenbach HS,1980) relates module electrical outputs (I and V) to irradiance (Irr) and cell temperature (T) by some coefficients measured at standard conditions of 1000W/m^2 and 25°C.

$$I = I_{sc}(1-C_1\{\exp[V/(C_2V_{oc})]-1\})$$

where

$$C_1 = [1-(I_{opt}/I_{sc})]\{\exp[-V_{opt}/(C_2V_{oc}]\}$$

and

$$C_2 = [(V_{opt}/V_{oc})-1][\ln(1-I_{opt}/I_{sc})]^{-1}$$

Under non-standard conditions the following corrections are applied to the voltage and current

$$V = V + \text{beta}(T-25)$$

$$I = I + I_{sc}(Irr/1000-1) + \text{alpha}(T-25)$$

I and V are electrical output parameters of the module and the coefficients at standard conditions of 1000W/m^2 and 25°C are:

I_{sc}	:short circuit current (A)
I_{opt}	:current at optimum power point (A)
V_{oc}	:open circuit voltage (V)
I_{opt}	:voltage at optimum power point (V)
alpha	:increase in I_{sc} per °C (A/°C)
beta	:increase in V_{oc} per °C (V/°C)

Fit of model to data

The IV data captured above covers a broad range of operational conditions. The basic model can easily be fitted to just one IV curve (886W/m^2 in this case), and parameters alpha (effect of temperature on I_{sc}) and beta (effect of temperature on V_{oc}) manually adjusted to the temperature extremes so that the model also fits the other curves.

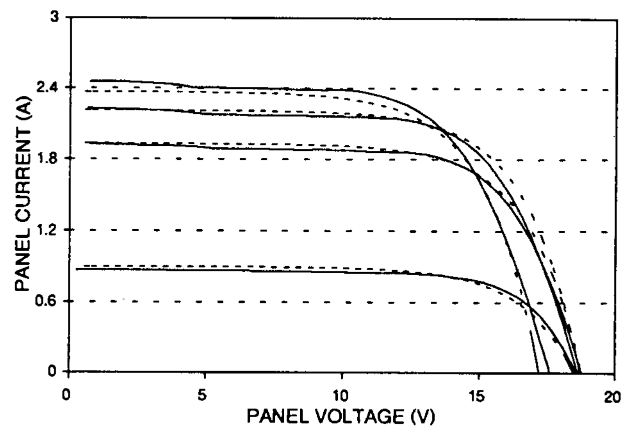


Figure 4.6 Fit of the model to the four selected experimental curves.

Figure 4.6 shows that the model seems to fit the experimental data well. The correlation coefficient obtained for the fitting of all four curves is R^2=0.9861 over the entire curve. (Unity correlation coefficient implies a perfect fit).

The model coefficients under standard conditions (1000W/m^2 and 25°C) are in table 4.2.

Table 4.2 Coefficients for the IV model at (1000W/m^2 and 25°C)

I_{sc}	:	2.0935A	
V_{oc}	:	20.4V	
I_{opt}	:	1.880A	
V_{opt}	:	16.01V	
P_{max}	:	29.7W$_p$,	(26.93W$_p$ @ 46°C, 27.76W$_p$ @ 40°C, 28.79W$_p$ @ 32°C)
alpha	:	0.009A/°C	
beta	:	-0.136V/°C	

Observations

From a practical perspective the model coefficients alpha and beta are particularly interesting in this case. Alpha shows a high positive dependence of I_{sc} on temperature (9mA per °C), and would explain the apparent non-linear relationship observed earlier between I_{sc} and irradiance. Beta, also, is higher than specified for most modules, but no specifications were available for the particular modules tested.

- the mathematical model seems to fit this experimental data well under a broad range of conditions, certainly well enough to predict module performance under many conditions. However, great care must be taken in obtaining reliable IV scans in order to use the model in the first place.

- the model coefficients highlight specific performance characteristics of modules tested.

4.5 Conclusions

- An outdoor, natural irradiance PV module testing facility has been set up which can automatically scan and record PV module performance characteristics measured under environmental conditions. Spectral conditions cannot, however, be measured at this stage.

- Initial indications are that for polycrystalline modules this performance data can be fitted to a mathematical model, which can explain some unexpected variations in characteristics under certain conditions.

- Some parameters of the mathematical model have physical meaning, and can therefore be used when comparing modules.

- The model should also be checked for accuracy and usefulness with monocrystalline and amorphous modules.

CHAPTER 5

PV SYSTEM PERFORMANCE TESTING

PV systems qualification tests, as opposed to testing of individual components, offer a way of checking the performance of stand-alone PV systems with battery storage against claims made by system suppliers, and can also predict the system performance in other locations where sufficient statistical weather data is available.

System performance is usefully presented as a loss of load probability for a given (fixed load) at a given site. This is determined by the actual battery autonomy and the actual effective panel output power. This is partly defined by average path efficiencies over the course of a depletion run from full charge to max DOD.

PV systems qualification or performance tests are well conceptualised, but practically are not well developed. Yet some form of pre-tender award qualification tests are urgently required for possible large-scale PV system implementation projects likely in the near future.

This chapter describes a set of tests conducted on three identical PV systems using a system test method developed at EDRC. Three identical results were expected. Results and possible problem areas are examined, and some recommendations are given as well.

5.1 Outline of test method

The full test method is documented in the RAPS Design Manual, Resource Files / PV System Testing, and in Appendix B of this report..

Test outputs

The test method provides two main results for each system:

- the autonomy or storage capacity of the battery in the system
- the effective array power as seen by the load in the system

These results can

- be used to compare the performance of systems tested under the same conditions
- predict the ability of the systems to support their design loads at the intended installation sites
- predict the maximum average daily load the systems could support at the intended installation sites

The results are a snapshot in time (eg 6 weeks), and no allowance is made for system stability, or battery loss of capacity through settling or component decay.

One exception, perhaps, is that batteries will fail during the test if regulator loadshed settings for battery over-discharge protection are too low. This kind of failure is, however, very easily predicted from battery data, and is only useful for convincing very stubborn designers that their settings are wrong. More subtle data on component failure cannot foreseeably be obtained from the test in an economical way.

Method

The test method depends on being able to determine the average path efficiency of energy flow from the array, through the regulator to the load, with a portion of the energy cycled through the battery with its associated storage losses over a depletion run. The useful battery capacity must also be determined.

The recommended method requires two separate experiments, and the array-to-load path energy efficiency is determined from the two results.

Autonomy test

The autonomy test is a kind of calibration or standard, in which the capacity of the battery storage is experimentally determined under operating conditions. The battery is brought to full charge using the voltage regulation of the PV system. The array is then disconnected and the battery discharged into a fixed load (preferably the actual system load, or else a fixed resistive load of the correct size) until the load is disabled by the loadshed protection of the regulator. The battery capacity is measured in watt-hours delivered to the load (E_b). The loadshed disconnection voltage of the regulator is recorded.

Recovery test

The battery is then brought up to full charge using the voltage regulation of the PV system in the recovery test. The characteristic loadshed reconnection is recorded, as well as the charge regulation characteristics of the regulator.

Depletion test

The depletion test discharges the battery over regular timed intervals. Unlike the autonomy test, the array remains connected for a period each day until a predetermined amount of solar insolation (POA) has fallen onto the array. The array component should be twice the battery component, so the load should be roughly 1.5 times the array delivery (the test procedure gives exact equations for determining this accurately), so that the battery is intermittently discharged over a period of about ten to fourteen days to the loadshed voltage in a series of charge/discharge cycles. The total amount of energy dissipated in the load is E_t.

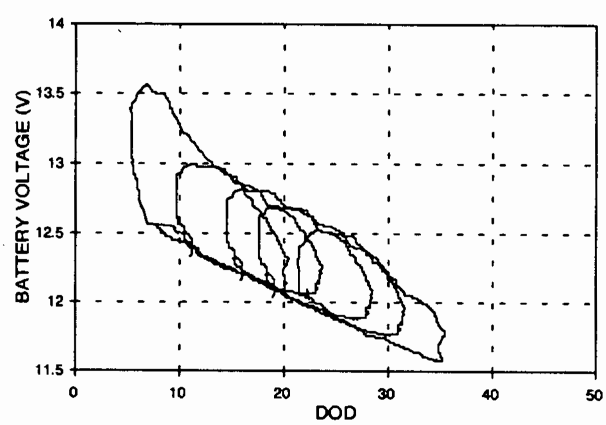


Figure 5.1 Depletion cycling occurs when there is insufficient energy to meet the load demand, and the battery cycles slowly towards loadshed.

The amount of energy from the panel that effectively reaches the load can be determined from the difference between the depletion test and the autonomy test energies. The total amount of insolation incident on the array during the depletion test is also known so the effective array power in the system can be determined.

$K_p = (E_t - E_b) / (POA * \text{duration of depletion test})$

Separate testing of the array to determine the operating curves (IV curves) under natural conditions gives an indication of actual potential energy output of the array compared with array performance in the system.

5.2 Advantages / potential problem areas / uncertainties

Advantages:

- The actual performance of the system is measured.
- The results can be used to predict performance in any other geographic location for which sufficient statistical weather data exists.
- The test may provide insight into system operation and identify inefficient or unsuitable components (provided sufficient understanding already exists about PV operation in general, as well as a solid understanding of the operation of individual components).

Problem areas:

- The performance prediction is a snap-shot in time. The test provides a performance indication for the system as tested, and no allowance is made for decay of components, particularly variation in battery capacity with age.
- The testing can be very expensive to perform, in terms of data capture and experimental equipment.
- The test takes a considerable amount of time, which means costly delays in the tendering process. The full suite of tests is estimated to take at least 30 days, although in practice it has, until now, never been completed in less than twice that number.
- Because all the separate test stages are required for a result, it is critical to ensure smooth operation. In particular, long sequences of uninterrupted data capture are required for the depletion test (typically two weeks or more). Test equipment failure can be devastating and require the whole procedure to be restarted. Uncertainty or variability in component behaviour could also cloud the results.

Uncertainties:

- The test method assumes that battery capacity is fixed for given discharge conditions. This may not be the case in practice, and over the course of a month the battery capacity could have settled to a very different value. Assumptions about fixed battery capacity could make the test results null and void.
- The battery capacity will decrease with time, and operating characteristics are likely to change, making long term prediction difficult.
- Array curve measurement is not trivial and can be the source of significant error. (See chapter 4)
- Any inaccuracies in irradiance measurement will impact heavily on test results.
- The statistical accuracies of any one K_p prediction result are not known. The test may have to be repeated many times to obtain a statistically

significant result.

5.3 Aims

The aims of conducting in-house PV testing were:

- to gain hands on experience in the test procedure;
- to identify problems areas and make recommendations;
- to gather statistical information of reducing uncertainties in results, by testing three 'identical' PV systems;
- to run tests in parallel with tests being conducted by ESKOM TR&I in the PWV area.

5.4 PV systems selected for testing

The system selected for evaluation is a single array, single battery system fairly typical of those supplied as 'domestic lighting kits'. The three identical systems consisted of

- single array (BP Solar $40W_p$ polycrystalline)
- single battery (Raylite RR2 100Ah 12V modified SLI type)
- battery regulator (PDI 12V 5A boost/float regulator with 5A loadshed protection and low voltage warning)

The estimated load available from the systems is 120 Wh/day, or about 10 Ah/day.

5.5 Test set-up/ data capture used

PC based data capture facilities were set up to gather the required experimental information.

The PV modules, a Class 1 pyrAnometer, a silicon reference cell with temperature output, and an ambient temperature sensor were installed on the roof of the laboratory. A five metre power wire linked the arrays to the regulators and batteries in the laboratory, where the measurement equipment was also housed.

The instrumentation and control system was better than recommended in the published test procedures.

- Current shunts were placed in circuit to measure array current and load current, replacing the battery current shunt in the procedures.
- Control of the array and load relays was automated to allow convenient and error-free control of the test procedures by the computer. The relays could be operated individually for each separate system.
- A calibrated reference cell of similar material to the arrays was used in addition to the class 1 pyronometer to measure insolation. The cell also provided a good estimate of the actual array operating temperatures through an embedded temperature-sensitive resistor.
- Sophisticated software with many error checks and fail-to-safe operation allowed the system to remain unattended for extended periods (including a two week period!)

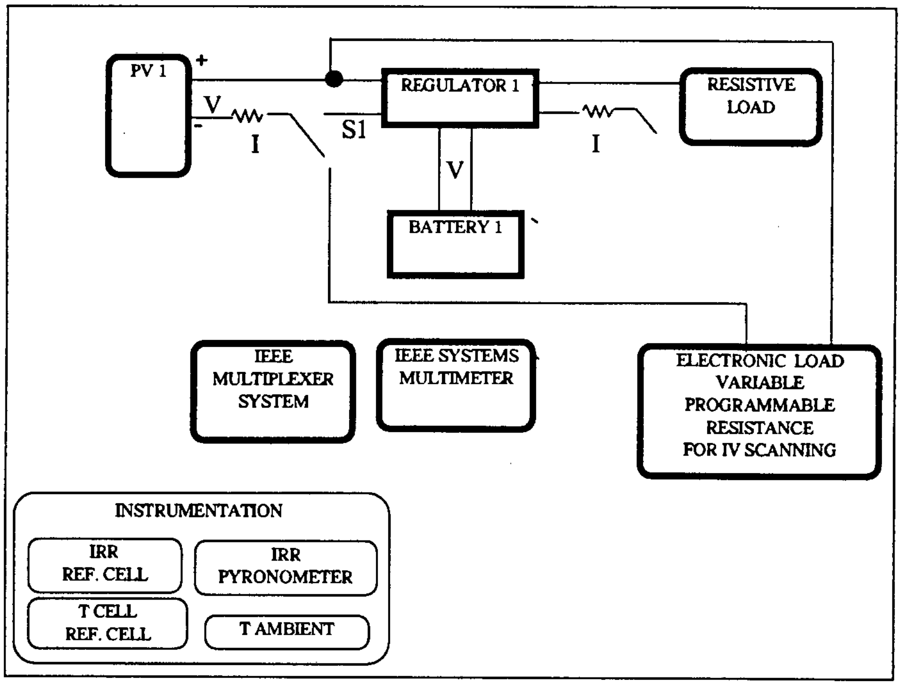


Figure 5.2 The logging system comprised a IEEE GPIB 5-digit multimeter capable of measuring ranges from hundreds of volts to micro-volts. No signal amplification equipment was required. The multimeter was multiplexed to the various instruments and system voltage and current shunts.

The complete logging system was powered through a UPS which provided approximately 24 hours of backup.

5.6 IV testing of the modules

IV curve testing under natural conditions is theoretically simple, but in practice few credible readings have been presented by SA experimenters:

- often equipment is poorly set up;
- manual measurements make the work onerous and accuracy and precision falls;
- manual measurements make collection of statistical data impractical and very time consuming.

An IV test procedure and experimental design superior to the EDRC recommended test procedure was developed, and is described in chapter 4.

IV testing was also automated with remote data capture by using the array relays to switch the individual arrays through a programmable IEEE-based DC electronic load which provided the variable resistance required for the IV scan. Array voltage was measured at the array output, and array current was measured using the individual array current shunt and system data capture equipment. Insolation and reference cell temperature were also automatically recorded as before.

A sophisticated software program scanned each array for IV curves every half-hour during daylight periods.

5.7 Testing procedure

The systems were preconditioned by removing the daily load and recharging through by the voltage regulated arrays for two weeks. They were then cycled repeatedly through:

- autonomy test
- recovery test
- depletion test
- recovery test.

IV scans were periodically taken.

Four autonomy tests and three depletion tests were completed, yielding six predictions of system energy output and path efficiency.

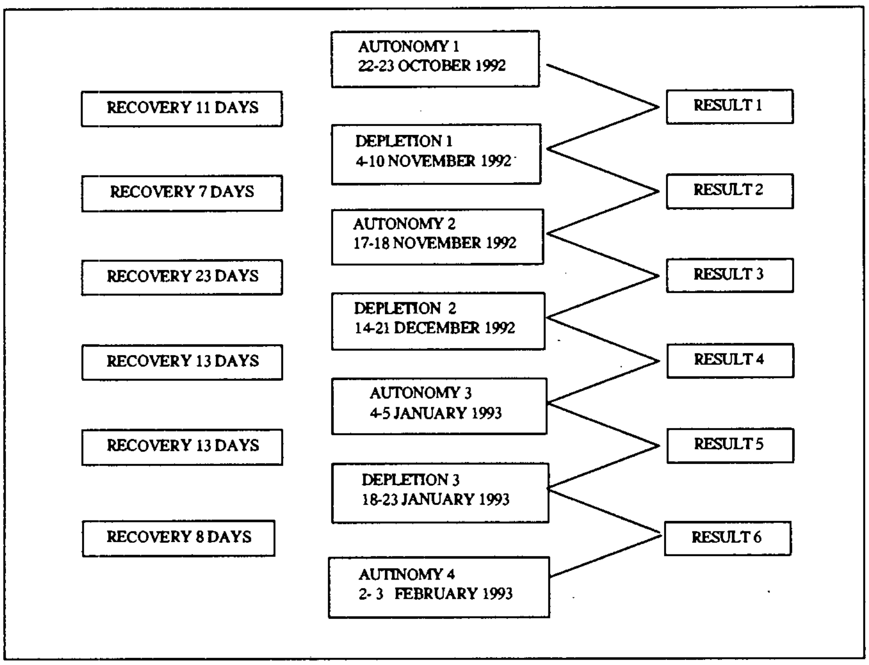


Figure 5.3 Experimental flow and source of results.

5.8 Results

Table 5.1 Results of tests and calculated values

CYCLE		SYSTEM 1	SYSTEM 2	SYSTEM 3
Autonomy 1	(Ah) Eb (Wh) loadshed (V)	47,6Ah 575Wh 11.729V	55.2Ah 688Wh 11.708V	62.4Ah 730Wh 11.726V
Autonomy 2	(Ah) Eb (Wh) loadshed V	47.8Ah 578.3Wh 11.735V	48.8Ah 587.4Wh 11.717V	47.9Ah 575.2Wh 11.728V
Autonomy 3	(Ah) Eb (Wh)	55.1Ah 665.5Wh 11.73V	58.3Ah 710.4Wh 11.71V	57.0.2Ah 697.1Wh 11.73V
Autonomy 3	(Ah) Eb (Wh)	54.9Ah 662.6Wh 11.73V	55.8Ah 674.3Wh 11.71V	55.0Ah 670.2Wh

CYCLE		SYSTEM 1	SYSTEM 2	SYSTEM 3
Depletion 1 (2500Wh/day insolation)	(Ah) Et (Wh)	84.1Ah 1028Wh 11.733V	90.5Ah 1109Wh 11.708V	83Ah 1015Wh 11.726V
Depletion 2 (2500Wh/day insolation)	(Ah) Et (Wh) loadshed V	80.3Ah 910.9Wh 11.73V	90.7Ah 1113.0Wh 11.70V	89.8Ah 1010Wh 11.73V
Depletion 3(2500 Wh/day insolation)	(Ah) Et (Wh)	34.9Ah 422.9Wh 11.77 V	70.8Ah 868.5Wh 11.70V	69.0Ah 843.2Wh 11.71V

CYCLE		SYSTEM 1	SYSTEM 2	SYSTEM 3
Result 1 POA =12900	El=Et-Eb (Wh) K_p*1000=El*POA*1000 (m^2)	409 31.73	374 28.99	242 18.75
Result 2 POA =12900	El(Wh) K_p*1000 (m^2)	406 31.48	475 36.79	397 30.75
Result 3 POA =12500	El(Wh) K_p*1000 (m^2)	294 23.52	478 38.27	478 38.25
Result 4 POA =12500	El(Wh) K_p*1000 (m^2)	207 16.54	355 28.46	356 28.51
Result 5 POA =5000	El(Wh) K_p*1000 (m^2)	NA	121 24.23	110 22.05
Result 6 POA =5000	El(Wh) K_p*1000 (m^2)	NA	156 31.37	137 27.41

The mean value of K_p is 28.56, with a standard deviation of 6.20.

5.9 Discussion of results and method

The experimental flow occurred as planned: there were straight runs of autonomy, recovery, depletion, and recovery cycles. There was no unplanned battery partial state-of-charge operation, nor were the batteries forced to remain at very low voltages as has happened before in test runs at other institutions. This data probably represents a best-case set of results!

The first autonomy test yielded variable results, but this was expected since the batteries have to settle. A further three autonomy test results indicated that battery capacity had eventually stabilised for all three systems. The autonomy test discharge curves and results compared fairly closely with laboratory battery discharge curves, which predicted a discharge capacity of about 48Ah for a continuous 2A discharge current. The battery autonomy results compared well with each other for each test run. The variation from test to test could be explained by the starting time of the test, hence the different rest intervals during the intermittent discharge, or by the battery settling into the PV system.

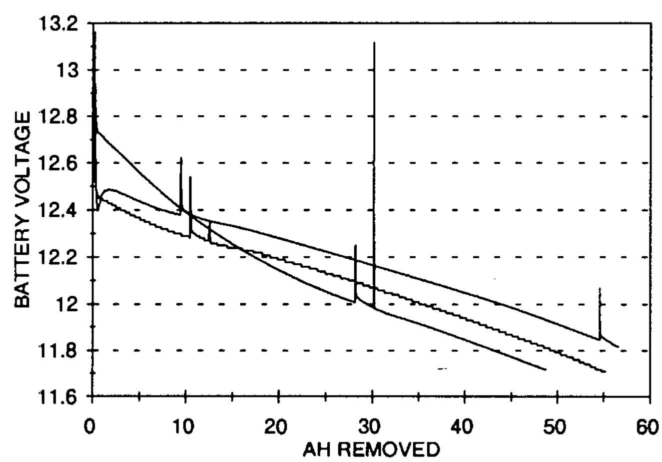


Figure 5.4 Autonomy test curves for system 2.

Depletion test Wh results were similar for the three systems, except for System 1 in which the battery seemed to lose capacity during the 2nd and 3rd depletion tests. (The autonomy results suggest, however, that this was not the cause. The battery in system 1 was found to be operating at lower discharge voltages and higher charge voltages than the other batteries in systems 2 and 3, probably as a result of some physical decay.)

Why the autonomy tests were not affected is difficult to say. Close examination of depletion test results showed that practically the same amount of charge was going into all three systems. Comparisons of autonomy test 3, depletion test 2 and depletion test 3 show the difference between battery curves for the three systems.

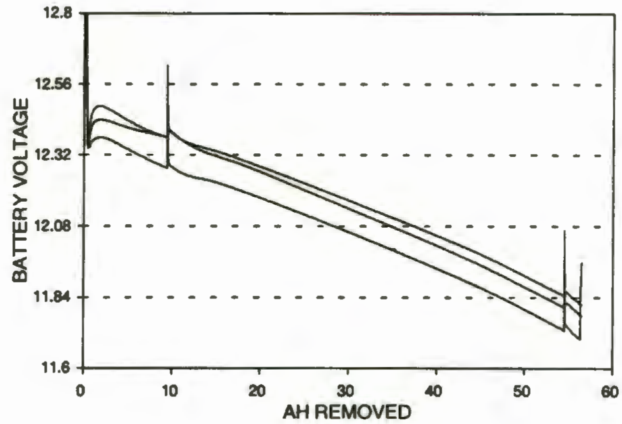


Figure 5.5 Autonomy Test 3, discharge curves for the three systems.

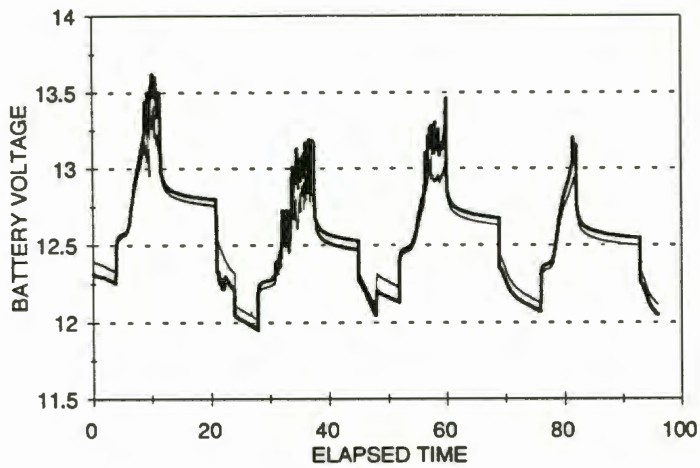


Figure 5.6 Depletion Test 2, discharge curves for four days, showing the higher voltage charge curves and lower voltage discharge curves in system 1.

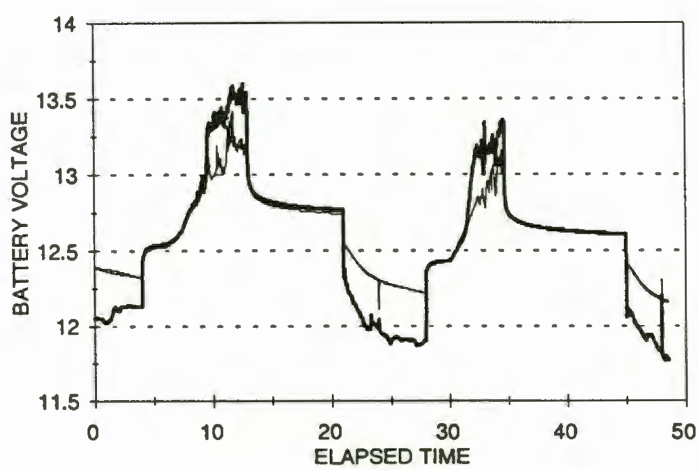


Figure 5.7 Depletion Test 3, discharge curves for two days, showing the higher voltage charge and lower voltage discharge curves in system 1.

It is possible that experimental errors may instead have crept into the depletion test.

The resultant values of K_p calculated were also variable. Some very high K_p values of 36-38 were obtained. In fact, some of these K_p values seem impossibly high when compared to module performance (see below), but it is difficult to guess which value is correct. If only one result were available per system tested, it would be impossible to know the accuracy of the result.

Based on the mean and standard deviation, the test would have to be run ... times to obtain a 10% certainty level in the output. Even this amount is probably insufficient for tender judgements, and a 5% level would be preferable.

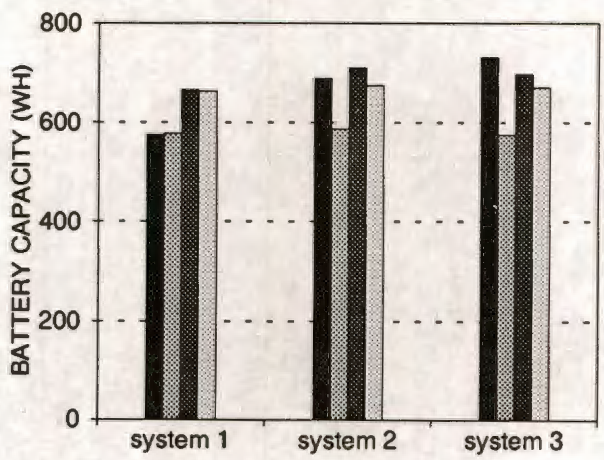


Figure 5.8 Autonomy test results

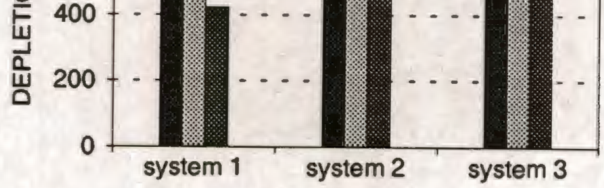


Figure 5.9 Depletion test results

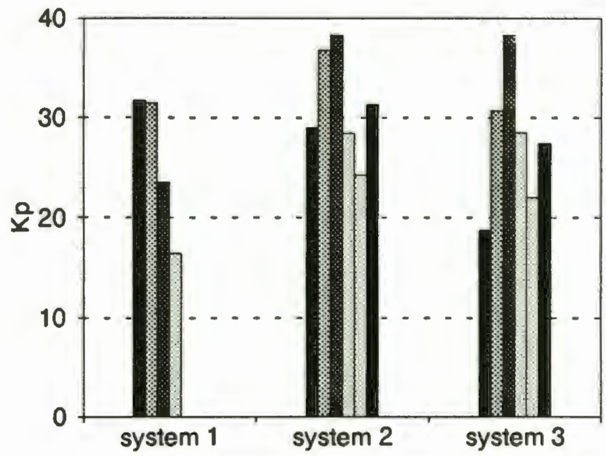


Figure 5.10 K_p values

The three panels performed similarly in the panel tests, and the measured results are tabulated below.

Table 5.4 Measured IV data for the three modules tested.

Test Conditions		Panel 1	Panel 2	Panel 3
1022W/m^2 50oC	Voc (V)	17.60	17.30	18.01
	Isc (A)	2.46	2.23	2.42
	Pmax (W)	28.3	25.2	30.0
	Vopt (V)	13.22	12.77	13.67
	Iopt (A)	2.14	1.98	2.20
	Isc/Insol (A/oC)	2.41	2.19	2.37
1000W/m^2 38oC	Voc (V)	18.64	18.18	19.01
	Isc (A)	2.23	2.05	2.20
	Pmax (W)	28.2	25.0	29.9
	Vopt (V)	14.05	13.61	14.93
	Iopt (A)	2.01	1.84	2.00
	Isc/Insol (A/oC)	2.23	2.05	2.20
886W/m^2 35oC	Voc (V)	18.79	18.79	18.79
	Isc (A)	1.93	1.93	1.93
	Pmax (W)	25.1	22.4	26.5
	Vopt (V)	14.44	13.99	15.31
	Iopt (A)	1.74	1.60	1.73
	Isc/Insol (A/oC)	2.18	2.18	2.18
446W/m^2 27oC	Voc (V)	18.60	18.22	19.00
	Isc (A)	0.87	0.82	0.86
	Pmax (W)	11.6	10.5	12.1
	Vopt (V)	15.11	14.68	15.12
	Iopt (A)	0.77	0.71	0.80
	Isc/Insol (A/oC)Voc	1.96	1.84	1.93

Panel performance in test

A test of panel performance under actual operating conditions in the system, is given by K_p/W_p. W_p is the peak rating of the module at 1000Wm^2 under normal operating conditions. The ratio should always be less than unity, sometimes just over. Array power ratings at 1000W/m^2 and 38°C were used as standard conditions during normal operation.

Table 5.5 K_p/W_p for the six results obtained. K_p/W_p should normally be less than unity.

	SYSTEM 1	SYSTEM 2	SYSTEM 3
ARRAY POWER AT 1000W/m^2 AND 38°C	28.2	25.0	29.9
RESULT 1	1.13	1.16	0.62
RESULT 2	1.12	1.47	1.03
RESULT 3	0.83	1.53	1.28
RESULT 4	0.59	1.14	0.95
RESULT 5	NA	0.97	0.74
RESULT 6	NA	1.25	0.92

These results cannot be believed without some concerted error analysis.

5.10 Causes of errors

The panels were not rated by the supplier, so there was no way of determining whether the IV test data was correct or where the errors crept in. The error is either in the IV panel test, or in the depletion radiation measurement, or in the sampling interval leading to cumulative errors. The autonomy results are probably OK in the 3rd and 4th runs.

The panel IV test described in chapter was repeated, with a lower scanning rate. Almost identical results were obtained and the IV curves and measured peak power performance of the three modules accepted as 28.2W_p, 25.0W_p and 29.9W_p at 1000W/m^2 and at NOCT.

The two other possible causes of the discrepancy are the autonomy test results and the depletion test results.

The autonomy results are consistent from battery to battery in each test, but in each battery there is some variability from test to test. They agree with the laboratory test data for the RR2 battery collected in the EDRC Battery Test Program. However, the variation in results emphasises the dangerous assumption that capacity is fixed.

The depletion test is complex and introduces several areas of error over and above those in the autonomy test. The main variant is the depletion radiation measurement. It is implicated by the message that an imprecisely measured amount of energy was going into the battery, while the autonomy tests suggest that the amount of energy flowing out was being easily and fairly accurately measured. (Easily, because it was at constant current over the hour, and accurately, because the results of the autonomy test are consistent.)

Radiation readings are difficult to check, but the Class 1 pyronometer and the ESPI calibrated reference cell performed very similarly.

Other methods of estimating the error were attempted.

Check 1

A plot of insolation versus array current during a day (20-1-93) of the depletion test showed very good alignment between the data. The average array output current for each panel was 2.14A/1000W/m^2 over the time that the array produced current (6h48 to 10h48). This figure is reassuringly close to the results produced by the IV tests (2.17A, 2.13A, and 2.44A respectively) at a normal operating temperature.

- So for the actual time that samples were taken the readings are probably accurate.
- The IV curve test is probably correct.

Check 2

The array IV curves, through the IV model, were used to translate array logged operating point data and reference cell temperature in order to estimate the insolation incident on the panels.

The estimate for the depletion run on 20-1-93 produced 2820Wh/m^2, compared with the recorded value of 2500W/m^2. 150Wh/m^2 of difference occurred before 8h48, when the sun was far from vertical and the energy was lowest, while the remaining 170Wh/m^2 occurred after over the following two hours. The same errors produced by lower average insolation indicates that the array IV model does not hold as well at lower insolations than at high insolations.

The possible error calculated in this way amount to (2820-2500)/2500 or 12.8%. This 12.8% sheds suspicion on calculated K_p values.

Check 3

Another significant contribution to the error is the sampling interval of 2 minutes, which could be problematic in cloudy or variable conditions.

An error of 10% could be expected here, resulting in under-measured insolation figures. If the figure of 2500W/m^2 were actually 10% higher, 2750W/m^2, the calculated K_p values would be significantly more believable.

But there is no way of knowing whether this is accurate.

Error conclusions

There is some error in K_p, and K_p/W_p would always be expected to be less than unity.

A 10% error in instantaneous insolation measurements is expected, and exacerbated by cumulative insolation recordings caused by low sampling rates. A continuous insolation integrator would reduce errors considerably.

A corrected insolation level is 10% higher than recorded. While this is not necessarily correct, it gives fairly believable results. It could be argued that a 10% error exists and comes from various places.

Table 5.7 Corrected insolation for the depletion tests.

	Measured Insolation (W/m^2)	Corrected Insolation (W/m^2)
Depletion 1	12900	16645
Depletion 2	12500	18961
Depletion 3	5000	6000

Table 5.8 Corrected K_p values

	SYSTEM 1	SYSTEM 2	SYSTEM 3
RESULT 1	24.59	22.47	14.53
RESULT 2	24.39	28.51	23.83
RESULT 3	15.50	25.23	25.22
RESULT 4	10.90	18.76	18.79
RESULT 5	NA	20.19	18.37
RESULT 6	NA	26.14	22.84

The mean value of K_p is 21.27, with a standard deviation of 4.65.

Table 5.8 Corrected K_p/W_p values

	SYSTEM 1	SYSTEM 2	SYSTEM 3
ARRAY POWER AT 1000W/m^2 AND 38°C	28.2	25.0	29.9
RESULT 1	0.87	0.90	0.49
RESULT 2	0.86	1.14	0.80
RESULT 3	0.55	1.01	0.84
RESULT 4	0.39	0.75	0.63
RESULT 5	NA	0.81	0.61
RESULT 6	NA	1.05	0.76

These corrected results are far more credible, though they still suggest that inaccuracies exist in the test.

5.11 Other practical problems

Though the PV performance test is supposed to be a simple test requiring a minimum of instrumentation, there are a host of small problems that can ruin a whole experimental run or require a complete restart.

Practical problems encountered during the EDRC test were:

- array mounting blew down;
- UPS problems;
- accuracy of irradiance measurements (at least they were noticed here);
- variation in autonomy test results.

Problems encountered by ESKOM during a tender evaluation

- lightning strike knocking data logger;
- software errors, causing data logging to cease without the test itself being terminated;
- inadequate software error checking, so inadequate software control to detect PV system errors and halt testing and save batteries from damage;

(the above problems all resulted in battery failure and total test reruns)

- IV curves were inaccurately or inadequately measured.

General problems are

- Cumulative errors, especially in radiation measurement;
- Offset errors, in all readings. Any data logger offsets must be removed;
- Battery failure can easily occur, as a result of testing problems rather than battery problems.

5.12 Conclusions

- The test method is elegant in philosophy, attempting to provide very usable results in a quick, economic and easy manner.

- The test method is not simple, and requires
  - high quality measurement equipment;
  - skilled personal to install;
  - well tested logging and control software. Manual readings are likely to produce results of totally insufficient accuracy;
  - skilled and committed personal to analyse the data to produce meaningful results.

- The recommended test procedure cycles the battery only once or twice, which is hardly sufficient to determine whether the battery cycling regime is suitable or not.

- The performance of tender systems should only be compared if tested together in the same batch. Ideally, test results should be transferable between batches but each experimental set-up will be slightly different, and it is far too easy for errors to slip in unnoticed.

- The results produced here are poor, not because the PV systems are poor, but for other reasons. In fact, by local standards the PV systems are conservatively designed.

CHAPTER 6

SIMULATED ARRAY PV SYSTEM LABORATORY TEST

The challenge of the PV system performance test (PVSPT) described in chapter 5 is one of estimating accurate array-to-load path efficiency when some energy is cycled through the battery. The recommended method is intended to be performed by technicians with no particular PV or testing experience, perhaps even on site after the system has been installed.

However, the results of chapter 7 show that the test method is not trivial and is quite prone to experimental error. The method invariably requires a skilled operator and analyst to produce credible results since it is sensitive to many external effects. It can also be time-consuming and expensive to perform.

A quicker laboratory based test procedure is proposed for determining the array-to-load path efficiency.

6.1 Test philosophy

Instead of becoming involved in the experimental uncertainties of conducting two separate tests (autonomy and depletion tests) and taking the difference in energy outputs to provide the required result, the new Simulated Array PV System Performance Test (SAPVSPT) method requires only one performance test involving the battery, (assuming that the battery has already been characterised in the component testing program, and that its capacity dependence on discharge current is known. Most components, aside from the modules of typical stand-alone systems encountered in SA, have been tested in the course of the EDRC component testing program.)

The new SAPVSPT estimates the path efficiency from only one charge/discharge cycle of the battery. The DOD range of this carefully chosen cycle is based on the average daily load and a typical solar day. The exact starting DOD is chosen so that the cycle is representative of partial-state-of-charge cycling (PSOC), and so that the battery is out of the gassing region and above the loadshed region.

The old PVSPT, in comparison, calculates an average array-to-load path efficiency over the whole range of battery DOD's encountered between full charge and eventual loadshed. Pictorially, the depletion test is shown in figure 6.1, where the battery is cycled from full charge downwards in a series of daily charge/discharge cycles, with more Ah being removed each day than are restored. The test assumes that the same amount of time will be spent at each battery DOD.

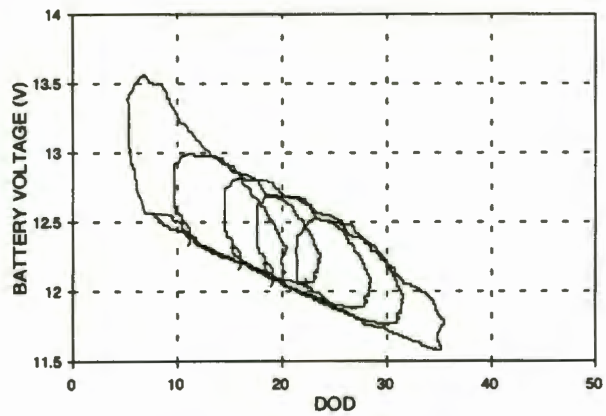


Figure 6.1 Many depletion cycles of the PVSPT.

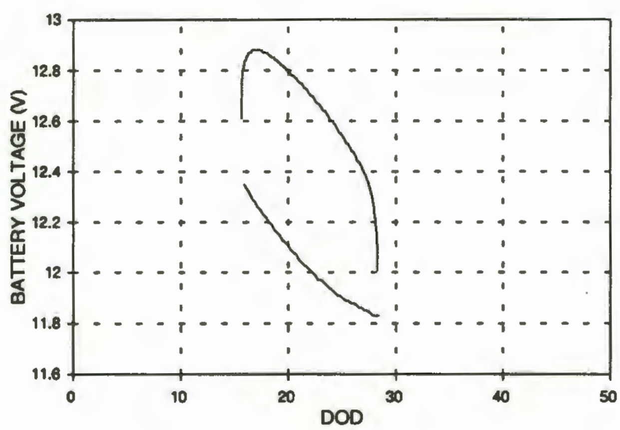


Figure 6.2 Single depletion cycle of the SAPVSPT.

In the new cycling method, all components of the PV system are used except for the array. The PV array is tested and simulated by the array model (chapter 5) on a computer which controls a programmable DC electronic power supply. The regulator, battery and wiring of the supplied system are wired to the simulated array, and hardware simulation is used to locate the array/battery operating point and determine energy input to the battery. A programmable electronic load simulates the load. Currents and voltages are measured at strategic locations in order to calculate energy flows around the system.

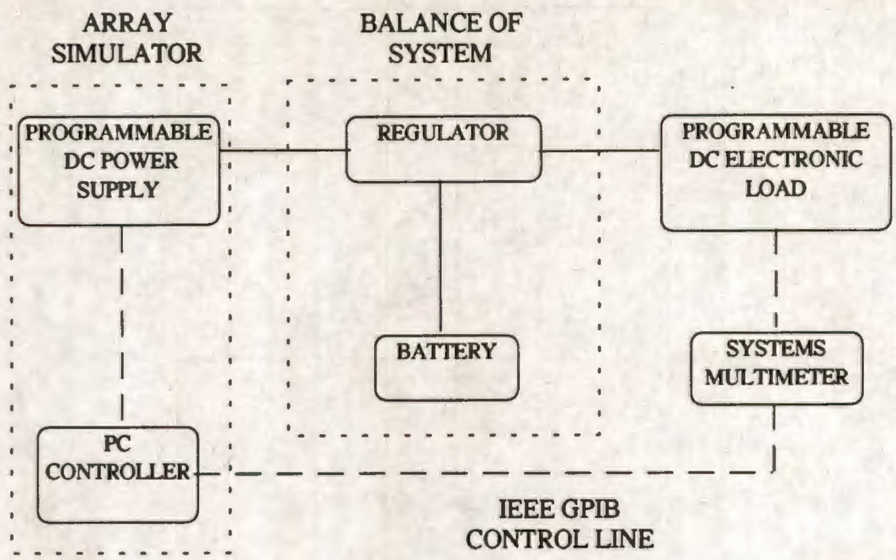


Figure 6.3 Experimental set-up.

6.2 Procedure for the SAPVSPT

1- The PV modules supplied are characterised in an IV test, and fitted to the PV model as described in the procedure recommended in chapter 4.

2- The regulator is tested in the laboratory to determine its loadshed voltage. Operating algorithm, power consumption under various conditions, loadshed voltage and charge cut-off voltage are also useful but non-essential data.

3- The current draw of the supplied load is measured, and the load is characterised in terms of constant current, constant resistance, constant voltage or constant power. The design load is also recorded in Ah/day ($Load_{design}$).

4- If the battery brand type has not been tested before in the laboratory, it is subjected to a capacity test at the rated load current till regulator loadshed voltage cut-off (C_{dis}).

5- The complete system (excluding the array) is wired up with the power supply connected in place of the array, and the programmable load in place of the real load.

6- The system is float-charged by the power supply until the battery reaches full charge on the charge regulator. Currents and voltages should not exceed the maximum array outputs, or else damage could occur to the regulator.

7- The array is then switched off, and the battery is partially discharged at the rated load current to the start DOD of the charge cycle. The number of Ah removed should be

$DOD_{start} = 0.5\ C_{dis} + 0.5\ Load_{design}$

8- The charge cycle begins using the simulated array under a typical daily insolation profile (Figure 6.4 daily insolation profile). The current through the battery current shunt to the battery is carefully recorded and integrated to accumulate Ah into the battery.

Alternatively, the Ah to the battery (Ah_{in}) can be estimated as:

Ah_{array} - (regulator power * hours of charge cycle)

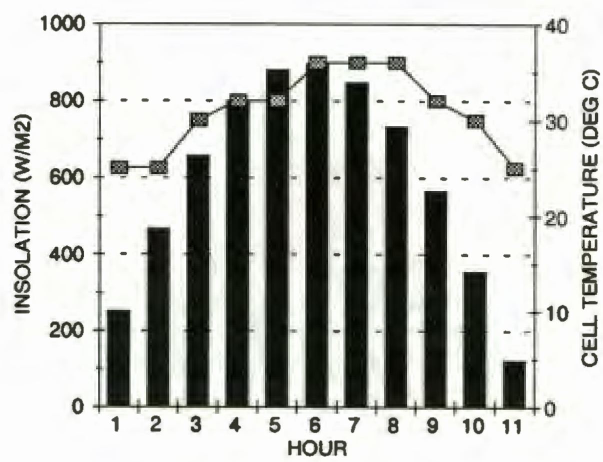


Figure 6.4 Daily insolation and temperature profile

9- The discharge cycle at the rated load current follows the charge cycle. The number of Ah removed should be exactly equal to the Ah replaced in the charge cycle (see 8 above). The discharge current is measured at the load, but the Ah removed are again based on the battery current through the battery current shunt, which also accounts for regulator power consumption.

Alternatively, The Ah removed from the battery can be estimated as:

$Ah_{out} = Ah_{load}$ + (regulator power) * discharge time

10- The factor K_p, which is an estimate of the array peak watt power rating after allowing for system efficiencies (over the course of a complete depletion run), can be calculated as follows:

$K_p = Wh_{out} / \sum Insol * 1000$

Wh_{out} =	total energy (Wh) delivered to the load.
$\sum$Insol =	daily insolation accumulated in the charge cycle (6520Wh/m2 in the control day).

The array performance relative to optimal performance at the maximum power point can be calculated as

K_p / W_p,

where W_p is the rated power at 1000Wm2 at NOCT.

11- If the battery capacity is required for further calculation, it can be obtained from stage 4. If data on suitability of battery operating regimes is required, battery cycling tests can be done in the laboratory.

The simulation/cycling test takes less than 24 hours to complete. This could be the duration of the complete SAPVSPT procedure if the other components have already been tested in the laboratory as part of routine product characterisation.

In effect all components are tested either individually or as part of the system in the performance simulation
- array (laboratory IV curve determination)
- regulator (laboratory and performance tests)
- battery (laboratory and performance and cycling tests)
- wiring (performance test only)

If the SAPVSPT test is to be carried on older PV systems where component degradation may have occurred, the componets may be quickly retested individually to provide the necessary input data.

(When a battery from the field has to be retested, a gentle float charge followed by a capacity test at the rated load current should suffice for preconditioning. After the performance test procedure, the battery is boost-charged and retested for capacity to detect recoverable capacity, which may indicate problems in the PV system charge regimes.)

6.3 Systems for testing

The procedure was tested using a sample PV system. The system was identical to those tested in the EDRC PV Systems Performance Test (chapter 7).

The system is detailed below:
- single array (BP Solar 40W_p poly-crystalline)
- single battery (Raylite RR2 100Ah 12V modified SLI type)
- battery regulator (PDI 12V 5A boost/float regulator with 5A loadshed protection and low voltage warning)
- wiring provided only for charge side. (Length 20m from regulator to array and back to regulator).

The design load for the system is 120Wh per day, (10Ah).

6.4 Test results

IV test

The module was tested as outlined in chapter 4. The actual module tested is described in that chapter. The results only are listed here for completeness.

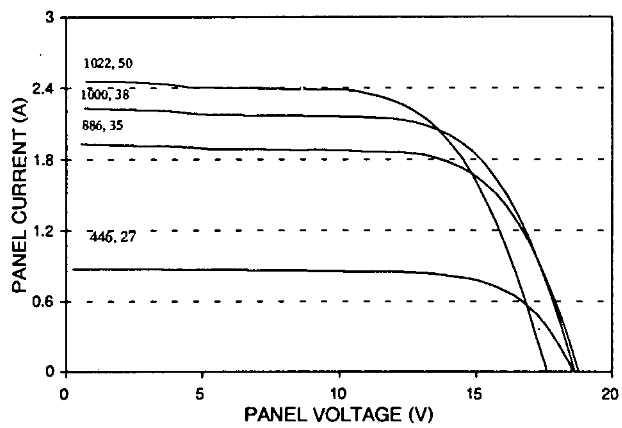


Figure 6.5 IV scan for four curves

The table below shows the measured output characteristics.

Table 6.1 Results of the module IV test.

Test condition	1022W/m² 50°C	1000W/m² 38°C	886W/m² 35°C	446W/m² 27°C
V_{oc} (V)	17.60	18.64	18.74	18.60
I_{sc} (A)	2.40	2.23	1.93	0.87
P_{max} (W)	28.3	28.2	25.1	11.6
V_{opt} (V)	13.22	14.05	14.44	15.11
I_{opt} (A)	2.14	2.01	1.74	.77
I_{sc}/Irr *1000	2.41	2.23	2.18	1.96

The array model coefficients (details in chapter 4) under standard conditions (1000W/m^2 and 25°C) are:

I_{sc}	:	2.09A
V_{oc}	:	20.4V
I_{opt}	:	1.880A
V_{opt}	:	16.01V
P_{max}	:	29.7W_p (26.93W_p at 46°C)
alpha	:	0.009A/°C
beta	:	-0.136V/°C

Wiring losses
The resistance of the wire length from the array to the regulator and back was measured as 0.4Ω.

Regulator test
The regulator was the relay type, using a boost/float algorithm.

The regulator loadshed voltage was 11.73V. The boost voltage was 14.4V, and the float setting was 13.8V. The power consumption under normal boost mode operation was 40mA.

Energy efficiency curves for the regulator were available from previous work.

Design load rate
The design load current was 3A, constant current operation.

Battery capacity test
A new Raylite RR2 battery was supplied. RR2's had previously been tested in the laboratory so it was unnecessary to do additional testing. Discharge curves required for determination of the cycling regime show the capacity at 3A to 11.73V as 48Ah.

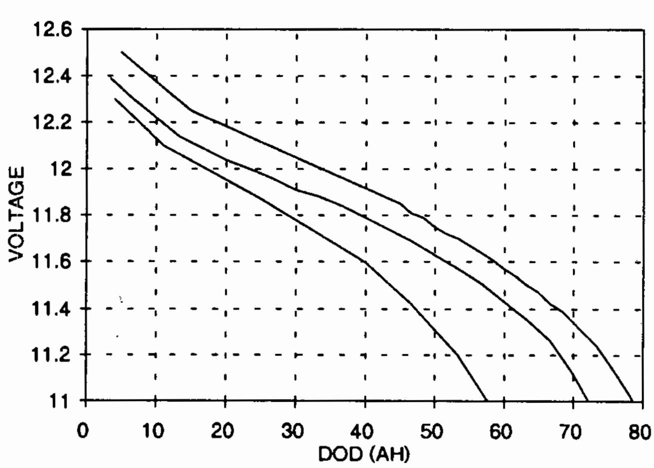


Figure 6.6 RR2 discharge curves at low load currents

Start DOD

The start DOD was calculated as

$$DOD_{start} = 0.5*48Ah + 0.5*10Ah = 29Ah.$$

The cycling regime was from a DOD of 29Ah to about 19Ah DOD and back to 29Ah DOD exactly.

Discharging to 29Ah DOD at 3A gave an end of discharge voltage of 12.01V at the battery terminals. The available battery capacity is estimated from the experiment to be about 50Ah to the loadshed voltage of 11.73V

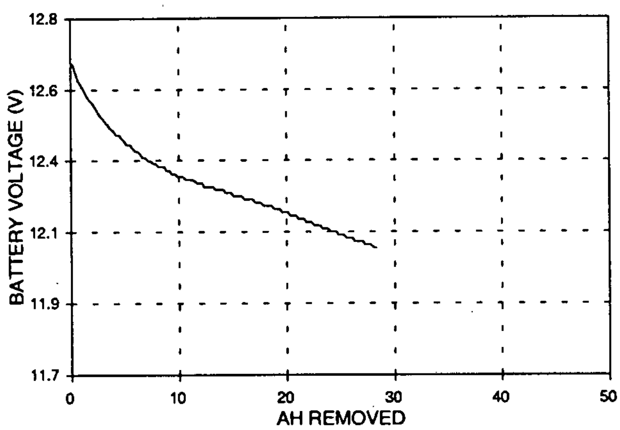


Figure 6.7 Discharge curve at 3A till 29Ah DOD.

Test plot (V vs Ah)

A plot of battery voltage versus DOD is presented for the charge/discharge cycle.

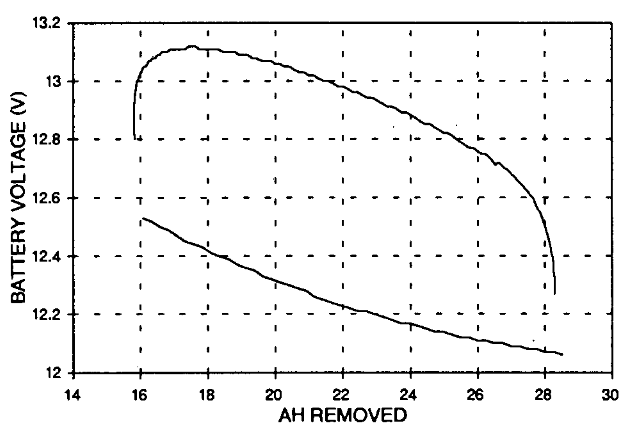


Figure 6.8 Plot of battery voltage versus DOD for the experimental run.

K_p array-to-load path efficiency indicator

The complete test procedure was repeated three times, each time recharging the battery completely.

Table 6.3 Results of the path efficiency tests.

		Test 1	Test 2	Test 3
CHARGE CYCLE	Ah in (battery)	12.89 Ah	12.47	12.61
	Wh in (battery)	155.8 Wh	161.8	159.8
	Wh in (panel)	173.2 Wh	178.4	177.0
	Max Wh in (panel)	180.5 Wh	180.5	180.5
	Insolation (W/m2)	6520	6520	6520
DISCHARGE CYCLE	Ah out (battery)	12.89 Ah	12.44	12.67
	Wh out (battery)	147.0 Wh	150.4	150.7
	Wh out (load)	141.0 Wh	145.6	145.2
RESULT	K_p	21.62	22.3	22.3

6.5 Discussion

A set of consistent K_p values has been obtained from this test method. Consistent estimates for battery autonomy were also obtained from the initial discharge.

Analysis of efficiencies.
This hardware approach allows easy analysis of individual path efficiencies within the system. Figure 6.9 shows the energy flows measured for the first test.

The results and efficiencies for the tests are tabulated.

Table 6.3 System energy flows

	TEST 1	TEST 2	TEST 3
Insolation	6522	6522	6522
Wh array	173.2	178.4	177.0
Wh regulator	155.8	161.8	159.8
Wh battery	147.0	150.4	150.7
Wh load	141.0	145.6	145.2

Table 6.4 System component energy efficiencies.

	TEST 1	TEST 2	TEST 3
Array opt power (potential in = 180.41Wh)	95.96%	98.89%	98.12%
array wiring and regulator efficiency	89.95%	90.69%	90.28%
battery cycle efficiency	94.35%	92.95%	94.31%
load wiring and regulator efficiency	95.92%	96.81%	96.35%
overall	77.86%	80.70%	80.49%

The results are easily reproducible.

Sub-System Efficiencies

array charge	battery wire & reg.	load wire & cycle reg. effic.	overall	
$\frac{173.2}{180.5}$ x	$\frac{155.8}{173.2}$ x	$\frac{147.0}{155.8}$ x	$\frac{141.0}{147.0}$	
95.96% x	89.95% x	94.35% x	95.92% =	77.86%

Array power = $29.70W_p$ @ $1000W/m^2$ and 25°C
$28.79W_p$ @ $1000W/m^2$ and 32°C
$27.76W_p$ @ $1000W/m^2$ and 40°C (NOCT)

Overall System efficiency can also be calculated from K_p/W_p
$= 21.62K_p / 27.76W_p = 77.88\%$ @ $1000W/m^2$ and 40°C

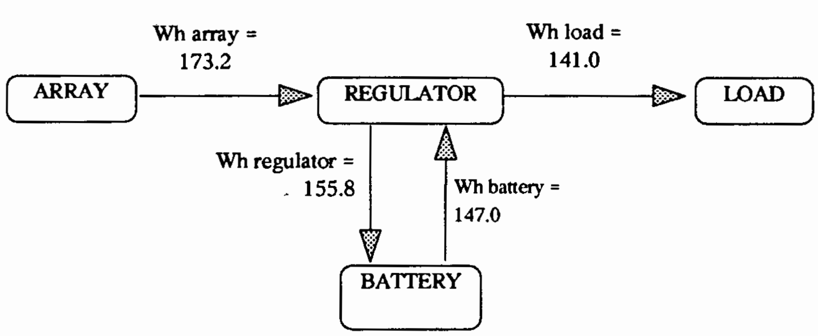


Figure 6.9 Energy flows for system/subsystem efficiencies for the first test.

6.6 Conclusions

A laboratory based method for determining array-to-load path efficiency has been proposed, and the practicalities of the method tested.

The method

- is easy for determining path efficiency.
- provides reproducible results.
- requires considerable hardware and software, but experimental errors are minimised.
- makes use of data already available.
- can be supplemented by additional laboratory data, ie battery cycling data that takes far too long to gather in real time.

In the proposed method, the PV array is tested and modelled, in an attempt to isolate the experimental uncertainties. The main errors in the method are introduced in the PV array testing stage, but uncertainties are small. PV arrays tested in specialist PV testing laboratories will introduce fewer errors as models can then be fitted with more confidence.

CHAPTER 7

PAPER-BASED PV SYSTEM EVALUATION METHOD

PV system design, and PV system performance tests (PVSPT) require calculation of the array-to-load path efficiency when some energy is cycled through the battery. Path efficiency information, data of usable battery capacity and data for a properly functioning charge/discharge regulator of specified algorithm and set-points, should enable a proper snapshot performance assessment of the PV system.

Almost all of this information is available from individual component tests, which are routinely performed as part of an EDRC Component Testing program. It is only the array-to-load path efficiency information that is not readily available, mainly because this depends on the combination of components selected.
In chapter 5 the full PV system performance test procedure was described and tested.

Chapter 6 outlined an approach for determining the array-to-load efficiency (compared with the rated array output) using a simplified laboratory-based hardware test.

This chapter describes a paper-based approach to the problem of predicting performance with combinations of components. This is particularly useful and economic from a time perspective if all of the components have already been characterised. The method also allows quick analysis of performance outcomes with different combinations of components, without the costs of redoing long sequences of expensive hardware measurements.

7.1 Test philosophy

The conventional PVSPT calculates an average array-to-load path efficiency over the whole range of battery depth-of-discharge (DOD's) encountered between full charge and eventual loadshed. The battery is cycled from full charge downwards in a series of daily charge/discharge cycles, with more Ah being removed each day than are restored. The test assumes that the same amount of time will be spent at each battery DOD.

The Paper-Based PV System Evaluation test, (and the laboratory method in Chapter 6) attempt to estimate the path efficiency from one battery charge/discharge cycle only. The DOD range of this carefully chosen cycle is based on the average daily load. The exact starting DOD should be chosen so that the cycle is representative of partial state-of-charge cycling, and so that the battery is out of the gassing region and above the loadshed region.

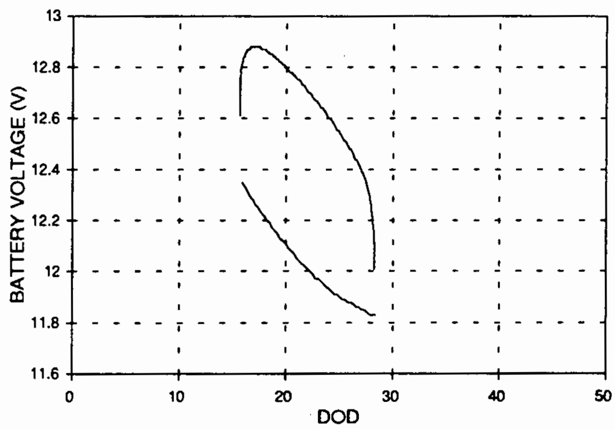


Figure 7.1 A single depletion cycle of the battery could provide an approximation of the array-to-load path efficiency.

Instead of hardware testing or simulation, the array/battery operating point is approximated graphically, by construction of graphs of module IV characteristics, battery charge curves and regulator voltage drop measurements. Load energy is determined from available battery discharge curves and regulator efficiency curves. Operating points for a complete solar day or charge/discharge cycle are conveniently determined in hourly increments, but could be done at finer time intervals if desired.

7.2 Procedure

1- The PV module output characteristics are fitted to a PV model (chapter 5). Modules must first be subjected to an IV test if this has not already been done. The model enables approximation of module performance under any conditions in the solar day.

2- The voltage regulator algorithm, power consumption under various conditions, loadshed voltage and charge cut-off voltage, and voltage drop test data are obtained from published data.

3- The load is characterised as one of constant current, constant resistance, constant voltage or constant power, and the load current noted, as well as the daily design load ($Load_{design}$, Wh).

4- If the battery brand type has not been tested before, it is subjected to a capacity test (C_{dis}) at the rated load current until regulator loadshed voltage cut-off. Charge curves at low charge rates are also required, and can be obtained from laboratory test data.

7- The start DOD for the array-to-load efficiency cycle is calculated as

$$DOD_{start} = 0.5\ C_{dis} + 0.5\ Load_{design}$$

8- Calculate the energy input (Wh) and the Ah into the battery.

The solar energy input is based on a typical daily insolation profile.

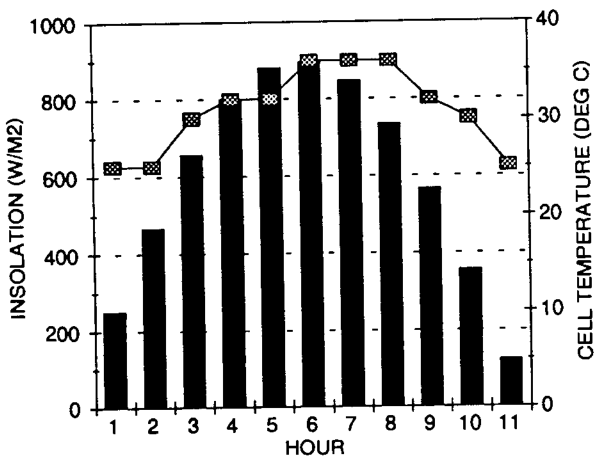


Figure 7.2 Hourly insolation and cell temperature profiles used as a representative solar day. The total irradiance is $6520 Wh/m^2$.

Calculating the actual energy input requires calculation of the array operating point. This point is the result of the interaction of the array and battery/regulator pair. The following steps should be followed.

a) draw the set of hourly IV curves for the PV array, based on the typical solar day and the fitted PV model.

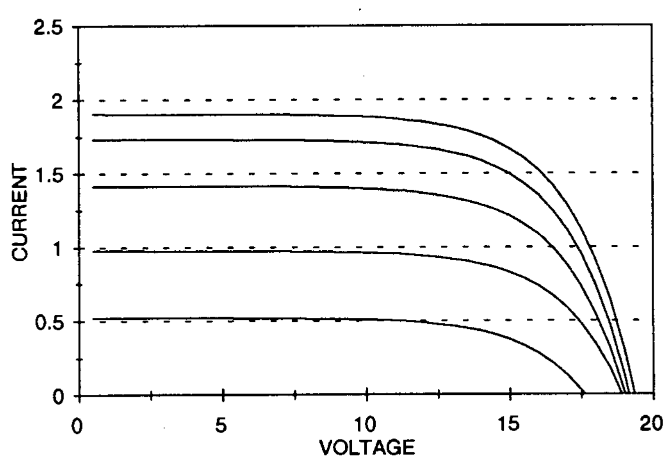


Figure 7.3 Hourly IV curves for the array, for the hourly insolation profile.

b) Construct and draw the battery/regulator/wiring IV curve. This involves the following steps:

- getting the battery IV vs DOD charge curves over range of battery operation.

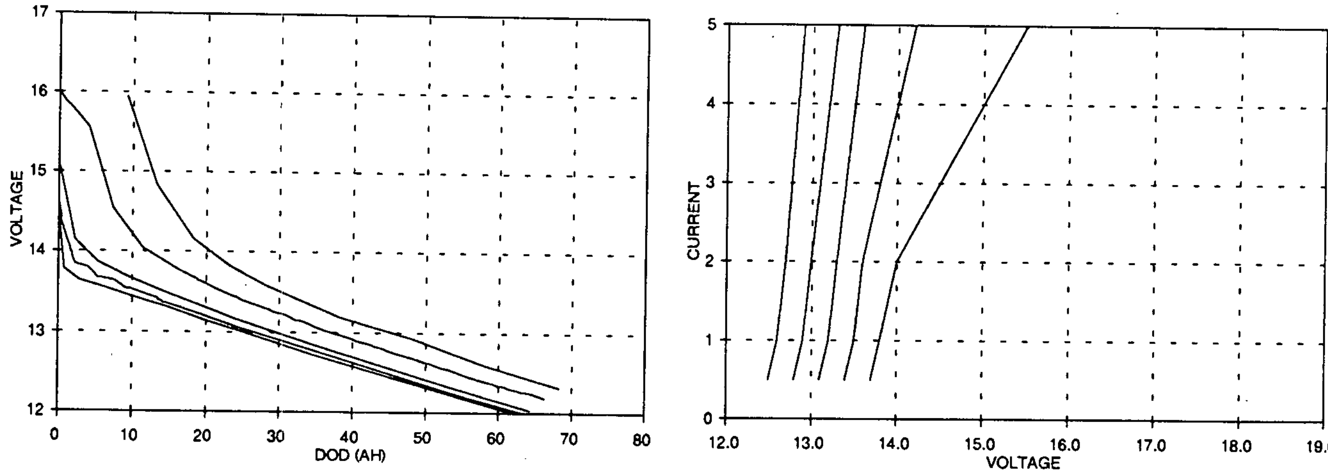


Figure 7.4 Battery charge curves can be converted to IV curves over a small SOC range. Here the IV curves are constructed over a range 29Ah DOD to 19AH DOD, in increments of 5Ah for the Raylite RR2 battery.

- adding regulator resistance
- adding wiring loss resistance

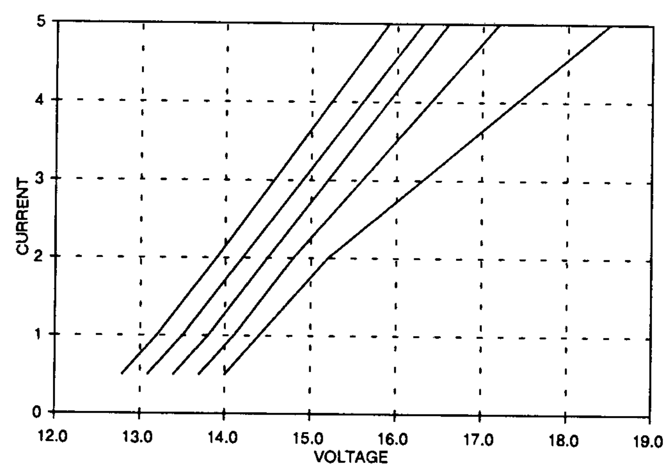


Figure 7.5 Battery/regulator/wiring IV curves. The regulator resistance is 0.1Ω, and the wiring 0.4Ω.

c) Calculate the hourly array current. This is simply the current given by the intersection of the array IV curve at the hour, and the battery/regulator IV curve at the DOD at that time.

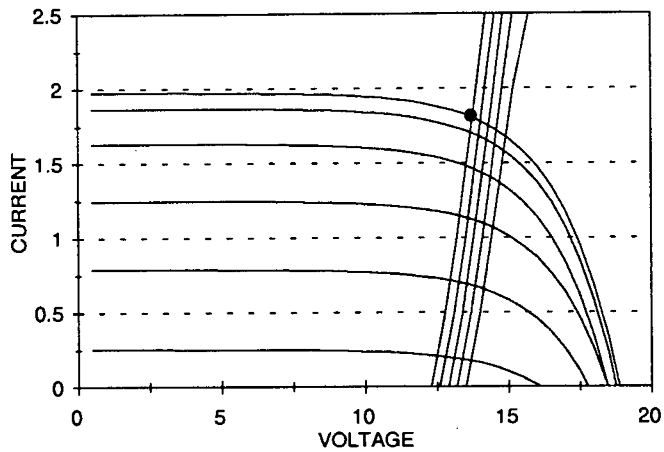


Figure 7.6 Operating point for the array and battery/regulator for an insolation of 734W/m^2 and temperature of 36°C (ie 14h00 of the typical solar day), with a battery DOD of 29Ah. Note that the operating point will in many systems be on the flat section of the module IV curve and not on the knee, so that this stage may be significantly simplified.

d) Accumulate the charge into the battery (Ah), allowing for regulator energy consumption, and determine the battery SOC at the end of the hour.

$$Ahin_{hour} = (\text{array current - regulator current})*\text{hour}$$

$$DOD_{new} = DOD_{old} + Ahin_{hour}$$

Keep recalculating the Ah_{in} till the end of the solar day, continually updating the battery DOD every hour and locating the operating point on the IV curves.

Record the DOD at the end of the charge cycle (DOD_{end}), and the total energy delivered to the battery ($Ahin_{cycle}$) where

$$Ahin_{cycle} = DOD_{start} - DOD_{end}$$

9- Calculating the energy output to the load.

During the load cycle, it is necessary to remove the same number of Ah from the battery as were put into the battery during the charge cycle ($Ahin_{cycle}$), so that the battery returns to the same DOD at which the cycle started.

To calculate the energy output to the load, one needs to compensate for the regulator energy consumption and load side voltage drops.

The following equations hold:

a) $Ahout_{cycle}$ = $Ahin_{cycle}$ = Ah to load + Ah to regulator

b) $current_{total}$ = $current_{load}$ + $current_{regulator}$

c) Discharge time = $Ahout_{cycle}/current_{total}$

d) $Energy_{load}$ =
$current_{load}$ * $(Vbattery_{(hour)}-current_{load}*resistance_{regulator})$

The battery voltage is obtained from the battery discharge curves for the particular discharge current and DOD relevant to that time.

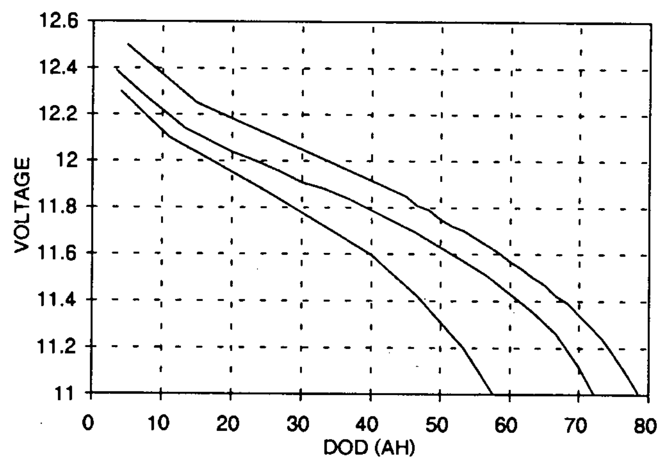


Figure 7.7 Energy output from the battery depends on the discharge current, DOD and voltage. At 19Ah DOD and a current of 3.04A, the energy over one hour will be 3.04*12.15=36.94W. The total energy to the load if the regulator consumption is 40mA and line losses are 0.5Ω will be 3.00*(12.15-3*0.5)=31.95W.

Step d) is repeated on an hourly basis till the discharge time as calculated is reached.

10- The factor K_p, which is an estimate of the array peak watt power rating after allowing for system efficiencies, can be calculated as follows:

$$K_p = Wh_{out} / \sum Insol * 1000$$

Wh_{out} = total energy (Wh) delivered to the load.
$\sum Insol$ = daily insolation accumulated in the charge cycle.

The array-to-load path efficiency can be approximated by comparing K_p to the rated array peak watt rating (W_p).

$$\eta_{array\text{-}load} = K_p / W_p$$

The evaluation should take only a few minutes if the information is readily available for the components.

The PBPVE method can easily be used to evaluate older systems where component degradation may have occurred.

Laboratory data showing irreversible or reversible decrease in battery capacity with age or degradation can be substituted for data derived from new batteries to check the effects on system performance.

7.3 Systems for testing

A system identical to those tested in the EDRC PV Systems Performance Test (chapter 5) and the Simulated Array Performance Test (chapter 6) was selected.

The system is detailed below:

- single array (BP Solar $40W_p$ poly-crystalline)
- single battery (Raylite RR2 100Ah 12V modified SLI type)
- battery regulator (PDI 12V 5A boost/float regulator with 5A loadshed protection and low voltage warning)
- wiring provided only for charge side. (Length 20m from regulator to array and back to regulator).

The design load for the system is 120Wh per day, (10Ah).

7,4 Test results

IV test

The module was tested as outlined in chapter 4, and the module tested is described in that chapter. The results and model correlation coefficients only are listed here:

Table 7.1 Measured output characteristics.

Test condition	1022W/m² 50°C	1000W/m² 38°C	886W/m² 35°C	446W/m² 27°C
V_{oc} (V)	17.60	18.64	18.74	18.60
I_{sc} (A)	2.40	2.23	1.93	0.87
P_{max} (W)	28.3	28.2	25.1	11.6
V_{opt} (V)	13.22	14.05	14.44	15.11
I_{opt} (A)	2.14	2.01	1.74	.77
I_{sc}/Irr *1000	2.41	2.23	2.18	1.96

The array model coefficients (details in chapter 4) under standard conditions (1000W/m^2 and 25°C) are:

I_{sc}	:	2.0935A	
V_{oc}	:	20.4V	
I_{opt}	:	1.880A	
V_{opt}	:	16.01V	
P_{max}	:	29.7W_p	(26.93W_p at 46°C, 27.76W_p @40°C, 28.79W_p @ 32°C)
alpha	:	0.009A/°C	
beta	:	-0.136V/°C	

Wiring losses

The resistance of the wire length from the array to the regulator and back was measured as 0.4Ω.

Load side wiring losses amounted to 0.2Ω.

Regulator test

The regulator was the relay type, using a boost/float algorithm.

The regulator loadshed voltage was 11.73V. The boost voltage was 14.4V, and the float setting was 13.8V. The current consumption under normal boost mode operation with loadshed inactive was 40mA.

Charge side resistance was 0.1Ω array to battery, and load side resistance was 0.1Ω from battery to load..

Design load rate

The design load current was 3A, constant current operation.

Battery capacity test

The test battery was a new Raylite RR2 battery, one of which had previously been tested in the EDRC laboratory. The capacity at 3A to 11.73V was estimated at 48Ah. Charge curves were also available.

Start DOD

The start DOD was calculated as

0.5*48Ah + 0.5*10Ah = 29Ah.

The cycling regime, calculated from the daily design load, was from a DOD of 29Ah to about 19Ah DOD and back to 29Ah DOD.

Results

The family of curves used for calculating operating points were shown earlier. Operating points were graphically determined.

(A computer simulation could easily be used to solve for the operating points. The PC simulation is likely to be adequate when the battery operating point is on the flat section of the array IV curve. When the operating point is likely to be near the knee of the array IV curve, any error in battery charging curve data will cause compounded errors in array current. In this case, neither the computer simulation nor paper-based approach will be accurate, and simulation of battery operation may be inappropriate. The hardware evaluation approach of chapter 6 may be better.)

The tables below show calculation tables and how results are usefully presented.

Table 7.2 Charge table..

PRELIMINARY CALCULATIONS

Load current (A)	3
Regulator consumption (mA)	0.04
Discharge current (A)	3.04
Battery capacity @ discharge current (Ah)	48
Design load (Wh)	120

CHARGE TABLE

Start DOD for charge cycle (Ah) 29

	Hour	Insolation	Array Tcell	Array MaxP		Array voltage	Array current	Ahin	Array Power
	1	250	25	6.1	13	13.22	0.44	0.44	5.8168
	2	467	25	12.5	13	13.425	0.85	1.29	11.41125
	3	657	30	18.2	13	13.645	1.29	2.58	17.60205
	4	799	32	22.5	13	13.795	1.59	4.17	21.93405
	5	881	32	24.6	13	13.875	1.75	5.92	24.28125
	6	897	36	25	13	13.885	1.77	7.69	24.57645
	7	847	36	23.6	13	13.895	1.79	9.48	24.87205
	8	734	36	20.2	13	13.72	1.44	10.92	19.7568
	9	567	32	15.4	13	13.55	1.1	12.02	14.905
	10	357	30	9.4	13	13.325	0.65	12.67	8.66125
	11	121	25	3	13	13.15	0.3	12.97	3.945
totals		6577		180.5			12.97		177.76195
regulator consumption (A)				0.04		0.44			
Ah to battery						12.53			
				0.5					
Array optimum power efficiency				98.5%					

Table 7.3 Discharge table..

DISCHARGE TABLE

Load current (A)	3
Regulator consumption (A)	0.04
Discharge current (A)	3.04
Discharge time (hrs)	4.12
Load wire resistance (ohms)	0.2

Start DOD for discharge cycle (Ah) 16.47

hour	Battery current	Battery DOD	Battery voltage	Battery energy	Load energy
1	3.04	19.51	12.25	37.24	35.39
2	3.04	22.55	12.2	37.09	35.24
3	3.04	25.59	12.15	36.94	35.09
4	3.04	28.63	12.1	36.78	34.94
4.12	3.04	29.00	12	4.44	4.22
totals				152.49	144.87

RESULTS

Kp = 22.03
Wp = 27.76 (@ 1000, 40degC)
System array-load efficiency 79.35%

K_p, path efficiencies and sub-system efficiencies

The calculated value of K_p from the paper based test is 22.43. This is the effective array peak watt value at $1000W/m^2$ at NOCT after the energy has been through the whole system. This figure can be compared with the measured module peak power at NOCT, which is $27.76W_p$ at 40°C. The array-to-load path efficiency is therefore

22.43/27.76 = 80.8%. [79.68%]

The module optimum power efficiency is the actual module energy output at the operating point / energy output at the maximum power point. Over the charge cycle,the optimum power point is

177.6 / 180.5 = 98.3%. [97.56%]

The paper based method does not allow for very rapid calculation of individual component efficiencies, though they can be easily obtained with a little time.

The battery cycle efficiency is
154.98/162.8 = 95.2% [93.87%]

Array to battery efficiency is
162.8/177.6 = 91.7% [90.31%]

battery to load efficiency is
147.23/154.98 = 94.99% [96.35%]

(These results are similar to those in the hardware simulation method of chapter 6, which are shown in square brackets [..%].

The usable battery capacity at the design load is 48Ah when the battery is in good condition. If the battery were to decay, according to decay data available (figure 7.8) the usable capacity would fall to 30Ah and the efficiencies would probably decrease.

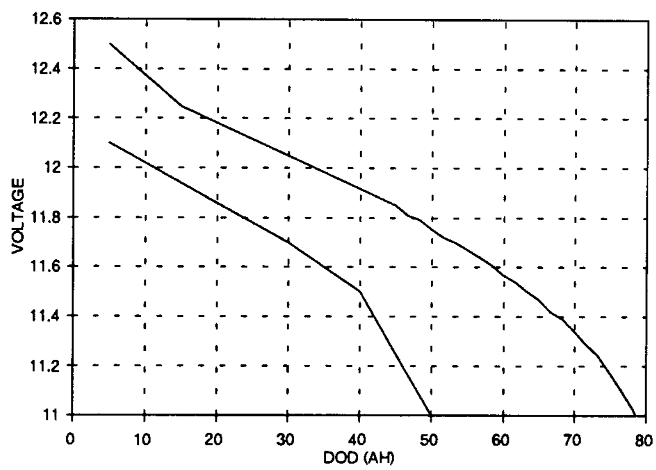


Figure 7.8 Batteries naturally lose capacity with age depending on treatment. An RR2 battery from a PV system showed a stable but reduced capacity. For the same discharge regime as before, the energy from the battery over one hour falls to 36.02Wh [36.94Wh], while after regulator and line losses the energy is 31.05Wh [31.94]. This difference may be small, but usable capacity drops from 50Ah to 30Ah at a cut-off of 11.7V.

7.5 CONCLUSIONS

The paper-based method of PV evaluation is a simple procedure that should also be used in the system design process. All data required ought to be available from published component data, with the exception, perhaps, of panel data.

The method yields straightforward, unambiguous results.

Suppliers of systems for tender could easily provide these results as part of specification documents. Suppliers should be encouraged to go through the calculation steps themselves as part of the design process anyway.

Battery decay prediction is usually a matter of judgement. System designers should ensure that they comply with recommended battery operating regimes to minimise decay, and use developed procedures aimed at making this judgement easier.

CHAPTER 8

DISCUSSION OF PV SYSTEM TESTING METHODS

PV system test methods have been developed to assist in the evaluation of small PV systems with battery storage, primarily for pre-tender award evaluation.

The tests are intended to provide:

- parameters to allow the performance of different PV systems to be compared;
- predictions of the ability of the systems to meet the design loads at acceptable availability at the installation sites;
- some indication of the suitability of the battery operating regimes, or how long the batteries may last.

The main outputs are 1) the usable battery capacity, and 2) the useful array power in the system (K_p). Sub-system efficiencies can also be calculated with some effort.

Three different experimental approaches to the test method were attempted in order to assess the practicalities of adopting any one method.

1 full scale system charge/discharge cycling and monitoring.
2 array characterisation, and laboratory evaluation of the balance of system by controlled charge/discharge cycling.
3 Array and balance of system component characterisation, and desktop system evaluation (or hourly simulation, which should yield the same results).

The investigation was undertaken because of the expense involved in undertaking full scale performance testing, and because of the need to know the accuracy and precision in each method.

8.1. Discussion of all results

Method 1

Eighteen sets of results were obtained for three systems using method 1. Battery capacity results were relatively consistent, but array power (K_p) was exceptionally variable, both from system to system and for each of the six test runs. Array power was calculated to be higher than rated in some of the runs. Error analysis suggests that the problem could be in the measurement of irradiance. After attempting to correct for the error, the results still showed a marked degree of scatter. Statistical analysis showed that for a 5% confidence interval, ... test runs would be required per system.

Table 8.1 Results for method 1, showing K_p results. K_p corrected results are also shown in parenthesis

	System 1	System 2	System 3
Run 1	31.73 [24.59]	28.99 [22.47]	18.75 [14.53]
Run 2	31.48 [24.39]	36.79 [28.51]	30.75 [23.83]
Run 3	23.52 [15.50]	38.27 [25.23]	38.25 [25.22]
Run 4	16.54 [10.90]	28.46 [18.76]	28.51 [18.79]
Run 5	NA [NA]	24.23 [20.19]	22.05 [18.37]
Run 6	NA [NA]	31.37 [26.14]	27.41 [22.84]

Method 2

Three sets of results were produced from the same system. Battery capacity was consistently estimated at about 48Ah, and the K_p value consistent around 22.2. Indications are that this consistency is the result of the finely controlled environment, in which uncertainties of radiation measurement are eliminated from the experiment.

Table 8.2 K_p results for method 2.

	K_p
Run 1	21.6
Run 2	22.3
Run 3	22.3

Method 3

For the result obtained using the paper-based method, the battery capacity was accurately predicted from data, and the K_p estimate was 22.43, close to the value from method 2.

Results were most easily obtained using method 3, then method 2, and relatively unsatisfactory results were obtained (with difficulty) using method 1.

8.2 Errors

The discussion of the experiments would not be complete without a brief analysis of the potential errors in each method.

The sources of errors in each method are listed:

Method 1

- Offset errors, which are accumulated.
- Radiation errors, possibly the big problem in depletion test.
- Sample interval errors (low frequency sampling).
- Errors in approach. The method requires both autonomy and depletion test results to calculate array power. Any variations in battery capacity or behaviour due to battery settling during that time will yield meaningless results. Large errors in the depletion test will yield meaningless results.

All of these errors and uncertainties are simultaneously present, making this an extremely problematic method.

Method 2

- Offset errors.
- Errors in initial IV scans.
- Errors in the IV model adopted.
- Errors caused by doing only one battery cycle, instead of a complete depletion cycle.

But these results should never be meaningless. K_p values calculated will always be relative to the array characteristics input to the array simulator model.

Method 3

- Errors in initial IV scans.
- Errors in battery component data.
- Errors in regulator component data.
- Errors caused by doing only hourly simulation.

Computer simulation will have errors due to the mathematical models used to represent the individual components in addition to the above errors.

8.3 Accuracy

How accurate can any method be expected to be?

Method 1 has been shown to produce such a broad range of results that its accuracy is not in question, but its ability to produce worthwhile results is in doubt.

Unskilled analysts could introduce more errors in analysing the data than the experiment itself produces.

Method 2 produced consistent results, but they could be consistently inaccurate. The results should be as good as the IV curve model, which could be checked in detail. The single charge/discharge cycle instead of a full depletion cycle should not compromise the results seriously unless the cycle DOD and range is incorrectly chosen.

Method 3 could be the least accurate, but because it will not produce nonsensical results it must remain an option. Like PV system computer simulation, the errors depend on the objectives of the simulation. For estimating energy flows over a single cycle the method is sufficient, but the cumulative errors over many cycles will differ from real life experimentation (as documented by Borchers) . The largest errors result from hourly estimation of the PV operating point. If the operating point is on the sensitive knee of the IV curve then the errors may be larger.

8.4 Recommendations

The usefulness of PV system performance testing cannot be questioned. The form of the testing and the economics and practicalities of the currently recommended method is still in doubt. Method 1 remains the most elegant, but practical concerns also make it the most difficult to undertake satisfactorily.

Recommendations on when to use each approach

Method 1

- When time is not critical;
- when longer term in-field evaluation is also required (6 months to one year);

and
- if a full-time person with considerable operating and maintenance experience and experimental skills is also available;

and
- if ultra-reliable logging and measurement equipment, and test-proven control software is available;

and
- if considerable data analysis skills and resources are available.

Method 2

- If suitable electronic simulation equipment is available, with proven control software;
- when results are needed quickly;
- when abuse or improper treatment may cause system or component failure.

Method 3

- For quick analysis;
- when component data is available;
- for assessing system decay, particularly the effect of battery decay.

Designers and suppliers of systems for tender should provide a paper-based assessment of their system array power, K_p, and usable battery capacity.
The test outputs (K_p and useful battery autonomy) should be adopted as standard ways of specifying system performance. A suitable method should be devised that an institution such as SABS could conceivably cope with.

A method for on-site evaluation of systems is being developed. The method will incorporate aspects of methods 1 and 2, and will also be suitable for post-installation qualification testing and subsequent annual performance-checking of installed systems. This is important, particularly since present methods do not have a built-in allowance for component degradation. Method 1, certainly, is not sufficiently consistent to be able to detect any component degradation, and requires backup data input.

CHAPTER 9

A REVIEW OF SOME TECHNICAL CONSIDERATIONS FOR GENSET-PLUS-BATTERY SYSTEMS

9.1 INTRODUCTION

Diesel and petrol engines connected to alternators are often used to provide electrical power for non-grid-connected applications. The technology is well established, and these systems are commonly known by their generic name, gensets. Installations vary in size from a few kilowatts for domestic or rural dwellings, to up to several megawatts typically encountered on power stations on islands, or for grid-connected standby power backup systems.

The genset runs for the duration of time that power is required. The size of the genset is normally just sufficient to meet the peak energy demand.

Problems

There are some problems with this configuration:

- The generator may often run without power being drawn, particularly in smaller, single user applications, where energy demand may be intermittent or extremely variable.
- The generator may often run at only a fraction of its design capacity.

Both these situations are exceptionally wasteful of fuel, and can also result in early engine failure. Gensets should not be frequently started and stopped to meet fluctuating demand since engines operate optimally and require less maintenance when properly warmed up.

Genset-plus-battery option

When a suitable form of energy storage is available, the genset can run at nearly full rated capacity while it replenishes the storage. It can then be switched off and the intermittent energy demand can be met by the storage capacity. The generator runs again and replenishes the storage when the storage levels run low.

There are necessarily some slight efficiency losses, primarily in energy storage/recovery (battery efficiency and conversion efficiencies).

This idealised and naive description of how genset-plus-battery systems might work certainly does not provide any clues to possible design problems or operational considerations. These questions can be challenging.

9.2 Key questions

Key technical issues centre around:

Design	-	Genset / alternator / charge regulator/ battery selection, sizing and matching, so that over the life of the system the energy costs are minimised, and the system performs reliably and can be easily maintained.
Operation	-	Genset running optimisation, minimising fuel costs, while maintaining and controlling battery condition and life. System operation and operating regimes are expected to play a significant role in design.

This discussion will deal with the questions of operation first, since this forms the basis of bigger design questions.

9.3 Operation

The main aims of operational management are to decrease running costs and maintenance and component replacement costs, to produce cheaper, more convenient electricity. Cost reductions over conventional genset systems are possible to achieve by radically improving the operating regime of the genset. In the simple discussion of operational considerations that follows only the two main components are considered, namely the engine / alternator and the battery.

The engine

- lasts longer when it is properly warmed up prior to operation;
- is most fuel efficient when running at close to its rated output power (high capacity factor), and becomes quite inefficient at low capacity factors (less than say 30% of its rated power);
- may need more frequent maintenance if it is not regularly run at high capacity factors.

The battery bank

- lasts longest if kept in a reasonably full state of charge and periodically boost-charged;
- performs most efficiently if the charging process is regulated, that is, there is a regulated decrease in power input to the battery as it approaches top of charge;
- may fail prematurely if charging is unregulated;
- may lose capacity if it is not fully charged;
- may lose capacity or fail prematurely if it is left undercharged for prolonged periods.

Genset engine life and operation

Diesel generators can be completely overhauled and reconditioned several times during their working life. The working life of a genset is sometimes defined as the number of operating hours after which the engine/alternator overhaul exceeds 60% of the replacements costs. In practice this corresponds to ±3 rebuild cycles per genset.

A typical small genset may have a life of 3000 hours, while very large sets could last many thousands of hours. The actual number of hours between overhauls depends on the operating conditions, primarily on the capacity factor, which is also determinant of the cause of engine failure.

Figure 9.1 shows approximately how capacity factor affects the engine life. At high capacity factor the useful life is exponentially higher than at low CF. At high CF failure is most likely to be due to wearing of the piston rings. At continual low CF operation, problems may occur with critical fuel injector wear, and valve- clogging due to residue build-up.

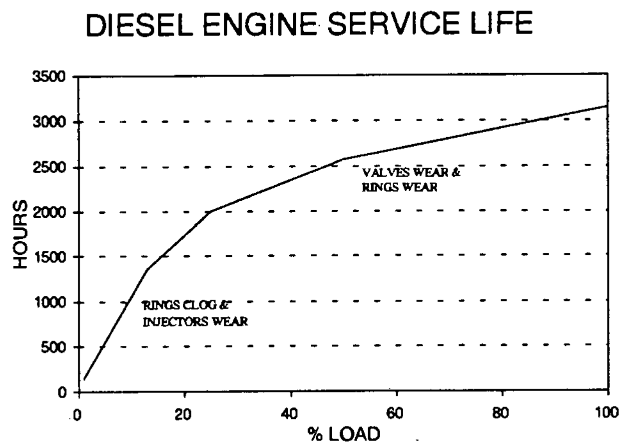


Figure 9.1 Engine life versus capacity factor. Causes of engine failure are also shown.

Generators rarely operate at a fixed capacity factor for prolonged periods. Repeatedly varying capacity factors cause a different failure mode, namely thermal stress and cycling fatigue. The effect of loading and unloading the engine causes sudden pressure changes within the engine, particularly affecting to the piston. Table 9.1 shows the effect of extreme duty cycling on expected life of an ADE 236 4 cylinder 55kW motor.

Table 9.1 Effect of engine duty cycle on engine life for an ADE 236, 4 cylinder 55kW diesel engine.

duty cycle	engine life (hours)
2 min @ 100% CF, 2 min @ 0%CF	200
2 min @ 90%CF, 2 min @ 0%CF	600
1 hour @ 100%CF, 3 hours @ 0%CF	1000

Thermal stress cycling is unlikely to be problematic in battery charging applications where the capacity factor starts off high for about three hours, and over a period of (typically) two hours drops off to about 20% as the battery regulation takes over near full charge. The next engine cycle would only begin the next day in most cases, when the engine has already cooled.

Engine researchers suggest that battery charging could be an almost ideal application provided the engine is well warmed up, starting CF is more than 80%, and that finishing CF's are not below 40%.

Uncertainty in engine life predictions.

As a very rough model of engine life under varying capacity factor, the incremental wear (ΔW) caused by running the engine for n hours at capacity factor C, when the expected engine life at that capacity factor is H_{cf} is

$$\Delta W = n / H_{cf}$$

The engine is in need of overhaul when the incremental wear has reached unity.

Running costs

Running and maintenance costs form a considerable proportion of total lifetime costs for diesel engines. Fuel costs are very dependant on the capacity factor during operation. The graph below for a large diesel genset shows that fuel consumption per kW increases dramatically at CF's below 40%. Fuel consumption figures are available from *engine maps* for most reputable engines.

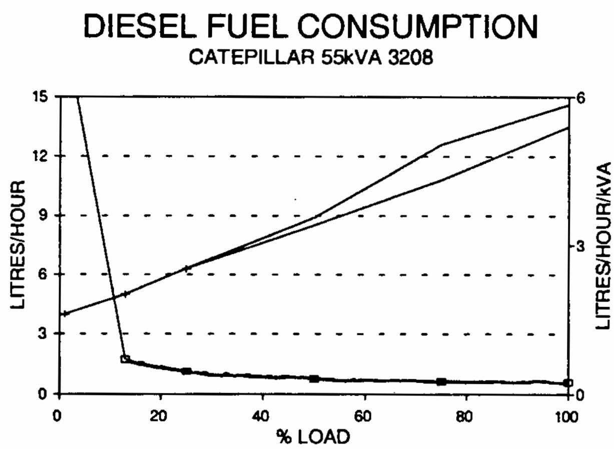


Figure 9.2 Fuel consumption as a function of capacity factor for a large diesel genset. The right vertical axis shows the fuel consumption per kW of power as a function of capacity factor.

Many straight genset systems require the genset to run continuously throughout the day, with capacity factors varying frequently between 40% right down to 5%. The fact that it is uneconomical to run engines at low CF's makes the genset-plus-battery configuration a feasible option. Provided that capacity factors can be substantially improved, fuel and maintenance savings justify the additional batteries and complexities of the system.

Battery life and operation

The cycle life of a lead-acid battery is dependant on its operating conditions. Battery life is over, and the battery scrapped, when its capacity has dropped to 80% of the original rated capacity. The cycle life is primarily dependant on the battery depth-of-discharge during cycling.

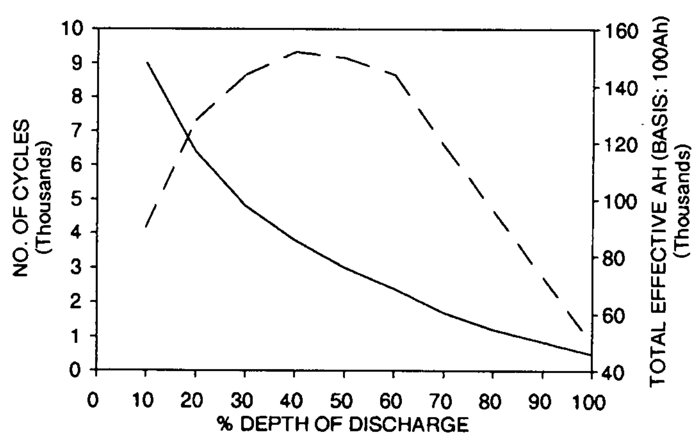


Figure 9.3 Lead-acid battery life cycle versus depth-of-discharge. The right vertical axis shows that there is a DOD for cycling which gives optimal usage of the battery.

The battery is a complex chemical system, which can exhibit a wide range of failure modes depending on the exact battery type, its operating regime and history. Any one failure mode could occur catastrophically at any time if the battery is consistently abused. The battery lifetime curves should therefore be used with absolute caution, and then only in conjunction with a sound knowledge of the likely battery operating regime.

Some failure modes are itemised below, but the reader is referred to other texts for more details.

Battery failure modes

The lead-acid battery can fail in many ways, depending on the environment and duty cycle of the service. Some battery designs are more suited to specific applications than others. This section is a summary of modes of failure.

- The positive plate generally limits cycle life because of *shedding of the active material and corrosion of the grid.*
- Deep discharge of batteries having calcium alloy grids can lead to formation of *insoluble calcium sulphate* in the corrosion layer, between the grid and the active material.
- Tubular plate batteries are designed for deep-discharge service. The positive tubular plate usually fails by *stress cracking* near the top of the lead spine. Pasted plate designs usually fail by shedding.
- The mechanical stresses during cycling give rise to *cracking and loss of electrical contact.* Thickening of the grid occurs during prolonged deep-discharge when sulphation occurs. Irrecoverable sulphation may result if the batteries are not recharged.
- The negative electrode can become *sulphated during prolonged cycling.* The large sulphate crystals cause loss of contact with the grid.
- Repeated cycling and undercharging can cause *stratification of the electrolyte,* which can contribute to uneven active material use and degradation in the long term.
- Excess *gassing* during unregulated charging can cause rapid *corrosion of the grid* in antimony alloy batteries. Gassing also causes water loss, which may expose the plates to the atmosphere. Sulphation will occur.

- Excess gassing can *scrub* some of the active material from the positive plate. Active material or sulphate that is lost from the plates by shedding or scrubbing will collect at the bottom of the battery as *sediment*. If the sediment reaches the bottom of the plates it will cause *shorting*.
- The sediment can be redeposited by *mossing*, and can accumulate to cause shorting around the separators and leading to stress of the grid.
- *Separators can degrade* and cause shorting across the electrodes.
- Operation of batteries at *higher temperatures* promotes grid corrosion and reduces cycle life.

Uncertainty in battery life predictions

Having practically discredited the battery cycle curves as useful data it would seem rash to use them for more complex modelling.

However, battery cycle life during cycling from full charge to various depths-of-discharge can be very approximately modelled by an incremental wear model

$$\Delta W = n/L_{DOD}$$

where battery life is complete when the incremental wear is unity, n is the number of cycles at the specified DOD, and L_{DOD} is the number of cycles expected at the specified DOD.

Battery charging

It must be emphasised that battery life is also strongly affected by the quality of charge regulation. In most cases a maximum starting current for charging is recommended. This current is maintained till the battery voltage rises to a defined level, whereupon charging is regulated at constant voltage and the current tapers as charging progresses. The power input to the battery also decreases.

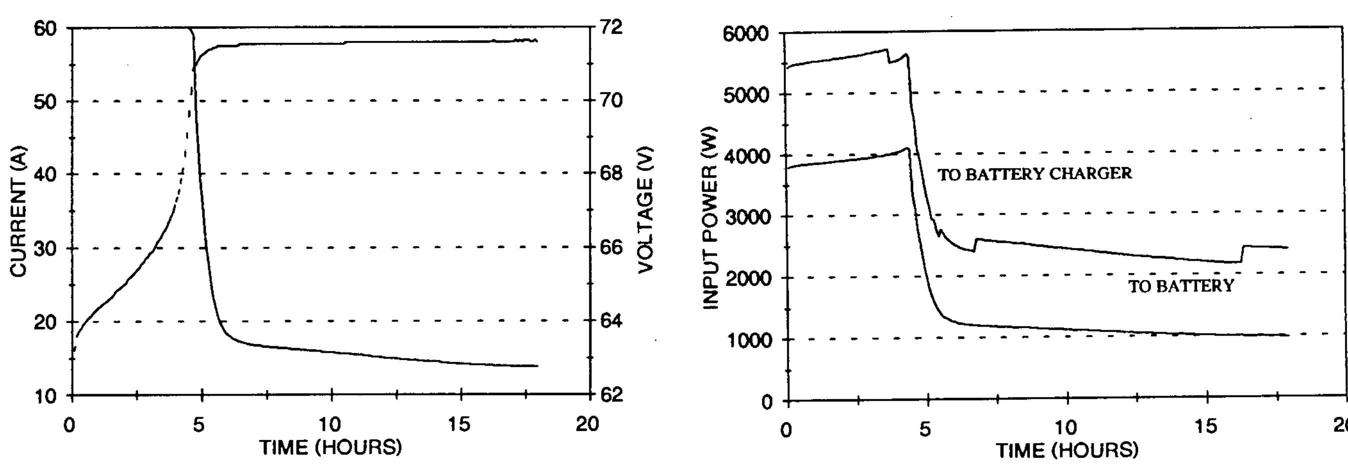


Figure 9.4 Battery voltage, current and power versus time during regulated battery charging.

Batteries left for long periods in incompletely charged states will show rapid capacity loss, and batteries that are not regularly equalise-charged will exhibit similar tendencies.

Batteries are discussed in much detail in other texts. This discussion serves only to highlight relevant problem areas.

Battery / genset system operation

Neither battery life nor genset life can be accurately determined from life curves since these are based largely on theoretical laboratory information. Practically, component life for both is extremely dependent on actual operating conditions.

Probably a more realistic approach to formulating operating regimes for both components in the system is to propose a set of '*best operating characteristics*' as well as a set of '*operating regimes to avoid*', rather than attempting to formulate some empirically optimised solutions.

An obvious trade-off or conflict occurs in deciding for how long to run the genset or when to stop charging the battery.

- When the battery has reached its ideal fully charged state (and it's rate of energy acceptance under regulated conditions has dropped to less than 20% of the initial rate); or
- when the genset capacity factor has dropped to about 40%, and its fuel usage is becoming inefficient, but the battery is not yet fully charged.

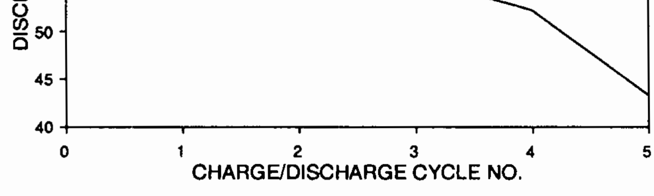


Figure 9.5 The figure illustrates the long term effect of consistent undercharging on the battery capacity. The graph was obtained experimentally by discharging till 40% depth-of-discharge based on battery voltage, and recharging the battery to a set voltage at constant current. Capacity decreased from an initial 80 Ah to 40 Ah after only 12 cycles. This battery operating regime is a result of a decision to operate the genset at constant capacity factor throughout the charge process, and is a subset of potential battery operating regimes in genset-plus-battery systems. (The charge/discharge cycle regime for the 100Ah battery was charge at 10A to 14.6V, discharge at 10A to 12V.)

Runtime model

A helpful decision tool would relate genset runtime, genset capacity factor, charge currents, voltages and battery state-of charge to facilitate in the operational decision process.

A simple runtime model has been developed to predict the generator runtimes required to charge the battery from the initial to the final states of charge, depending also on the initial charge current and battery regulation voltage. The model is based on battery test data evolved at EDRC. (The model itself is presented in Appendix C). The model has been verified against further experimental data.

Genset capacity factor can be approximated from the runtime model. The instantaneous capacity factor can easily be integrated to give an average capacity factor over the charging cycle.

However, a primary constraint is that the model is based on battery behaviour, while genset capacity factor will in reality be dependant also on battery charger efficiencies between the genset and the battery bank. These efficiencies are very unlikely to be constant or even linear, and the model in its present form is good only for a first approximation of capacity factor.

9.4 Practical / design considerations

There are some practical concerns and other important components that need to be considered before attempting to design or even to operate genset-plus-battery systems.

Most of the practical concerns revolve around the fact that the genset is a *limited power source;* that is, unlike the electrical grid, it cannot supply infinite power to meet peak or surge power demands. During short periods of sudden peak demand higher than rated output (even for milliseconds) the AC output voltage of the alternator will drop.

The focus of this discussion is therefore on the electrical interaction between the battery charger load and the alternator.

Battery chargers

The electrical output of the genset is invariably not suited for direct input to the battery bank. A regulated DC battery charger provides the best automatic protection to the batteries. Battery chargers are of very varied AC/DC efficiencies, AC input characteristics, DC output characteristics and types of regulation; and all these could affect the performance and choice of charger. Input characteristics could also affect performance of the genset alternator.

DC output characteristics

DC output characteristics would primarily affect the battery operating regime. Many industrial chargers produce DC output with a significant ripple voltage superimposed. Some chargers conduct current only on the peak DC voltages, pulse charging the battery and resulting in higher RMS values of the input current. There have been cases of very basic battery chargers not being able to charge certain batteries in genset-plus applications.

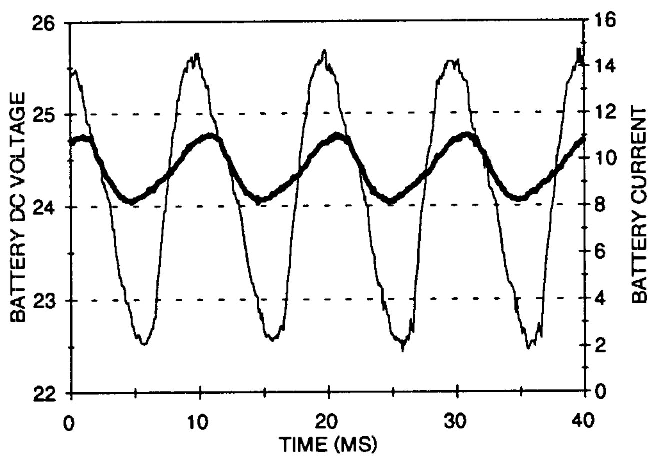


Figure 9.6 Some battery chargers produce DC output with considerable output ripple. For these chargers current flows only when the DC voltage is greater than the battery voltage, resulting in peaky conduction periods and higher RMS currents on the AC side.

AC input characteristics

Peaky input characteristics, non-unity power factors, high input harmonics and high RMS currents may require derating of the alternator. Non-sinusoidal characteristics interfere with other AC loads if they are connected directly to the alternator.

Battery chargers with capacitive inputs may affect the AC voltage regulation circuits on the alternator of the genset system, sometimes yielding them inoperable.

A fold-back shut-down situation could occur with some peaky input battery chargers: the sudden peak current demand could cause the alternator AC voltage to drop, resulting in a lower charger DC output voltage. The lower DC voltage limits the DC current that the battery can accept, and the net result is that the charger cannot reach its full output power. Implications of this are quite severe:

- genset capacity factors will be lower than desired, and certainly far from the design values;
- runtimes are longer and costs of electricity necessarily higher;
- in extreme cases the charger may not charge the battery at all.

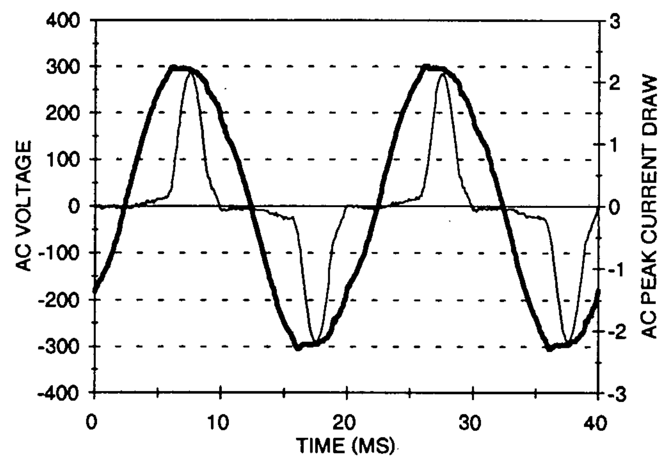


Figure 9.7 Input waveforms, with significant distortion.

AC/DC conversion efficiencies

Battery charger efficiencies are typically not more than 80% at peak, and are often lower for lower power outputs. Efficiencies are affected by non-unity power factor and other undesirable effects that often prevail. Low conversion efficiencies directly affect the storage efficiency of the genset-plus-system.

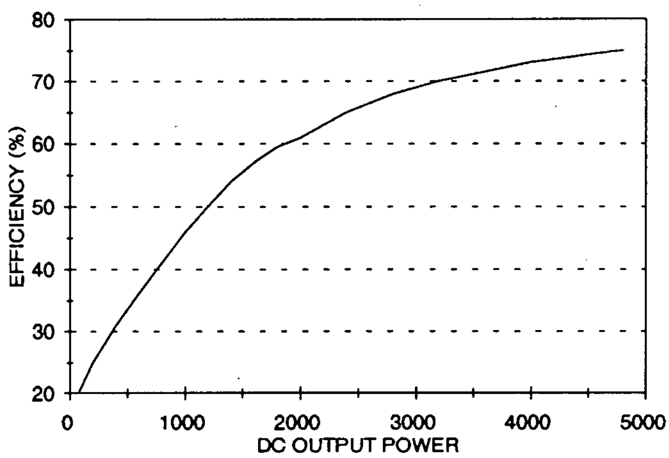


Figure 9.8 Charger efficiency curve.

Types of battery charger

Four distinct categories of battery charger have been identified. The main characteristics are listed only, and should be referred to the discussion above.

- Single diode rectifier with variable take-off transformer
    - high RMS currents, conducts only on peaks
    - unity PF
    - may not properly charge batteries in certain applications
- Full diode rectifier bridge with variable take-off transformer
    - conducts only on peaks
    - unity PF
    - may not charge batteries in certain applications
- Thyristor (SCR) rectifier
    - poor PF (0.7)
    - high harmonics and high RMS current
    - may have capacitive load characteristics.
- Switch mode power supply
    - high RMS current
    - may have capacitive load characteristics
    - unity PF
    - can have sine-wave input as an option, reducing RMS current problems, but will then be a capacitive load.

Some of these characteristics require further investigation.

Alternators and genset AC regulation

Most alternators are rated for power output in kVA at 0.8pf inductive for temperatures up to 50°C. The power is derated by 2% per 5°C up till 65°C. In addition, an RMS current rating stipulates the maximum allowed current. Most large alternators can sustain 300% over-rating of RMS current for 300-400mS.

Electrical design and basic operation

A voltage is induced in a coil of a wire moving through a magnetic field. Alternating current is produced as a result of mechánical rotation of a coil within a field, resulting in the conversion of mechanical energy to useful electrical energy output.

In practice, the magnetic field is produced by passing direct current through a small field winding, requiring only a small amount of current for excitation. The electricity is produced in the larger armature. For practical reasons, the heavier armature is kept stationary, and the field winding is rotated inside it. The armature is the stator. Collector rings maintain contact between the rotating field winding and the DC supply. The stationary armature configuration results in fewer electrical and mechanical losses.

Often the field current is obtained from the generator output. A rectifier converts the generator AC output to DC suitable for the field winding.

AC voltage output regulation.

The voltage is dependant on the reactive speeds of the field winding and the armature, and on the strength of the magnetic field. Since a fixed AC frequency is usually required, it is not possible to vary the speed. Gensets are therefore constant speed engine applications.

The alternator output voltage is maintained by control of the current in the field winding. This is done by using silicon controlled rectifiers (SCR's), which can adjust the field current by a feedback control loop based on the alternator output.

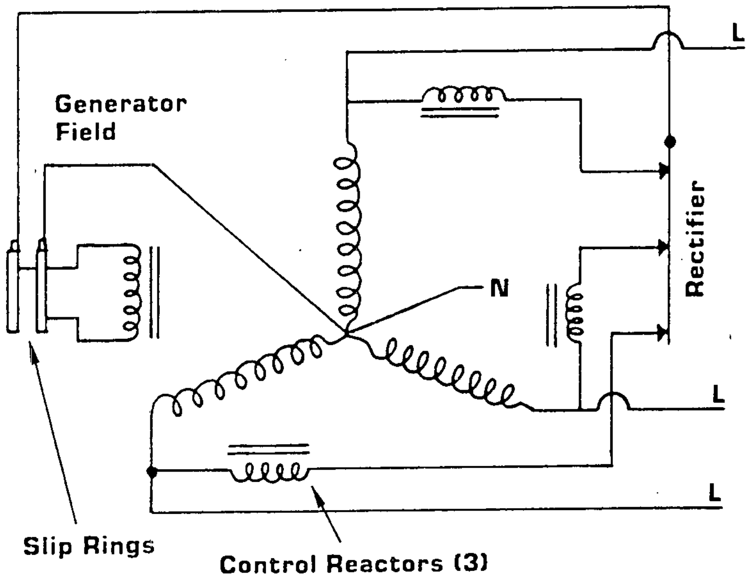


Figure 9.9 Three-phase half wave controlled SCR supplies rotating field winding through slip rings.

High harmonics and RMS currents caused by particular loads result in higher armature winding losses which affect electrical output, but provided temperatures are kept under control, there should be no increased core losses or core saturation.

kW and kVA requirements of the load

The alternator size is selected to meet the kW and kVA requirements of the load.

The kW size of the load depends on the battery charger, allowing for AC/DC conversion efficiencies as well. The kVA size requirement is established after the power factor has been taken into account. In the case of very high harmonics or lower power factor requirements than the alternator nameplate ratings (0.8pf typically), the alternator should be derated by 10-15%. The RMS current ratings should never be exceeded.

In practice the alternator is usually sized at 20-25% more than the actual maximum load conditions to enable it to meet power demands characterised by frequent peaks, and to better approximate a zero impedance power source, by overcoming the limited source characteristics mentioned earlier.

Motor size

Gensets are normally supplied as complete units of matched motor and alternator pairs. When low load power factors are likely to be encountered it may be preferable to increase the size of the alternator to cater for the additional kVA through its higher current carrying capacity. The motor, however, need only be rated for the kW requirements, which will always be lower.

9.5. Design and optimisation proposals

The key questions around genset-plus-battery component selection and matching have been raised. There are some significant practical considerations, particularly surrounding the choice of battery charger, its efficiency, and its effect on overall system performance. Some derating may be required if specific chargers are selected.

Genset operation with batteries can be optimised, but this is likely to be an inexact science, requiring a good feel for battery requirements as well as genset engine requirements.

Considerable data is available for genset systems from larger, established suppliers. Less data is available from more recent entrants to the market, a smaller range of gensets, mainly from the East.

Battery charger information is scarce, particularly for the lower power end of the scale, which are likely to be locally supplied and manufactured units. This data is important if the charger is likely to be rated close to the alternator output.

Further research work is proposed:

- to characterise the main battery charger types in terms of input/output characteristics;
- on charger conversion efficiencies;
- charger regulation;
- alternator output, particularly how this is affected by charger input characteristics. (Specifically, conduction and distorted RMS currents, and maximum power output).

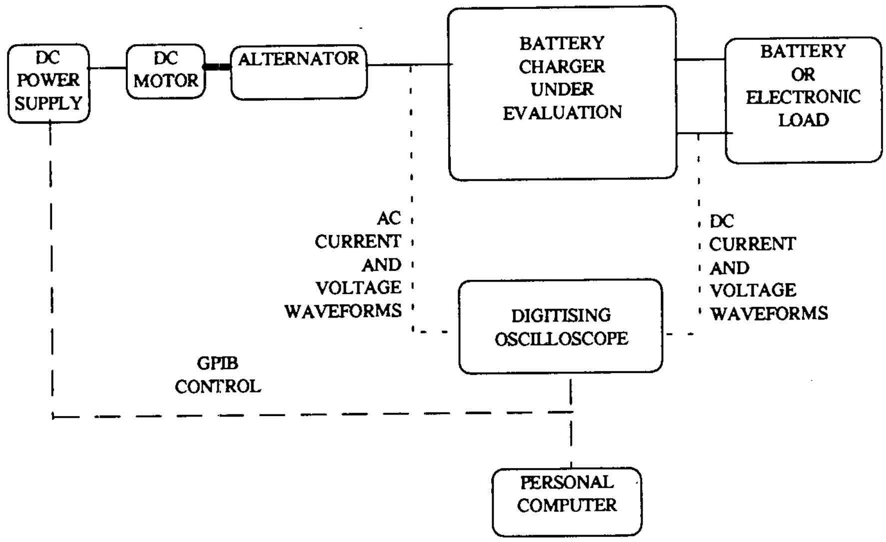


Figure 9.10 Layout of the proposed experimental test-rig for battery charger and alternator characterisation.

The proposed experimental layout for charger characterisation would utilise an existing computer test-rig used for waveform capture and analysis. Chargers would initially be powered from the mains supply. The effect of limited alternator output impedance on the chargers is more complex, but the same test-rig could capture waveform data and could monitor charger performance with a range of different alternator types and sizes. Alternator speed and power could be controlled by a DC power supply driving a DC motor directly coupled to the alternator.

This work would be directly relevant to the proposed hybrid system design research to take place at EDRC in 1993.

CHAPTER 10

CONCLUSIONS AND RECOMMENDATIONS

Initially, the main objectives of component characterisation were to determine accurate empirical data for locally available components which could be used in PV systems. Batteries, regulators and inverters have been the focus of attention.

This data was to be provided in a format useful for PV system designers, since this data is often not available, or incomplete, or is in a format unsuitable for use in system design.

The data and findings were intended to be made available to two parallel research projects at EDRC.

- The data and improved knowledge in component performance was intended to contribute to the accuracy of PV system simulation methods developed at EDRC. Simulation tools offer an attractive way of evaluating design options. Battery behaviour was the most problematic component. Regulator and inverter models were in need of validation.

- The RAPS information and dissemination project, incorporating the RAPS Design Manual, was intended to present the performance and economic data, together with design guidelines and recommendations in an appropriate format for PV system designers. Battery performance and lifetimes are major determinants of PV systems costs. Battery lifetimes and economics are determined by system design, battery cycling regimes, and effective charge and discharge regulation. Charge regulator algorithm and set-points are critical.

The component data was also intended to provide design feedback to manufacturers and suppliers of locally available components. Encouraging the participation of suppliers was a primary aim. Future large-scale funded PV projects will increasingly rely on the industry to provide documentation for components and systems to an acceptable international standard.

Another objective was to link the component data with PV systems performance testing methodologies. PV testing methods offer a system performance specification which could greatly assist in management of large PV projects and of tender awards. Simulation already offers one way of assessing system design. Experimental PV testing methods are in reality complex to analyze and are of presently unknown accuracy. Experience in experimental techniques gained during component testing could provide valuable feedback.

10.1 Test facilities

A major objective of the project was to design and develop test facilities for component characterisation. Versatile and accurate hardware was purchased, in-house electronic designs undertaken, and control software written. Test methods were investigated and developed.

At the end of phase II of the component project, a range of testing facilities and test methods exist at EDRC.

Battery testing and methods

A microcomputer-controlled battery cycling unit was the first equipment to be installed. The unit consists of a 3kW power supply and a 1.8kW load.

The control software supports conventional constant current battery discharge testing, and constant current / constant voltage recharging. Software also supports a variety of charge/discharge cycling profiles, with time constraints, voltage constraints, current limits, charge accumulation limits etcetera. A graphical output of any logged parameters is available at any time.

A primary limitation of the facility is the inability to test more than one battery bank at any time. The software could easily be modified to cater for more tests at one time, but the need for additional power supplies and loads would be expensive.

In the interests of testing efficiency, a detailed review of testing literature was undertaken and innovative methods developed.

A short method of determining charge curves was developed. This method entails periodically and incrementally varying the charge current over a suitable range and maintaining the current till the voltage stabilises. The stabilised voltage is taken as one point on the charge curve, and points of constant current can be joined to form the charge curve. This approach was particularly useful for determining low-rate charge curves typical of PV systems, which would otherwise be impractical and time consuming.

Instantaneous charging efficiencies were determined by monitoring battery gassing rates, and charge curves were corrected for the charging inefficiencies indicated by the gassing curves.

For longer term performance testing and evaluation, a range of battery cycling tests were used. Temporary and reversible capacity losses caused by stratification and undercharging, and permanent losses leading to battery failure, were also monitored through the cycling tests. Variation in charge and discharge curves during cycling was noted, and runaway effects or implications for system design recorded.

Regulator testing

Regulator tests can be divided into two groups: i) characterisation, and ii) performance testing.

Regulator characterisation involves determination of setpoints for top-of-charge and for loadshed, including any time delays and temperature compensation of the setpoints. Voltage losses through the regulator, and regulator energy consumption under various switch conditions are also important data.

A microcomputer controlled test and measurement unit consisting of an array-simulator power supply, battery simulator and controlled loads was set up for characterisation tests. The system ramps the battery simulator voltage, while monitoring array and load currents to automatically detect whether charge regulation or loadshedding has occurred. The unit can also measure parasitic power consumption and voltage losses.

For performance testing, the battery simulator is replaced by a real battery, and the regulator and battery pair monitored under controlled cycling conditions. An array model is used to ensure that the array simulator puts out true IV characteristics under the control solar day used. Tests are conducted for overcharge, recharge efficiency and steady-state operation for different battery types.

Inverter testing

Inverter performance characterisation is simpler than for other system components, primarily because the only PV system variable to consider is the battery voltage. In most cases a snap-shot performance assessment is sufficient.

A computer controlled waveform analyzer was designed using off-the-shelf hardware and customised software. A high frequency oscilloscope captures isolated DC and AC voltage and current waveforms, and communicates these to a host computer. In the computer the waveforms are processed, and true RMS values, true efficiencies, waveform distortion and power factor calculated. For accurate measurements a systems multimeter is also used. Data is stored for later recall or analysis. Sophisticated software allows for high-volume throughput during repetitive testing. DC input voltage is controlled by programmable DC power supplies. New AC electronic loads coming onto the market could allow for fully automated tests with variable AC output power and capacitance or inductance.

Performance was monitored at various AC resistive loads, DC input voltages and real loads. Overload, shortcircuit, reverse polarity, and battery protection features were checked. Electromagnetic interference tests were conducted at a specially equipped private laboratory.

Module testing under natural light

PV module testing is conventionally a snapshot electrical output test done under controlled indoor conditions. A facility was set-up for simple IV curve scanning under natural light conditions. Although spectral composition of the light cannot at this stage be monitored, other important variables are, and the robust equipment allows for easy, accurate IV scans throughout the day.

A data capture facility was set up that automatically scans and records IV curves for up to four modules at a time. Accurate instrumentation and electronic loads were used to generate data over a range of irradiance and temperature conditions throughout the day. Sufficiently accurate data can be generated in quantities for statistical curve or model validation.

Previous attempts by other institutions had resulted in poor data quality and accuracy, and insufficient quantity to justify detailed analysis. Methods had mostly required intimate operator involvement.

PV systems performance testing

PV systems performance following the EDRC recommended procedure is a simple process, but local institutions attempting the procedure have failed repeatedly to deliver reproducible results or any results at all. As part of an investigation into the method, facilities were set up for automatic testing.

Facilities were set up for PV systems monitoring. All the major insolation, temperature and energy flows were recorded using accurate multimeters that required no input signal amplification.
The crux of the system, however, is customised software for automatic test control and error detection. Array and load relays are opened and closed under software control (and array IV scans are actually taken during the test as well). The software ensures that errors do not result in catastrophic failure of any system, and that operator involvement is limited. Failure can mean restarting the whole test sequence, which takes a minimum of thirty days, but usually up to sixty days. PV systems testing, as with IV testing, could be a full-time commitment for at least one person unless automated. For accurate results, the test should be repeated several times.

Ad-hoc and future testing

Facilities also exist for ad-hoc testing of non-PV system components. A petrol generator/alternator system has been evaluated. In future the inverter test software will be modified to enable battery charger testing. Water pump characterisation is planned, and hybrid system controllers will be evaluated where necessary.

10.2 Test results (Phase II)

Genset-plus-battery

A review and preliminary investigation into genset-plus-battery configuration was undertaken.

In both system design and operation, a major trade-off is the conflict between optimal battery operating regimes and optimal diesel engine operating regimes. It is difficult to determine an empirical solution or reach a decision, since there is so much uncertainty involved in both genset and battery life cycle curves, as well as failure modes under different conditions.
Certain battery chargers are likely to introduce complications as they may interact unfavourably with the alternator, resulting in systems that cannot recharge the battery. Systems efficiencies may also be adversely affected.

Battery testing and research

Six generic battery types have been characterised up to now.

Emphasis in battery testing has now shifted from short-term characterisation tests to longer-term cycling tests under the PV regime, and to ways of estimating battery lifetime. Battery operating regimes play the most significant role in determining how the battery will perform in the longer term.

Economics is increasingly the deciding factor in battery selection and system design. Battery economics has been linked in this project to battery operating regimes and charge protection. Instead of striving to design technically sound and reliably configured systems, economics demonstrates the possible costs of failing to take certain design precautions.

Both the technical and economic aspects of battery behaviour and selection have been included in the battery section of the RAPS Design Manual, as well as some step-by-step procedures for regulator set-point determination.

Finally, given the economic risks of using batteries that are not designed specifically for PV cycling, the Rand value of the PV battery market in South Africa has been estimated. The time may be ripe for a locally developed specialist PV battery (with stipulated cycle life guarantees).

Two distinct markets exist, one for new PV systems, and one for replacement batteries for older systems. The total market for PV batteries is estimated at R15M/annum (compared with module sales of about R14M/annum). Within that battery market there are two main battery groups, i) heavy duty batteries, and ii) modified SLI batteries used in PV systems. Heavy duty batteries account for about R5M/annum in PV systems, while the balance of R10M is for modified SLI. By 1996, batteries in PV systems will be costing R22M/annum, of which 65% will be for replacement batteries.

Regulator testing

Regulator behaviour and setpoints critically affect battery lifetimes. It is rarely possible for PV systems to operate for sustained periods without charge and discharge regulation.

Locally available load-shed units which respond only to battery voltage would be ineffective in maintaining the desired battery maximum depth-of-discharge in shallow cycling regimes.

Some locally available regulators are not able to completely recharge batteries in PV systems. This is primarily due to a combination of high parasitic power consumption, charge algorithm and inappropriate charge set points.

No conclusions can at this stage be drawn about charge algorithms, other than to say that linear charge algorithms would, logically, be more capable of reversing battery decay once it began to set in, while on-off regulators might exacerbate the problem. A great deal depends on the system configuration. Regulators that prevent overcharge most effectively do not necessarily recharge batteries more slowly than others.

Data from regulator testing has been in the form of setpoint, power consumption and efficiency data published in the RAPS Design Manual. Less precise performance data from recharge tests together with more subtle background and literature data could provide the required confidence to use the data.

PV module testing under natural conditions

PV module characteristics are the single largest determinant of system behaviour if the load is well known and defined.

PV modules are specified within loose tolerances by suppliers, often ±10%.

Modules are usually over-specified rather than under specified.

Accurate, hourly IV scans for three identical poly-crystalline modules were obtained over the course of a sunny and a cloudy day. Although the modules were not rated by the supplier (since they were old), output ratings for the three ranged from $25W_p$ to $30W_p$ at $1000Wm^{-2}$ and NOCT. Open circuit voltage also varied significantly.

The characteristics of one module were fitted to a mathematical model. The Rauschenbasch model was found to correspond closely with other IV scans at different irradiances and panel temperatures taken during the day for that module.

The model also highlighted specific module characteristics, particularly the unusually strong positive effect of temperature on short circuit current.

PV systems performance testing

Three identical PV systems were tested using the recommended EDRC PV System Performance Testing method. Usually the test is run only once due to time constraints, but this cycle was run four times, yielding six sets of results for each system. The test procedure ran smoothly, without any of the catastrophies that have plagued other institutions attempting the method, and the outputs conceivably represent a best case set of data. Eighteen identical results were therefore expected.

A very broad range of results was recorded, some of which were impossible as they implied higher output power than the PV panels could deliver. Other results were unbelievably low.

The standard deviation of the mean (for the array-to-load peak power) was 21% of the mean, suggesting poor accuracy.

A detailed error investigation could not pinpoint the source of the error. It seems probable, however, that cumulative inaccuracies in irradiance measurements are mainly to blame. It is unlikely that more accurate irradiance measurements could be taken without more sophisticated equipment. Irradiance inaccuracies in the depletion test combined with varying battery autonomy results can destabilise results significantly.

A hardware-based PV systems test, using an array model with electronics supplying the modelled power, provided excellent and very consistent results. (These results depend on being able to measure the array IV characteristics accurately.) The good results obtained by eliminating the array and irradiance measurements from the performance experiment implicate the irradiance measurements in the original system test as a source of extreme uncertainty.

A paper-based method was also used to determine the array-to-load peak power, and was consistent with the hardware-based test. This test was easy to perform, and other system options using previously characterised components were easily investigated.

10.3 Recommendations

PV systems testing

The EDRC PV systems test method does not easily provide reliable results, and certainly not if only one experimental run is performed. The data is difficult to analyze. The test procedure should be upgraded or modified.

Hardware-based system testing methods are more reliable, and could be utilised as a practical alternative provided accurate module IV data can be obtained. Their main weakness is their dependence on the array IV model. This seems to be a trade-off, but in practice there are few advantages to using the EDRC method as it stands, since it does not yield believable results.

The paper-based method is most elegant. PV designers and suppliers should submit their estimates of their system performance predictions using the paper-based method when tendering systems for evaluation.

An on-site PV evaluation method should be developed and tested in the field for accuracy and reproducibility.

PV module testing under natural conditions

Indications are that more accurate irradiance equipment may be required, mainly to back up PV systems test results. IV scanning would also benefit.

Other module types should be evaluated on the test bench. Modules that have been rated by the supplier should also be tested.

The array model should be validated with different types of module, as this has implications for the hardware-based PV systems test method.

Regulator testing

Regulator characterisation testing is necessarily accurate, but regulator performance tests depend primarily on battery behaviour, which is variable from battery to battery and with age.

As it is uneconomical to test every regulator / battery pair, an open analytical approach should be adopted which allows logical use of background knowledge and available regulator and battery data to determine suitability of particular combinations.

Battery testing

New modified battery cycling tests could provide useful design data. Battery testing could provide for variations caused by different regulator designs.

Cycling data could be used directly in paper-based PV systems tests or design to provide more than a snap-shot estimate of performance. Battery decay data can indicate the sensitivity of system design and performance to battery aging.

Genset plus battery

Battery chargers should be characterised in terms of their main types and input/output characteristics.

Charger conversion efficiencies should be investigated.

The interaction between limited power source alternators and certain battery chargers should be investigated.

Appendix A: Comments on experimental procedure and interpretation of results in Chapter 5

(written by Bill Cowan, project leader)

There are some features of the work reported in Chapter 5 of this document which require comment. That chapter sets out to evaluate the accuracy and practicality of a PV system testing method devised by the project leader[1], and concludes that the testing method is neither accurate nor practicable. In my judgement, however, the experimental procedures and results presented in Chapter 5 were not valid. The following brief critique should be examined before accepting the author's conclusions based on those results.

It is highly desirable that co-researchers should apply themselves to identify areas of weakness or error in the output of colleagues. They are in a favourable position to understand the details, and they are therefore in a better position to perform the essential scientific task of submitting assumptions and hypotheses to stringent critical test - usually one of the most rapid ways of discerning fact and fallacy.

For the same reason, it is not desirable to smooth over points of disagreement amongst co-researchers, nor to use the hierarchical responsibilities of project administration to conceal differences of opinion. The scientific ethic, and the search for useful understanding, are served better by debate and critique. Of course, conclusions should only be carried forward if they withstand such critique.

Summary of objections

1. In the experiments, some important elements of the testing procedure were not followed.

2. The test method sets out certain criteria which need to be satisfied before results from the tests can be used with any expectation of validity. All the test results reported by the author violated one or more of these criteria.

3. Apparently anomalous data patterns are not explained. Without explanation or further enquiry, it is difficult to know whether anomalous patterns arose from experimental errors or instead reflect real variations in the behaviour of the systems tested.

Procedural errors

(a) The PV system performance test essentially comprises a sequence of separate battery discharge cycles. Before each discharge cycle, the batteries need to be brought to a reference state, by means of PV re-charge, followed each time by a specified "battery pre-conditioning" procedure. This reduces the experimental uncertainties arising from the difficulty of establishing when a

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[1] See Cowan and Morris (1992) *Solar testing in South Africa - Phase 2*, Final Report, National Energy Council, Pretoria; or Cowan (1992) (ed) *Remote Area Power Supply Design Manual*, Vol 2, EDRC/DMEA, Cape Town. The test method referred to is set out for reference in Appendix B of this report.

battery is "fully charged". The author did not perform these pre-conditioning procedures.

(b) The 'controlled depletion test' entails exposing the PV arrays to a calculated amount of solar irradiation each day, which is slightly less than the irradiation required to support the test load, with the aim of bringing the system to battery load-shed over about 14 days. During this test, the energy provided to the load by the PV array should be at least twice the energy provided by battery reserve. This reduces the uncertainty, arising from separate battery capacity tests on either side of the depletion test, by approximately 50%.

The author however used a very low daily solar irradiation dose, with the result that uncertainties would be levered up by a factor of up to 400%, instead of reduced by 50%. This aspect is discussed further below, since it is likely to invalidate the extraction of all test results.

In addition, increased measurement errors are a probable consequence of using such a low solar irradiation threshold. The tests were conducted in summer, and the PV modules were mounted approximately horizontally (following wind damage, when the modules were mounted at a tilt). The low solar irradiation threshold was typically reached early in the day. Most of this irradiation was therefore received (by the pyranometer and by the PV modules) at high incidence angles. This can cause two significant problems, impairing validity:

(i) Slight angular differences between pyranometer and PV modules have a strong effect on solar irradiation received at high incidence angles. For example, if the incidence angle is 70°, then a 2° misalignment of the pyranometer relative to the modules can produce about 7% error in solar radiation measurement.

(ii) PV modules have reduced conversion efficiency at high incidence angles, due to reflection from the glass and the directional properties of the cells. The correspondence between measured irradiation and PV array output under such conditions is unlikely to be reliable.

Acceptance criteria in the PV System Test Method

There are a number of criteria, regarding accuracy of measurement, experimental procedure and consistency of measured quantities, which need to be satisfied before valid results can be derived from this testing method. These criteria are set out in detail in Appendix B. (The criteria were developed from a step-by-step uncertainty analysis of test measurements and their combined impact on subsequent calculations.)

Two of the central criteria are as follows. These criteria are embedded in the test approach, and therefore have a different status from ubiquitous criteria such as accuracy-ranges for the various measurements taken during the test sequences.

1. **The change in measured battery capacity between successive battery autonomy tests must be less than 10%.**

If this is *not* the case, test results cannot be used for derivation of system performance parameters, such as k_p (the array-to-load power coefficient) nor for long-term system performance predictions. In cases where batteries in a tested system show a change of capacity outside this limit, attention moves towards (i) diagnosing causes for battery degradation within the tested system, or (ii) checking whether incorrect experimental procedures have caused the discrepancy.

If the two battery capacity measurements, on either side of a controlled depletion test, differ by *less than 10%*, it is assumed that the battery reserve energy delivered during the controlled depletion test is best predicted by the mean of the two battery capacity measurements. (The author did not observe this step, in performing calculations.) However, it judicious to assume that this prediction can still have an uncertainty of at least ± 5%, since (a) there is no knowledge whether the depletion test capacity was closer to one or other of the capacity test measurements, and (b) the intermittent charge/discharge cycles during the controlled depletion test are different from the intermittent discharge cycles during the capacity tests. Point (b) is probably the most vulnerable aspect of the test methodology, even when the tests are conducted correctly. And even if the two battery capacity measurements either side of the controlled depletion test show 0% discrepancy, there is remaining uncertainty because of point (b). It is therefore vital to reduce the impact of this uncertainty by observing criterion 2 as well (see below).

Status of experimental results, in terms of Criterion 1:
(This refers to results presented in Table 5.1, page 53 of the draft report)

Shaded cells indicate violation of criterion 1, i.e. greater than 10% disparity between successive capacity tests. These disparities could be due to battery degradation, experimental error, or intrinsic instability in such capacity measurements. Note the systematic increase in measured capacities between capacity tests 2 and 3. Batteries only received 7 days recharge before capacity test 2, perhaps invalidating the first two rows of the table, and any results making use of capacity test 2. However there is insufficient evidence to judge this.

STABILITY OF BATTERY CAPACITY MEASUREMENTS

	SYSTEM 1	SYSTEM 2	SYSTEM 3
CAPACITY TEST 2 ÷ CAPACITY TEST 1	0%	-15%	-21%
CAPACITY TEST 3 ÷ CAPACITY TEST 2	+15%	+21%	+21%
CAPACITY TEST 4 ÷ CAPACITY TEST 3	0%	-5%	-4%

2. **During the controlled depletion test, the overall energy contribution of the PV array should be at least double the energy provided by battery reserve.**

In the controlled depletion test, the PV array is exposed to a limited amount of solar irradiation each day, insufficient to fully support the load, and as a consequence, the battery slowly cycles down to its load-shed maximum depth-of-discharge. Both the array and the battery reserve contribute energy to the load. The aim is to evaluate the energy contribution of the array (as a function of solar irradiation received during the test). Total load energy consumption equals the array contribution plus the battery contribution. As outlined above, there is inevitably an uncertainty in evaluating the battery's contribution, because this is judged from separate capacity tests before and after this controlled depletion test. To gain acceptable accuracy, (a) the battery capacity measurements should meet Criterion 1, and (b) the array energy contribution should outweigh the battery energy contribution by a factor of at least two (thus reducing any inaccuracies from battery capacity measurement by at least 50%).

Status of experimental results, in terms of Criterion 2:
(This refers to results presented in Table 5.1, page 53 of the draft report)

All the results fail the second criterion, presumably due to a miscalculation of the solar irradiation thresholds appropriate for the "controlled depletion tests", or in order to save time. Such results would not be utilisable in a public testing application (e.g. for system qualification tests prior to tender), because they magnify any uncertainty, from battery capacity determination, when calculating the array-to-load power coefficient. For example, the effect of a ratio of 0.25 for { ARRAY CONTRIBUTION ÷ BATTERY CONTRIBUTION } has the effect of multiplying errors by a factor of 4. Thus an instability of battery capacity of say 5% will lead to an uncertainty of 20% in the k_p extraction.

All the values for this ratio were less than one, instead of greater than two. In these circumstances one would expect grave scatter in k_p values. It would be unwise to attempt calculations under such conditions.

RATIOS FOR [ARRAY CONTRIBUTION ÷ BATTERY CONTRIBUTION]

	SYSTEM 1	SYSTEM 2	SYSTEM 3
DEPLETION TEST 1	0.78	0.76	0.61
DEPLETION TEST 2	0.38	0.57	0.45
DEPLETION TEST 3	negative!	0.29	0.26

Anomalies in the data presented

There are a number of queries, which require closer investigation. Amongst the apparent anomalies:

- It seems strange that three batteries in three independent systems should all gain 15 - 21% capacity for no identified reason (see Table 5.1, capacity tests #3 and #2). One should look for extraneous variables or changes in experimental conditions when an unexpected pattern like this is presented.

- The energy contributions from the PV arrays, in the third depletion test, seem to have ranged from negative to negligible, over 5 days exposure to solar irradiation. This suggests an error in measurement, calculations, experimental procedure, or equipment malfunction, but is not explained.

The author could provide more information about the experimental procedures, and such surprise measurements. He does allude to a shortened battery re-charge before capacity test #2, and to the possibility of experimental error in depletion test #3, but continues to present results based on these measurements, except where that is impossible to do (i.e. where the array contribution in System 1, depletion test #3, appears to be negative).

Methodology

The aim of attempting to invalidate the PV System Performance Test procedures is a worthy one, but unfortunately it is difficult to do this in the manner chosen, owing to the complexity of PV system performance on the one hand, and the Test[2] procedures on the other. The author's approach was essentially to find out if inconsistent Test results could be obtained while testing three similar systems under shared conditions. It is always tempting to try to validate or invalidate theories about complex systems by observing overall system behaviour (or in this case, extracted parameters which are supposed to represent overall system performance attributes). However, this approach to experimental falsification is extremely demanding, because (i) so many variables are involved, (ii) the Test Method incorporates probabilistic uncertainty margins, (iii) the Test Method allows for measurement variations (e.g. changes in measured battery capacity) which are held to invalidate the application of the Test Method calculations, but which are considered to be valid findings about the lack of performance stability of the system under test (assuming reliable measurement and proper Test procedures).

Karl Popper's useful precepts on quick routes to falsification, through critical experiment, include suggestions that the hypothesis to be tested should be as bold and simple as possible; incorporate as few variables as possible; and (roughly) that a theory or model should be tested at its weakest spot, under the conditions most likely to reveal error. Trying to falsify the present PV Performance Test Method by means

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[2] It is awkward to talk about two 'tests' at the same time. Capitals are used here to refer to the published PV System Performance Test Method procedures, which in turn were subjected to experimental test.

of a few repeated system-inclusive implementations is something of a nightmare, in terms of these precepts.

A fundamental requirement of a reliable PV System Performance Test Method is that is produces consistent and accurate results when correctly applied. If anomalous results are obtained, these *could prove* that the Test Method is unreliable, but only if there is full confidence that (a) the Test Method was implemented according to specification, (b) the anomalies are not the product of experimental errors, (c) the anomalies are not the result of malfunctioning of the tested systems, and (d) the anomalies fall outside the uncertainty margins predicted by the Test Method. This makes it very difficult to invalidate the Test Method by simple system-level experimentation. Any errors in experimental measurement or procedure which cannot be resolved and corrected leave the results in an inconclusive status. Replication within the experiment does not help, if experimental errors are also replicated.

In the present case, even if the author had satisfied (a), it would require scrupulous experimentation to establish (b) and (c), and careful analysis to establish (d). Without establishing (a), (b) and (c) the experimental results unfortunately cast little light on whether the Test Method is reliable.

By similar logic, no firm conclusions could be deduced if repeated tests on three systems delivered identical ('valid'?) results for each system. There is always the possibility that two or more errors could be counteracting one another, to produce what appears to be a 'validation' of the Test Method.

It would probably be more effective to isolate the theoretical assumptions in the Test Method which are thought to be most vulnerable to disproof, and to seek to invalidate these assumptions in a maximally controlled critical test, bringing in as few variables as possible.

The author's argument is that the data obtained "probably represents a best-case set of results", and that since the results show a high degree of scatter, this proves that the test method is (i) intrinsically unreliable and (ii) impracticable. However, one seriously-flawed experimental run, despite repeated measurements and parallel application to three systems, does not justify either conclusion.

Conclusions

- The conclusions drawn by the author *could* still be valid, despite the apparent lack of valid experimental evidence; but it is not scientifically tenable to have any confidence in these conclusions, since the experimental results are suspect. The author's conclusions should therefore be regarded as hypotheses which still need to be tested properly.

- One conclusion which I believe the author's work supports is that it can be difficult to implement the PV System Test Method correctly. This is an important drawback. A public test method must be robust, and resilient to experimenter error. Although the errors in the present implementation should have been readily identified (at least in hindsight, and at the stage of analysing and interpreting experimental data), there is considerable scope for making other mistakes in conducting the tests.

- There are also practical difficulties, for example in collecting continuous data without interruption over periods of up to two weeks.

- Despite these difficulties of implementation, the Test Method may still be the most informative PV system evaluation procedure presently available, potentially providing long-term performance predictions as well as immediate diagnostic checks.

- The discussion above proposes that the validity of the Test Method has not been demonstrated — either way — by the research presented in this report. It should also be noted here that several other possible threats to the accuracy of the Test Method (e.g. variations in spectral irradiation and PV module temperatures during the controlled depletion test) have not been explored experimentally. The slow development, refinement and acceptance of solar test methods in the international standards arena is a reminder that considerable resources are required for detailed investigation (typically, many laboratories will test the Test).

- In practice, the continued application and critical appraisal of the Test Method will probably depend on supply and demand in the local PV standards arena. A lot will depend on (a) whether there are institutions willing and able to perform a PV system testing service, and (b) whether there is perceived value in this testing, on the part of system suppliers, users and/or regulators. This pragmatic dynamic is vital in the process of developing better standards and test methods.

To fulfil its purpose, a test method must be reliable and fair, and it must also be perceived as reliable and fair. I therefore recommend (i) that any well-founded doubts about the reliability of the present Test Method should be critically examined by research and testing institutions, but (ii) that any unsubstantiated conclusions about the validity of the method should be treated with caution, as they may hinder rather than help the process.

PV System Performance Test Method

Introduction

The following test procedures have been devised to assist in the evaluation of small stand-alone PV systems with battery storage.

The tests are intended to provide the following:

- Measurements which allow the performance of different tendered systems to be compared under the same test conditions
- Indicators of the suitability or otherwise of the battery operating regimes of the tendered systems
- Predictions of the ability of the tendered systems to support their design loads at acceptable availability levels at the intended installation sites
- Predictions of the maximum average daily load which the tested systems could support at intended installation sites

These outputs can be achieved through a sequence of system tests, essentially

- a battery capacity test
- a "controlled depletion test" in which the systems are operated in restricted solar irradiation until they reach a depletion state
- a second battery capacity test

followed by calculations for predicting system performance from the results of these tests.

Approach

In outline the method is simple: it aims to establish the energy supply capacity of the system's storage batteries, within the system-defined battery cycling limits and with no input from the PV array, and then to establish the energy supply capacity of the PV array and battery together. The latter takes account of both array power and array-to-load path efficiencies. Combining the two sources of information permits extraction of two parameters which are sufficient to predict PV system performance, in the form of a loss of power probability (LOPP) prediction, at any site for which suitable solar irradiation data is available.

The key concept which underlies the method is that of a "critical depletion run", namely a run of days of "bad weather" where load energy demand exceeds supply, progressively leading to depletion of the reserve battery capacity. The test method seeks to establish system performance parameters over such a depletion run, while the long-term performance prediction method calculates the probability of weather/load conditions which would occasion such depletion of the battery and hence loss of power to load.

The theoretical basis for the LOPP prediction model has been reported in *A critical-run loss of power probability method for sizing stand-alone photovoltaic systems with battery storage* (Cowan, 1990).

Limitations of scope

The test method does not directly address durability or reliability of components, safety, the performance characteristics of components (except in relation to overall system performance), or the quality of user service provided by the appliances offered. System performance is evaluated for the systems *as tested* and lifetime degradation is not addressed in the tests. However, the tests have proved to be capable of identifying certain system design weaknesses which could threaten long-term performance or reliability.

Summary of test method

The systems are tested outdoors, in identical environmental conditions. Performance of the array-battery power subsystems is tested in relation to reference loads. The reference load for each system should preferably be the specified design load, obtained by operating the appliances provided by the supplier/vendor for the specified periods of daily operation. Alternatively, substitute loads may be operated instead.

The primary aims are to establish the battery reserve capacity and the PV array capacity in relation to the reference load. Path efficiencies from solar conversion to load power consumption must be taken into account. Since components in a PV system can exhibit non-linear characteristics, the tests are designed to establish average efficiencies suitable for making predictions of long-term system performance.

The limiting power supply capacity of a PV-battery system is determined in periods of poor weather, over a number of days, leading to inability of the array to recharge the batteries, depletion of the batteries to their lowest permitted depth of discharge, and consequently loss of power to load. For a given load and given solar irradiation conditions, the resilience of the system to failure depends on both the battery reserve and the array power.

The tests are designed to measure battery reserve capacity (with no power coming from the array) by means of an "autonomy" test, while the effective array-to-load power is measured in a "controlled depletion" test. In the latter, a controlled amount of solar irradiation is received each day by the PV array, but this is set to a level which ensures eventual system failure. Both PV power and battery reserve will contribute to the length of this depletion cycle, and since battery reserve capacity has been measured independently, it is possible to isolate the energy contribution of the array, yielding an "array to load power coefficient" which can be compared as between different systems and which can also be used in predicting performance in non-test solar radiation conditions.

Secondary aims of the tests are to check system settings for battery charge regulation and load-shed control and to assess the daily and maximum depths of cycle of the batteries. These parameters are strong determinants of battery lifetime, which is the most unpredictable element in PV system performance and the main contributor to replacement costs during the life of a system.

1. Set up

The supplied PV systems are set up outdoors. PV modules/arrays must have the same exposure to solar radiation. Batteries, regulators, load appliances and test equipment should be suitably housed close by. Cable losses should be representative of installed systems.

2. Instrumentation

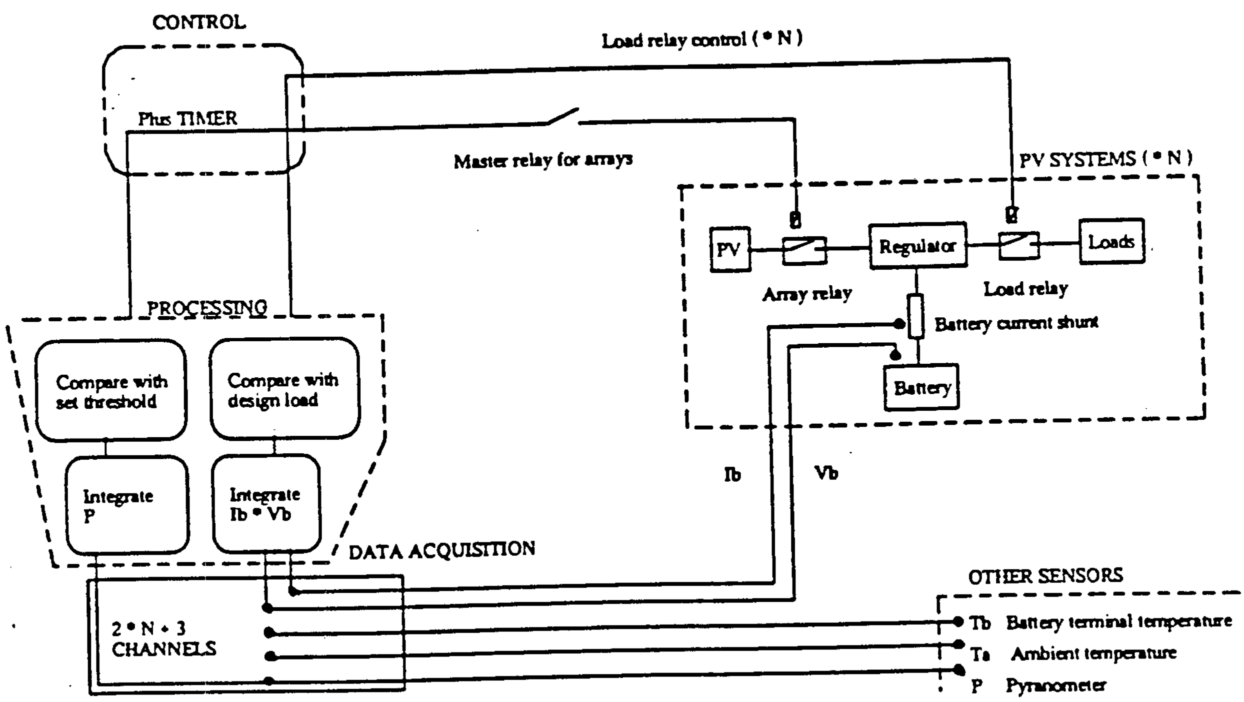
i) For full-system tests, minimum instrumentation requirements are: measurement of battery terminal voltage for each system (monitored at least every 10 minutes during system tests), and solar irradiation measurement using a Class 1 pyranometer coplanar with the PV arrays. A preferred option, in addition to measuring battery voltages, is to measure currents in and out of the batteries.

   The temperature of one battery in the batch should be monitored (probe attached to terminal) as well as the ambient temperature in the vicinity of regulators.

3. Test control apparatus

i) Load relays to switch in loads for set periods during the night (minimum requirement) or these relays to be controlled by monitoring volts and currents to load and switching off when a set load energy has been recorded (preferred option).

ii) Relays to disconnect arrays each day after a predetermined amount of solar irradiation has been measured. This requires integrated measurement of daily solar irradiance in the plane of the PV arrays.



Instrumentation and control for system tests.

4 Test parameters from suppliers' specifications

Systems are intended to be tested as supplied, in accordance with the average daily design load specified by the system supplier. If this is not suitable (e.g. if an unrealistic design load has been specified) adjustments may be required to determine the reference load against which the system should be tested.

Suppliers' specifications for rated PV array power are also used, in conjunction with other information, to determine the amount of solar irradiation which will be used for the controlled depletion test.

5 Initial battery cycle (full cycle)

Batteries as received are discharged until they reach their loadshed point, then recharged by PV power (no load connected) until top-of-charge regulation by the battery regulator is activated. The purpose is to reduce any differences between different batteries owing to their initial state of charge and to help establish battery equilibrium within the charge regulator settings.

6. Pre-conditioning

Batteries are discharged by the amount of one day's load, then recharged under array power (no load connected) until a set amount of solar irradiation has been received by the PV arrays. A suitable amount is 9 kWh/m^2 (more than could be expected on a full-sun day, but not excessively so). The aim is to bring the batteries of all systems to a comparable state before the next test. This state should reflect the top-of-charge regulation mode of the installed charge regulator, under reasonably realistic conditions.

7. First battery capacity test

With PV array disconnected, loads are operated "daily" (the test may be accelerated, providing load discharge currents are not exceeded) until batteries reach their set loadshed voltage. The energy consumed by the load, down to loadshed, is measured and recorded.

8. Recovery cycle

Immediately after loadshed, arrays are reconnected. Systems are operated until loads reconnect, in order to check loadshed hysteresis. Thereafter, loads are disconnected again and batteries are brought to full charge by PV power.

9 Controlled depletion test

Before the start of this test, batteries should be in a comparable state to their condition at the start of the battery autonomy test. The pre-conditioning procedure (step 6) is repeated.

During the controlled depletion test, systems are subjected to a daily test load, normally the design load for the system. The daily test load could however be adjusted, as long as discharge currents are representative of the intended application. For systems where the load would normally occur at night (e.g. domestic lighting systems) it is convenient to operate the loads at night.

Solar irradiation received by the PV array is controlled each day to a suitable predetermined level. After the predetermined amount has been recorded, arrays are disconnected. The amount of controlled irradiation is calculated to be less than the system requires in order to support the test load. As a result, the batteries progressively discharge to loadshed condition.

The energy consumed by the loads, from the beginning of this test until battery loadshed is reached, is measured and recorded. In addition, the total irradiation received by the array over the course of this test is recorded.

10. Second battery capacity test

After loadshed in the previous test, batteries are immediately brought back to full charge under array power (no loads connected), allowed to stabilise, and pre-conditioned again following the procedure of step 6. The aim is to bring the batteries to a state as close as possible to their system-defined state at the beginning of the first capacity test and the controlled depletion test.

The capacity test, as in step 7, is then repeated, to check that batteries have not degraded by a significant amount. This is particularly necessary if installed loadshed units permit such deep discharge of batteries that they can suffer reversible or irreversible damage during the previous test cycles.

Time required for tests

The time required for the full test sequence depends on a number of factors, including the sizing of tested systems in relation to their specified design load (if oversized, the tests can take longer). For typically sized systems, the minimum time requirements are approximately:

Initial battery cycle :	5 - 10 days
Pre-conditioning (1) :	3 - 4 days
Battery capacity test (1) :	2 - 4 days
Recovery cycle (1) :	4 - 10 days
Pre-conditioning (2) :	2 - 4 days
Controlled depletion test :	10 - 14 days
Recovery cycle (2) :	4 - 10 days
Pre-conditioning (3) :	2 - 4 days
Battery capacity test (2) :	2 - 4 days

The total from these estimates is between 34 and 64 days, or approximately 5 - 9 weeks.

Test Method Details

Set up

It is advisable to mount the PV modules at a tilt which maximises daily solar irradiation. This helps to shorten the time required for recovery cycles. The precise tilt angle is unimportant, but it is essential that all PV modules being tested and the pyranometer have exactly the same tilt and orientation (better than 2 degrees). Care should be taken to avoid any obstacles in the field of view, or uneven reflecting surfaces, which could result in different systems receiving different irradiation.

PV modules are responsive to the spectral composition of irradiation. This cannot be controlled in outdoor tests. For maximum accuracy, the emphasis is therefore on *comparative* tests of PV system performance, in which all systems are exposed to the same spectral conditions. For validity of long-term predictions in non-test conditions, it is desirable that spectral conditions during the tests should be reasonably representative of conditions expected at the installation site/s. Because this is a source of uncertainty, a margin of uncertainty is reported with long-term predictions. Unusual spectral conditions (e.g. polluted atmosphere) should be avoided at the test site.

The housing for batteries, etc., should ensure that temperatures are moderate and representative of probable indoors conditions at the site. Ideally, an indoors mean temperature of about 15 - 20 degrees would be appropriate. Changes in battery electrolyte temperature affect capacity, for example by 10% for a temperature range 18 to 35°C. Daily cycle temperature variations should be evened out to a large extent by the battery thermal time constant (about 6 hours in a water bath and perhaps about 18 hours in air) but to reduce daily swings the batteries should be on wooden racks and the building/structure should be as thermally stable as possible. Measurement of battery temperature will allow for the possibility of corrections being made for temperature drift if necessary.

Instrumentation

Battery terminal voltage should be measured to within ± 25mV. The record of battery voltages for each system must have a real time base. A sampling interval of 10 minutes should give adequate definition to detect the time of loadshed, etc.

If resistive loads are used, it is not absolutely necessary to monitor currents into and out of the battery. Resistances of the loads (and cabling) can be measured in advance, making it possible to derive energy flows out of the battery on the basis of (a) battery terminal voltages and (b) the timing of load operation.

However if the data acquisition facilities have sufficient channels it is preferable to monitor these currents. Current shunts should be of low enough resistance to have an insignificant effect on voltages, and current measurements should be accurate to within 0.5% at design load currents. In the preferred approach, battery terminal voltage and discharge current need to be multiplied and integrated to update the load energy count which is used to control the load relays for each system.

Temperatures: battery electrolyte temperature should be monitored to within a few degrees, and for this purpose (assuming shared environmental conditions and similar low-current charging and discharge rates) it should be sufficient to attach a thermocouple to the terminal of one battery in the batch. Ambient temperature in the vicinity of the charge regulators should be monitored. Temperatures can be logged at the same frequency as voltages.

The pyranometer should be a thermopile type, such as a Kipp and Zonen solarimeter, which has a broad spectral response. This is in order to be able to reference test performance parameters to weather station solar radiation records, which are based on broad-band measurements. As a check of spectral deviations which could affect PV performance relative to spectrally non-selective pyranometer measurements, an option is to make parallel measurements with another instrument, either a silicon-cell pyranometer or for greater accuracy a calibrated photovoltaic reference cell or module, if available. Pyranometer/s should have been calibrated recently (SA Weather Bureau provide a calibration service) and must be mounted according to instructions (to avoid azimuth error, the "lead" of Kipp and Zonen pyranometers should point N). For signal amplification: typical output voltages from Kipp and Zonen C5 instruments are in the region of 10 - 20 mV per 1000 W/m^2.

Instantaneous solar irradiance measurements should be sampled with a frequency of at least every two minutes. For the controlled depletion test, the arrays are disconnected after a predetermined quantity of solar irradiation has been measured. It is therefore necessary to integrate the sampled measurements, and the updated total must be available to control array disconnect.

The power consumption of supplied appliances may be tested manually to see if their consumption conforms with specifications. If this is done, it may be sufficient to do this at two battery states of charge, i.e. at full charge and at close to maximum depth of discharge.

Test control

Relays are required to connect and disconnect the loads, unless this is done manually. Separate relay control may be required for each system, if there is considerable variation in design loads and/or system sizing.

For testing PV systems designed for home lighting, loads should be operated when the array is not connected, or not producing power (e.g. at night) forcing all load energy to be cycled through the batteries.

Relays are also required for disconnecting PV arrays in the controlled depletion test, unless this is done manually. In either case, an integrated measurement of irradiance samples over time is required.

Options for data acquisition and test control

An accurate ready-to-go data logging system such as an HP 75000 data acquisition system, or equivalent, will save set-up time. The data acquisition and control system should be configured to accept sufficient data channels and with relay control boards. This will depend on the number of systems being tested simultaneously. The data acquisition and control software must be capable of integrating solar irradiation measurements, and taking action on the integrated amount.

Alternatively, a PC with one or more A/D boards can be programmed to handle the requirements, along with suitable signal conditioning, and amplification of control signals where necessary. Multiplexing the signals directly to an accurate multimeter card is an attractive option, avoiding uncertainties from signal amplification.

Whatever data acquisition and control equipment is used, it must be robust, since single failures could invalidate an entire test, losing several days of testing time. Programs should have error traps against disk write errors and a UPS is an advisable safeguard against possible power cuts.

If it is desired to conduct the tests with a minimum of instrumentation (which will however increase the need for human attendance) the bare minimum would be a manual record of battery voltages at periodic intervals while loads are running, and a means of integrated solar radiation measurement. It is possible to adapt the test method for manual operation, even on-site, at somewhat reduced accuracy.

Setting test loads

In the battery autonomy test and controlled depletion test, batteries are discharged in units or multiples of the design load. (Suppliers should be clear that the design load refers to energy available to power the appliances and therefore excludes generated energy dissipated in system losses.)

There are options for achieving the design load units in the system tests, depending on instrumentation and on how the design loads are specified.

1) If the design load is specified both in terms of Wh/day and hours of usage of the supplied appliances, the first preference is to use the supplied appliances (eg. lights) as the test loads, and to monitor both battery discharge voltage and current in order to record energy consumption. The design load energy draw should be achieved after the specified number of hours of operation, but the { current * voltage } record will show any deviation from the specified load in Wh. A disadvantage is the possibility of appliance failure during a test: failure

of one appliance could require fairly swift remedial action if the comparative tests are to remain valid.

Note: Whichever option is used, it is important that the current draw should always be maintained at a suitably selected and representative level, otherwise available battery capacity will be affected.

2) The second choice, if there are not sufficient data acquisition channels for current measurements, is to rely only on battery voltage measurements, and time, for controlling load energy consumption. This will be most accurate if resistive loads are used instead of the appliances, so that for known R the energy consumption is the time integral of V^2/R.

In this case, different design load units for the different systems can be set by integrating V^2/R, using the real time voltage measurements, and operating the loads until the appropriate load energy has been consumed. Similar control to that above is required to operate the load relays.

Note: Precise load control is not essential. What is important is accurate measurement of load energy consumed.

Resistive loads must be set in accordance with the design current draw of the different systems.

The advantages of this approach are greater simplicity and hardware reliability, and reduced instrumentation requirements. A disadvantage is that appliances need to be tested separately to determine their power consumption at different voltages, if this information is required.

3) The third choice is to use the appliances as the test load and control them purely by timing. If the design load has been specified only as so many hours per day of appliance use, this method would be appropriate. Both comparative test results and prediction of system performance in non-test conditions can be achieved without actually measuring load consumptions - the results will be in terms of hours of appliance use. But if instead it is desired to evaluate system energy supply capacity in Wh/day, this option would entail approximation (unless the appliances are constant power loads). Approximate corrections could be made to convert hours of use (at falling voltages) to Wh.

An advantage of this option is simplicity of operation and instrumentation, while the disadvantages are the degree of inaccuracy introduced and the need to test the appliances separately. The method might be favoured in on-site system performance tests, eg. under manual user control.

Setting PV array disconnect

In the controlled depletion test the PV arrays are disconnected when a predetermined quantity of solar irradiation has been recorded each day. This could perhaps be done manually, since it is not crucial that the daily amount be exactly the same from day to day. But to reduce supervision requirements over a fairly lengthy and continuous test it would be preferable to automate the process, with relays between the PV array and battery of each system. Control of these relays is common to all systems tested (since each system should receive identical irradiation), and should include facilities for timing array connect, and for setting array disconnect when the integrated solar radiation measurement has reached a set threshold value.

Preconditioning

The accuracy of performance predictions which can be made from the battery autonomy and controlled depletion tests will depend to a great degree on the batteries being in a comparable state at the beginning of these tests. Battery "full charge" is difficult to specify or obtain and so instead system settings should be used to obtain a stable "full charge" state. Secondly, available capacity depends to some extent on immediate battery history.

It is recommended that at the start of the test sequence, batteries should be subjected to one full cycle (down to their maximum permitted depth of discharge, then recharged under array power). Some batteries may require a full cycle to reach a representative starting equilibrium. It may be helpful to record the capacity delivered in this initial cycle, to help judge cases where batteries later show degradation of capacity.

Then before each capacity test, and also before the controlled depletion test, preconditioning consists of one design load discharge (array disconnected) followed by two or three days system operation with loads disconnected. Different types of charge regulator bring batteries to full charge in different ways, and at different rates, so for fairness and replicability, each system should receive the same amount of solar irradiation, sufficient to bring batteries to full charge after one design load discharge, but not unrealistically excessive. (In practice, most systems which are regularly used every day will seldom receive more than a few hours of "float charging", so it is rather unrealistic to expose the tested systems to prolonged float charging.) A well designed system should be able to recharge its battery, after one design load discharge, in one day of average weather in the worst month of the year (approximately). A slightly more generous allowance is recommended, 9 kWh/m^2.

In testing systems which are designed to have daytime loads operating (e.g. refrigerators) the top-of-charge regulation can be affected by the current draw of the load. It has been suggested that it would be better to include periods of load operation in the preconditioning recharge period, in these cases, but we have not investigated this experimentally.

The purpose of strict preconditioning procedures is to give the batteries a shared immediate history, and to give the batteries their best chance of starting each test in the same state.

Accuracy concerns in relation to battery capacity

The reliability and fairness of comparative test results depends mainly on all systems being subjected to the same test procedures, in a way which does not discriminate in favour of any system.

This could be threatened if test procedures are damaging to a system. For example, if system suppliers have specified a maximum depth of discharge which is excessive for their battery, it is possible that the deep cycles during the tests could impair battery capacity. This could be regarded as a fault in the system design, and would be revealed in the second battery capacity test.

Unfortunately, if at that time it is shown that significant battery degradation has occurred, it will not be possible to use the test results for long-term performance predictions. For performance prediction estimates made from the test results, an energy balance calculation is used which combines information from the autonomy (battery capacity) and controlled depletion tests, to separate the energy contribution from the array and the battery. Here it is important that the capacity delivered in the autonomy test is the same as the capacity delivered in the controlled depletion test, in order for the calculations to be accurate. Apart from the inaccuracy which would result from any significant battery capacity degradation, the main sources of variation here are (a) the possibility of temperature drift from one test to the other, although corrections could be made for this if necessary, (b) the effects of different discharge regimes in the two tests, and (c) the effects of any differences in pre-conditioning.

The two discharge regimes can be described as intermittent constant current discharge (autonomy test) and intermittent constant current discharge with partial charge cycles (depletion test). If batteries do not degrade significantly, the differences in delivered capacity should be less than 5 - 10%, and the impact of the difference is further reduced by the design of the controlled depletion test.

Battery capacity tests

After preconditioning, arrays are disconnected. Batteries are discharged in units of the total daily design load for each system, with rest periods of one hour between each discharge. The purpose of the one hour rest periods is to maintain an intermittent discharge regime more typical of load use in a small domestic PV system.

From the record of measured battery voltage under discharge, or combination of voltage and current measurements, the following information is obtained:

1) Discharge time taken to reach the "recommended maximum depth of discharge" of the particular battery and the corresponding voltage cut-point. Such recommendations (if different from suppliers' specifications) should be made in consultation with suppliers, battery manufacturers and experienced photovoltaic battery testers.

2) Discharge cut-off voltage and time taken to reach what the supplier has specified as the "design maximum depth of discharge" (as a % of rated capacity). This should be obtainable from battery discharge curve specs. The test provides a check against battery manufacturer's data.

3) The discharge voltage at which loadshed was activated and the time taken to reach that point.

The conversion from these measurements to battery capacity measurements will depend on the option selected for setting the design load.

If currents and voltages have been measured, the battery capacity delivered down to a certain cut-off voltage can be calculated in Wh or Ah. Either can be used to calculate corresponding percentage depths of discharge, although the Ah measurement is more convenient. To express the delivered capacity in terms of "days autonomy" the Wh values are more convenient.

The secondary result is a record of the tested loadshed voltage, to check the accuracy of the specified setting. Mean temperatures during the test will be reported as well as the ambient temperature at the time of loadshed.

Difficulties arise in testing a system without loadshed control. A decision should be made by the tester (in consultation with the supplier) about when to terminate battery discharge, and this must be done by external control.

Use of battery autonomy test results

There is no single "correct" value for the days autonomy of the battery. The power supply capacity of the PV/battery system in given conditions depends both on battery capacity and array power (together with path efficiencies). However, the "days autonomy" is a readily understood concept, and provides a way of comparing the reliability of systems which have the same array-to-load power ratio.

Reliability in a longer-term sense brings in the question of battery lifetime. For example, a system with 90% permitted maximum depth of discharge may offer high battery capacity and high system availability, ignoring degradation, but such deep cycles could be disastrous for the life of the battery.

Three aims of the battery tests are therefore:

1) to provide straightforward test results for installed battery autonomy

2) to use these results in combination with tests of array power to estimate the overall power supply capacity of a tested system in expected site conditions

3) to assess battery operating regimes with a view to ensuring satisfactory battery life

For aim (3) a certain amount of informed judgement and interpretation will be required. It is proposed that the following be evaluated in terms of available knowledge for a particular battery:

	Percent of rated capacity	Estimated cycle life at this depth of discharge	Source of estimate
Normal daily depth of discharge			
Optimal average depth of discharge	[Range]		
Recommended maximum depth of discharge			
Maximum depth of discharge set by installed loadshed control			

Estimates of cycle life of batteries are notoriously inexact, but since battery replacement costs are the main source of unpredictable expense to the user it is justified to present the information above, noting the source from which the life cycle estimates were obtained (typically from battery manufacturers' information).

It would also be possible, by means of computer simulation runs, to estimate the effective average depth of cycle of batteries in a given system under on-site operation at the design load, but this is probably beyond the scope of the present evaluation tests, whereas the information above can be presented easily, or marked non-available if there is no source for cycle-life estimates.

Other concerns to do with the battery operating regime as set by system parameters and system sizing include

1) whether top-of-charge regulation is suitable for the battery

2) whether prolonged states of partial charge can be expected (depending on the array power to load ratio - see below) which could damage some types of battery

3) whether array power and voltages, under the range of operating conditions, are sufficient to bring batteries to full charge and provide

overcharge gassing requirements for types of batteries which benefit from overcharge

All the above concerns could be satisfied if PV system suppliers were in a position to provide guarantees of battery lifetime in installed systems. However in view of the state of knowledge about battery performance, and intrinsic uncertainties, it is not surprising that PV system suppliers and local battery manufacturers are not keen to provide such guarantees.

Recovery cycle

As soon as batteries have reached loadshed, in the capacity tests and also the controlled depletion test, arrays should be reconnected, to avoid batteries standing in a discharged state. The loads should also be physically connected, but it is likely that the systems' battery regulators will keep the loads switched out until the battery voltages have recovered to a reconnect setpoint. Load reconnection should be observed (the battery terminal voltage record will be sufficient to determine when load-reconnect occurs) in order to check that the hysteresis between loadshed and load-reconnect is suitable.

Thereafter, to save testing time, batteries should be brought up to full charge (i.e. until top-of-charge regulation is activated) with the loads physically disconnected.

Top-of-charge regulation should be observed, in terms of voltage setpoints on the charge regulator, and preferably also in terms of charging currents under float or boost/float charging.

Before the next test (e.g. the controlled depletion test) the one-day's-load discharge and recharge preconditioning sequence should be repeated.

Controlled depletion test

The main purpose of this test is to establish the separate energy contributions of the array and battery, taking array to load path efficiencies into account. This is done by depleting the system, starting at full charge, ending at loadshed, while the loads operate and while a controlled amount of solar irradiation is received by the array each day. The time taken to reach depletion depends on the battery autonomy and on the array power (together with array to load path efficiencies). Battery autonomy has already been measured, so it is possible to separate the array contribution over the depletion cycle.

PV system efficiencies vary according to operating conditions. In particular, battery roundtrip energy efficiency is reduced during cycles close to full charge and is higher in cycles at partial states of charge. Array conversion efficiency is affected by PV cell temperature, the angle of incidence of irradiation and its spectral content, and also by the state of charge of the battery (which affects the intersection of the array's IV curve with the battery charging loadline). The aim in the depletion test is therefore to cover a representative range of system efficiencies corresponding to a full depletion cycle. In actual operation, the behaviour of a system in depletion conditions is what determines its limiting power supply capacity.

During the depletion test, batteries are operating in their efficient charge/discharge range for most of the test - which is representative of real depletion cycles. A full range of battery states of charge is covered in the test, giving a representative average for battery charging loadlines. By controlling the amount (and timing) of solar irradiation, an attempt is made to cover a representative range of module conversion efficiencies and module temperatures.

The calculation procedures for deriving results from the test are set out in a section below. An "array-to-load power coefficient" is derived, k_p, which can be interpreted very similarly to the "peak watt power rating of the array" - except that k_p additionally takes system losses into account. This can be used for comparing the real array to load power of different systems and also for predicting system power supply capacity in non-test conditions.

Determining the appropriate controlled daily irradiation and daily test loads

There are several criteria to be balanced in designing this test.

1) The duration of the test must be acceptably short, in terms of available testing time.
2) The array energy contribution should be larger than the battery reserve energy contribution. This reduces the impact of any error in using the previously measured battery autonomy in deriving the results.
3) If the test is too long, some types of battery may be damaged by being at partial state of charge for a prolonged period.
4) For comparative tests of various systems, each should receive the same irradiation (both spectral and total irradiation).

In order to satisfy criterion (2) above, it is recommended that the test should be designed so that total load energy consumption over the course of the test should be in the region of three times the available battery capacity. This has the effect of approximately halving any error introduced in using previous battery autonomy test results.

The duration of the test can be controlled by choice of the daily POA irradiation received, and/or by controlling the daily test load during the test. Decreasing the POA irradiation or increasing the test load will shorten the test.

In fact, by suitably adjusting the daily test load, it would usually be possible to conduct the test without controlling daily POA irradiation received. For on-site tests this option may be preferred. However, for a number of reasons, it is recommended rather that control over the duration of the test should be achieved by controlling the amount of POA irradiation received each day, preferably using the daily design load as the daily test load, but if necessary adapting the duration of the daily design load as well in order to have a predicted test duration of some 10 - 14 days. Adjusting the daily test load will be necessary if several systems are being tested with substantially different array powers, battery capacities, or design loads.

■ Simple approach

For a simple situation, where tested systems have an available battery capacity relative to design load of 3 to 5 days autonomy, and an accurately specified design load, it is relatively simple to estimate the controlled daily irradiation required. For a test length which is three times the days of battery autonomy of a system,

$$POA' = L / P \text{ approx}$$

and the predicted duration of the tests is

$$T = 3 * N_B \text{ approx}$$

where

POA' :	controlled daily POA irradiation	$kWh/m^2/day$
L :	daily total design load	Wh/day
P :	rated array power at STC	peak Watts
N_B :	battery autonomy at design load	days
T :	target duration of test	days

An assumption used for the above equations is that the loss factor in delivering solar energy to the load is approximately 0.7, on average, as in

$$\text{Daily array energy supplied to load} = 0.7 \, (POA' * P) \text{ approx}$$

For example, if T is 15 days, rated array power 48 Wp, daily design load 195 Wh/day and battery autonomy 5 days, then POA' would be approximately 4 $kWh/m^2/day$.

The loss factor referred to above may be less than 0.7 if there are unusual system inefficiencies. This would lead to systems reaching depletion in a shorter time than estimated above. If the loss factor were 0.6 the POA' should be increased proportionally, by 0.7 ÷ 0.6.

It is necessary that POA' is within bounds for expectable plane of array irradiation at the test site (which will vary at different times of year). It is not essential that the irradiation received is exactly the same each day (but it must be exactly recorded).

If POA' is not achieved on any day, one option is to allow longer exposures on subsequent days to restore the running average per day to POA'. Alternatively, loads can be reduced or interrupted to restore the average received per day. The average irradiation "per day" in this case is interpreted as average per "load day".

Depending on system sizing, the average irradiation per load day can be quite critical to ensure appropriate depletion test duration, and it is unwise to allow the running average to vary from calculated POA' by more than 5 to 10%. during the test, as this could lead to premature system depletion and poor definition in the results of the test.

Generalised approach

The following calculations are recommended if several systems are being tested in parallel, and these systems have widely differing energy supply capacity, relative to specified design loads, or widely different array : battery ratios.

- In order to bring such systems to depletion in approximately the same time, while ensuring they receive the same irradiation, it is necessary to adjust their loading.
- Secondly, the aim should be to bring the "weakest" system to depletion in a suitable time (in the range 10 - 14 days). As soon as one system has reached loadshed, the arrays are disconnected from all other systems, and they are discharged further, to their loadshed points, without further array input.

The calculations require knowing, or estimating the following, for each system:

1) available battery capacity (preferably from the first battery capacity test, or alternatively from loadshed specifications in conjunction with battery discharge curves at the appropriate discharge current)

2) the power rating of the PV array (from specifications)

3) an estimate of the average loss factor, relative to specified array power ratings, in delivering array energy to the load

The average loss factor will usually be in the range 0.65 to 0.7 but this initial estimate should be checked theoretically and possibly also by a few initial test measurements.

Theoretically,

i) Determine the battery voltage which is midway between the top-of-charge voltage and the charging voltage at maximum permitted depth of discharge. This gives an **average battery charging voltage.** (Note: the charging voltage at maximum depth of discharge is always higher than the loadshed setpoint, since the latter is a discharge voltage.)

ii) Add on to this average battery charging voltage the voltage drop between the array and the battery, caused by the battery regulator while charging, cables and any diodes. This now gives an estimate for **average array operating voltage.**

iii) Using manufacturer's curves for PV module performance at "Normal Operating Cell Temperature" (NOCT, 800 W/m^2 irradiance), find the rated module **current** which corresponds to this operating voltage.

iv) Multiply this **current** by the **average battery charging voltage** defined in (i) to get a value in watts.

v) Divide this value in watts by { 0.8 * the peak watt rating of the module at Standard Test Conditions }.

The result gives you an estimate of the loss factor for battery charging, relative to the STC power rating of the array. Two further steps are required to get an overall array-to-load loss factor.

vi) Multiply this result by an estimate for the battery watt-hour cycling efficiency. Since batteries will be in a partial state of charge during the depletion test, efficiencies tend to be high, and a value of 0.9 is appropriate for estimating the battery cycling efficiency under these conditions.

vii) Any power losses between the battery and the load, due to the battery regulator (discharge mode) and cabling should be factored in.

The average loss factor, calculated in this way, is denoted as "k" in the calculations below. The main source of potential inaccuracy is that modules may perform below the manufacturer's specifications.

Improvements by test measurements:

Measure current and power reaching the battery (under charge, at a state of charge midway between full charge and maximum depth of discharge) and simultaneous solar irradiance on the array. Solar irradiance should preferably be about 800 W/m^2. Divide the power reaching the battery (W) by the irradiance (W/m^2) and multiply by 1000. Now divide by the module or array's specified STC power (peak watts). This provides a better estimate for the result in step (v) above, and does not rely on the accuracy of manufacturer's specifications.

Calculation method

Symbols:

P: Rated array power, in peak Watts at Standard Test Conditions (ie. output power in W for an irradiance of 1000 W/m^2 at 25 °C cell temperature).

k: Loss factor, expressing the average derating of rated array power above, in delivering energy to the load.

L′: The daily load to be used in the controlled depletion test (Wh/day) which may have to be different from the design daily load.

POA′: The controlled daily plane of array irradiation for the controlled depletion test ($kWh/m^2/day$)

C: Available capacity of the fully charged battery (Wh)

T: Duration of the depletion test (days)

The depletion test starts with a discharge of L′, and after that, for the system to survive for T days, it must deliver a further T * L′ Wh to the load. In total, load energy consumption will be (T + 1) * L′.

Over T days the array can provide T * P * k * POA′ Wh to the load. The battery can supply C Wh altogether. Thus, for depletion in T days,

$$(T + 1) * L' = T * P * k * POA' + C$$

To determine appropriate values for POA′, L′ and T:

(a) POA′ can be chosen, subject to the following guidelines:

- POA′ must be expectable with reasonable confidence at the test site at the time of the tests, at least on most days
- Energy from the array over the test should be about twice the energy from the batteries, i.e.

$$P * k * POA' * T = 2 * C \text{ (approx)}$$

The target for T should be about 10 - 14 days. If tested systems have excessive battery capacity relative to array power, it may not be possible to ensure that the array contribution is about twice the battery's energy contribution within a 10 - 14 day depletion run, and accuracy may be reduced.

(b) **Having set POA′ and T provisionally, L′ can be calculated:**

$$P * k * POA' * T = (T + 1) * L' - C$$

$$L' = (P * k * POA' * T + C) / (T + 1)$$

This should be done for each system. Note that L′ should be manipulated by controlling the *duration* of loading, rather than by varying the load power, as the latter would affect battery discharge currents and hence available battery capacity.

For the typical case where a depletion test target is 12 days and the controlled daily POA′ is 4 $kWh/m^2/day$, calculation of the loading is simplified to:

$$L' = (48 * k * P + C) / 11$$

At times of year when weather is uncertain, a lower value of POA′ might be preferred.

Depletion test procedure summary

1) For each system, determine the available battery capacity. This is established in the battery autonomy test. It can also be approximated from system specifications. Determine the appropriate controlled daily plane of array irradiation, POA′ $kWh/m^2/day$, as detailed above, and the associated daily load for this test, L′.

2) Ensure that the "pre-conditioning" of the batteries before the start of the depletion test has been as close as possible to the pre-conditioning before the start of the first battery capacity test.

3) Discharge the batteries by the amount L′ Wh. (All discharges should happen "at night", i.e. when the array is disconnected.)

4) From then onwards, connect the arrays for a period each day until the controlled irradiation POA′ has been recorded. This requires integration of readings taken with a pyranometer coplanar with the PV arrays, and preferably relays which disconnect all the arrays when the measured total irradiation reaches POA′. It could however be performed manually, since POA′ does not have to be exact on any single day.

   Every "night", discharge the batteries by the amount L′ Wh, eg. by appropriately timing the load-on period.

5) If, on any day, POA′ is not attained due to bad weather, either make up the deficit the following day (if the deficit is small); or withhold the night loads until the deficit has been recovered.

6) When the first system reaches loadshed, which will happen at a time when arrays are disconnected, discontinue array power to all of the remaining systems.

    Note: an exception is if a system has failed early due to some failure. This step should only be taken if an adequate number of test days have been completed (e.g more than 9 or 10 days).

7) Continue discharging the remaining systems in multiples of L′, with one hour breaks between each L′ unit, as in the battery capacity test, until all systems have reached loadshed. In this way, all systems should be brought to loadshed within a short period of one another.

8) Ensure that all systems are put back on charge as soon as possible after loadshed has been reached.

Measurements:

- Battery terminal voltages and (optional, as in battery capacity tests) currents into and out of batteries. Battery terminal voltages are used to identify when loadshed is reached, and to check the battery discharge voltage at which loadshed occurs. Voltages and time and (optional) currents are used to monitor discharge energy.

- Plane of array irradiation, using a broad-band pyranometer. Instantaneous irradiance measurements sampled at least every two minutes are integrated to give POA irradiation daily totals. These are recorded to give total POA irradiation received by connected arrays for the whole test.

- Battery electrolyte temperature, to check that changes in battery temperature over the course of the depletion test do not unduly affect battery capacity, and to check that battery temperatures are approximately the same as in the autonomy test. If this is not the case, calculated adjustments may be necessary.

All above measurements must be on a time base.

Second recovery cycle
Second battery capacity test

These are repeated as before. The second battery capacity test is intended as a check of possible battery degradation over the course of the sequence of tests.

If battery capacity has altered by more than about 10% between the first and second capacity tests, long-term performance predictions will be inaccurate. The interpretation of results from the controlled depletion test will also be subject to a margin of uncertainty. The main conclusions should be that the battery is inadequately protected from the maximum allowable depths of cycle, and attention should focus on diagnosing reasons for the observed battery degradation. These may lie in the charge regulator settings, inappropriate choice of battery type, or inadequate array power relative to the installed battery capacity.

If slight battery degradation has occurred, the accuracy of calculations can be improved by using the average of the measured battery capacity in the first and second battery capacity tests, in the calculation of test results set out below.

Deriving results from the depletion test

Results are derived from the depletion test in conjunction with the battery capacity tests.

The primary result is a derived coefficient, k_p, which indicates the measured power of the array to deliver energy to the load (taking account of average conversion and transmission efficiencies over the course of a depletion cycle).

k_p is defined as follows:

$$E_L = k_p * POA$$

where

E_L :	Energy supplied to load by array	(Wh)
POA:	Plane of array irradiation energy	(kWh/m^2)

over the course of a depletion cycle.

The units of k_p are $m^2/1000$. This is similar to the units in which PV modules and arrays are rated. (The "peak watt" rating of a PV module is in fact a measure of output watts per 1000 W/m^2 irradiance, and has the units $m^2/1000$.)

k_p can be compared with the rated peak watt power of the array as follows:

Peak watt rating:	specified maximum power output of array at 1000 W/m^2 irradiance and Standard Test Conditions
k_p :	array power available to the load, per 1000 W/m^2 irradiance, in operating conditions averaged over the depletion cycle

k_p is less than the peak watt rating because of

- the energy efficiency of battery storage (in these tests, all array energy passes through the batteries)

- reduced conversion efficiency of the array as a result of higher PV cell temperatures, and irradiance occurring at higher incidence angles and with different spectral distributions compared with Standard Test Conditions
- the array not operating at its maximum power points, usually as a result of battery charging voltages being lower than the array's optimum power voltages
- possible below-specification module performance
- any other losses in transmission of array energy to the load (eg. blocking diodes, charge regulator efficiencies, wiring losses, etc.)

These factors need to be incorporated in an assessment of the design and performance of a PV system and hence k_p is a valuable indicator, taking all these effects into account.

Calculations

Calculations are based on an energy balance over the course of the depletion test.

Symbols:

E_L :	Energy consumed by load	(Wh)
E_B :	Energy supplied to load by battery reserve	(Wh)
E_A :	Energy supplied to load from PV array	(Wh)

For energy balance,

$$E_L = E_B + E_A$$

Energy consumed by the load, E_L

For each system tested, the energy consumed by the load is calculated as the sum of the load discharges over the depletion test until loadshed is reached.

Energy supplied to the load by battery reserve, E_B

The energy supplied to the load by the battery reserve is calculated as the load energy consumption during the battery capacity tests, or equivalently as the battery autonomy (in days) corresponding to the daily total design load, multiplied by the daily total design load (Wh/day), giving energy supply to load from the battery in Wh.

Calculated adjustments may be made for electrolyte temperature deviations and loadshed voltage deviations if necessary.

Energy supplied to the load from PV array, E_A

This is derived from

$$E_A = E_L - E_B \quad \text{(Wh)}$$

The ***array to load power coefficient*** is then obtained by equating

$E_A = k_p * \{\text{total POA}\}$

where

{total POA} : the total plane of array irradiation received by the PV array over the course of the depletion test (kWh/m^2)

Interpretation of results

The array to load power coefficient, k_p, can be interpreted in the following useful ways:

1) k_p's for each system can be compared, giving a relative comparison of the effective array power of each system.

   If systems have different design loads, their effective array power relative to their design loads can be compared, using the ratio k_p/L, where L is the design load (Wh/day) of each system.

2) k_p can be compared with the rated STC power of the PV array in peak watts. The ratio k_p / (STC specified Wp) is a measure of the array power reaching the load compared with specified array power.

   Unless rated array power is under-specified, the ratio will be less than one, reflecting the performance of the array in realistic operating conditions and a number of system losses in delivery of array power to load.

   The ratios for different systems can be compared, and if a system has a significantly lower ratio than other systems, this could indicate:

- PV array output below specs
- inefficient matching of array and battery charge voltages (eg. array voltages inefficiently high)
- unusually high system transmission losses
- low battery energy efficiency

3) As a rough guide that the array is suitably sized for the design load (L Wh/day) and the intended site, the ratio

$$ß = k_p * POA_d / L$$

should be approximately equal to one.

POA_d is the "design POA irradiation" for the intended site, usually taken (in approximate sizing methods) as the average daily plane-of-array irradiation in the worst month of the year.

If ß is considerably greater than 1, this indicates that the array (as tested) may be oversized for the design load. Note that

i) This applies to array power as tested. No margins have been added for possible lifetime degradation, losses through shading or faulty cells, or deviations in module output performance across a production batch. Normal system losses however have been incorporated in deriving k_p.

ii) System availability will depend on battery capacity in addition to array power. An oversized array may be an economic solution (in terms of expected life-cycle costs) if it allows less battery capacity to be used. System availability can be checked more accurately in the Loss of Power Probability predictions presented below.

iii) Systems designed for very high reliability levels (e.g. PV systems for vaccine refrigeration) should have over-sized arrays.

If ß is significantly less than 1, this indicates that the array (as tested) may be undersized for the design load. However system availability will depend on battery capacity in addition to array power. System availability can be checked more accurately by Loss of Power Probability predictions.

The main concern, if ß is less than 1, is that batteries may spend prolonged periods at partial states of charge in poor weather conditions, because power to the load from the array is predicted to be less than required in the design month. If this is indicated it is most important to check whether the type of battery employed is capable of operating at prolonged states of partial charge without serious capacity degradation.

Predictions of System Performance in Non-Test Conditions

The results of the battery autonomy test and controlled depletion test can be used to predict the performance of systems (as tested) in non-test conditions. Performance can be predicted for different design loads and for different solar irradiation regimes.

The procedure is simple to implement, but requires solar radiation statistics in a particular form, namely long-term centiles for average daily POA irradiation received over runs of days from runlength 1 to 30 days.

Suitable statistics have been prepared by EDRC for twelve major SA weather stations. When predictions are required for locations other than these, adjustments and interpolations may be necessary, making use of the patterns for primary weather stations adapted according to less detailed solar radiation records for nearby localities.

Method

The method used is the critical-run loss of power probability sizing method developed at EDRC, which equates

(1) the POA irradiation requirements needed by a specified system to avoid depletion of the batteries, over depletion runs of 1 to N days

with

(2) the probabilistic expectation of average daily POA irradiation at the site for runs of 1 to N days.

Different probability levels can be chosen, but for present purposes the probability level used is P = 0.01. Solar irradiation expectations at this probability level will be used to predict the ability of the tested PV systems to support a specified load with a long-term loss of power probability of 0.01.

A loss of power probability of 0.01 denotes an average annual loss of power to load of approximately 3.6 days a year, due to insufficient solar irradiation.

This is generally reckoned to be a sufficiently high level of availability for PV systems, unless the consequences of non-availability are particularly severe (as in some telecommunications applications). It is sometimes recommended that the loss of power probability for non-critical applications such as domestic electricity supply should be even higher than 0.01.

For example, a LOPP of 0.05 is recommended by Sandia Laboratories for non-critical systems. This leads to more economical system design. It should be borne in mind, however, that a system with an *average long-term* LOPP of 0.01 may have considerably greater loss of power in a "bad" year.

Researchers in the USA (Sandia National Laboratories, 1990) estimate from PV simulation studies that a long-term LOPP of 0.01 could typically mean a spread as follows:

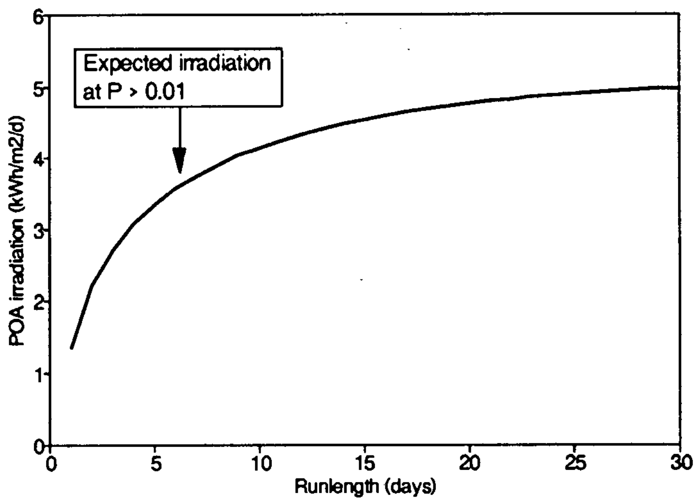
Out of 20 years,

	7 years:	loss of full power on	less than 1 day per year
	8 years:	loss of full power on	1 - 10 days per year
about	5 years:	loss of full power on	10 - 22 days per year

(Users would normally accommodate periods of reduced power by reducing their consumption.)

Expected plane of array irradiation:

For illustration, the graph below shows average daily POA irradiation, as a function of runlength, for Pretoria, at a probability of P = 0.01. The interpretation is: that over any run of N days, the expected minimum POA irradiation, in Wh/m^2/day, is given by the line in the graph; the long-term probability of receiving less than this amount is predicted to be 0.01 and the probability that more than this amount will be received is 0.99.



Minimum daily POA irradiation expected at Pretoria with probability P = 0.01, over runs of days.

PV system's irradiation requirement, to avoid loss of power to load:

The plane of array irradiation requirement depends on the load energy demand, the available battery capacity, the array power and the path efficiencies in transmitting array power to the load.

For a system with the following parameters

Design load:	L_d	Wh/day
Battery capacity:	C	Wh
Array-to-load power coefficient	k_p	$m^2/1000$

the average daily plane of array irradiation required to prevent the system from reaching depletion can be expressed as a function of the length of a depletion run. (Due to the "autonomy" of the battery, irradiation requirements are zero for the first few days of a depletion run.) This is the basis for predicting system performance, using the EDRC critical-run loss of power probability model described elsewhere in this manual.

A critical run is defined as a sequence of N days, starting with fully charged batteries of available capacity C (Wh), during which the average daily solar irradiation POA_{avg} (kWh/m²/day) is insufficient to meet the load energy requirements, L (Wh/day). The critical run results in loss of power to load, after N_c days, if the battery reaches loadshed.

The controlled depletion test is a controlled emulation of such a critical run. This is why system performance characteristics measured in the controlled depletion test are particularly suitable for use in this LOPP prediction method.

In general, to *avoid* loadshed over any run of N days, starting with fully charged batteries, the average daily irradiation requirement is given by

Load energy < battery energy + array energy available to load

or

$$N * L < C + (N * POA_{avg}) * k_p$$

Assuming that all load energy is cycled through the batteries (as in a night-load system) an adjustment is made, to allow for the first night's discharge of the battery:

$$N * L < (C - L) + (N * POA_{avg}) * k_p$$

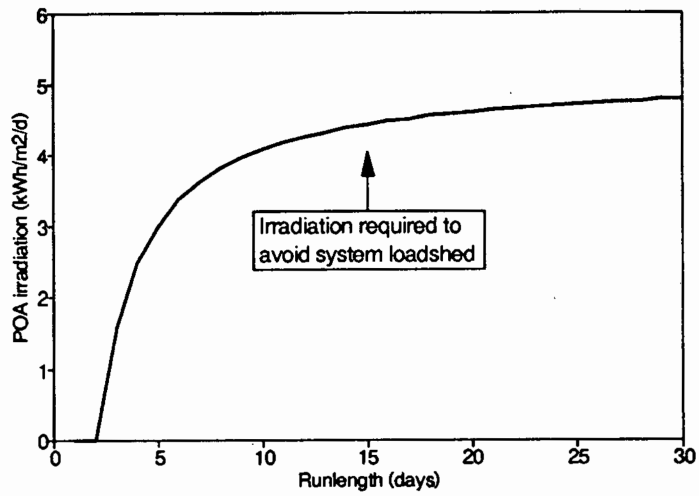
(In other words, the system starts any run of N daylight days with the batteries discharged by one night's load.) The corresponding solar irradiation requirement POA_{req}, to avoid loadshed, is now

$$POA_{req} > [(N + 1) * L - C] / (k_p * N)$$

for any N

The stipulation "for any N" covers the assumption that ***at some point*** the battery was fully charged. In practice, for PV systems designed for southern African conditions where it is uneconomical to use batteries for seasonal storage, it is sufficient to consider the range N = 1 to 30.

Using N = 1 to 30, and measured values for C and k_p, the last formula above can be entered in a spreadsheet. L can either be a variable or the specified daily design load. Plotting this function will give a curve for the minimum required daily irradiation (average kWh/m^2/day) required to avoid loadshed.



Minimum irradiation requirement

This curve can now be compared with the expected irradiation for the site under consideration. The expected irradiation, POA_{exp} (average kWh/m^2/day) over any run of N days can be expressed as

$$POA_{exp} = f(N, P)$$

where P is the probability of obtaining less than POA_{exp}, derived from statistical analysis of long-term weather data.

On the facing page, the functions for POA_{exp} for twelve weather stations are provided. They take the form of fairly simple equations, which can also be entered in a spreadsheet, using the same range for N = 1 to 30 as was used for POA_{req}.

Expected solar irradiation functions

After processing long-term solar irradiation probabilities for the following stations, the curves were fitted using the equation

$$POA_{exp}(N, P) = a + bN + c / N + d (\ln (N))$$

where POA_{exp} is in $Wh/m^2/day$, N is the number of days in any run, P is the probability of obtaining less than POA_{exp}, and a, b, c and d are coefficients obtained through fitting the curves. The coefficients for twelve sites, at four different LOPP levels, are provided below, to assist with spreadsheet calculations.

	LOPP	a	b	c	d
Windhoek	0.1	5256.17	-7.62	-20.85	376.63
	0.05	4553.60	-9.05	-116.04	542.47
	0.01	3017.17	-16.63	-296.72	962.82
	0.005	2741.73	-11.34	-583.91	974.92
	0.001	1693.78	-9.41	-369.31	1210.22
Keetmanshoop	0.1	5526.38	-18.33	442.37	558.43
	0.05	5159.17	-14.94	-34.43	608.72
	0.01	3949.53	-22.19	-736.62	969.07
	0.005	3153.92	-45.70	-555.09	1353.69
	0.001	3104.42	-44.93	-2243.76	1341.35
Alexander Bay	0.1	5247.42	-7.72	-454.90	311.59
	0.05	5054.52	-3.34	-1299.79	305.56
	0.01	3252.77	-20.08	-1244.91	912.79
	0.005	2228.87	-32.70	-643.57	1294.82
	0.001	-656.95	-75.01	1700.33	2419.37
Cape Town	0.1	3693.42	-13.42	-943.33	358.12
	0.05	2757.22	-24.19	-1118.85	658.22
	0.01	313.89	-48.58	446.68	1458.27
	0.005	-470.37	-45.49	1061.03	1628.78
	0.001	-663.79	-1.92	959.98	1227.45
Upington	0.1	5124.35	-14.90	362.39	507.89
	0.05	4833.48	-11.18	-434.41	523.29
	0.01	3678.12	-30.37	-1402.65	907.86
	0.005	3196.39	-41.67	-1506.59	1075.89
	0.001	1073.09	-74.48	-132.35	1846.67
Port Elizabeth	0.1	3972.47	-9.99	-1105.20	415.01
	0.05	3008.13	-22.33	-1123.65	748.23
	0.01	230.18	-55.76	664.84	1731.23
	0.005	-473.61	-59.25	1101.99	1897.71
	0.001	-1252.56	-33.67	1558.52	1788.30
Grootfontein	0.1	4660.82	-8.54	-358.89	439.00
	0.05	4042.16	-6.41	-1044.03	548.76
	0.01	1270.68	-42.57	-71.77	1536.79
	0.005	323.26	-47.44	-578.15	1817.46
	0.001	-2563.47	-95.66	3098.09	2961.60
Bloemfontein	0.1	4373.86	-19.05	255.53	679.04
	0.05	3350.92	-25.71	5.70	974.41
	0.01	1802.58	-19.60	-434.21	1276.09
	0.005	1424.37	-10.66	-474.85	1246.02
	0.001	-625.85	-25.64	932.57	1758.23
Pretoria	0.1	4086.80	-16.12	-1.90	549.17
	0.05	3416.31	-13.42	-361.88	677.63
	0.01	1145.62	-36.42	255.07	1444.89
	0.005	382.06	-34.63	597.86	1627.18
	0.001	-1328.91	-50.08	1818.50	2180.02
Roodeplaat	0.1	4158.84	-13.17	38.09	543.44
	0.05	3375.08	-18.40	-235.60	759.98
	0.01	1642.40	-22.43	-245.06	1214.63
	0.005	647.90	-31.14	385.22	1542.60
	0.001	-1631.27	-54.97	2205.44	2335.48
Nelspruit	0.1	3634.14	-10.00	-893.98	501.90
	0.05	2826.87	-15.57	-1097.25	742.29
	0.01	561.04	-48.97	369.59	1542.80
	0.005	-105.67	-52.62	825.93	1723.56
	0.001	-1152.17	-46.03	1581.21	1893.61
Durban	0.1	3578.31	-6.94	-1513.67	354.28
	0.05	2303.88	-29.50	-908.93	851.68
	0.01	-165.45	-56.40	950.97	1678.72
	0.005	-899.75	-55.68	1591.75	1857.26
	0.001	-2232.15	-58.61	2699.86	2156.70

Suppose the POA_{exp} function for a LOPP of 0.01 for Pretoria is used. The appropriate equation is

$$POA_{exp}\ (N, 0.01) = 1146 - 36.42N + 255 / N + 1445 \ln N$$

The simplest way of establishing how POA_{req} compares with POA_{exp} is to plot the two curves on the same graph, using a spreadsheet. System failure is predicted if the POA_{req} curve crosses the POA_{exp} curve.

In this way, it is possible to answer the following questions:

Can the system (as tested) support its design load?

To check whether a tested system can support its design load at this LOPP (0.01) at the intended site, the requirement is

$$POA_{exp} > POA_{req}, \text{ for all } N$$

Expressed visually, this condition is that the POA_{req} curve should never touch the POA_{exp} curve.

What is the maximum daily load for this system?

The maximum daily load which the system is predicted to support at LOPP=0.01 at the intended site is given by varying L in the POA_{req} equation, until

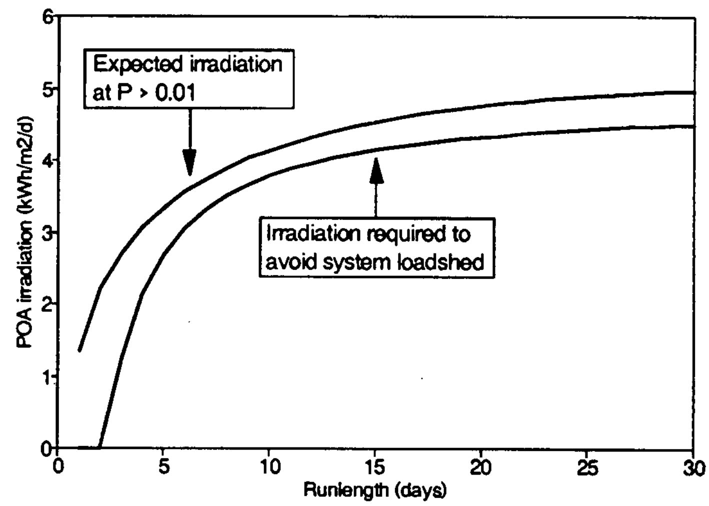
$$POA_{exp} = POA_{req}, \text{ for some } N = N_C$$

and

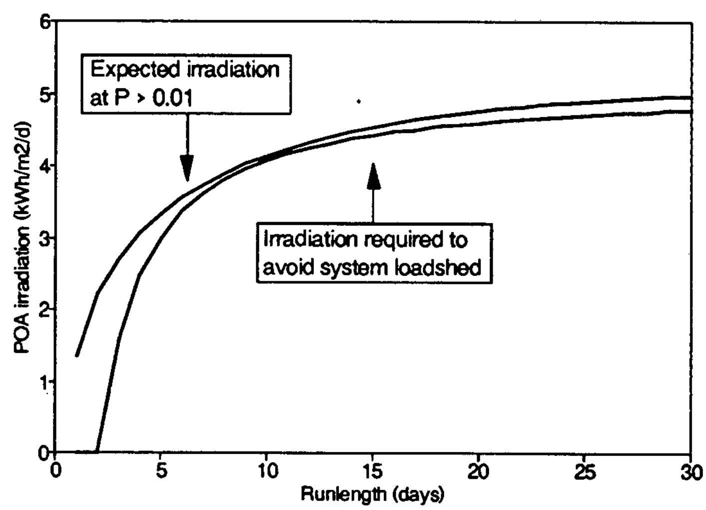
$$POAexp > POA_{req}, \text{ for all other } N$$

This can be done in the spreadsheet calculations by varying L until the POA_{req} function just touches the POA_{exp} function.

The graphs on the facing page illustrate these conditions.



The system is predicted to support its design load at LOPP=0.01. The expected irradiation exceeds the required irradiation, at this probability level.



The load has been increased to L_{max}. Now the required irradiation curve just touches the expected irradiation curve.

The same procedure can be followed to predict system performance at other sites for which solar irradiation functions are available, and for different loss of power probabilities.

Interpretation of LOPP predictions

The LOPP predictions are for system performance averaged over many years (corresponding to solar radiation patterns analysed over many years). In any single year, the incidence of loss of power to load could be less than or greater than the long-term average, as discussed above.

The predictions are based on measurements of the PV system *as tested*. It can be expected that components will degrade over time, so degradation margins should be included to make long-term performance predictions more realistic. In addition, spectral variations in solar irradiation are unpredictable. It is advisable to include a margin for this source of uncertainty. The following margins are presently recommended:

- for battery capacity, reduce the measured battery capacity by at least 10% to account for degradation averaged over the battery's useful life
- for spectral variations and other sources of array degradation, reduce the measured array power, i.e. reduce k_p , by 10%
- in the case of amorphous silicon modules which are expected to degrade significantly, long-term performance predictions are very uncertain; if manufacturers' data or warranties serve as a guide, reduce k_p accordingly; deratings of 30% or more could be advisable, but no accuracy can be expected

The effect of derating both battery capacity and array power by 10% is to reduce the predicted system energy supply capacity by 10%.

Uncertainties in the performance predictions

Uncertainty in the predictions arises, firstly, from uncertainty in the solar radiation data used, which can be substantial where estimations are required for sites other than the primary weather stations. This uncertainty has been estimated as ± 13% for sites requiring interpolation, but should be in the order of 5 - 8% for primary weather stations.

Uncertainties arising from the test method, as applied here for predicting long-term system performance, have been estimated as ± 12%.

Combining a ± 8% uncertainty for solar radiation and a ± 12% uncertainty for test parameter extraction and application produces an estimate of about ± 14% for the overall prediction. Thus a prediction of the maximum load which a system could support at loss of power probability 0.01 for primary weather station locations should be stated at ± 14%. For secondary locations requiring solar irradiation interpolation, the uncertainty rises to about ± 18%.

When the method is used to **compare** the power supply capacity of different systems, the uncertainties in the reference solar radiation data do not enter the comparison, and uncertainties arising from the test method are reduced. It is estimated that such comparisons should be valid to within ± 10% or better.

APPENDIX C:

GENSET PLUS BATTERY RUNTIME MODEL

Generator plus battery power systems provide the opportunity of running generators for much shorter periods than for straight generator systems. Often the generator life is increased by the improved mean capacity factor, which together with decreased maintenance costs contribute to a lower cost of energy.

One of the problems in sizing and optimising genset plus battery systems is in estimating the generator runtime, especially during the period when the battery rate of charge acceptance decreases as the battery approaches full charge. It will usually not be optimal to recharge the battery fully because the runtimes increase exponentially as full charge is approached (figure 1), but capacity factor falls dramatically as the charge current tapers.

A simple model has been developed to estimate generator runtimes based on battery data evolved at EDRC. Starting and finishing state of charge (SOC) are input, and the runtime is the output. The model requires that the generator output is capable of current tapering or constant voltage charging, and the voltage limit is less than 2.4V/cell. In most genset plus battery systems the generator supplies a constant voltage, current limited battery charger. Sometimes the generator powers an alternator (which is current limited) that charges the battery through an automotive-type three terminal regulator.

Model development

Figure 1 shows a charging curve for a current limited, voltage limited system. The initial current is limited to I_s and the voltage limited to V_c. The finishing current at full charge is I_f, determined mainly by the voltage limit. The finishing current is consumed entirely by battery gassing, and can be obtained from experimental data. The charge into the battery is shown in figure 2. The instantaneous current after tapering begins is approximately exponential, given by

$$I = I_f + (I_s - I_f)e^{-kt} \qquad (1)$$

The SOC at which voltage limiting takes control is SOC_{crit} at t_c (Figure 3). The SOC at any time is given by

$$SOC_t = SOC_{crit} + \sum \frac{(I_t - I_f)}{Ah} t \qquad (2)$$

or

$$SOC_t = SOC_{crit} + \int_{t_c}^{t} \frac{(I_f + (I_s - I_f)e^{-k(t-t_c)} - I_f)}{Ah} dt \qquad (3)$$

Differentiating,

$$\frac{dSOC}{dt}=\frac{I_s-I_f}{Ah}e^{-k(t-t_c)} \quad (4)$$

but

$$\frac{dSOC}{dI}=\frac{dSOC}{dt}\times\frac{dt}{dI} \quad (5)$$

now

$$\frac{dI}{dt}=-k(I_f-I_s)e^{-k(t-t_c)} \quad (6)$$

and

$$\frac{dSOC}{dI}=\frac{1}{-k} \quad (7)$$

This shown by the straight line in figure 2, which was experimentally determined. The constant k is independent of battery size, but dependant on generic battery type. Typical dimensions are 0.75 $hours^{-1}$.

If equation 4 is integrated then

$$SOC_t=\frac{I_s-I_f}{-kAh}e^{-k(t-t_c)}+C \quad (8)$$

Solving for C at t_c, C = 100. SOC_{crit} falls out in the solution as the relationship

$$SOC_{crit}=\frac{I_f-I_s}{kAh}+1 \quad (9)$$

Rearranging,

$$(t-t_c)=\frac{1}{-k}\ln\left(\frac{-kAh}{(I_s-I_f)}(SOC_t-1)\right) \quad (10)$$

and substituting equation 9 and generalising,

$$t_2-t_1=\frac{1}{-k}\ln\left(\frac{1-SOC_{t_2}}{1-SOC_{t_1}}\right) \quad (11)$$

The model therefore becomes:
SOC_{crit} derived by the relationship

$$SOC_{crit} = \frac{I_f - I_s}{k\,Ah} + 1 \tag{12}$$

The runtime calculation depends on the starting start of charge, SOC_{start}.
If $SOC_{start} > SOC_{crit}$ then

$$runtime = \frac{1}{-k} \ln\left(\frac{1 - SOC_{finish}}{1 - SOC_{start}}\right) \tag{13}$$

if $SOC_{start} < SOC_{crit}$ then

$$runtime_1 = (SOC_{crit} - SOC_{start}) \frac{Ah}{I_s} \tag{14}$$

$$runtime = runtime_1 + \frac{1}{-k} \ln\left(\frac{1 - SOC_{finish}}{1 - SOC_{crit}}\right) \tag{15}$$

Conclusions

In summary, generator runtimes for current and voltage limited genset plus battery charging systems can be calculated knowing

- V_{ch} and I_f at V_{ch},
- I_s,
- SOC_{start} and SOC_{finish},
- the battery capacity in ampere-hours.

The main constraint is that the charging voltage limit must be below 2.4V/cell for the battery charging model to be accurate.

The model can easily be rearranged to the most practical form. It may be desirable to eliminate SOC_{crit} from the equations and to use I_f, I_s and k. The model is also easily made dimensionless, so that I_f and I_s are percent of battery capacity instead of actual current values.

The model has not been tested for any conventional battery chargers, but at this stage it is recognised that many are not suitable for genset plus battery charging. The intention is to locate suitable battery chargers, and to evaluate both model and chargers.

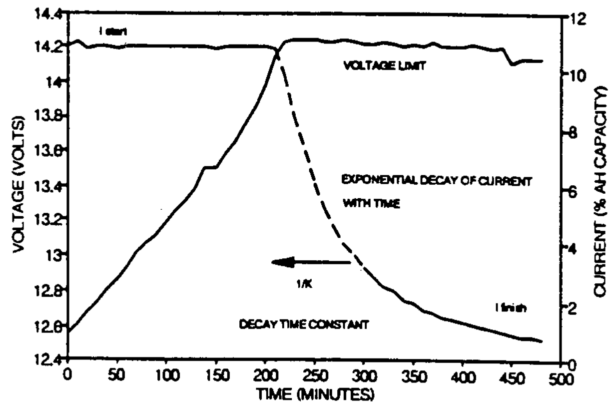


Figure 1. Current and voltage limited battery charging curves show exponential decay of the current during prolonged charging under constant voltage conditions. The charge current decays with a time constant of 1/k, and reaches an assymtotic lower limit, I_{finish}.

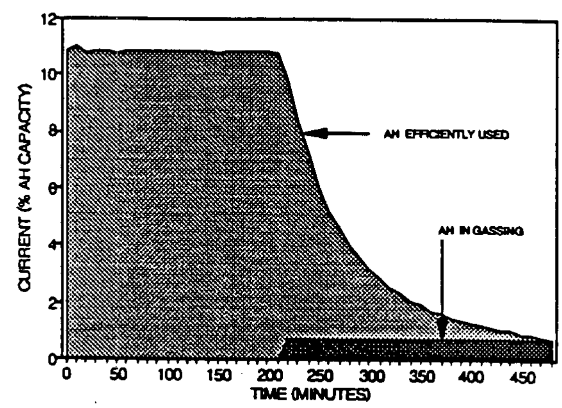


Figure 2. The total charge replaced is the area under the charge curve. Most of the charge is efficeintly used in recharging the battery, but some is lost through gassing.

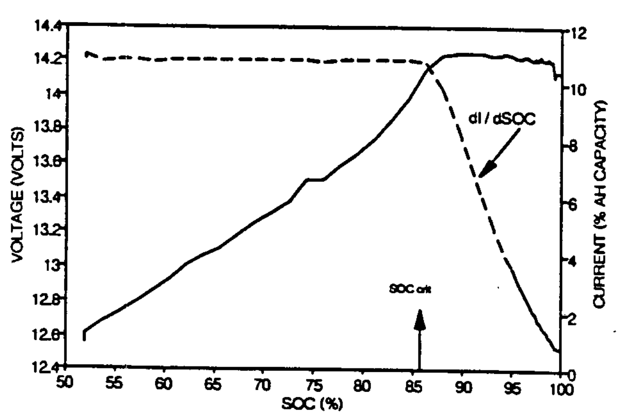


Figure 3. The charging curve plotted versus state-of-charge shows an almost steady decrease of current with SOC after the critical state-of-charge, SOC_{crit}.