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EVALUATING THE TECHNICAL AND ECONOMIC PERFORMANCE OF PHOTOVOLTAIC PUMPING SYSTEMS

A METHODOLOGY

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LESO

PREFACE

This report has been prepared by IT Power Inc, of Washington, D.C., for the United States Agency for International Development, Africa Bureau, under contract no AFR-0510-C-00-4042-00. The work described has been performed by IT Power working closely with the Laboratoire de l'Energie Solaire (LESO) of Mali, and involving two visits by IT Power engineers to LESO. A methodology for testing, monitoring and evaluation of photovoltaic pumping systems has been developed and applied.

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SUMMARY

The introduction of appropriate technologies into rural areas of the developing world can only be achieved successfully if sufficient data is collected on the technical performance, economic viability and social acceptability of competing technologies. Small scale renewable energy technologies are widely promoted as an attractive means to address some of the problems of the rural population but their viability is often not known. Thus the purpose of the work reported here is to define a methodology to determine the technical and economic viability of one of the most widespread solar photovoltaic technologies - small scale water pumps, and to apply the methodology to Mali where there are over eighty solar pumps in operation.

Water pumping, for irrigation and the provision of drinking water, is of obvious importance to development. Agriculture and water specialists who have to select water pumping technologies have very limited information available to them on the comparative technical and economic performance of water pumping systems. Thus decisions are generally made based on inadequate realistic data, and often without consideration being given to pumping systems powered by renewable energy technologies (in particular solar and wind pumps). The methodology presented here should be viewed in the context of selecting the best pumping system when compared with all the alternatives, for a given set of conditions. There is also clearly a need for data on other pumping systems, including traditional and conventional methods, as there is for a standardized approach to making comparisons. Hence there is still a need for other methodologies to complement this one.

The methodology consists of up to three performance tests and a procedure to calculate the unit water cost. The three tests are:

o PV Rating Test

o Short Term Performance Test

o Long Term Performance Test.

The instruments, procedures and data analysis for each test are listed step by step. Engineering skills are required to carry out the former two tests. These tests are suitable for an acceptance procedure on a system and for repeated durability trials at annual intervals. They can be carried out in one or two days.

The Long Term Test is the simplest of the three procedures. This provides information that can be used to calculate the unit water cost for a system and can be undertaken by an unskilled worker at the village level (three meters are read each day). The data analysis requires elementary mathematical skills.

An overall test and evaluation of a solar pump can be carried out at three different levels. A complete evaluation (Level 3) in which all three tests are carried out, answers the following questions:-

(i) What is the cost of water from the pump?
(ii) Is the solar pump realiable?
(iii) How well is the water utilized?
(iv) Does the pump meet an acceptable performance?
(v) How well do the components perform?

A Level 2 evaluation (Short Term and Long Term Tests) answers questions (i) to (iv) and a Level 1 evaluation (Long Term Test only) answers question (i) and (ii).

It is important to note that the simplest schedule (Level 1) although providing much useful data is not adequate alone.

A format for presentation of the results from the three tests is specified - this consists of a summary sheet and data sheets giving the results of the tests.

The test procedures were drafted prior to field visits to sites in Mali and the PV Rating and Short Term Tests have been carried out on five solar pumping systems. The Short Term Test was found to be easy to do whereas some problems were experienced with the original PV Rating Test, and consequently the procedure for the Rating Test has been revised.

Of the five sites selected, three systems were performing well, producing water at unit costs between $0.20 and $0.35 per cubic meter - these costs are based on the measured performance and actual system costs (see Note below). One system had a problem with the motor/pump subsystem and was working at only one third of its potential performance (hence a unit cost of $1.59 per cubic meter) and the other system would not pump water due to the high suction head and leaks in the rising main. A sixth site was visited but no tests were carried out. These sites were selected at random and are not known to be representative of solar pumps in Mali.

Each site has a local institution that is responsible for maintenance, and the villagers collect money by sale of the water (or local taxes) in order to pay for the maintenance. The water is generally sold at below the actual economic cost (since the villagers are only responsible for maintenance). However considerable financial profits can be made by irrigating small gardens even if the water is sold at its true cost. For example water costing $0.22 per cubic meter can be used to yield 1300 kg of potatoes at a water cost of $93 and the potatoes can be sold in the market for $510.

One problem is that the villagers are unaware of the potential performance (ie output) of the pump and thus may not realize if a fault develops.

It is recommended that the methodology be circulated, together with the sample results obtained in Mali, to organizations installing/operating solar pumps. This could be followed by a workshop to develop a consensus amongst experts on the methodology. The end result would be an agreed methodology which could be applied within AID projects involving solar pumps, and more broadly on an international basis, with the objective of providing information on the cost effectiveness of solar pumps for users and commercial ventures.

An effective method of getting the methodology into use and generating and exchanging ideas would be through a network.

Note - the costs given are based on a 15 year system lifetime, a 5% discount rate and solar insolation for Bamako, Mali.

1. INTRODUCTION

1.1. Background to Project

Prior to the, so-called, "energy-crisis" of 1973 fossil fuels were widely available and real costs were reducing. At the time development assistance programs generally believed that, for example, improved agriculture and health care would achieve the goal of better living conditions for the rural populations in developing countries. The energy inputs to these processes and activities, together with impending fuelwood shortages, were hardly noticed.

Over the past several years the non availability or non-affordability of energy has been recognised as a key constraint to economic development. Subsistence living requires energy - for cooking, for lifting water, which is generally provided by firewood or human muscle power, while improved agriculture and health care also require energy inputs (eg irrigation pumping, vaccine refrigeration). As a result of this situation all the development assistance agencies, in particular AID, have conducted energy programs.

The "fuel-crisis" (a more appropriate title than energy crisis) in the industrialised countries produced a tremendous interest in the development and use of renewable energy sources. All developed countries initiated research, development and demonstration programs, with that of the United States being by far the largest. It was widely believed that renewable energy technologies would be particularly appropriate to the needs of developing countries and in a relatively short period of time a large number of "renewable energy technology for developing country" projects were designed and started. In 1977 as part of AID's overall energy activity the Bureau for Africa initiated a program to apply renewable energy technologies and by 1982 this comprised 24 renewable energy projects in 15 countries together with 15 fuelwood and forestry projects in 12 countries.

Most early projects were considered in the traditional manner, (as noted by Howe, 1983). That is either as an end in itself (eg. to bring water to a given village) or as a teaching or demonstration experience (eg. to demonstrate how to bring water to rural areas). Unfortunately most renewable energy technologies were at the time (as many are today) still at the experimental stage and certainly not adequately developed for use in rural areas of developing countries. Thus there were many failures. Solar pumps (solar-thermodynamic type) were particularly notorious; they would not operate except with continuous skilled attention and maintenance, and thus did not either provide the end requirement (pump water) or demonstrate anything (other than total failure).

In a lot of projects there was an element of testing the technologies (using the developing countries as outdoor laboratories) but almost invariably this aspect only represented a small part of the total effort. Many projects have involved the important component of all aid projects, which is to evaluate the social and cultural effects or acceptability of the particular technology. But because in so many cases the technology would not actually perform its function, such evaluations could not be meaningfully carried out.

In late 1982 the Bureau for Africa decided to quickly assess what had been learned from the field experience in AID's and other donors projects in Africa. This led to a major field assessment, which is referred to later, and at the same time the suggestion of the need for the present project.

Only comparatively recently (again, as noted by Howe, 1983) have projects been considered as a learning experience (eg to learn how best to bring water to rural areas). Had this generally been the case earlier then most of the renewable energy technologies placed in developing countries by aid programs would not yet be there (they would not yet have emerged from the laboratory). Once this is accepted as an approach which should be adopted then the old concept of new (e.g. renewable energy) technologies immediately changes. It becomes clear that, firstly: the technology must be properly developed and tested in the laboratory; secondly: it must then be subjected to field trials - which monitor the technical performance, economic viability, and acceptability when used under real conditions by real users, and evaluates these parameters with alternative means of achieving the same end, thirdly: only then should the technology be disseminated, by commercial or other means. (ie. decisions to purchase and use the particular technology should not be made until its cost, performance etc is adequately known).

The purpose of the project reported here is to facilitate this approach for a particular technology - photovoltaic water pumping. (For a description of the technology see Kenna & Gillett, 1985). To efficiently conduct testing, monitoring and evaluation referred to above, there needs to be a methodology, peferably one which is widely adopted. Such a methodology is presented in the principal section of this report.

The methodology has been developed, and is now in use, in Mali, this country having been chosen because of the significant level of activity in their area, including a relevant AID project. IT Power and LESO have previously developed and used solar pump testing methodologies, and worked together in country, and LESO engineers have been trained at the IT Power/Halcrow test facility.

Around 80 solar pumps have been installed in Mali. Examples include those supplied by the AID funded Mali Renewable Energy

Program. (4 already installed, 4 more ordered). The cost of installing a typical solar pump to supply water to an average village of 1000 inhabitants is today around $15,000. To supply a handpump might cost $ 1,000, and a diesel engine powered pump would cost about $ 5,000. The solar pump appears to be very expensive, so why does anyone bother to install them? Solar pumps have been installed for a variety of reasons, most for the supposed "end in itself" or "demonstration" purpose referred to above, or more simply because they are fashionable. The justification for installing a solar pump should be either because it has been shown to be better (ie cheaper overall, more convenient etc) than the alternatives, or, so that it can be tested/monitored/evaluated. However, solar pumps (or any other pumps) have not yet been proven to be the best option for Mali and no installations have incoporated the type of evaluation described here (until this study).

1.2. Why testing, monitoring & evaluation?

It is obvious that all new technologies and products must be tested, to prove that they perform the function required of them, before they will find widespread acceptance in the marketplace. Financial and economic viability must also be 'tested'; if the product is too expensive for the job it does, few people will buy it.

Small-scale renewable energy technologies are widely promoted as an attractive means to address some of the problems of the rural populations developing countries. Like all new products, these must be put to the test - technical and economic, before they will be puchased and used in any signifcant numbers.

It is often stated that the only important test is the test of the marketplace. This is clearly the case with consumer products in industrialised countries, where the user buys the product he or she likes best. In the future this might also be the situation in what are today termed developing countries. But at present it is quite different.

The users are poor villagers and farmers. They cannot afford to buy anything except the best, cheapest, most appropriate product for a particular application. It is the duty of the rest of the world to help these people choose the best. This is the case. For example, governments and development assistance agencies supposedly choose the best pumping systems to provide drinking water in villages. But how is the choice made? Ideally the agency making the selection will compare all the alternatives, taking into account performance, cost, user convenience etc. etc. The important question which arises is "how do solar pumps compare with other pumping systems?"

Before starting to answer the above question, a second should be asked. A geat deal of money has been spent on the installation of renewable energy technologies in developing countries. For example the 80 solar pumps in Mali must have cost around $2 million (and there are around 1500 solar pumps world-wide|), so does this mean that solar pumps compare well and are a good thing for Mali, and that is why the development assistance agencies have spent so much money on their installation?

The answer to both these questions is "don't know". The reason for this answer is because, perhaps surprisingly, the questions have not generally been asked or the answers sought, at least not in a quantitative or scientific way. Comparatively recently such questions have come to the forefront.

Asking these questions and finding the answers is "testing monitoring and evaluation". The purpose of the present study is, for the case of solar pumps, to define the questions precisely, and provide a means to obtain the answers, ie. design a methodology.

1.3. The importance of quantitative monitoring

Often it is assumed that informal observation of whether a particular technology "works" or "doesn't work" is sufficient to evaluate the technology. There are many projects reported which include statements such as "solar pump worked well" which may simply mean that on some occasions water was being pumped. Similarly the "test of the marketplace" is applied and it is reported that "the villagers are very happy with their solar pump". Such a simplistic approach is obviously of very little value. The villagers will not have paid for the solar pump and if it falls apart a year later they will not have money to repair or replace it. If costs are not incorporated in the evaluation mechanism then it is meaningless.

Assuming that the technology has been adequately tested in the laboratory, so that it can be expected to operate reliably in the field, it should then be tested in the field. Field testing should provide accurate and objective performance and reliability data.

There are special requirements for all renewable energy technologies, for three principal reasons:

(i) the end-use need (amount of water required from the pump) is not generally known and there are other factors (water depth) which effect the energy requirement (load) which are also unknown.

(ii) the energy input to the system (in the case of solar energy, the Sun) is variable from day to day and over the year, and data on the amount of energy which is received at a particular location is generally not available.

(iii) it is energy, not power requirement, which determines the size and hence cost of power source (the photovoltaic array,). Conventional technologies are generally sized on the power requirement and are often over sized. To do this with a renewable power source would be prohibitively expensive. Hence it is important to know the energy flows in a system.

If there is no quantitative measurement of the energy received (cumulative solar irradiation) and delivered (cumulative flow of water and pumped head) by the installation, then nothing is learned which will help to improve the technology. For example if the efficiency is low compared with what is theoretically possible then more development work may be required. Similarly the technology cannot be better matched to the end use if there is no end use requirement data.

Hence if there is a requirement for a solar pump, the procedure will be for the designer to estimate the load (water requirement, water depth) and solar energy availability and then apply a large " safety factor" to the size of the photovoltaic array so as to ensure satisfactory operation. Thus the array may be twice the capacity which should be necessary, and as this is the most expensive component in the system, the final cost will be must more than it should be.

This is a reasonable approach provided there is monitoring. In the absence of monitoring, the system can be seen to either "work" or "not work". However, if it works successfully, little is learned because a large proportion of the array output or the water pumped, may be dumped, without the end-user knowing, and so the array is oversized and the system over-priced. Whereas if the system is properly monitored if an oversized array is detected then someting very valuable has been learned. The next installation with similar, or proportionally related requirements, will be smaller and better matched to the end-use needs, and most significantly, it will be cheaper.

1.4. Scope of this report

The main purpose of this document is to present the methodology which has been developed and apply it to PV solar pumps in Mali. The remainder of the report includes a review of present methods for monitoring and evaluation, and describes previous work in this area (Chapter 2). The methodology itself is presented in Chapter 3. It is anticipated that this section will be used as a stand-alone document - e.g. circulated as a draft with a request for comment by other practitioners. An overview of photovoltaics in Mali, and summary of their results obtained through trial use of the methodology is presented in Chapter 4. Finally conclusions and recommendations and proposals for expanding its use, are given in Chapter 5.

2. PRESENT AND PAST METHODS OF MONITORING AND EVALUATION

It was noted in Chapter 1 that relatively large numbers of solar pumps have been installed (e.g. in Mali) but most projects have not had testing/monitoring/evaluation as their main goal. Few projects have yielded quantitative data. This section summarises experience to date. In particular a World Bank/UNDP project is reported, because the present project could be considered as a logical follow-on to this.

2.1. World Bank/UNDP Solar Pumping Project

One project which was quite different in its concept from other developing country renewable energy activities was the "Small Scale Solar Powered Pumping Systems Project", executed by the World Bank on behalf of the United Nations Development Programme. This was undertaken between 1979 & 1984 by IT Power/Halcrow, working with in-country institutions including LESO. (See Halcrow/IT Power 1984). Other countries involved were Philippines and Sudan from the start and Egypt later.

At the commencement of this project the technical feasibility of solar powered pumping had been demonstrated using several different methods of energy conversion, but up to then it had generally appeared that the technology was unreliable and too expensive to be economically viable, when compared with conventional alternatives. Furthermore, the equipment was generally not sufficiently simple and robust to be appropriate for use and upkeep by farmers or villagers in developing countries, nor had it yet been developed to the stage of being a mature product. With few exceptions all the solar pumping equipment available was of prototype status, few models having been manufactured in any quantity.

2.1.1. Field Trials

The first phase of the Project was structured in the belief that independent tests on the performance, operation and reliability of systems and components are essential before responsible decisions can be made about the future development of the technology. The basic purpose of the field trials was to permit the performance and reliability of selected small-scale solar pumping systems to be evaluated objectively, under the sort of conditions found on farms in the developing world. The systems were instrumented and monitored so that their efficiency and performance could be measured.

Considering the difficulty and expense of gathering reliable field data, it is perhaps not surprising that so little of it was being collected by other projects. It was certain however, that progress could only be made on the basis of such data, and so considerable emphasis was placed on this aspect of the work.

The principal interest was in the following performance parameters:

- o solar irradiance at any instant (global and in plane of array)
- o cumulative solar irradiation
- o power, voltage and/or current output from array
- o daily electrical energy delivered by the array
- o static head at any instant and averaged over day
- o pumped head at any instant

o flow rate at any instant

o cumulative volume pumped over a day

Because of restraints it was not possible to measure every parameter at every site but a cost-effective program was devised which produced sufficient data for an assessment of system performance. Some data on ambient conditions (temperature, humidity and wind) was also collected.

The primary data collected on performance was of two main types:

(i) Continuous data on solar irradiance (global and in the plane of the array), array power output, water flow rate and pumped head. Chart recorders were used to make assessments of instantaneous values of irradiance, array power and voltage output, and flow, while other parameters were monitored at 15 and 30 minute intervals. From this information system efficiency and performance could be determined throughout the day and as a function of solar irradiance.

The collection of this information required relatively sophisticated instruments operated by staff from the participating agencies with assistance from expatriot experts.

(ii) Daily cumulative data which gave a picture of the total solar energy input to the array (solar irradiation), electrical energy delivered to the array and the pumped output over a complete day. This information was obtained from integrating counters. It was thought that this information was probably simple enough for it to be obtained by farmers, but during the trials the staff of the participating agencies were usually involved.

The normal field procedure envisaged visits each day to each system to record daily cumulative measurements of system performance and one visit per week to each system to make continuous measurements on system performance throughout the day. A record was also to be kept of any fault, breakdown or other incident which affected the operation of the system. It was, however, expected that local variations would need to be made according to the circumstances encountered and this program, desirable though it was, made logistical and managment demands which outstripped the resources available to the participating national institutions.

Great stress was laid on the need to check and calibrate the monitoring instruments used. Experience had shown that, under field conditions, the calibration of some of the measuring instruments will drift. Care was taken therefore to check their calibrations regularly as well as to protect the instruments from rain and direct solar radiation. Any data recorded from instruments with calibrations in doubt were excluded.

It was important to have enough data to check that each system was behaving consistently over a period of time and to obtain information about its performance over the whole range of irradiance values.

2.1.2. Economic evaluations

It was impossible to make absolute economic judgements on small-scale solar pumps because the technology was so immature, but also evaluation is made difficult by the variability and uncertainty of many parameters that affect the pump system economics. Despite such uncertainties it was possible to set up a plausible economic model and use this as a tool to investigate the sensitivity of solar pumping system costs to variation of different parameters. Such a model was developed and used to indicate the relative costs of a solar pump compared with alternative and competitive options.

A generalised analysis was conducted in purely economic terms and in principle considered all the costs to the economy regardless of who incurs them. Financial costs, e.g. subsidies and taxes, were excluded. See Halcrow/IT Power, 1984, for full details.

2.2. Other photovoltaic pump evaluation methodologies

It is known that there are a number of organizations, funded by a variety of donor agencies, who have installed, and in some cases are testing and evaluating, photovoltaic pumping systems. Unfortunately few reports giving the procedures used or the results obtained, have been identified or obtained during the course of this study. LESO, in collaboration with CRES (Centre Regional de l'Energie Solaire), has carried out acceptance tests on recent solar pumps financed by the European Development Fund (FED) and UNDP. A brief test procedure has been written.

2.3. Other relevant data collection activities

As mentioned earlier, in late 1982 the Bureau for Africa of AID decided to undertake a project to determine what had been learned from the field experience with renewable energy projects in Africa. A large number of projects, in seven countries, covering all the renewable energy technologies, were visited by a team who interviewed users and installers of the technologies, using a questionnaire which had been specially developed for the purpose. The completed questionnaires were subsequently analysed in the United States to answer a number of specific questions, relating to:

- o observed technical performance
- o social acceptance etc.
- o level of monitoring and evaluation
- o potential for these technologies in the future.

A major report presenting the findings was then produced (Ward et al., 1983)

This type of activity is complementary to the development and use of an evaluation methodology as undertaken in the present projects. For a number of technologies including photovoltaic pumping there needs to be a methodology, and results produced by it, before the above approach can be successfully applied. The AID evaluation noted that many installations, assuming they are in operation, do not have any adequate measurements made on them. Thus questions on the technical and economic performance are impossible to answer.

Following completion of this evaluation and a direct follow-on activity Associates in Rural Development (ARD),who were the principal consultants for the evaluation prepared a "Data Collection Handbook for Energy Systems in Developing Countries", for AID's Office of Energy. (ARD, 1984). This includes a number of very useful pro-forma sheets, including one for photovoltaic electric systems, on which to record the results of installation monitoring. Procedures or instructions on how to do the monitoring and process the results (methodologies) are not detailed.

3. TEST AND EVALUATION PROCEDURE FOR PHOTOVOLTAIC SOLAR PUMPS

3.1. Introduction

This chapter explains the methodology for evaluating the technical and economic viability of photovoltaic powered solar pumping systems. The methodology was drafted following discussions with LESO and prior to subsequent field tests performed on five installations during a second visit to Mali. It has been revised and updated in view of the experience gained from these tests.

The three step-by-step test procedures described have been designed to obtain the essential performance characteristics of a solar pump in a simple way and with a minimum of sophisticated equipment. Instrumentation requirements to undertake the tests are specified and a procedure to evaluate the unit water cost for a pump, using measured performance, is given.

The procedures detailed in this chapter are intended for field use by graduate engineers.

The three performance tests are:

- o PV Array Rating Test
- o Short Term System Test
- o Long Term System Test

The first two tests should be used as an acceptance test on a new system and to check the durability and performance of the system at annual intervals. The PV Array Rating Test provides a simple and quick way of checking that the array output meets the suppliers specification. The Short Term System Test can be carried out in one or two days and the results can be used to estimate long term potential performance, check the suppliers specification and to calculate the cost of the water delivered. It also provides information on the performance of the PV Array and the motor/pump subsystem. Engineering skills are required to carry out and to evaluate both the Short Term and PV Rating Tests.

Long Term System Tests need to be undertaken over a period of at least twelve months. They provide information which can be used to assess the unit water cost, the reliability of the solar pump and coupled with the results of a Short Term Test, how well the water is utilised at a particular location. The long term test is the simplest of the procedures and while the instruments must be installed by a skilled engineer, the measurements can be made by unskilled workers at the village level, and the evaluation subsequently carried out by the skilled worker.

For a complete evaluation of a solar pump it is necessary to carry out all three tests but different levels of information can be obtained by carrying out only one or two of the test procedures. The information provided from each test is discussed in the following section and three Test Schedules (referred to as Levels 1,2, and 3) are suggested in section 3.2.2.

It must be emphasised that there is no substitute to quantitative measurements - there is no short cut to evaluating pump performance. The minimum information that could be used to assess the effectiveness of a system is obtained from the long term test. However, it is advisable to carry out an acceptance test on a new system by undertaking the PV Rating and Short Term tests. In the past donors have not systematically sought to check whether the systems meet the specifications.

3.2. Test Objectives, Measurements and Accuracy

3.2.1 Overall Objectives

The overall objectives of the test and evaluation procedure is to answer the following five questions:

- Does the pump meet an acceptable performance?
- How well do the components perform and should they be better?
- What is the cost of water from the pump?
- How well is the water utilized?
- Is the solar pump reliable?

The third and fifth questions can be answered by a Long Term System Test alone, but a minimum of one years data is required. This test does not provide any information on the component performance. Further the test will not show how well the water is utilized; it does not distinguish between poor performance and poor utilization. Consequently it is advisable that Short Term Tests should also be carried out to answer the other three questions: provide component performance data, give a measure of the potential output and an estimate of unit water cost.

The PV Rating Test provides information on the performance of the PV Array that cannot be obtained on a Short Term Test alone, it provides a measurement of the PV array rated power which may be required to check the suppliers specification.

If information on component performance is not required, then it is not necessary to carry out the PV Rating Test (and the parameters to be measured on the Short Term Test may be reduced - See section 3.5). However it should be remembered that without data on component performance it will not be possible to identify the reason for a malfunction nor to identify areas for improving performance.

Table 3.1 indicates tests that must be carried out to provide the given level of information.

Information	Does test need to be carried out?		
	Long Term	Short Term	PV Rating
Acceptable Overall performance	No	Yes	No
Component Performance	No	Yes	Yes
Water Cost	Yes	No*	No
Water Utilization	Yes	Yes	No
Reliability	Yes	No	No

* water cost can also be estimated from a Short Term Test

Table 3.1 Tests that must be carried out to provide a given level of information

Note that it is necessary to distinguish between two quantities of water when assessing the viability of a stand alone solar pump:

(a) the potential water that can be provided by the pump - this can be estimated from a Short Term System Test

(b) the useful water that is actually required by the users. This will generally be less than the potential output of the solar pump because of the mismatch between availability and demand - the pump may be turned off during periods of high solar insolation. The useful water pumped is measured by the Long Term System Test.

By comparing the estimate of the Short Term Test with the measurements of the Long Term Test the utilization factor can be calculated:

$$\text{Utilization Factor} = \frac{\text{Useful Volume of Water Required}}{\text{Potential Volume of Water that could be Pumped}}$$

Since the unit water cost is based on the useful water required, it is necessary to estimate the Utilization Factor when making a calculation of the unit water cost from data obtained during a Short Term Test.

3.2.2 Overall Test Schedules

From Table 3.1, it can be seen that tests can be carried out at three levels:

Level 1.

Carry out Long Term Test (Section 3.6) and a Cost Appraisal (Section 3.7) to answer the following questions:

- What is the actual unit water cost?

- Is the solar pump reliable?

<u>Level 2.</u>

(a) Carry out a Short Term Test (Seciton 3.5). Make an estimate of long term potential performance and unit water cost (Section 3.7). At the end of this test the following questions can be answered:

- Is the overall system performance acceptable?

- Is the motor and pump subsystem performance acceptable?

- What is a good estimate of the potential volume of water pumped per year?

- What is a good estimate of the unit water cost?

(b) Using the instruments that were installed for the Short Term Test, arrange for local farmers/villagers to record the data required for a Long Term Test. Analyse the data to give the useful volume of water pumped per year and the unit water cost. At the end of this test the following questions can be answered:

- What is the useful volume of water that was pumped?

- How well is the solar pump matched to the user's requirements?

- What is the actual unit water cost?

- o What problems and maintenance requirements were experienced?

(c) Repeat the Short Term test at annual intervals. This will provide information on the change in performance with time.

Level 3

This level will give a complete solar pump evaluation. Carry out the PV Rating Test in addition to the Short Term Test under items (a) and (c) of the Level 2 Test Schedule. In addition to the questions answered under Level 2 it will be possible to answer the question:

- o Does the PV array meet the manufacturers specification?

3.2.3 Measurements to be made

Table 3.2 lists the parameters that must be measured for each of the three tests. Figure 3.1 shows the position of the instruments in relation to the components and energy flows in a solar pump. The analytical objectives of the field measurements together with the formulae used are discussed below.

PV Rating Test. The objective is to determine the rated power output from the PV Array. This is achieved by taking measurements of voltage and current at the maximum power point to give the maximum power:

$$\text{Power} = \text{Voltage} \times \text{Current} \qquad (1)$$

Since the maximum power is a function of solar cell temperature and solar irradiance, measurements of cell temperature and irradiance are also made. The measured maximum power can

Parameter (Units)	Test			Instrument	Precision Required	Calibration Interval
	PV Rating	Short Term	Long Term			
Solar irradiance in plane of PV Array (W/m^2)	x			Class A Pryanometer	±5%	1 year
Solar irradiation in (MJ/m^2) plane of PV Array over				Class A Pyranometer & Integrator		
(i) 10 minute period		x			±5%	1 year
(ii) daily			x			
Module Temperature (°C)	x			Thermocouple	±0.5°C	1 year
Volume of water (m^3) in						
(i) ten minute period		x	x	See Table 3.4	±2%	each test
(ii) daily		x	x		±2%	3 months
Static head (m)		x	x	Well dipper	±1%	each test
Pumped head (m)		x	x	Pressure gauge	±1%	or 1 year
Voltage (Volts)	x			Voltmeter	±1%	each test
Current (Amps)	x			Ammeter or Current shunt & millivolt-meter	±1%	each test
Electrical Energy (MJ) in ten minute period		x		Energy Meter	±1%	each test

Table 3.2. Summary of parameters to be measured and accuracy required

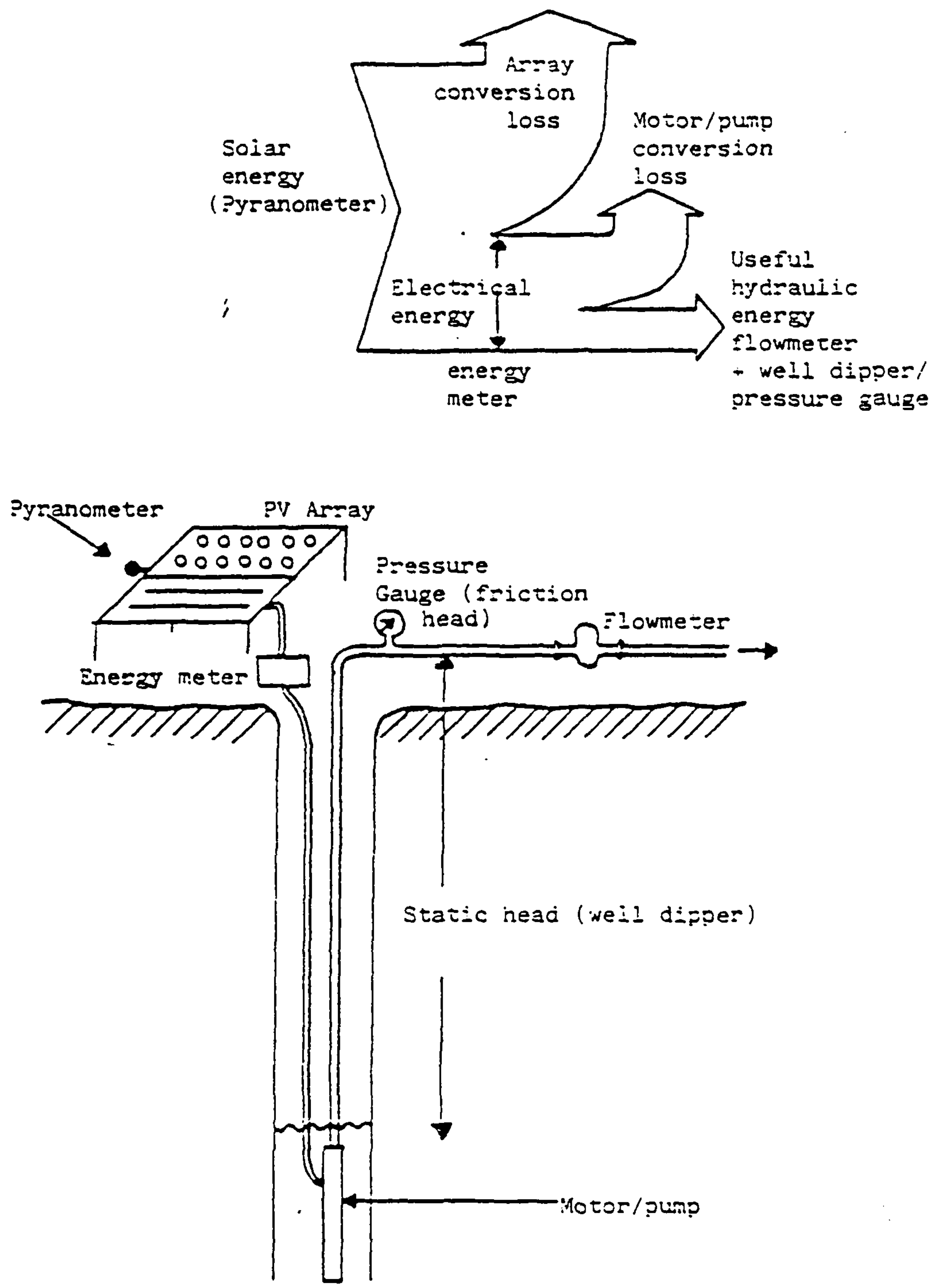


Figure 3.1 Position of instrumentation used on the test procedures.

then be corrected to the rated power output at reference conditions of a solar iradiance of 1000 w/m^2 and a cell temperature of 25°C.

Short Term System Test. The objective is to determine the efficiency of the PV Array, the motor/pump subsystem and the overall system as a function of solar irradiance. These efficiencies are defined as

$$\text{PV Array efficiency} = \frac{\text{array power output}}{\text{solar irradiance x array cell area}} \quad (2)$$

$$\text{Subsystem efficiency} = \frac{\text{water flow rate x pumped head x g}}{\text{array power output}} \quad (3)$$

with g = gravitational acceleration (9.81 m/s^2)

$$\text{System efficiency} = \frac{\text{PV water flow rate x pumped head x g}}{\text{solar iradiance x array cell area}} \quad (4)$$

Each test point is measured over a ten minute period to give time integrated measurements. These are then turned into averages (by dividing by the time period). Hence the following measurements must be made:

- o solar irradiation
- o water volume
- o pumped head
- o electrical energy

If information on component performance is not required it is not necessary to measure the PV array electrical energy output.

Long Term System Test. The objective of this test is to determine the average daily useful volume of water pumped as a function of average daily solar irradiation for periods of one month.

The following measurements must be made:

- o solar irradiation
- o volume of water
- o static head

Measurements should be made at daily intervals. Comparisons between the Long Term and Short Term Tests give a measurement of how well the potential output of the pump is utilized.

3.2.4 Errors

There are three sources of error that will arise in the tests

- o Systematic error due to the instruments - The typical error in a calculated parameter (such as efficiency) is given by the square root of the sum of the squares of the error in each measurement. For example using instruments of the accuracy given in Table 3.1, array power can be measured to a typical accuracy of $1^2 + 1^2 = 2 = 1.4\%$. (Since array power is the product of voltage and current). Similarly other calculated parameters can be measured to the accuracies given in Table 3.3.

- o random error due to experimental technique. This can be reduced by taking a statistically significant number of measurements. For this reason a minimum number of measurements are stipulated for each test.

- errors due to variations in environmental conditions
  Since cell temperature has some effect on the efficiency of the array there will be errors due to changes in air temperature and solar irradiance. This will be shown up by scatter on the efficiency characteristics and is not an experimental error as such. However it governs the confidence limits in the efficiency for a particular solar irradiance.

Likely estimates of the overall error bounds are given in Table 3.3.

Test	Parameter	Systematic Error	Estimated overall Error Bound
PV Rating	Power	± 1.4%	10%
	Irradiance	± 5.0%	5%
Short Term	PV Efficiency	± 5.1%	7%
	Subsystem efficiency	± 3.0%	6%
	System efficiency	± 5.7%	10%
	Irradiance	± 5.0%	5%
Long Term	Water volume	± 2.0%	5%
	Irradiation	± 5.0%	5%

Table 3.3. Estimated Systematic and Overall Error Bounds for each parameter

3.3. Instruments and Calibration

This section specifies the type of instruments and measurement techniques that should be used to achieve the instrument accuracy given in Table 3.2. Also calibration procedures and intervals are discussed.

3.3.1. Measurement of solar irradiance and irradiation.

The instrument for the measurement of solar irradiance should be a WMO Class A pyranometer such as the instrument shown in Figure 3.2. It should be mounted such that the detector is located in the plane of the array. Prior to testing, the transparent cover should be cleaned.

For measurement of solar irradiation an integrator with an accuracy of ± 1% should be used with the pyranometer. The pyranometer should be calibrated by returning the instruments to the manufacturer (or sending it to a national meteorological institute with calibration facilities) at annual intervals.

3.3.2. Measurement of temperature.

Module temperature must be measured for the PV Array Rating Test. It should be measured to an accuracy of 0.5°C using thermocouples such as copper/constantan, iron/constantan chromel/alumel. The thermocouple should be calibrated at three monthly intervals over the range 0°C to 100°C by comparison against an accurate mercury in glass themometer.

The thermocouples should be mounted on the rear of the module.

3.3.3. Measurement of volume of water.

Fluid flow rate should be measured to an accuracy of within ± 2%. It is recommended that the flow meter is calibrated before each short term test and at intervals of 3 months for long term tests. The calibration can be undertaken with the flow meter in-situ by diverting the water flow to a vessel and measuring the volume of water delivered in a measured time period. A container of sufficient volume to hold water for a ten minute period should be used.

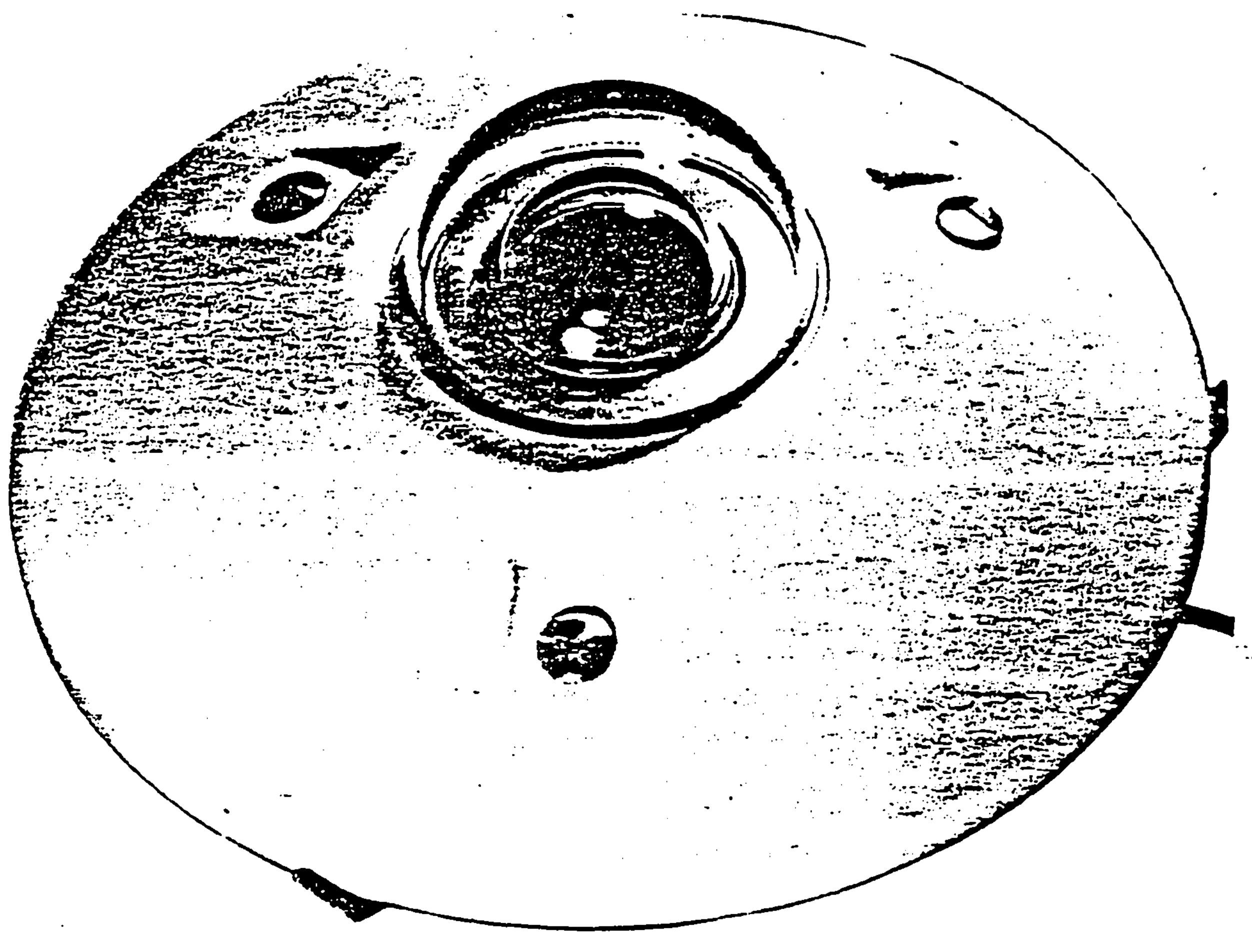


Figure 3.2 A Pyranometer with an accuracy to WMO Class A.

The flow meter should have a low head loss and be resistant to dirt particles. Table 3.4 summarises the properties of the main types of flowmeter. It is essential that the flowmeter is fitted so that the flowmeter pipe always runs full of water. Figure 3.3 shows some of the main types of flowmeter.

Type	Min flow for 2% acc (l/sec)	Head Loss @ 2.7 l/sec	Particle Resistance
In-line Turbine	0.25	Good 0.2m	Good
Pelton Wheel	0.22	Poor 2.5m	Medium
Positive displacement	0.03	Poor 3m	Poor
Paddle Wheel	0.17	Negligible	Good

Table 3.4 Properties of the main types of flowmeter

3.3.4. Measurement of pumped head.

Head is the most difficult parameter to measure since pumps are usually submerged and boreholes often enclosed. The total pumped head comprises the static lift plus the head loss in the pipes plus the velocity head at the outlet.

$$h_p = h_s + h_f + \frac{v^2}{2g} \qquad (5)$$

To be drawn

Figure 3.3 Alternative types of flowmeter.

where h_p = pumped head

h_s = static head

h_f = head loss in the pipework due to friction

$v^2/2g$ = velocity head at the outlet

v = velocity of the water at the outlet.

Three options are given below for measuring pumped head:

(i) The preferred method is to place pressure transducers on the inlet and outlet of the pump and measure the pressure increase across the pump (See Fig 3.4a). This pressure increase is equal to the static head plus the head loss in the pipework. The velocity head must be calculated. Hence, if possible, pressure taps should be fitted to the pump prior to installation.

(ii) If there is only a small static head above ground level a pipe may be brought to the surface to measure the pumped head as indicated in Figure 3.4b. Alternatively an electrical pressure transducer can be fitted to the pump outlet and electrical wires brought to the surface. The water level must also be measured and the velocity head must be calculated.

(iii) If it is impossible to place a pressure tap down the borehole, a pressure gauge can be fitted in pipework above ground (Figure 3.4c). However this method will not record the pressure loss in the rising main and a correction must be made as shown in Appendix 3. The water level must be measured and the velocity head calculated.

For cases (ii) and (iii) the water level must be measured using a well dipper or by inserting an air pipe into the borehole as indicated in Figure 3.4d.

Where the static head only can be measured the head loss in the pipework may be estimated as shown in Appendix 3. In all cases the velocity head is not measured by pressure transducers - it must be calculated from the flowrate and pipework size and added onto the static head and the head loss in the pipes.

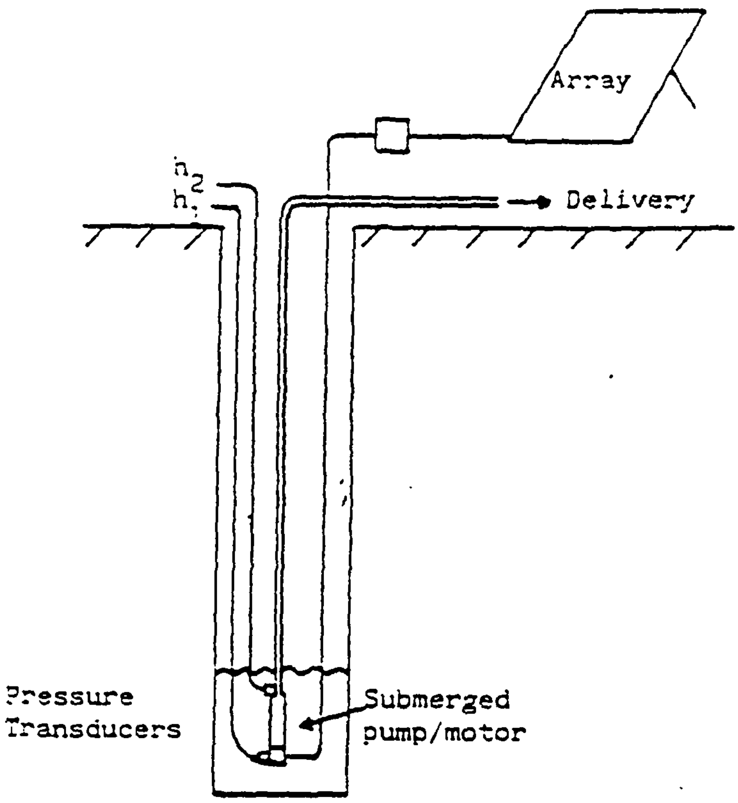
3.3.5. Measurement of electrical energy, voltage and current

Electrical energy, voltage and current can be measured relatively easily and accurately by commercially available equipment. These parameters should be measured to an accuracy of ± 1% and the instruments must be recalibrated annually.

3.4. PV Rating Test

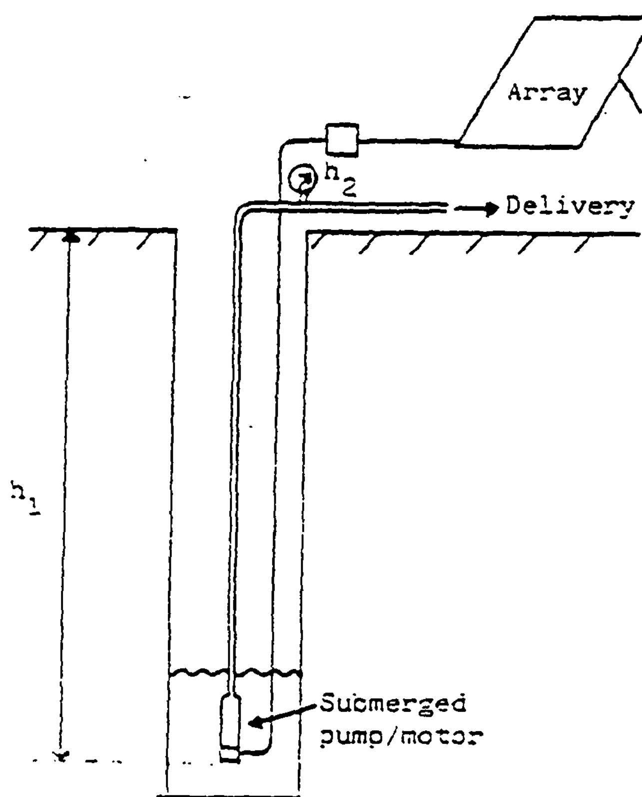
The objective of this test, which is carried out under a Level 3 Test Schedule, is to determine the rated power output of the PV array to within 10% accuracy and compare the measurement with the manufacturers specification. This test will indicate any malfunction in the PV array. It does not give information that is used for water cost calculations or for calculation of the utilization factor. The test is undertaken by taking measurements of

(i) array current and voltage near the maximum power point
(ii) solar irradiance for the above current and voltage
(iii) cell temperature (measured at the rear of the module)
(iv) short circuit current and open circuit voltage and the corresponding solar irradiance.



3.4a The static head + friction head is measured by placing pressure transducers on the inlet and outlet of the pump and reading the difference:-

$$h_s + h_f = h_2 - h_1$$

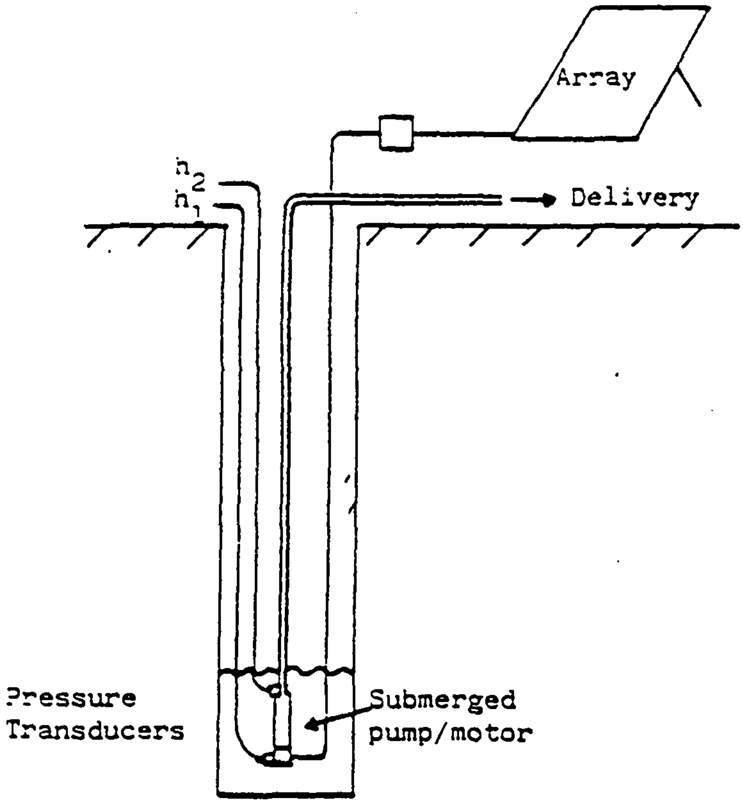


3.4b A pressure guage is placed in pipework at the surface. It measures the friction head downstream of the guage plus the static lift between the pump outlet and guage. The pump depth must be known and the friction head is

$$h_f = h_2 - h_1 + h_3$$

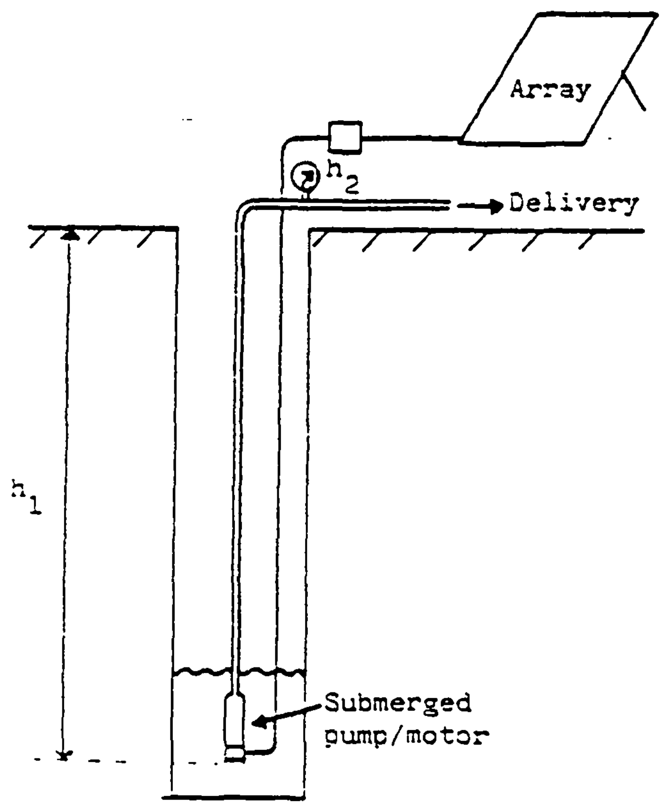
where h_3 is the friction head in the rising main (estimated).

Figure 3.4 Measurement of head.



3.4a The static head + friction head is measured by placing pressure transducers on the inlet and outlet of the pump and reading the difference:-

$$h_s + h_f = h_2 - h_1$$

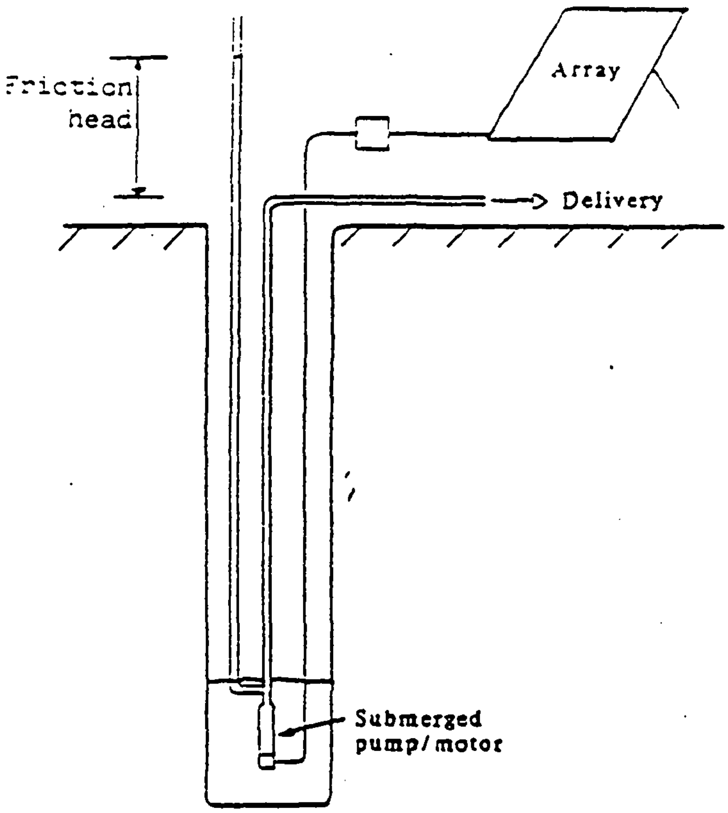


3.4b A pressure guage is placed in pipework at the surface. It measures the friction head downstream of the guage plus the static lift between the pump outlet and guage. The pump depth must be known and the friction head is

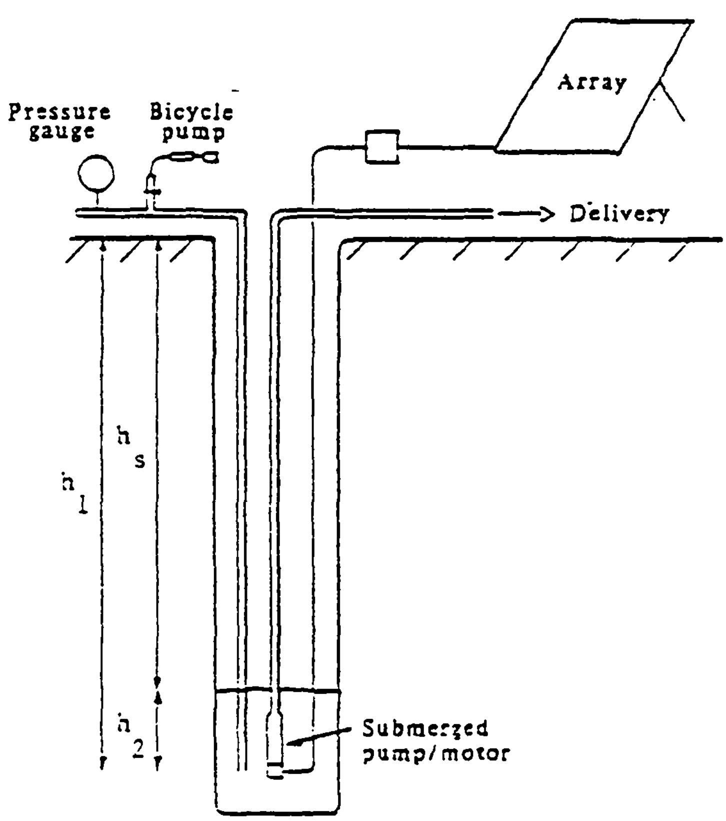
$$h_f = h_2 - h_1 + h_3$$

where h_3 is the friction head in the rising main (estimated).

Figure 3.4 Measurement of head.



3.4 - The friction head is measured by bringing an open pipe above the surface. The water level must also be measured.



3.4d. The static head (hs) can be determined from

$$hs = h_1 - h_2$$

The pressure at the bicycle pump is increased until it is equal to a maximum value (h_2) and h_2 can be read directly from the pressure gauge. The pipe length (h_1) must be measured at installation.

The maximum power point is found by varying the resistive load on the PV Array. Figure 3.5 shows the electrical characteristics of a Photovoltaic Array. The current/voltage curve varies with incident solar irradiance. At any given solar irradiance there is a particular electrical load which will give a voltage and current on the curve corresponding to a maximum power. During the test it is necessary to vary a resistive load (a potentiometer) until the maximum power is found.

Since photovoltaic arrays have a rated output at reference conditions of a solar irradiance of 1000 W/m^2 and a cell temperature of 25°C it is necessary to correct the measured output to the reference conditions. The procedure is outlined below.

At a solar irradiance (G) the maximum power output is given by

$$P_{max} = V_{max} I_{max} \tag{6}$$

where P_{max} = maximum power
V_{max} = voltage at maximum power
I_{max} = current at maximum power

The power output given by equation (6) differs from the rated power output because the short circuit current and open circuit voltage change with solar irradiance and cell temperature. If measurements of short circuit current (I_{sc}) and open circuit voltage (V_{oc}) are made at a solar irradiance (G), together with a measurement of cell temperature (T_{cell}) they can be corrected to reference conditions by applying standard equations (see equations 15 and 16) i.e.

$$I_{sco} = f\,(I_{sc}, G, T_{cell}) \tag{7}$$

$$V_{oco} = f\,(V_{oc}, G, T_{cell}) \tag{8}$$

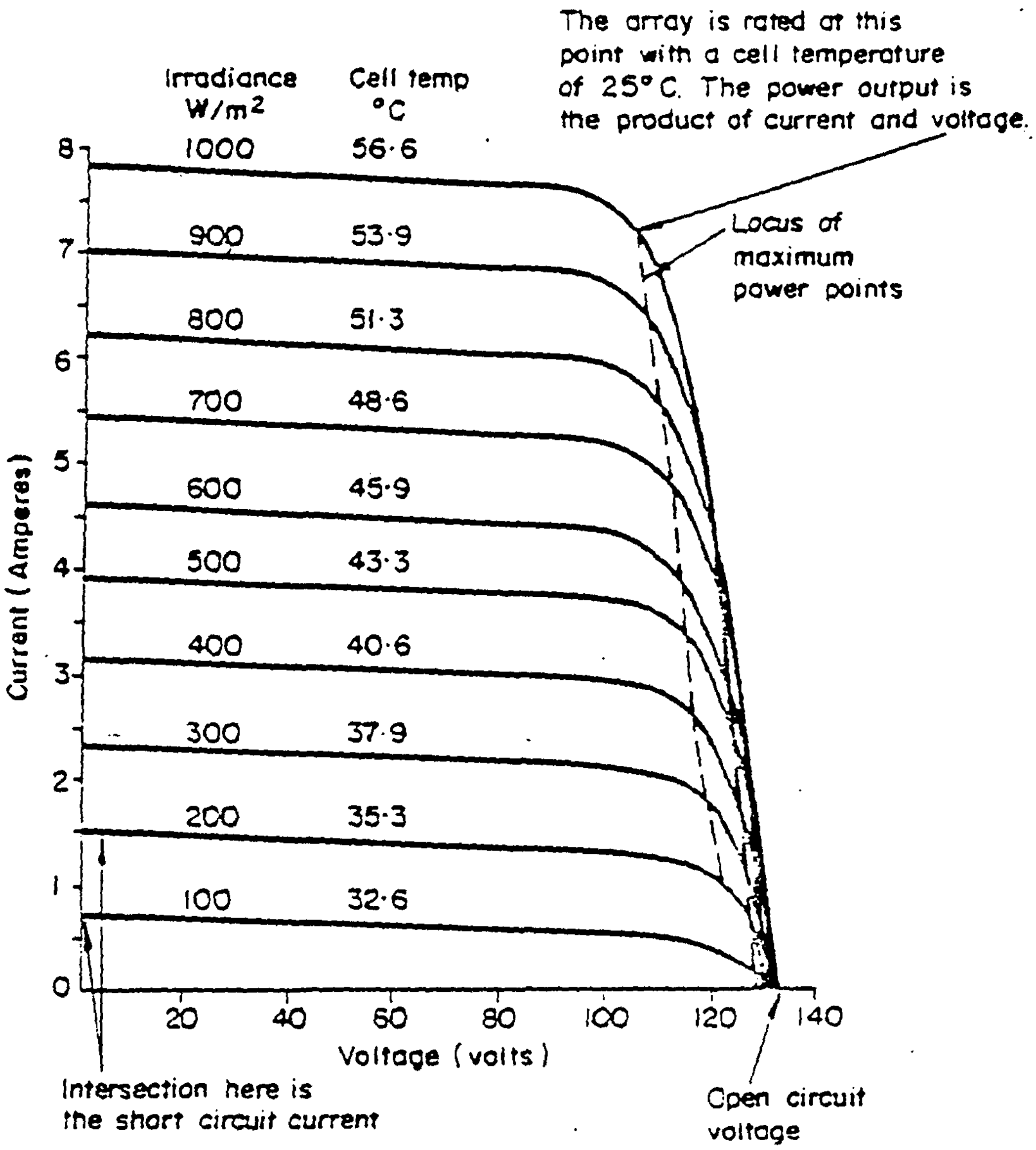


Figure 3.5 Electrical characteristics of a Photovoltaic Array.

Where I_{sco} is the reference short circuit current and V_{oco} is the reference open circuit voltage both at a cell temperature of 25°C and a solar irradiance of 1000 W/m^2.

To find the rated power output the reference short circuit current and open circuit voltage is simply multiplied by the fill factor (FF):

$$P_{rated} = FF \times I_{sco} \times V_{oco} \quad (9)$$

where (FF) is defined as the ratio of maximum power to the product of open circuit voltage and short circuit and can be calculated from the measurements as:

$$FF = \frac{V_{max} \; I_{max}}{V_{oc} \; I_{sc}} \quad (10)$$

Instruments

- Potentiometer (see note 6 for estimation of resistance range and current rating.)
- Voltmeter
- Ammeter or current shunt and voltmeter
- Pyranometer
- Thermocouple and digital thermometer
- 2 x 1 meter cables rated at the array currrent
- clipboard and blank format sheets (Table 3.5)

Procedure

1. Wire the potentiometer, voltmeter and ammeter to the array under test as shown in Figure 3.6. Ensure that the power is disconnected whilst wiring the circuit.

PV RATING TEST - FORMAT FOR DATA ANALYSIS

Array

Date

Tester

Time | Module Temperature 47.2 °C

Voltage (Volts)	56.5	55.1	54.0	52.6	52.0	51.4	49.0	48.4	48.0	47.6
Current (Amps)	17.74	18.8	19.7	20.4	20.5	21.0	22.1	22.7	21.7	21.5
Array Power (Watts)	1000	1035	1066	1070	1066	1077	1078	1097	1091	1023
Irradiance W/m^2	930	931	984	931	925	936	929	945	988	971
$\frac{\text{Power}}{\text{Irradiance}} = \frac{P}{G}$	1.07	1.11	1.08	1.15	1.15	1.15	1.16	1.16	1.10	1.05

Irradiance G 900 W/m^2 Short Circuit Current: 30.0 Amps Open Circuit Voltage: 70.0 Volts

Maximum Power/Irradiance 1.16 | Maximum power at G 1044 Watts | Fill Factor: 0.50

Reference Short Circuit Current: 34.8 amps. | Reference Open Circuit Voltage: 71.8 volts

Rated Power: 1249 Watts.

Table 3.5. Format Sheet for recording PV Rating Test

2. Clean the surface of the array.

3. Position the pyranometer in the plane of the array.

4. The test should be carried out under clear sky conditions between 11.00 and 13.00. The irradiance in the plane of the array must exceed 800 W/m^2.

5. Determine the approximate resistance corresponding to the maximum power by trial and error. This can be achieved by making measurements of voltage and current, and calculating the power. Change the resistance such that the power increases until a maximum is found.

6. Record the voltage, current and irradiance at 10 resistance values close to the maximum power point using the format sheet (Table 3.5). Ensure that the power output passes through a maximum. A recommended way of doing this is to start at a voltage above (or below) the voltage corresponding to maximum power and change the voltage (by varying the potentiometer resistance) until the voltage is below (or above) the maximum power point. Since the irradiance is likely to vary slightly during this procedure it is easier to find the position of the maximum power point by calculating the ratio of power to irradiance and looking for a maximum value of this ratio.

   Array voltage does not vary significantly over a small irradiance range. Hence it is useful to look for the array voltage that corresponds to maximum power and take readings on either side of this voltage.

7. Record the short circuit current (I_{sc}) and the open circuit voltage (V_{oc}) at a solar irradiance (G).

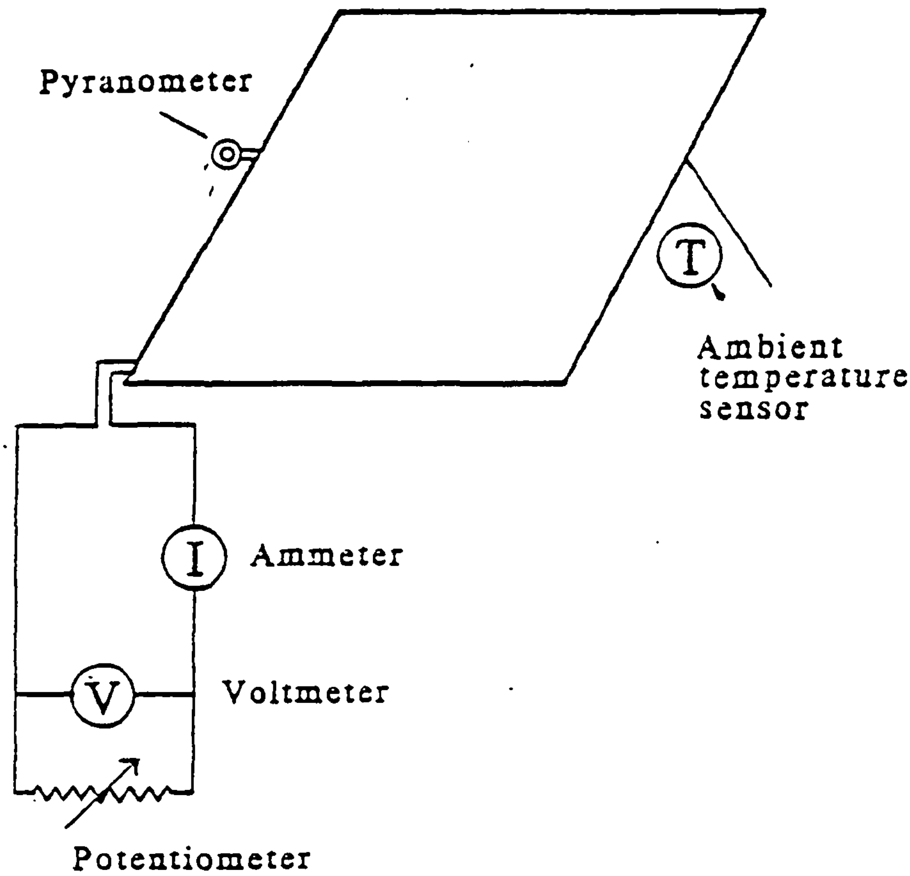


Figure 3.6 Test circuit to determine PV Array Rating.

8. Measure the cell temperature at the rear of the module.

9. Carry out the analysis given below to determine the array rated power.

10. Repeat steps 6-9 four times to give four values of the array rated power. These results should be averaged using the procedure given below.

Data analysis.

Use the format sheet (Table 3.5) to carry out the analysis given below. Table 3.5 has been completed using example data to illustrate the analysis.

1. For each test point calculate the array output power given by

$$\text{Array power} = \text{array current} \times \text{array voltage} \quad (11)$$

2. At each test point determine the array power per unit solar irradiance (P/G)

$$P/G = \text{array power}/\text{solar irradiance} \quad (12)$$

Determine the maximum value of the power to irradiance ratio $(P/G)_{max}$. For example, this value is 1.16.

3. Calculate the maximum power output (P_{max}) at the solar irradiance (G) that corresponds to the measurements of short circuit current and open circuit voltage.

$$P_{max} = (P/G)_{max} \times G \quad (13)$$

In the example (Table 3.5) the irradiance corresponding to the short circuit current/open circuit voltage measurement is 900 W/m^2. The maximum power at 900 W/m^2 is (1.16 x 900) = 1044 Watts.

4. From the manufacturers specification determine the following module characteristics. (Assume the values given in brackets if it is not possible to obtain these).

   β_I = rate of change of short circuit current with cell temperature (0.002/°C)

   β_V = rate of change of open circuit voltage with cell temperature (0.08 V/°C)

   β_{vg} = exponent governing the rate of change of open circuit voltage with irradiance (0.6) (see Note 4).

5. Calculate the Array rated power using the following procedure:

   5.1. Determine the measured fill factor (FF):

$$FF = P_{max}/(V_{oc} \times I_{sc}) \tag{14}$$

For the example the fill factor is 0.5

5.2. Determine the short circuit current at reference conditions (I_{sco}):

$$I_{sco} = I_{sc}(1000/G)/(1 + \beta_I(T_{cell} - 25)) \tag{15}$$

Assume that the cell temperature is equal to the rear module temperature.

For the example, a value of α_I = 0.002 has been used which, together with a cell temperature of 47.2°C gives a reference short circuit current of 34.8 Amps.

5.3 Determine the open circuit voltage at reference conditions:

$$V_{oco} = V_{oc} + \beta_v (T_{cell} - 25) + \gamma_{vg} \log(1000/G) \qquad (16)$$

For the example values of β_v = 0.08 and γ_{vg} = 0.6 have been used giving a reference open circuit voltage of 71.8 volts.

5.4. The array rated power is then given by:

$$P_{rated} = I_{sco} \times V_{oco} \times FF \qquad (17)$$

For the example the rated power is 1249 Watts

6. The procedure is repeated four times to give four values of the rated power. The average of all the tests should be calculated.

$$\text{Average Rated Power} \quad \bar{P}_{rated} = \frac{\sum_{i=1}^{i=4} P_{ratedi}}{4} \qquad (18)$$

where P_{ratedi} is the ith test result.

An estimate of the random error in the average rated power is given by twice the standard deviation:

$$\text{Random error} = \frac{2 \sum_{i=1}^{i=4} (\bar{P}_{rated} - P_{ratedi})^2}{3} \qquad (19)$$

If the random error is greater than ± 10% the result should be rejected.

Notes.

1. The array rated power is defined as the maximum output from the array under a solar irradiance of 1000 W/m^2 when the cell temperature is 25°C.

2. Under actual operating conditions the cell temperature may be 50°C to 60°C. Since array power decreases by approximately 0.5% per °C change in cell temperature the drop in array power from the reference condition (25°C) to actual operating conditions (50°C) can be 12%. Hence it is necessary to correct the power measured under actual conditions.

3. It is assumed that the rear module temperature is equal to the cell temperature and that the change in open circuit voltage and short circuit current with cell temperature is linear. In practice cell temperature may be 2 - 3°C greater than rear module temperature but this will only introduce an error of less than 1%.

4. The open circuit voltage is assumed to change logarithmically with irradiance, i.e. the open circuit voltage at an irradiance G is:

$$V_{oc} = V_{oco} - \beta_{vg} \log (1000/G) \qquad (20)$$

where β_{vg} is a constant

5. The fill factor is assumed to be constant over the range of the test, i.e. the fill factor under operating conditions is the same as the fill factor under reference conditions.

6. The resistance range of the potentiometer can be found as follows:

Determine the manufacturers specification for array power (P) nominal operating voltage (V) and reference short circuit current

Calculate the array current I = P/V

Calculate the resistance at maximum power R = V/I

The potentiometer should have a range 0.5R to 2R and a current rating equal to the reference short circuit current.

Interpretation of Results

The measured output of the array should be within ±10% of the manufacturers rated power. Power ratings below this indicate that there is a fault in the module connection or in the module itself.

3.5. Short Term System Test

The objective of this test, which is carried out as part of Levels 2 or 3 Test Schedules, is to determine the operating efficiency of the PV Array, the motor/pump subsystem and the overall system as a function of solar irradiance. By integrating the efficiency/irradiance characteristic with typical daily solar irradiance profiles, it is possible to obtain an estimate of the volume of water pumped as a function of daily solar irradiation. This can then be used to estimate the unit water cost for a particular location and combined with a Long Term Test allows a calculation of the Utilization factor.

The test is undertaken by taking measurements of:

- o solar irradiation in a ten minute period
- o PV Array energy output in a ten minute period
- o volume of water pumped in a ten minute period
- o pumped head at the start and finish of the ten minute period

If information on component performance is not required, measurements of PV Array energy are not necessary.

A ten minute period is used to allow for the thermal time response of the solar cells (typically 5 minutes). This period ensures that the output from the system corresponds to the input.

Since three of the measurements made are integrated values (i.e. irradiation rather than irradiance, volume of water rather than flow rate, electrical energy rather than power) they must be divided by the time period (10 minutes) to determine the average values of

- o irradiance
- o PV array power output
- o flow rate

From these the PV array efficiency, the subsystem efficiency and the overall system efficiency can be calculated using equations 2 to 4.

Instruments.

- Pyranometer and integrator
- Integrating flow meter
- Energy meter
- Pressure gauge(s) and/or well dipper.
- Clipboard and blank format sheets. (Tables 3.6 and 3.7)
- Watch

Procedure.

1. Connect the instruments as indicated in figure 3.7. The pyranometer should be in the plane of the photovoltaic array. The flow meter should be installed in a straight run of pipework at the outlet side of the pump. Allow at least ten pipe diameters on either side of the flow meter. For open wells the static head is easily measured using a well dipper. For closed boreholes a pressure gauge and airpipe may be used to determine the head as shown in section 3.3. The delivery head should be measured using a pressure gauge or open pipe as shown in Figure 3.4. Where the delivery pipes are short and less than 2m above ground level the delivery head can be estimated as shown in Appendix 3.

2. Clean the surface of the array

3. The test should be carried out over a complete day, under clear sky conditions. Results should be recorded on the format sheet shown in Table 3.6.

4. The objective of the test is to obtain 10 minute average performance data for a range of solar irradiance from start up to at least 800 W/m^2. The solar irradiance must not change by $\pm$ 50 W/m^2 during the period of a 10 minute test.

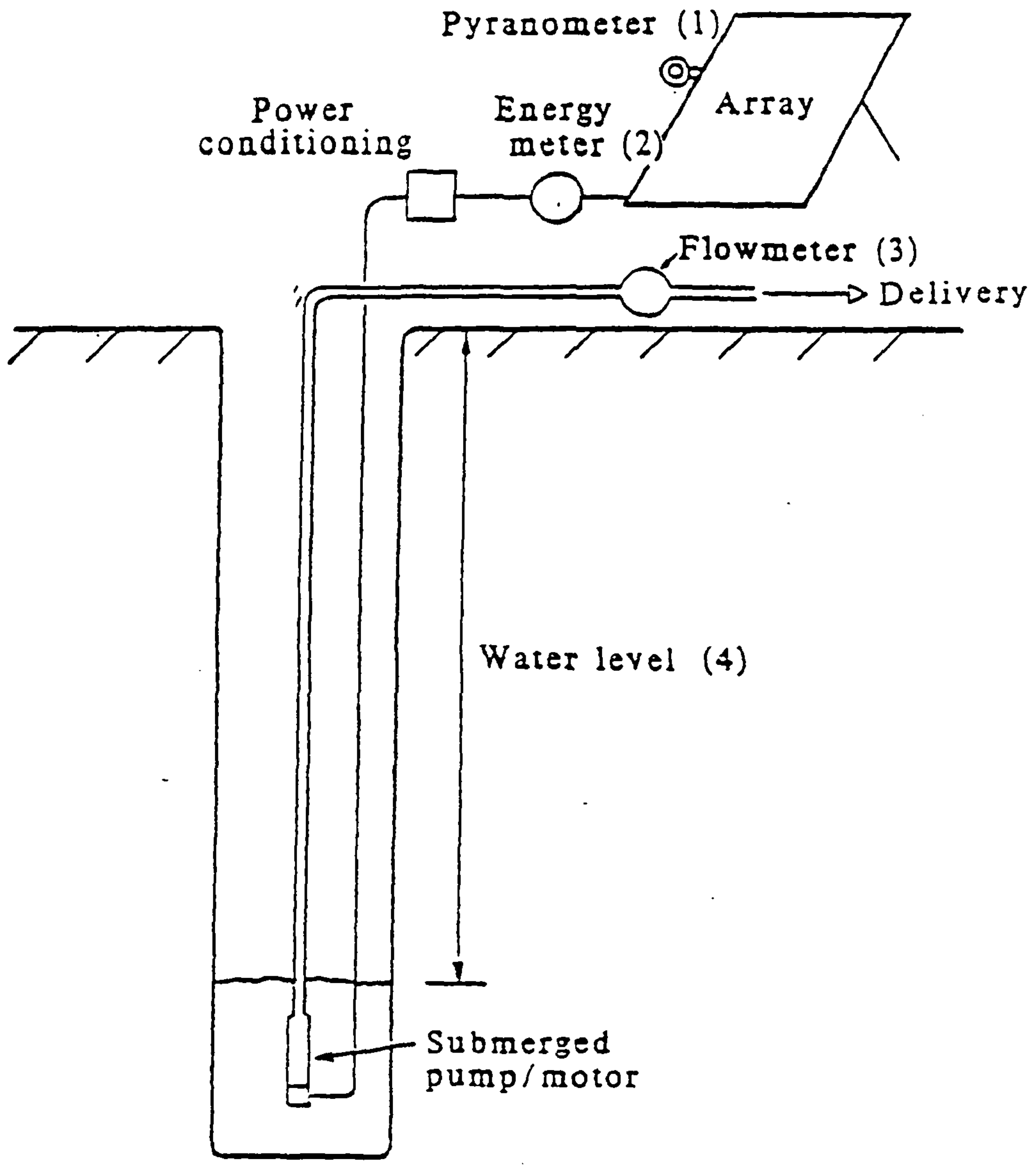


Figure 3.7 Test circuit to determine Short Term System Performance.

SHORT TERM SOLAR PUMP TEST
DATA SHEET

Location:				Latitude:			Date: / Tester:			
Time	Pyranometer Reading Start	Pyranometer Reading Start	Energy Meter Reading Start	Energy Meter Reading Finish	Flow Meter Reading Start	Flow Meter Reading Finish	Static Head Reading Start	Static Head Reading Finish	Friction Head Reading Start	Friction Head Reading Finish

Table 3.6 Format Sheet for recording short term performance data

SHORT TERM SOLAR PUMP TEST

Location:	Latitude:	Date:
Array make and rating:		Tester:
Motor make and rating:		Cell Area:
Pump make and rating:		Water Rest Level:

Time	Irradiance W/m^2	Array Output W	Flow l/sec	Head m	Hydraulic power W	Array efficiency %	Subsystem efficiency %	System efficiency %

Table 3. Format sheet for presentation of short term test data

5. When the pump starts to pump water record:

- (i) the time
- (ii) the pyranometer reading
- (iii) the flowmeter reading
- (iv) the energymeter reading
- (v) the pressure gauge and/or water level.

Make a note of the irradiance at which the pumps starts. Take a further set of readings 10 minutes later.

6. Take repeat readings at intervals throughout the day such there is a minimum of 10, ten minute test points, i.e. a minimum of 20 readings.

Data Analysis

1. The data should be analysed and recorded on the format sheet shown in Table 3.7.

2. For each 10 minute test point calculate
   - o the average irradiance = $(H_2 - H_1)/0.167$ W/m^2
   - o the average array output power = $(E_2 - E_1)/0.167$ W
   - o the average flow rate = $(Q_2 - Q_1)/0.6$ lit/sec
   - o the average head. = $(h_{s1} + h_{f1} + \frac{v_1^2}{2g} + h_{s2} + h_{f2} + \frac{v_2^2}{2})$ 0.5 m

Where H is the solarimeter reading in Wh/m^2
E is the energy meter reading in Wh
Q is the flowmeter reading in cubic meters
h_s is the static head in m
h_f is the head loss in the pipes in m
v is the velocity of the water at the pipe outlet and is given by

$$v = \frac{4V}{\pi d^2} \qquad (21)$$

with V the flow rate in m^3/sec
d the pipe diameter in m

The subscripts 1 and 2 refer to the reading before and after the ten minute period respectively.

3. Calculate the hydraulic power using the equation

Hydraulic Power = flow rate x pumped head x g watts (22)
with g the gravitational acceleration (9.81 m/s^2)

4. Calculate the following efficiencies

$$\text{Array efficiency} = \frac{\text{Array output power}}{\text{irradiance x cell area}} \qquad (23)$$

$$\text{Subsystem efficiency} = \frac{\text{hydraulic power}}{\text{array output power}} \qquad (24)$$

$$\text{System efficiency} = \frac{\text{Hydraulic Power}}{\text{irradiance x cell area}} \qquad (25)$$

NB. If array power has not been measured only the system efficiency can be calculated.

5. Plot graphs of efficiency versus irradiance using the format sheet shown in Figure 3.8.

Notes

1. The response time of the module temeperature to changes in irradiance is typically five minutes. Hence it is more

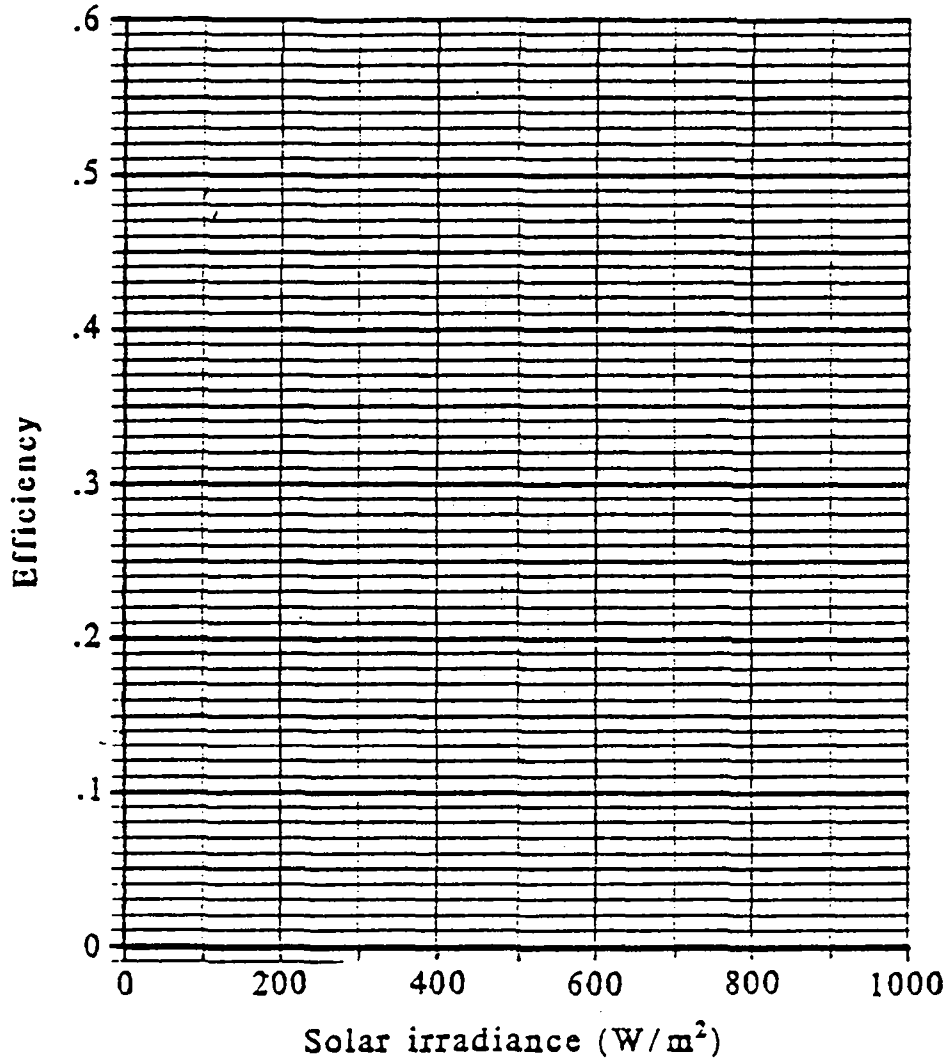


Figure 3.8 Efficiency versus solar irradiance.

appropriate to measure ten minute average performance, than instantaneous performance.

2. The array and system efficiency are based on the array cell area since this is a more representative parameter of the physical performance of the system. An alternative definition of array and system efficiency would be to base them on gross array area.

3. The subsystem efficiency is an important characteristic of the pump because it determines the size of array that is required to perform a given hydraulic duty. The definition given in equation 24 means that power conditioning losses are included in the subsystem.

4. The array efficiency is not simply a property of the array - it also depends on the subsystem since the operating point on the current/voltage curve (and hence array efficiency) is dependent on the load on the array. A well matched subsystem will lead to a more efficient array.

Interpretation of Results

1. Subsystem efficiency should peak at between 35% and 40%. Measured values significantly below this indicate that there is a fault in the subsystem or that it is not well matched to the PV array. A well matched motor/pump subsystem should have a relatively constant subsystem efficiency.

2. Array efficiency should be 8 - 10% or greater. Values below this indicate that the array is not operating near its maximum power point and that the motor is not well matched to the array. If the array power output measured in the "PV Array Rating Test" is not satisfactory then there is a fault with the PV array.

3. The potential volume of water pumped in a day should be estimated using the formula:

$$\text{Volume } (m^3/\text{day}) = \frac{\sum_{i=1}^{i=24} \eta_{sys} \, G_i \times A_{cell} \, \Delta t}{\rho \times g \times \text{system head}} \qquad (26)$$

With G_i the solar irradiance at hour i - standard values for 12 hour days with 2-6 kWh/m^2 solar irradiation are given in Table 3.8.

A_{cell} is the array cell area (m^2)

η_{sys} is the system efficiency at the irradiance G_i and is obtained from the measured performance (Figure 3.8)

ρ is the density of water (1000 kg/m^3)

g is the gravitational acceleration 9.81 m/s^2

Δt is the number of seconds in an hour

The numerator in equation 2, is the hydraulic energy output of the pump in a day.

4. The volume pumped per day can be calculated for solar irradiation levels between 2-6 kWh/m^2. A plot of potential volume pumped per day versus solar irradiation should be made using the format sheet given in Figure 3.9. This gives the characteristic performance curve for the solar pump which can be used to determine the unit water cost (section 3.7).

3.6. Long Term System Test

The prime objective of this test, which must be carried out for all Test Schedules, is to determine the characteristic curve

Solar Irradiation (kWh/m^2)	Solar Irradiance (W/m^2)				
	2	3	4	5	6
HOUR					
1	.0	.0	.0	.0	.0
2	.0	.0	.0	.0	.0
3	.0	.0	.0	.0	.0
4	.0	.0	.0	.0	.0
5	.0	.0	.0	.0	.0
6	1.0	1.0	1.0	1.0	1.0
7	57.0	81.0	105.0	160.0	154.0
8	118.0	173.0	229.0	286.0	343.0
9	177.0	267.0	357.0	447.0	537.0
10	232.0	352.0	471.0	589.0	708.0
11	271.0	410.0	548.0	686.0	824.0
12	285.0	431.0	576.0	721.0	865.0
13	271.0	410.0	548.0	686.0	824.0
14	232.0	352.0	471.0	589.0	708.0
15	177.0	267.0	357.0	447.0	537.0
16	118.0	173.0	229.0	286.0	343.0
17	57.0	81.0	105.0	130.0	154.0
18	1.0	1.0	1.2	1.5	1.0
19	.0	.0	.0	.0	.0
20	.0	.0	.0	.0	.0
21	.0	.0	.0	.0	.0
22	.0	.0	.0	.0	.0
23	.0	.0	.0	.0	.0
24	.0	.0	.0	.0	.0

Table 3.8. Specification of standard days, showing hourly values of solar irradiance in W/m^2 for a range of daily solar irradiation levels.

of the solar pump relating useful volume of water pumped per day to daily average solar irradiation for a month. This performance curve is dependent on the system head and is strongly dependent on the location. The curve is used to calculate the unit water cost as shown in section 3.7.

A further objective is to collect data on reliability, maintenance and durability of the solar pump.

The test is undertaken by taking measurements at daily intervals of:

- o solar irradiation
- o volume of water pumped
- o static head

Instruments

- Pyranometer and integrator
- Integrating flow meter
- Well dipper or air pipe and bicycle pump
- Log book.

Procedure

1. The flowmeter and pyranometer are configured in exactly the same way as for a Short Term Test.

2. A local site operator should be trained to read the instruments and shown how to measure the static head. Adequate time should be allowed for explaining the procedure, learning to use the instruments and generally to become familiar with the systems. Financial incentives should be given to the site operator where appropriate.

3. The PV Array surface should be cleaned at weekly (or less if appropriate) intervals. The site operator must be instructed not to let the storage tank overflow since this will distort the measurement of useful volume of water.

4. A log book should be provided at the site such that the site operator can record maintenance visits, failures etc.

5. The flowmeter and pyranometer should be read each day and the static head measured by the site operator. A format sheet for recording the results is given in Table 3.9. Only monthly readings are used in the analysis; however, taking daily measurements minimises the chance of missing a reading.

6. Site visits by graduate engineers should be made at intervals of 3 months at which time the flowmeter should be recalibrated. Data should be retrieved and the system inspected for durability:

- o inspect cells for discoloration
- o ensure that module sealant is still intact
- o inspect glass covers for cracks
- o ensure pump seals are not leaking
- o check motor bearings for wear and noise
- o check pipework for corrosion
- o check condition of connecting cables

Analysis

1. For each month determine the average daily volume of water pumped, the average daily solar irradiation and the average static head.

$$\text{Average volume } (m^3 \text{ day}) = (Q_2 - Q_1)/N \qquad (27)$$

Location:	Latitude:	Month:

System description:

Date	Pyranometer Reading	Flowmeter Reading	Static Head m	Solar Irradiation kWh/m^2	Volume pumped m^3

Average monthly solar irradiation	$MJ/m^2/day$
Average daily water pumped	m^3/day

Table 3.9. Data Sheet for recording Long Term Performance

$$\text{Average solar irradiation } (kWh/m^2) = (H_2 - H_1)/N \qquad (28)$$

$$\text{Average static head} = \sum_{i=1}^{i=N} h_i/N \qquad (29)$$

with Q = flowmeter reading in m^3

H = pyranometer integrator reading in kWh/m^2

h_i = ith daily reading of static head

N = number of days in a month

2. Plot a graph of daily volume of water pumped versus daily average irradiation using the format sheet shown in Figure 3.9.

Interpretation of Results

1. A comparison between the estimates of volume of water pumped from the Short Term System Test and the measurements made during the Long Term System Test should be made. The utilization factor can be calculated from

$$\text{Utilization factor} = \frac{Qyr}{\sum_{i=1}^{i=12} Q(H_i)\, N_i} \qquad (30)$$

Where Qyr is the useful volume of water pumped in a year as measured by the Long Term Test.

$Q(H_i)$ is the average daily volume of water pumped for a month with average daily solar irradiation H_i as determined from the Short Term Test. The summation should be made using the twelve monthly values of solar irradiation that were measured on the Long Term Test.

N_i is the number of days in month i.

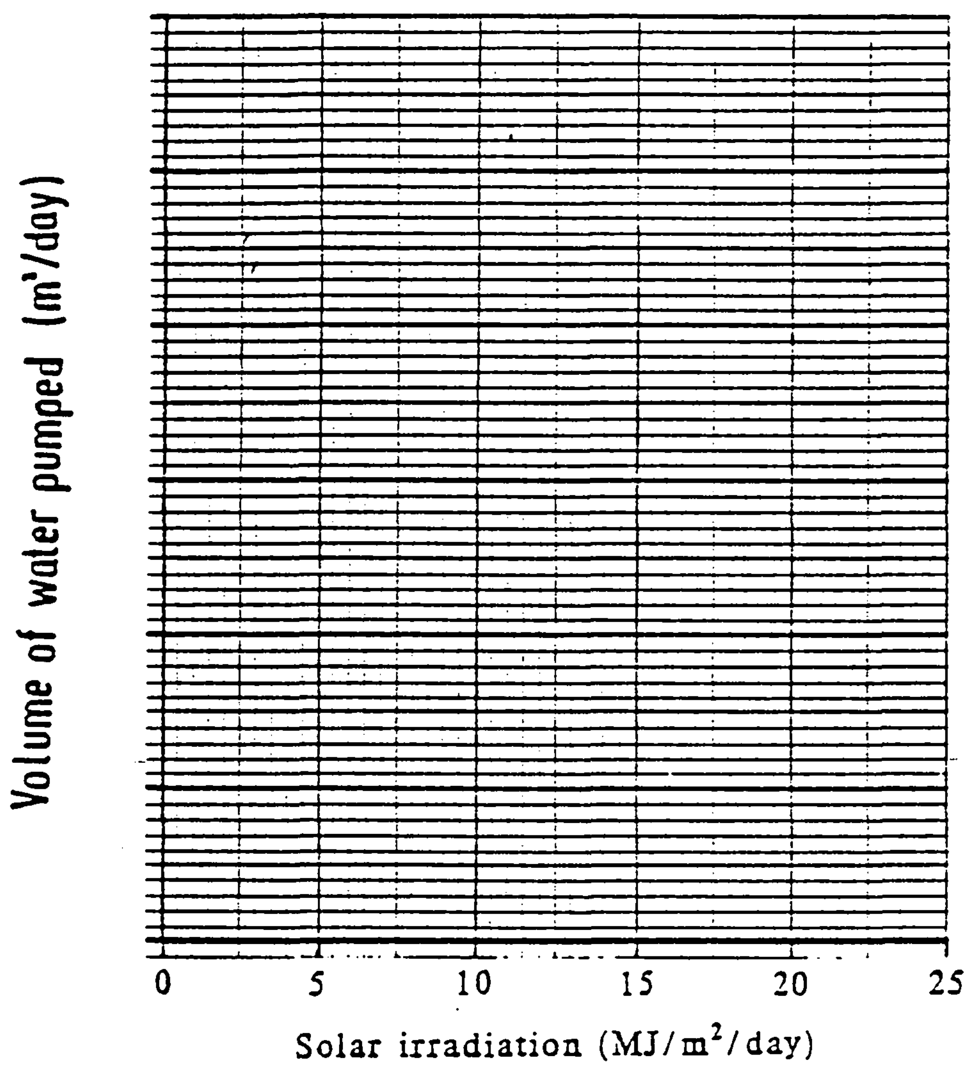


Figure 3.9 Volume of water pumped versus solar irradiation (The user should scale the y axis as appropriate to the solar pump under test).

A low utilization factor will be due to either:

(i) a degradation in the performance of the system. This can be checked by carrying out a repeat Short Term Test.

(ii) A low utilization of the water - the pump is oversized for the application.

2. Using the measured data calculate the unit water cost as shown in the following section.

3.7. Cost appraisal

One of the overall objectives of this test and evaluation procedure is to determine a measure of the cost effectiveness of the pump under test. The procedure given below shows how to calculate the unit cost of water from the measured performance. It takes into account all the identifyable costs, but ignores the benefits gained by the users of the water. Consequently it does not indicate whether the water pumping system is economically viable per se (for example whether additional crops grown using water supplied by irrigation are worth more than the cost of the water provided). However, the procedure can be used to make a comparison with alternative pumping systems by comparing the unit water cost.

The procedure will be carried out either:

(i) Using potential volume/irradiation data calculated from a Short Term Test in which case an estimate of the utilization factor will have to be made.

(ii) using useful volume/irradiation data measured during a Long Term Test.

Data required

Capital cost	C_c
Annual maintenance and operating cost	C_{om}
Replacement cost of modules	C_{rm}
Replacement cost of subsystem	C_{rs}
Lifetime of modules	Ym
Lifetime of subsystem	Ys
Volume of water pumped as a function of irradiation for monthly periods	$Q\ (H_i)$
Monthly average solar irradiation for a period of 12 months, for the location under consideration. (This is measured on the Long Term Test).	H_i

Analysis

The unit water cost can be calculated using the following procedure. Life cycle costs over a period of Y years are analysed. Costs are discounted to the present at a rate of d%. The recommended values for Y and d are 15 years and 5% respectively.

1. Determine the number of replacement modules (Nm) and sybsystems (Ns) required in the period of analysis. From this determine the present worth of the replacements:

$$C_r = C_{rm} \sum_{i=1}^{i=Nm} 1/\ (1+d)^{iYm} \quad + \quad C_{rs} \sum_{i=1}^{i=Ns} 1/\ (1+d)^{iYs} \qquad (31)$$

2. Calculate the present worth of the operating and maintenance (O & M) costs:

$$C_a = C_{om}\ Pa \qquad (32)$$

where Pa is the present worth factor obtained from Table 3.10. It is equal to 10.4 for a 15 year period at 5% discount rate.

Discount Rate	Present Worth Factor for given number of years					
	5	10	15	20	25	30
0	5.0	10.0	15.0	20.0	25.0	30.0
5	4.3	7.7	10.4	12.5	14.1	15.4
10	3.8	6.1	7.6	8.5	9.1	9.4
15	3.3	5.0	5.9	6.3	6.5	6.6
20	3.0	4.2	4.7	4.9	5.0	5.0

Table 3.10 Present Worth Factors

3. Calculate the life cycle costs:

Life cycle cost = capital cost + present worth of replacements + present worth of O & M costs.

$$LCC = C + C_r + C_a \qquad (33)$$

4. Calculate the annual equivalent of the life cycle cost (ALCC)

$$ALCC = LCC/Pa \qquad (34)$$

5a. If the unit cost is calculated from a Short Term Test then estimate useful volume of water pumped in a year:

$$Q_{yr} = K \sum_{i=1}^{i=12} Q(H_i)\, N_i \qquad (35)$$

with $Q\,(H_i)$ the average daily volume of water pumped for a month with solar irradiation H_i and is obtained from Figure 3.9.
N_i is the number of days in the month i
Q_{yr} is the annual volume of water pumped
K is the Utilization Factor which must be estimated.

5b. If the unit cost is calculated from a Long Term Test then determine the volume of water pumped in the year.

6. The unit water cost is

$$C_w = \frac{ALCC}{Q_{yr}} \qquad (36)$$

with Q_{yr} the useful volume of water pumped in a year.

3.8. Presentation of Results

The format sheet given in Table 3.11 should be used to present the results obtained from the three test procedures and the cost appraisal. The format is split into five parts:

(1) detils of system supplier; finance and cost etc.

(2) manufacturers specification.

(3) results of the PV Rating test (Level 3 Test Schedule only (and Short Term Test (Level 2,3 Test schedules only). The output in cubic meters per day should correspond to the same head and solar irradiation as given in the manufacturers specification. This allows a direct comparison between the measurements and the manufacturers specification.

(4) Cost analysis obtained from data collected on a Long Term Test, showing the useful volume of water pumped and the Utilization Factor.

(5) Comments - should be used for observations on water use, cost effectiveness of system, maintenance requirements reliability etc.

The following data should be appended when presenting the results of the tests:

PV Rating test - 4 completed data sheets (Table 3.5)

Short Term Test - completed analysis sheet (Table 3.7)
- completed efficiency graph (Fig. 3.8)
- completed potential performance graph (Fig 3.9)

Long Term Test - completed analysis sheets (Table 3.9)
- completed useful performance graph (Fig.3.9)

PHOTOVOLTAIC SOLAR PUMP

PERFORMANCE EVALUATION

COUNTRY:	LOCATION:
Supplied by: Installed by: Financed by: Maintained by:	Date Installed: Capital Cost: Maintenance Cost:

MANUFACTURERS SPECIFICATION

Array Rating: Wp

Output: m^3 per day @ m head @ kWh/m^2

TEST RESULTS

Date(s) of Test(s): Test Engineer(s):

Date of last calibration of solarimeter:
flowmeter:
pressure gauge:

Array rating: Wp

Output: m^3 per day @ m head @ kWh/m^2

COST ANALYSIS

Period of analysis	years	Discount Rate	%
Module lifetime	years	Subsystem lifetime	years
Annual water pumped		Utilization factor	
Units Water cost			

COMMENTS.

Signature of test engineer(s): Date:

Table 3.11. Summary Sheet

4. APPLICATION TO MALI

4.1. Photovoltaic systems in Mali

Growth of the use of photovoltaics in Mali has been rapid and effective. Following the installation of the first pumping system at Koni in 1977, approximately 100 installations, comprising pumping, lighting, refrigeration and communications now exist in the field, with a total power capacity exceeding 100 kW. A list of installations, compiled by LESO, is presented in Appendix 1.

There are four organisations that install and maintain solar pumps in Mali:

- LESO
- Mali Aqua Viva
- Elf Mali- installed systems on behalf of the Department of Water Resources (Direction Nationale des Hydraulique Energie, hereafter referred to as l'Hydraulique) but has now closed down.
- Somimad - represents the solar pump company Solarforce.

Most of the solar pumps in Mali have been donated and maintenance comes under the responsibility of one of the above organizations. Mali Aqua Viva and l'Hydraulique require that the villagers pay for maintenance - the method of collecting the money varies from village to village (see section 4.2). L'Hydraulique proposes a charge of 5 CFA (0.1 cents) per 20 litres for the water, equivalent to 250 CFA ($0.50) per cubic meter. While the solar pumps are under warranty (2 years from installation), the villagers do not pay for maintenance.

At present LESO does not require payment for maintenance but will do so in September 1985 at the end of the AID Renewable Energy Project.

LESO under the AID Renewable Energy Project, has installed

- o 4 photovoltaic pumps and Samanko, Camp Modibo, Dilly, and Mopti

- o 4 solar refrigerators in dispensaries at N'torosso, Nioro, Ansongo and Oulessebougou

- o 7 lighting systems and 5 solar rechargeable battery flashlights in villages among the 20 under the LESO survey program since 1980.

Under the present phase of work, due for completion in 1985, LESO will install:

- o 4 solar refrigerators.

- o 4 photovoltaic pumps (in the Nioro and Gao regions)

- o 1 photovoltaic powered 3-HP grain mill with a capacity of 300 kg/day (designed and assembled by the Laboratory)

- o 6 original lighting systems designed and assembled by the Laboratory.

- o an uninterruptable power supply to counteract the possible negative impacts of national electric grid system power failures on sensitive Laboratory electronic devices and on micro-computer equipment.

Elf is also responsible for:

- o 2 photovoltaic pumps (at Magnambougou and Ouelessebougou)
- o a portion of the Kolokani hospital lighting system, and
- o follow-up of 10 photovoltaic pumps recently installed in the Bougouni and Kolokani regions.

Mali-Aqua Viva (MAV) is very deeply involved with photovoltaic pumps. Like LESO, MAV has a well-trained and well-equipped team for follow-up and maintenance of the PV pumps they install, which number approximately 50 and are all in the region of San.

The rapid growth and acceptance of photovoltaic technologies by the users is clear evidence of a well-adapted technology which offers operational advantages over conventional technology options. The economic attractiveness of photovoltaic systems is less clear.

4.2. Techno-economic evaluation of selected solar pumps in Mali

Six solar pumping sites were visited in order to try out the test procedures and to evaluate the performance of the selected solar pumps. The sites, their characteristics and a summary of the results obtained are given in Table 4.1. The data collected is presented in Appendix 2, in accordance with the test procedure.

During the visit, four Short Term Tests and four PV Array Rating Tests were carried out. The weather conditions were not ideal since there was a large amount of dust in the atmosphere. Consequently only two of the PV Array Rating Tests are acceptable (since the solar irradiance was too low on the other two). The Short Term Test proved to be very easy to carry out while some problems were encountered with the PV Rating tests as detailed in the draft methodology. Hence the PV Rating test was revised accordingly.

Table 4.1 shows that three of the five pumps tested (i.e. Nonsombougou, Tioribougou and Tiemena) had an acceptable technical performance. A Short Term Test was carried out on the solar pump at Samanko (this pump was funded by USAID), but the efficiency of the motor/pump subsystem is well below an acceptable figure and this site requires further maintenance. A P.V. Rating Test was carried out at Babougou but it was not possible to do a short term tests because the pump would not operate. No test was carried out on the sixth site (Yangasso) because it was not pumping water during the visit.

It is significant that the three sites that were performing well were installed in the last two years and that the other three are between three and seven years old.

Details of the individual sites and results are give below.

Tioribougou

This system was financed by UNDP and installed by Elf Mali on behalf of l'Hydraulique who are now responsible for maintenance. It is one of ten Photowatt systems purchased by UNDP. The Photovoltaic Array is rated at 1056 Watts and the motor/pump unit is submersible. The system supplies domestic water for a village of approximately 500 people and also supplies irrigation water for several small gardens.

This installation was subjected to an acceptance test by CRES (Centre Regional De l'Energie Solaire) and LESO on 22nd June 1983. The performance was thought to be acceptable. Since the system was installed the submersible motor has had to be replaced (under guarantee).

Site	Year Installed	Use (2)	Head m	Manufacturers Spec.		Measured Performance		Capital Cost (1) $	Unit Water Cost (3) $/$m^3$
				Array Rating Wp	Output m @ 6 kWh/m^3	Array Rating Wp	output m @ 6 kWh/m^3		
Tioribougou	1984	D,I	24	1056	22	890	22	18350	0.35
Nonsombougou	1984	D,I	20	3816	122	-	122	85000	0.22
Tiemena	1984	D,L	25	1400	40	-	25	15000	0.20
Samanko	1982	D,I	19	1300	30	1088	10	33000	1.59
Babougou	1980	D	10	250	-	170	-	14000	
Yangasso	1979	D	19	1300	-	-	-		

Notes: (1) at year of installation
(2) D = domestic
L = livestock
I = irrigation

(3) The unit water cost is based on irradiation data for Bamako (annual average 5.3 kWh/m^2, the measured output the actual capital cost, and assumed maintenance cost of $100 p.a., over a 15 year period at 5% discount.

Table 4.1. Summary of sites under test.

The village has a committee who decide on priorities for the water and there is a 'Gardien' who supervises the solar pump and is paid directly by l'Hydraulique. From 8.00 to 12.00 the water is used for domestic purposes - there is no charge. From 12.00 water is sold in 200 litre drums at 50 CFA ($0.10) per drum (equivalent to 250 CFA ($0.50) per cubic meter). This water is used for construction. Water for irrigation is sold at 5 CFA ($0.01) per square meter of garden per month, in the afternoon. At this price considerable profit cn be made by growing vegetables. For example 528 m^2 of land growing potatoes yields 1300 kg and this can be sold in the market for 259000 CFA ($510). The cost of water to irrigate this in the four month growing season is 10560 CFA ($21.12) or 26CFA ($0.05) per cubic meter).

The tests carried out show that the pump was performing satisfactorily. The unit cost of water, based on the measured performance is $0.35 per cubic meter.

Nonsombougou

This Solarforce system was financed by FED (the European Development Fund) and is maintained by l'Hydraulique. It has a surface motor and submerged pump with a France-Photon Array rated at 3816 Watts. The water is managed by a committee - water will be sold at the following rates: (at present the system is under warranty so there is no charge for the water).

500 CFA ($1.00) per person per year
200 CFA ($0.40) per animal per year (for villagers)
25 CFA ($0.05) per animal (for outsiders)
25000 CFA (£5.00) per hectare per year

Note that the cost of water for irrigation will be 1/24th of the cost at Tioribougou and is considerably below the actual cost. There is a large 1.8 ha vegetable plot owned by one man who uses most of the water.

This system was found to perform exceptionally well. Two short term tests were performed - one with dust on the modules and one after the modules had been cleaned. The effect of dust was found to reduce the performance by 33% in this case. Normally the PV Array is cleaned once per week but since there was a strong wind and the system is close to a laterite road the dust had been particularly bad.

The cost of water from this system is $0.22 per cubic meter.

Tiemena

This system was installed and is maintained by Mali Aqua Viva and appears to be used largely for cattle watering. It has a 1400 Watt Arco Solar Array and a submersible a.c. Grundfos motor/pump.

The system was found to perform well and based on the measured performance, the unit water cost is $0.22 per cubic meter.

Samanko

This Solarforce system with a surface motor/submerged pump and 1300 Watt France Photon array was installed and is maintained by LESO. It was funded under the AID Renewable Energy Project. A PV Array Rating test was carried out - the power output is acceptable. However the short term test gave very low efficiencies for the motor/pump subsystem; the output is a third of its potential performance. Some maintenance work is required to determine the cause and rectify the fault.

Babougou

This system, made by Briau, was installed under the UNDO/World Bank "Small Scale Solar Pumping Project" by LESO/IT Power/Halcrow. Tests were made in 1979 and in 1982. On both occasions the system was found to perform well. The water is used for drinking and washing for a seed growing establishment. At the time of the visit the system would not pump water. It had functioned well until November 1984, after which it had been turned off because it was thought that there was not enough sun to operate the pump.

On inspection it was found that one of the electrical connectors on a PV module was faulty. When this was repaired a PV Rating Test was carried out - the rated output was found to be 170 Watts compared to the original 250 Watts. However two of the module glass covers had been smashed (clearly by stones) which would reduce the output. A further two module covers had minor cracks probably due to thermal stresses. (There are 16 modules in total).

There were several other faults with the system:

- o The rising main flexible pipe was badly worn. Since the pump is at ground level and operates on suction, no water could be pumped because the system could not be cleared of air.
- o the on/off switch was faulty
- o the float switch was broken
- o the drive belt had been broken but also repaired.

Since this system has had no maintenance since it was installed it has performed commendably well.

Yangasso

This pump, manufactured by Solarforce, was installed by Mali Aqua Viva in 1979. It was tested under the UNDP/World Bank Project. Test results were obtained in 1979 and 1982. On the latter occasion the performance of the motor and pump had degraded by 50%. The system was repaired by Mali Aqua Viva at a cost to the villageers of 45000 CFA ($90.00) - this was paid from local taxes.

During the visit it appeared that another fault had developed because although the pump was turning, no water was being pumped and the Chef said that there has been a problem over the last two days. The delivery pipe from the outlet of the pump to the water storage tank had been disconnected; it was clear that when the pump was in operation water was wasted because there is effectively no storage.

5. CONCLUSIONS AND RECOMMENDATIONS.

5.1. Application of the test procedure in Mali

The PV Array Rating and Short Term Tests have been modified and applied successfully in Mali. They are both relatively easy to use and since LESO has a strong ability in this field, LESO has the capability to use the methodology in the future. It is recommended that all photovoltaic pumps installed by LESO undergone the PV Rating And Short Term Tests.

Of the five sites tested, Tioribougou, Nonsombougou and Tiemena were performing well and producing water at $0.35, $0.22, $0.20 per cubic meter respectively. These costs are based on the measured performance and actual system costs. The system at Samanko (funded by AID) had a problem with the motor/pump and was only working at one third of its potential performance. The systems at Babougou and Yangasso were not operating.

It is significant that the sites that were performing well were installed in the last two years whereas the others are between 3 and 6 years old. An effective system of maintenance checks need to be set up of the technology is to operate satisfactorily.

5.2. Further Development and use of the methodology

As noted above this methodology is now in use in Mali, and the indications are that it is suitable for application in the country with useful results being generated. Of course some of the measurements are made over a period of time longer than the duration of the project, and so more time must elapse before the full utility of the methodology can be determined. (Note that funding is required for LESO to continue applying the methodology as commenced under this project).

Results are sufficiently encouraging for recommendations to be presented on the further development (if necessary) and use of the methodology.

Knowledge on the real performance of photovoltaic pumps and how they compare with alternative technologies, should be sought, not only from Mali, but from other countries where photovoltaic pumps have been installed, or where there are indications that there would be an appropriate method of water lifting. Now that a properly documented methodology has been prepared this should facilitate the collection of the necessary data. This of course requires that potential users are provided with the methodology. But prior to this it is believed the views of other experts should be sought and if found necessary the methodology should be modified or extended. This can best be achieved by firstly circulating the methodology together with sample results to a number of other organizations installing and/or operating photovoltaic pumps, and seeking their comments. This would be followed by a workshop to develop a consensus among experts on the methodology. The participants in this exercise could be selected from AID projects only, or more broadly. The end result would be agreed methodology which would be applied within AID projects involving photovoltaic pumps (which are several in number) or if other donors and projects were well represented an international standard methodology would be the outcome. This latter approach is recommended.

Some agencies and organizations who are currently involved with photovoltaic pumping and who could particpate in this process are listed in Table 5.1.

An effective method of getting the methodology into use and generating and exchanging useful results would be through a network. There are already networks dealing with gasifiers, fuelwood production and woodstoves, and a windpump network in

COUNTRY	ORGANIZATION	DONOR AGENCIES (funding pv pumps)
Botswana	Botswana Technology Centre Botswana Renewable Energy Project	 USAID
Mali	Laboratoire de l'Energie Solaire	USAID
Morocco	Centre de Developpement des Energies Renouvelables (CEEK)	USAID
Zimbabwe	Institute of Agricultural Engineering	
Egypt	Egyptian Electricity Authority	USAID
Philippines	Energy Research & Development - Division - PNOC	GTZ
Pakistan	National Agricultural Research Centre	
Thailand	Asian Instutute of Technology	Various

Table 5.1. Organisations and Agencies actively involved with photovoltaic pumping.

embrionic form (see Klein, 1984). Because of the large number of photovoltaic pumps installed and operated within donor agency programs it should not be difficult to bring network members into active co-operation. Obviously if an expert workshop were held this could also suggest the network establishment and the workshop participants could become the nucleus of the network.

The network could be established by AID (or another agency) taking the lead in setting up the network (perhaps initially among users of AID funded photovoltaic pumps) and then inviting others to join in. An alternative aproach might be for AID to call a meeting of donors and developing countries interested in photovoltaic pumping, to discuss the question of whether to establish a network and make decisions on who might take on the task.

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Appendix 1. PHOTOVOLTAIC PUMPING & MICRO-ELECTRIFICATION SYSTEM. IN MALI

1. Water Pumps.

SITE	DATE INSTALLED	ORGANISATION RESPONSIBLE FOR MAINTENANCE & FOLLOW-UP	TECH. CHARACTERISTIC POWER (Wp)	HEAD (m)	FLOW (m^3/d)	FINANCE AMOUNT $x10^3$FF	SOURCE
NABASSO	1977	MAV	900	-	21.3	20	CEC/EDF
KONI 1	1978	"	900	-	19.6	20	"
TOMINIAN 1	1978	"	1.300	-	33.6	20	CCFD/EDF
YANGASSO	1975	"	1.300	-	22.4	15	"
SAN hospital	1979	"	900	-	14.6	16	FAC/CEC
YANGASSO 2	1979	"	1,300	-	16.8	20	"
DIENNA	1980	"	1,300	-	28	15	USA/MAV
KIMPARANA	1980	"	1,300	-	47.3	18	FMVJ/CEC
BE	1980	"	1,300	-	19.6	20	AFVP/CEC
SAFOLO	1980	"	1,300	-	22.4	20	CEC/SOS-S
BAN MARKALA	1980	"	1,300	-	36.4	-	CFCMCF/ MAV/Village
TERIYABOUGOU (sur BANI)	1980	"	900	-	150	18	CMDT/FED
NWORO (sur BANI)	1981	"	5,200	-	350	-	DP Canada
TION	1980	"	600	-	17.4	22	CEAO
BOSSONI	1980	"	1,300	-	32.5	-	CEE
KORO	1980	"	1,300	-	14.8	20	CMDT
WASSASSO	1980	"	1,300	-	39.2	20	MAV/Village
NDOSSO	1981	"	1,800	-	39.2	22	

SITE	DATE INSTALLED	ORGANISATION RESPONSIBLE FOR MAINTENANCE & FOLLOW-UP	TECH. CHARACTERISTIC POWER (Wp)	HEAD (m)	FLOW (m^3/d)	FINANCE AMOUNT $x10^3$FF	SOURCE
KOTOBE	1981	"	900	-	20.2	-	MAV
NIOUGUESSO	1981	"	1,300	-	28	-	SOS-S
WOLONI	1981	"	1,300	-	39.2	-	
SINZARA	1981	"	1,800	-	56	-	CMDT
TOMINIAN 2	1981	"	800	-	44.8	-	CMDT
NTIESSO	1982	"	900	-	25.2	-	CMDT
NTOBA	1982	"	900	-	25.2	18	CMDT
SORONTONA	1982	"	200	-	7.8	-	PWI
TOMINIAN 3	1983	"	600	-	78.4	-	pwi
TIORIBOUGOU	1983	ASEM	1,056	-	4.9	-	UNDP
DIDIENI	1983	"	792	-	3.6	-	UNDP
MANTA	1983	"	660	-	2.9	-	UNDP
SIRAKOROBA	1983	"	792	-	3.0	-	UNDP
DOUBALA	1983	"	1,188	-	5.5	-	UNDP
KOLOKANI (hospital)	1981	"	530	25	6	-	FAC/AFME
KOLOKANI (market)	1983	"	1,716	25	6	-	US-AID
DAMBA DIAWARA	1981	LESO	1,800	-	60	-	US-AID
CAMP MODIBO	1983	"	2,600	-	60	-	EDF
KARADIE	1984	ASEM	3,000	-	120	-	EDF
KOUMI	1984	"	1,300	-	50	-	EDF
SEBEKORO 2	1984	"	1,300	-	30	-	EDF

SITE	DATE INSTALLED	ORGANISATION RESPONSIBLE FOR MAINTENANCE & FOLLOW-UP	TECH. CHARACTERISTIC			FINANCE	
			POWER (Wp)	HEAD (m)	FLOW (m^3/d)	AMOUNT $X10^3$FF	SOURCE
NIONSOMBOUGOU	1984	"	2,600	-	110	-	EDF
MADINA KAGORO	1984	"	2,000	-	80	-	EDF
DALLY	1984	"	1,300	-	25	-	EDF
MAGNAMBOUGOU	1981	ASEM	1,300	-	15	14	SNEA
SAMANKO	1982	LESO	1,300	-	34	-	US-AID
MENAKA	1982		1,300	-	-	40	FMVJ
TIN AG EL HADJ	-	ILES DE PAIX	-	-	15	-	EDF
KABARA	1978	ILES DE PAIX	1,200		100	31	"
BANKASS	1981	OMM	5,200		95	10	USAID
MOPTI	1980	ODEM	1,300		160	23	USAID
YASSA (near de BONI)	1979	MAV	2,600		150	-	BIRD
GAO (hospital)	1982		3,000				EURO-ACTION
KOLONDIEBA	1983	ASEM	1,584		5.1		UNDP
KOLOGO	1983	ASEM	1,056		3.5		UNDP
FARAGOUARAN	1983	ASEM	792		3.7		UNDP
MANANKORO	1983	ASEM	1,056		4.1		UNDP
KELEYA	1983	ASEM	1,183		3.7		UNDP
WELESSEBOUGOU	1983	ASEM	292		7		HELVETAS SNEA
BABOUGOU (DIORO)	1983	LESO					USAID

SITE	DATE INSTALLED	ORGANISATION RESPONSIBLE FOR MAINTENANCE & FOLLOW-UP	TECH. CHARACTERISTIC POWER (Wp)	FINANCE AMOUNT x10[3] FF	SOURCE
MICROELECTRIFICATION					
SAN (hospital)	1979	M.A.V.	8,500	135	FAC/COMES
KIMPARANA (school)	1980	"	160	-	FMVJ
KOLOKANI (hospital)	1981	ASEM	2,280	17	SNEA
KOLOKANI (maternite eclairage)	1982	"	66	2	CIDA
KOLOKANI (maternite refrigeration)	1981	"	260	-	UNICEF
ENI	-	ENI	-	-	-
ANSONGO (eclairage)	1983	LESO	40	$1,350	
BOUREM IN ALY	1982	ILES DE PAIX	5,760	63	FAC/AFME
DIOILA (Dispensary)	1982	-	-		FAC/AFME
NIORO (eclairage)	1983	LESO	40	1.320	USAID
NIORO (eclairage refrigerateur)	1982	LESO	132		USAID
SOMO (eclair ecole)	1982	LESO	132	1.320	USAID
NTOROSSO (eclairage)	1983	LESO	132	1.320	USAID
NTOROSSO (refrigerat)	1983	LESO			

SITE	DATE INSTALLED	ORGANISATION RESPONSIBLE FOR MAINTENANCE & FOLLOW-UP	TECH. CHARACTERISTIC POWER (Wp)	FINANCE AMOUNT $X10^3FF$	SOURCE
ZANTIEBOUGOU	1983		40	1.320	USAID
TORAKORO	1983	LESO	40		USAID
1 er Arrondt.	1982	-	100	-	-
2 eme Arrondt.	1982	-	100	-	-
3 eme Arrondt.	1982	-	100	-	-
4 eme Arrondt.	1982	-	100	-	-
5 eme Arrondt.	1982	-	100	-	-
6 eme Arrondt.	1982	-	100	-	-
Comm. KOULOUBA	1982	-	100	-	-
Aeroport SENOU	1982	-	100	-	-
Ex-Base aerienne	1982	-	100	-	-
Police Spec. Ch.de Fer	1982	-	100	-	-
Ecole de Police	1982	-	100	-	-
KIDIRA	1982	CFM	33	0.49	CFM
DIBOLI	1982	CFM	33	0.48	CFM
AMBIDEDI	1982	CFM	33	0.51	CFM
DAIMOU	1982	CFM	33	0.49	CFM
MAHINA	1982	CFM	132	1.54	CFM
WALIA	1982	CFM	33	0.48	CFM
TOUKOTO	1981	CFM	66	0.84	CFM
KASSARO	1982	CFM	33	0.51	CFM
NAFADIE KOURA	1982	CFM	33	0.48	CFM

SITE	DATE INSTALLED	ORGANISATION RESPONSIBLE FOR MAINTENANCE & FOLLOW-UP	TECH. CHARACTERISTIC POWER (Wp)	FINANCE AMOUNT $x10^3$FF	SOURCE
NEGALA	1982	CFM	33	0.51	CFM
KATI	1979	CFM	12	0.10	CFM
Siege BAMAKO	-	CFM	33	-	CFM

Key
ASEM = Association Solaire Elf Mali
LESO = Laboratoire de l'Energie Solaire
CIDA = Canadian International Development Agency
ENI = Ecole National D'Ingenieur
SNEA = Societe Nationale Elf Aquitaine
OMM = Operation Mils Mopti
ODEM = Operation
IBRD = International Bank for Reconstruction & Development
CFM = Chemin de Fer du Mali

Appendix 2. DATA OBTAINED IN MALI

Contents

PHOTOVOLTAIC SOLAR PUMP

PERFORMANCE EVALUATION

COUNTRY: Mali	LOCATION: Tioribougou
Supplied by: Photowatt Installed by: Elf Mali Financed by: UNDP Maintained by: Elf Mali (L'Hydraulique)	Date Installed: 1983 Capital Cost: 8410000 CFA Maintenance Cost: Not known

MANUFACTURERS SPECIFICATION

Array Rating: 1056 Wp

Output: 25 m^3 per day @ 24 m head @ 6 kWh/m^2

TEST RESULTS

Date(s) of Test(s): 22-23 Feb, 1985 Test Engineer(s): JPK, MD

Date of last calibration of solarimeter: 23 Feb, 1985
flowmeter: 23 Feb, 1985
pressure gauge: Not used

Array rating: 890 Wp

Output: 22 m^3 per day @ 24 m head @ 6 kWh/m^2

COST ANALYSIS

Period of analysis	15 years	Discount Rate	5 %
Module lifetime	15 years	Subsystem lifetime	7.5 years
Annual water pumped	6052m^3	Utilization factor	100%
Units Water cost	\$0.35/m^3		

COMMENTS.

Signature of test engineer(s): Date: 3 March, 1985

Summary Sheet - Tioribougou

SHORT TERM SOLAR PUMP TEST

Location: TIORIBOUGOU | Latitude: 13° | Date: 22-23 Feb 85

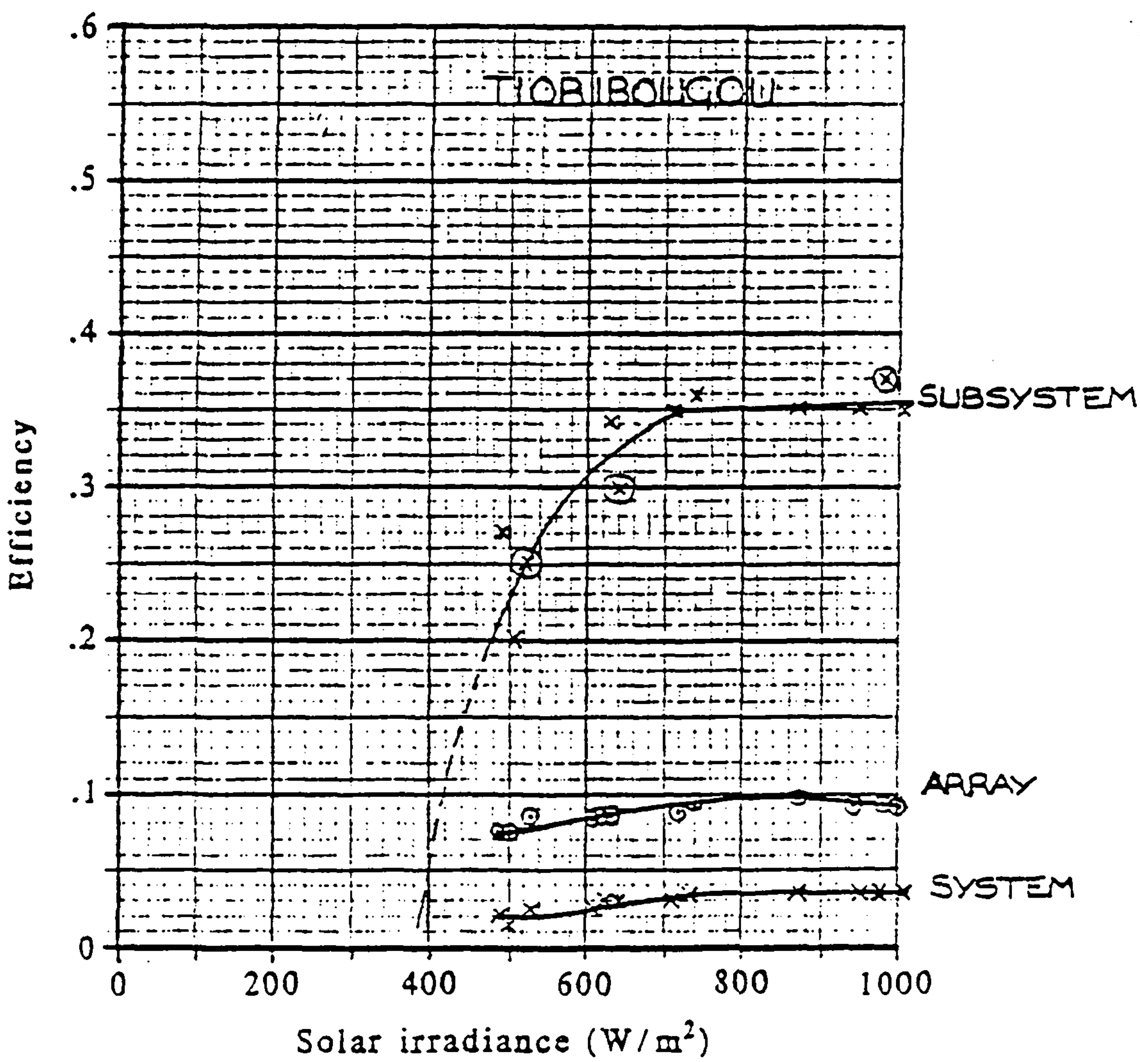
Array make and rating: FRANCE PHOTON 1056 Wp | Tester: JPK, MD

Motor make and rating: Submersible | Cell Area: 9.05 m^2

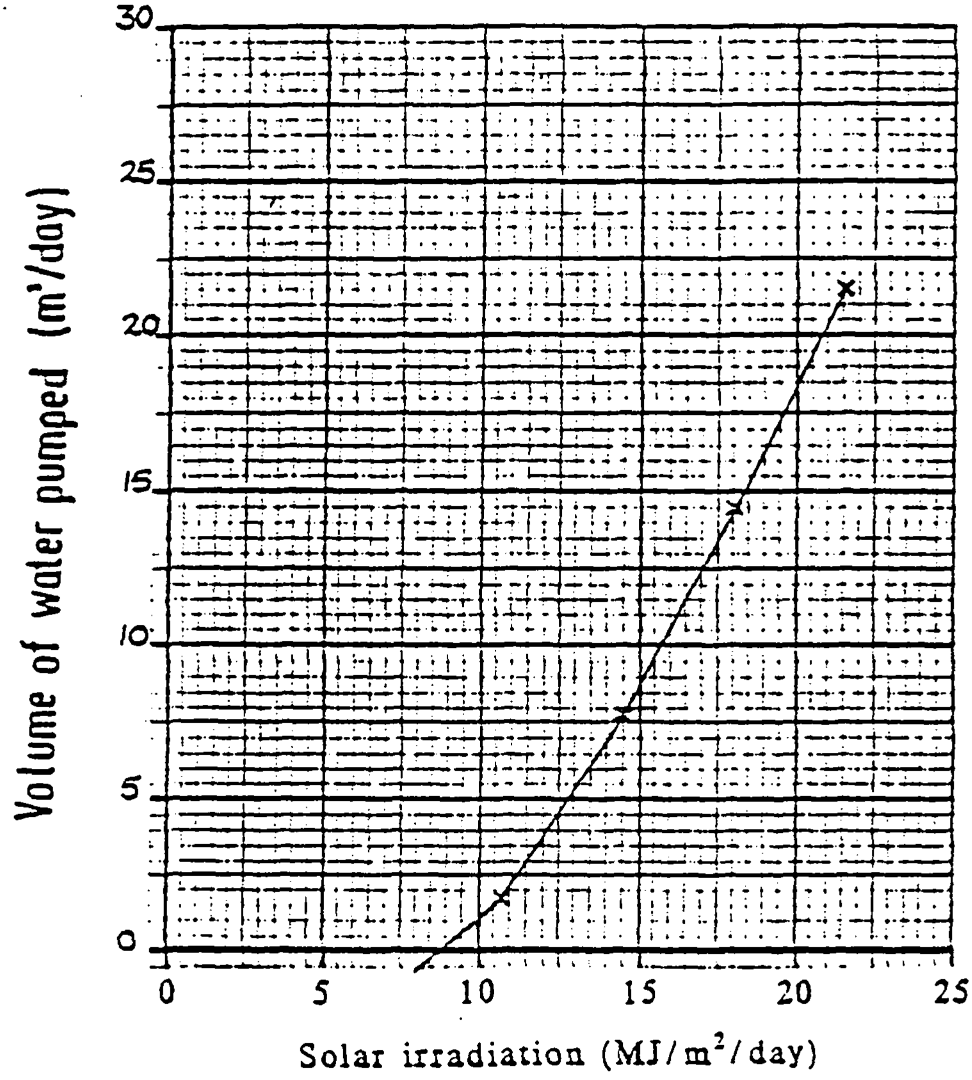
Pump make and rating: Submersible | Water Rest Level: 23 m

Time	Irradiance W/m^2	Array Output W	Flow l/sec	Head m	Hydraulic power W	Array efficiency %	Subsystem efficiency %	System efficiency %
14.50	712	576	0.83	24.7	201	8.94	34.7	3.10
15.10	644	516	0.52	30.3	154	8.85	30.0	2.65
15.30	610	462	0.58	24.5	140	8.37	30.3	2.53
15.40	520	408	0.35	30.2	102	8.51	25.1	2.13
16.00	502	348	0.29	24.4	70	7.66	20.2	1.55
09.00	490	342	0.40	23.8	94	7.71	27.1	2.09
09.30	616	480	0.69	24.1	164	8.61	34.1	2.94
10.00	741	624	0.94	24.7	226	9.30	36.2	3.36
10.30	866	762	1.11	25.0	272	9.72	35.7	3.46
11.00	946	804	1.14	25.3	282	9.40	35.1	3.24
11.30	975	834	1.02	31.2	311	9.45	37.3	3.52
11.40	1003	834	1.19	25.5	296	9.19	37.2	3.42

SHORT TERM PERFORMANCE - TIORIBOUGOU



Efficiency versus solar irradiance for Tioribougou



Volume of water pumped versus solar irradiation for Tioribougou

PHOTOVOLTAIC SOLAR PUMP

PERFORMANCE EVALUATION

COUNTRY: Mali Supplied by: Solarforce Installed by: Elf-Mali Financed by: FED Maintained by: Elf-Mali (L'Hydraulique)	**LOCATION:** Nonsombougou Date Installed: 1984 Capital Cost: 32632550 CFA Maintenance Cost: Not known

MANUFACTURERS SPECIFICATION

Array Rating: 3816 Wp

Output: 132 m^3 per day @ 20 m head @ 6 kWh/m^2

TEST RESULTS

Date(s) of Test(s): 21-22 Feb, 1985 Test Engineer(s): JPK, MD

Date of last calibration of solarimeter: 22 Feb, 1985
flowmeter: 22 Feb, 1985
pressure gauge: Not used

Array rating: - Wp

Output: - 122 m^3 per day @ 20 m head @ 6 kWh/m^2

COST ANALYSIS

Period of analysis	15	years	Discount Rate	5	%
Module lifetime	15	years	Subsystem lifetime	7.5	years
Annual water pumped	40515m³		Utilization factor	100%	
Units Water cost	$0.22/m³				

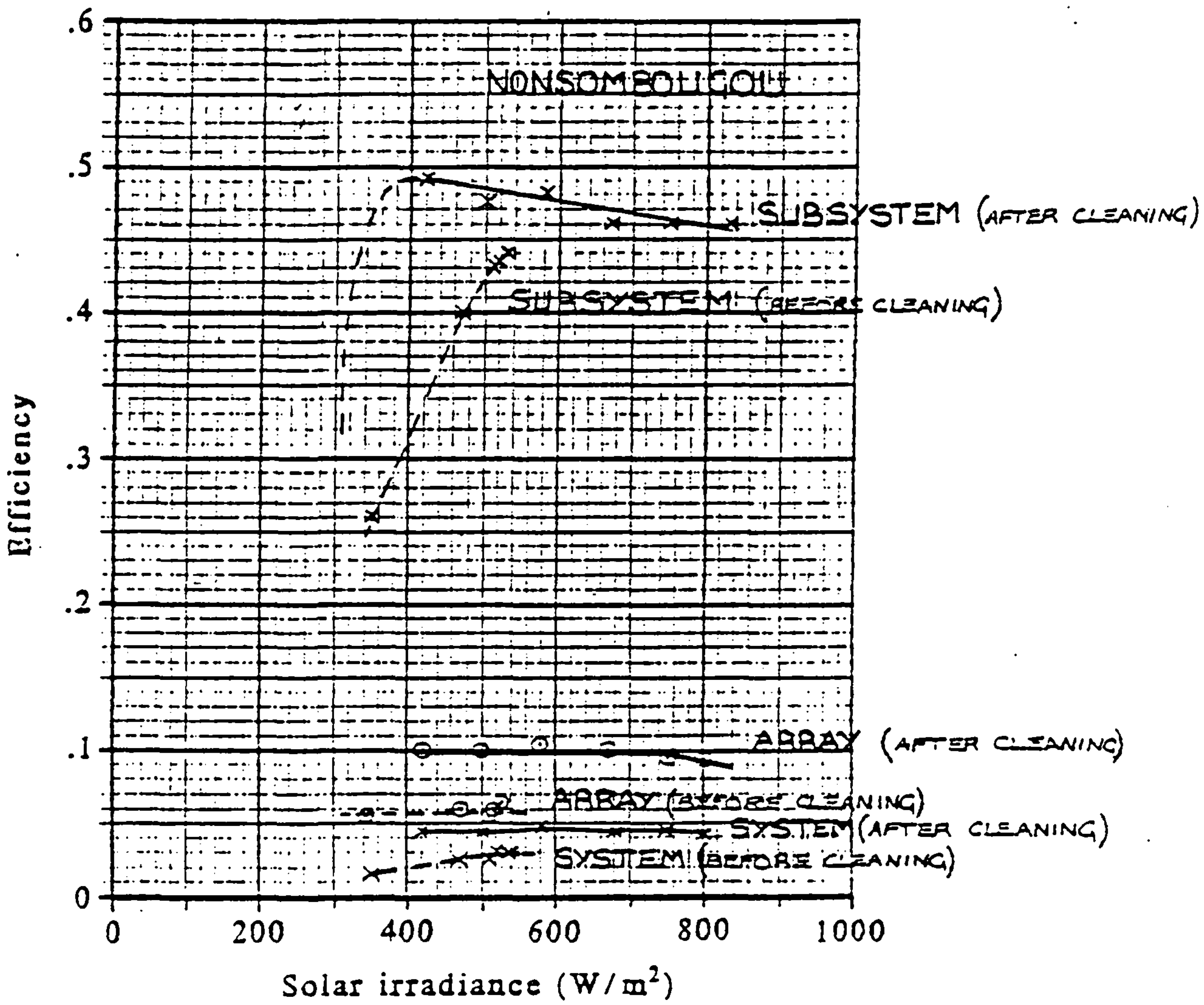
COMMENTS.

Signature of test engineer(s): Date: 3 March, 1985

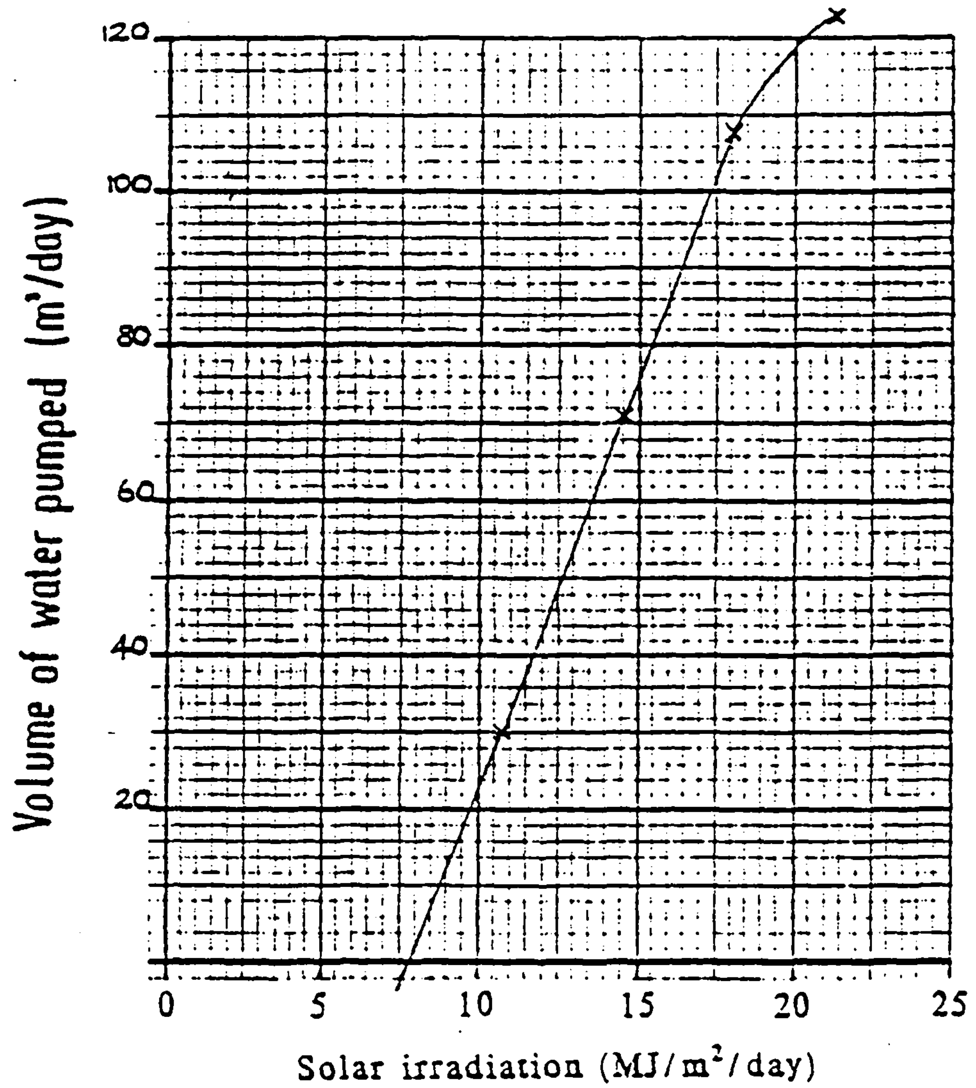
Summary Sheet - Nonsombougou

SHORT TERM SOLAR PUMP TEST								
Location: NONSOMBOUGOU				Latitude: 13°			Date: 21-22 Feb 85	
Array make and rating: FRANCE PHOTON 3816 Wp							Tester: JPK, MD	
Motor make and rating: Alta X							Cell Area: 29.96m²	
Pump make and rating: Alta X						Water Rest Level: 10 m		
Time	Irradiance W/m²	Array Output W	Flow l/sec	Head m	Hydraulic power W	Array efficiency %	Subsystem efficiency %	System efficiency %
14.05	534	1010	2.42	18.9	448	6.31	44.3	2.79
14.27	523	998	2.33	18.9	433	6.39	43.3	2.75
15.00	518	961	2.20	18.9	408	6.19	42.4	2.62
15.30	470	842	1.80	18.8	332	5.98	39.4	2.35
16.00	356	605	0.87	18.5	157	5.66	26.0	1.47
ARRAY CLEANED								
9.40	422	1241	3.20	19.0	600	9.80	48.7	4.77
10.00	497	1454	3.68	19.1	690	9.75	47.5	4.63
10.30	580	1794	4.53	19.4	862	10.31	48.0	4.95
11.00	675	2009	4.78	19.8	928	9.92	46.2	4.58
11.30	745	2115	5.03	19.9	982	9.46	46.4	4.39
12.00	794	2178	5.07	20.1	1000	9.14	45.9	4.20
12.30	815	2003	3.71					

SHORT TERM PERFORMANCE - NONSOMBOUGOU



Efficiency versus solar irradiance for Nonsombouçou



Volume of water pumped versus solar irradiation for Nonsombougou

PHOTOVOLTAIC SOLAR PUMP

PERFORMANCE EVALUATION

COUNTRY: Mali	LOCATION: Tiemena
Supplied by: Grundfos Installed by: Mali Aqua Viva Financed by: Maintained by: Mali Aqua Viva	Date Installed: 1984 Capital Cost: 7500000 CFA Maintenance Cost: *Not known*

MANUFACTURERS SPECIFICATION

Array Rating: 1400 Wp

Output: 40 m^3 per day @ 25 m head @ 6 kWh/m^2

TEST RESULTS

Date(s) of Test(s): 27 Feb, 1985 Test Engineer(s): JPK, MD

Date of last calibration of solarimeter: 23 Feb, 1985
flowmeter: 27 Feb, 1985
pressure gauge:

Array rating: - Wp

Output: 25 m^3 per day @ 25 m head @ 6 kWh/m^2

COST ANALYSIS

Period of analysis	15	years	Discount Rate	5	%.
Module lifetime	15	years	Subsystem lifetime	7.5	years
Annual water pumped	5614m^3		Utilization factor	100%	
Units Water cost	$0.20/$m^3$				

COMMENTS.

Signature of test engineer(s): Date: 3 March, 1985

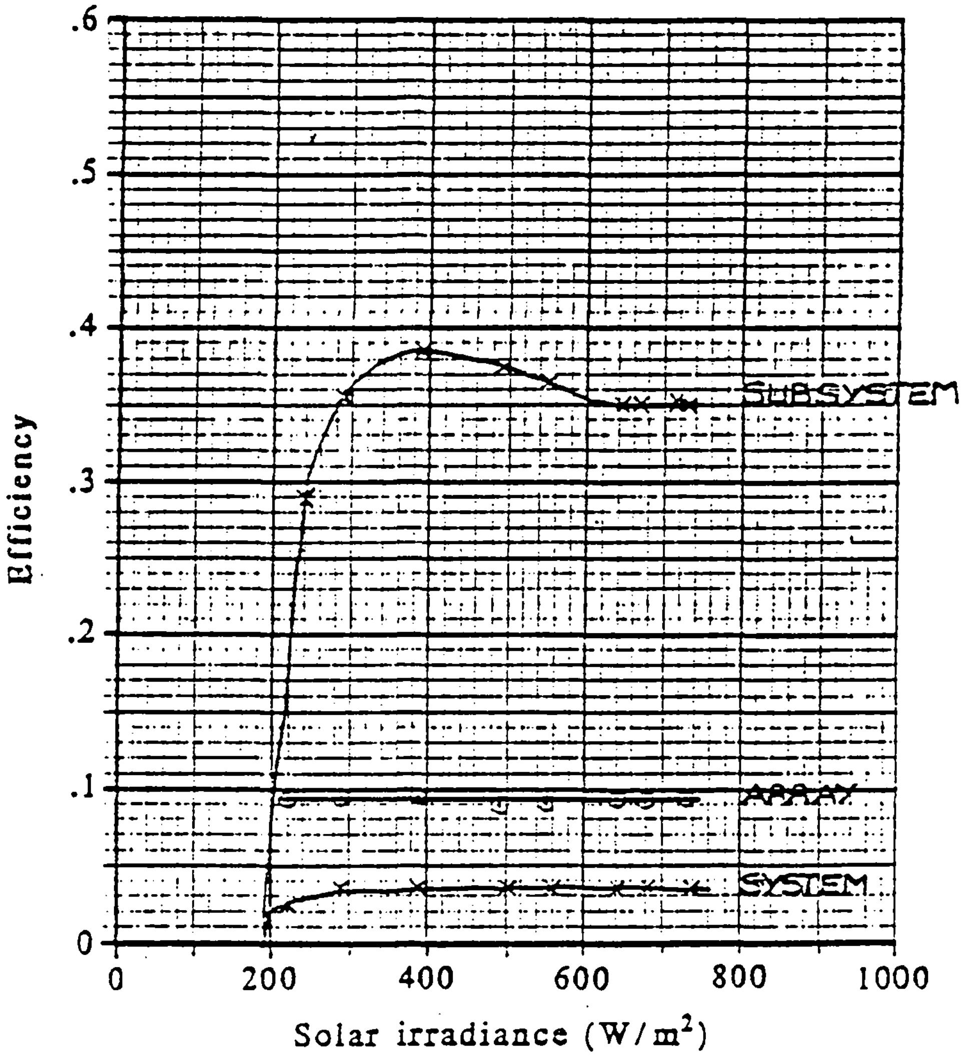
Summary Sheet - Tiemena

SHORT TERM SOLAR PUMP TEST

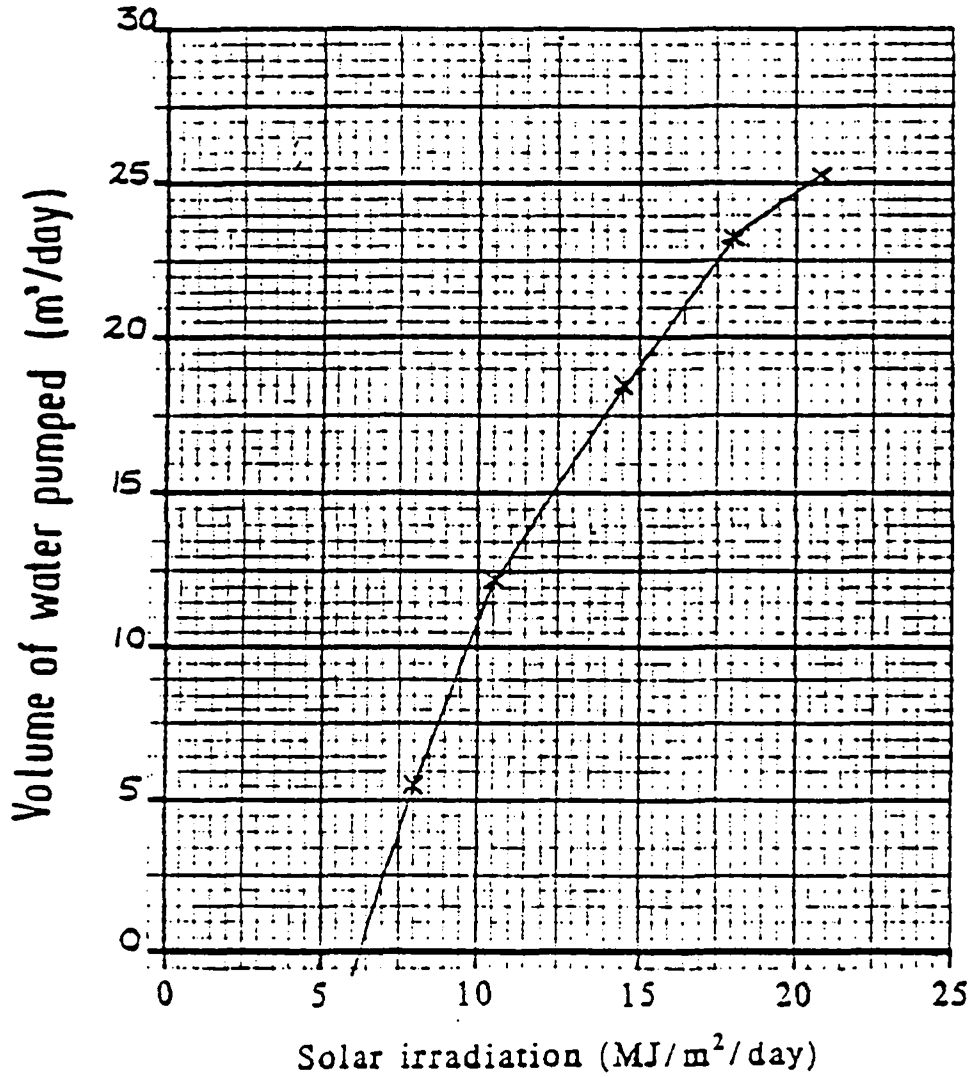
Location: TIEMENA	Latitude: 12.5	Date: 27 Feb 85
Array make and rating: ARCO SOLAR M51		Tester: JPK, MD
Motor make and rating: GRUNDFOS SUBMERSIBLE		Cell Area: 9.9 m^2
Pump make and rating: GRUNDFOS SUMBERSIBLE		Water Rest Level: 26 m

Time	Irradiance W/m^2	Array Output W	Flow l/sec	Head m	Hydraulic power W	Array efficiency %	Subsystem efficiency %	System efficiency %
12.35	707	666	0.85	27.7	231	9.5	34.7	3.3
13.00	713	678	0.85	27.7	231	9.6	34.1	3.3
13.30	670	636	0.83	27.6	225	9.6	35.3	3.4
14.00	637	606	0.78	27.6	212	9.6	35.0	3.4
14.30	556	534	0.725	27.6	196	9.7	36.7	3.6
15.00	486	462	0.65	27.4	175	9.6	37.8	3.6
15.30	389	366	0.525	27.4	141	9.5	38.5	3.6
15.55	286	270	0.36	27.3	96	9.5	35.5	3.4
16.15	243	216	0.23	27.2	62	9.0	28.8	2.6

SHORT TERM PERFORMANCE - TIEMENA



Efficiency versus solar irradiance for Tiemena



Volume of water pumped versus solar irradiation for Tiemena

PHOTOVOLTAIC SOLAR PUMP

PERFORMANCE EVALUATION

COUNTRY: Mali	**LOCATION:** Samanko
Supplied by: Solarforce Installed by: LESO Financed by: A.I.D Maintained by: LESO	Date Installed: 1982 Capital Cost: 11300000 CFA Maintenance Cost: Not known

MANUFACTURERS SPECIFICATION

Array Rating: 1300 Wp

Output: 30 m^3 per day @ 30 m head @ 6 kWh/m^2

TEST RESULTS

Date(s) of Test(s): 19-20 Feb, 1985 Test Engineer(s): JPK, MD, OS

Date of last calibration of solarimeter: 20 Feb, 1985
flowmeter: 19 Feb, 1985
pressure gauge: Not used

Array rating: 1088 Wp

Output: 10 m^3 per day @ 30 m head @ 6 kWh/m^2

COST ANALYSIS

Period of analysis	15 years	Discount Rate	5 %
Module lifetime	15 years	Subsystem lifetime	7.5 years
Annual water pumped	2336	Utilization factor	100%
Units Water cost	$1.59/$m^3$		

COMMENTS.

Signature of test engineer(s): Date: 3 March, 1985

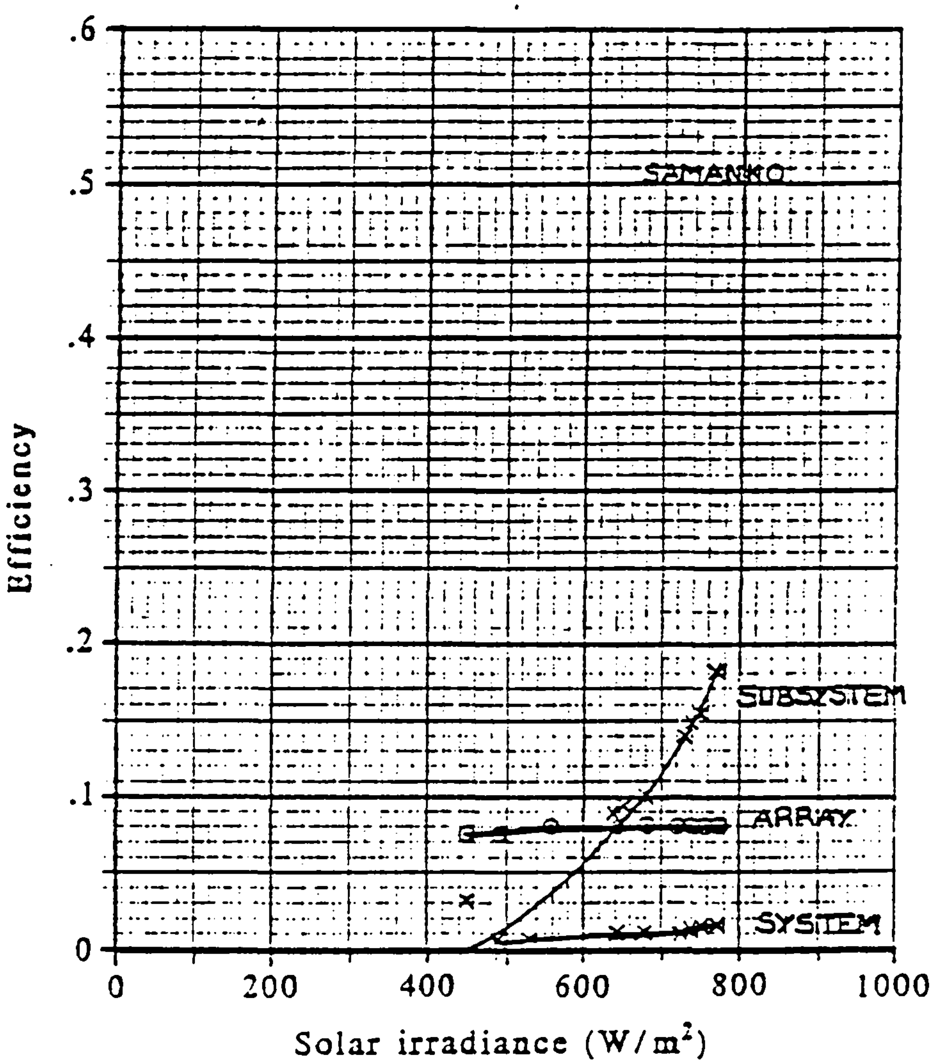
Summary Sheet - Samanko

SHORT TERM SOLAR PUMP TEST

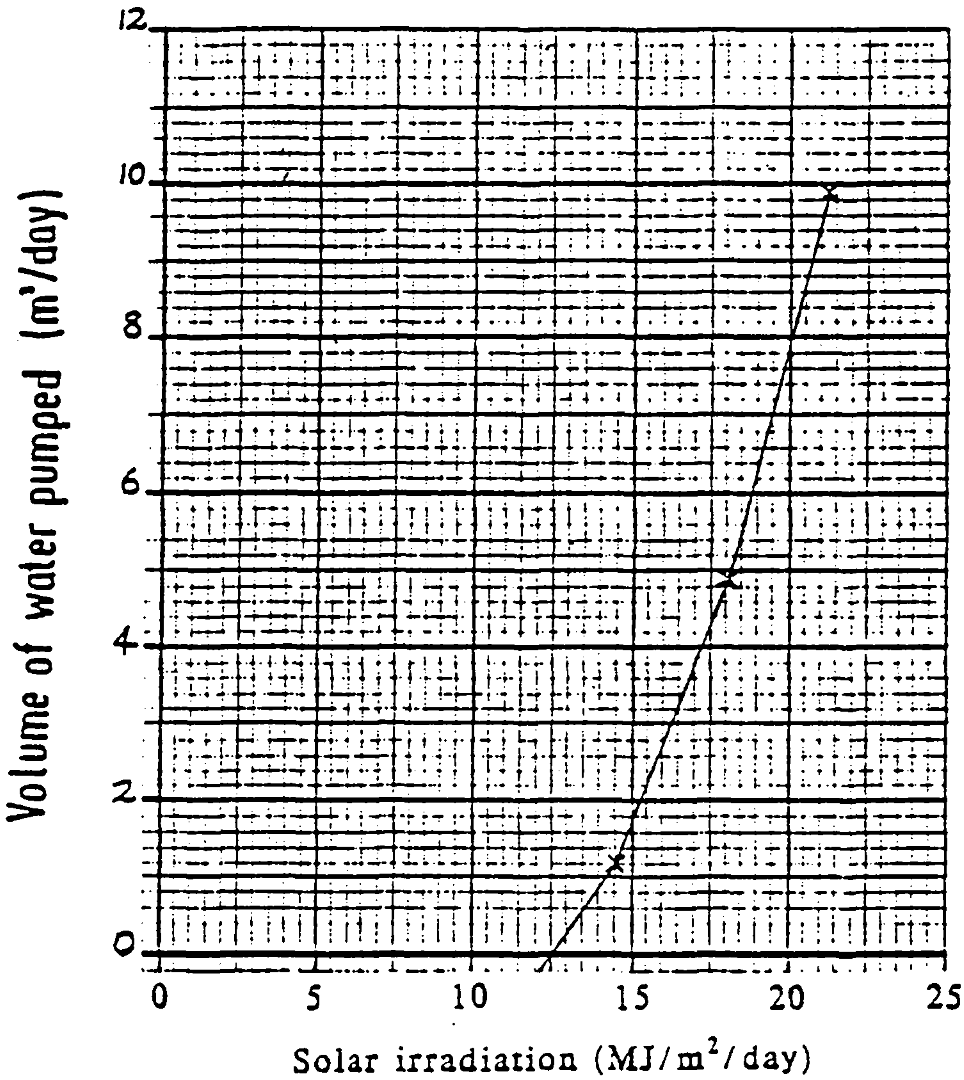
Location: Samanko	Latitude: 12.5°	Date: 19-20 Feb 85
Array make and rating: France Photon 1300 Wp.		Tester: JPK, MD, OS
Motor make and rating: Alta X		Cell Area: 9.52 m²
Pump make and rating: Alta X		Water Rest Level: 13 m

Time	Irradiance W/m^2	Array Output W	Flow l/sec	Head m	Hydraulic power W	Array efficiency %	Subsystem efficiency %	System efficiency %
13.26	621	492	0.26	17.05	43	8.32	8.84	0.73
13.41	675	534	0.32	17.05	53	8.31	9.97	0.83
14.00	643	504	0.26	18.05	46	8.23	9.13	0.75
14.30	564	445	0.09	20.00	17	8.29	3.97	0.33
15.00	491	366	0.008	20.00	1.6	7.83	0.45	0.03
10.00	453	336	0.05	18.00	9.7	7.79	2.89	0.22
11.30	680	534	0.27	19.30	51	8.25	9.50	0.78
12.00	740	582	0.48	18.00	85	8.26	14.6	1.20
12.30	767	582	0.60	18.00	106	7.97	18.2	1.45
12.40	751	582	0.68	13.5	90	8.14	15.5	1.26
13.00	745	576	0.62	13.5	82	8.12	14.2	1.15

SHORT TERM PERFORMANCE - SAMANKO



Efficiency versus solar irradiance for Samanko



Volume of water pumped versus solar irradiation for Samanko

PHOTOVOLTAIC SOLAR PUMP

PERFORMANCE EVALUATION

COUNTRY: Mali	**LOCATION:** Babougou
Supplied by: Briau Installed by: LESO Financed by: UNDP Maintained by: -	Date Installed: 1980 Capital Cost: 7000000 CFA Maintenance Cost: Not known

MANUFACTURERS SPECIFICATION

Array Rating: 250 Wp

Output: m^3 per day @ m head @ kWh/m^2

TEST RESULTS

Date(s) of Test(s): 26 Feb, 1985 Test Engineer(s): JPK, MD

Date of last calibration of solarimeter: 23 Feb, 1985
flowmeter: Not used
pressure gauge: Not used

Array rating: 170 Wp

Output: m^3 per day @ m head @ kWh/m^2

COST ANALYSIS

Period of analysis	years	Discount Rate	%.
Module lifetime	years	Subsystem lifetime	years
Annual water pumped		Utilization factor	
Units Water cost			

COMMENTS.

Signature of test engineer(s): Date: 3 March, 1985

Summary Sheet - Babougou

Appendix 3. CALCULATION OF FRICTION AND VELOCITY HEAD

Velocity head

The velocity head is not measured. It must be calculated and added on to the static and friction head. The velocity head is given by

$$h_v = \frac{v^2}{2g} \tag{A1}$$

where h_v is the velocity head in meters
v is the velocity of the water at the pipe outlet in m/s
g is the gravitational acceleration (9.8/m/s^2)

The velocity of the water at the pipe outlet is calculated from the measured flow rate

$$V = \frac{4Q}{\Pi d^2} \tag{A2}$$

where Q is the flow rate in m^3/s
d is the diameter of the outlet pipe in m

Friction head

Where possible the friction head should be measured. However if measurement is not possible the friction head can be estimated from the Darcy equation:

$$h_f = \frac{64 f l Q^2}{2g\Pi^2 d^5} \tag{A3}$$

where h_f is the friction head in meters
l is the pipe length in meters
Q is the water flow rate in m^3/s
d is the pipe diameter in meters
g is the gravitational acceleration (9.81m/s^2)
f is the Darcy coefficient

The Darcy coefficient depends on the roughness of the pipes. Plastic and aluminium have low roughness and a Darcy coefficient in the region of 0.02; steel pipes have medium - high friction and a Darcy coefficient in the region of 0.03.

Pipe fittings can be taken into account by assuming an equivalent straight length as shown in Table A1.

Pipe size (mm)	50	75	100
	Length of straight pipe with a similar head loss (m)		
Elbows and bends	1.25	1.75	3.0
T-junction	3.0	4.5	6.0

Table A1. Head loss in pipe fittings.