CAPE PENINSULA UNIVERSITY OF TECHNOLOGY

DEPARTMENT OF MECHANICAL ENGINEERING

FACULTY OF ENGINEERING

Remote Monitoring and Evaluation of a Photovoltaic (PV) Groundwater Pumping System

By

Selbourne Rapoone Makhomo

In partial fulfilment of the requirements of the Master's Degree in Technology (Mtech)

Under the supervision of

Mr. Ilyas Omar and Prof. Eugene Cairncross

NOVEMBER 2005

DECLARATION

I, the undersigned, hereby declare that the dissertation presented here is my own work and the opinions contained herein are my own and do not necessarily reflect those of the Cape Peninsula University of Technology. All references used have been accurately reported.

Name: SELBOURNE MATHOMO

Signature: ....

Date: 29/11/05

ABSTRACT

Potable water, and especially the accessibility to it, is an essential part of everyday life. Of particular note, is the challenge that residents of remote rural African villages face in order to gain access to this basic requirement. Specifically, the rural areas in the Northern Cape (Province north of Cape Town) region in South Africa is one such example that illustrates this problem very well. In order to address the requirements for drinkable water, various types of water pumping technologies have been used. Up to now, the two competing water pumping systems, diesel and photovoltaic (PV), have been the primary technologies deployed in selected sites in the Northern Cape.

The manual data collection of water pumping system data in the Northern Cape is fraught with impracticalities such as travel costs and requirements for skilled personnel. Therefore, as a preliminary step to accelerate development and testing, a local experimental laboratory PV water pumping rig was set-up within the Department of Mechanical Engineering at the Cape University of Technology. A short-term analysis was performed over a period of three weeks on the rig and the experimental results indicated the following: array efficiency of 16.3%, system efficiency of 15.0% and an average system efficiency of 1.47%. However, the results do indicate that long-term monitoring of PV water pumping systems can be suitable in serving to determine dynamic system performance and system life cycle costs.

The purpose of this project is two-fold – firstly, to present the results on the work done on the experimental PV system. Additionally, due to the specific challenges of limited communications infrastructure in the rural Northern Cape regions, the report presents the telemetry method employed for the remote monitoring of the proposed water pumping systems in the Northern Cape as well as monitoring results. The complete hardware and software set-up of the experimental system has been presented in the report as well as the present work done in order to move from the laboratory to the actual field implementation.

The remotely monitored field results taken over a period of two months show an array efficiency of 3.0%, a system efficiency of 32.0% and an overall system efficiency of 1.3%. The array and overall efficiencies are lower than expected due to the pump operating at off-design conditions (3.6m^3/day). If the pump were operating at near-design conditions (20m^3/day), the array and overall efficiencies would be high as 20.0% and 4.0% respectively.

A PV water pumping 15-year life cycle cost analysis has indicated a unit water cost of *R15.08/m*^{3} or *1.5 cents/l* and an energy cost of *30 cents/m*^{4}. A diesel 15-year life cycle cost analysis has indicated a unit water cost of *R3.12/m*^{3} or *0.31 cents/l* and an energy cost of 9 *cents/m*^{4}. If near-design conditions were assumed for the PV system the costs would be *0.27 cents/l* and *5.4 cents/m*^{4} respectively.

The findings of this study do support the existing body of evidence, which indicates that PV pumping can be competitive with diesel water pumping under specific head and flow conditions. However, the results obtained in this text are short-term results, making it difficult to make valid judgements with regard to how this system behaves in the long run. Yet the socio-institutional implementation strategies are crucial to the techno-economic success of actual pumping schemes. Even if diesel generators or other conventional pumping systems may appear to be cheaper on a life cycle cost comparison, it might be preferable to go for a PV system because of the operational advantages. Future work will evaluate a larger number of systems and eventually record long-term results which will be used to assess the reliability and functionality of the systems.

ACKNOWLEDGEMENTS

The author wishes to thank the following persons and institutions for their valuable contribution towards the completion of this work.

- Mr I Omar, the supervisor, deserves valuable credit for the efforts he put towards the compilation of this report. His assistance and advice during the various stages of this report are highly appreciated.

- Prof. E Cairncross, the co-supervisor, also deserves valuable credit by thorough reading and helpful comments he offered.

- Ms R Ziegler, is thanked for editing and proof-reading.

- Peninsula Technikon and the Cape Peninsula University of Technology are also thanked for the financial support they provided me for the entire study period. The Technikon also provided me with the testing facility.

- Allpower, Shell Renewables and Total Energie SA, for their donation of some of the water pumps, modules and controllers.

- Jason Witkowsky, his assistance on the monitoring side has been helpful and is highly appreciated. The information and comments he provided were so helpful – I enjoyed our interaction.

- Thanks to my parents for their patience, encouragement and financial support during difficult times.

- Finally, to my colleagues at the Department of Mechanical Engineering for their assistance and support during the preparation of this work.

TABLE OF CONTENTS

Contents **Page**

LIST OF FIGURES

LIST OF TABLES

ABBREVIATIONS AND LIST OF SYMBOLS

Abbreviations

CPUT	Cape Peninsula University of Technology
PV	Photovoltaic
PVWPS	Photovoltaic water pumping system
DAS	Data acquisition system
DAE	Data acquisition equipment
MPPT	Maximum power point tracker
STC	Standard test conditions
LED	Light emitting diode
LCC	Life cycle costs
LEO	Low earth orbit
RF	Radio frequency
GSM	Global System for Mobile Communications
CRF	Capital recovery factor
RV	Residual value
Wp	peak power generated by PV panels (W)
R	South African currency
c	cents(100 cents=R1)
UWC	Unit water cost in rand per cubic meter (R/m^3)
EC	Energy/pumping cost (R/m^4)

Symbols		**Units**
H_s	static head	m
H_t	total head	m
T_{amb}	ambient temperature	°C
Q	water flow rate	m^3/s
ρ	density	kg/m^3
g	gravitational acceleration	9.81 m/s^2
I_m	module current	A
V_m	module voltage	V
I_c	converter current	A
V_c	converter voltage	V
G	irradiance	W/m^2

A	area of the modules	m^2
P_{irr}	irradiance power	W
P_{arr}	array power	W
P_{con}	converter power	W
η_{Array}	array efficiency	%
$\eta_{Converter}$	converter efficiency	%
η_{System}	system efficiency	%
$\eta_{Overall}$	overall efficiency	%

Chapter 1

INTRODUCTION

1.1. BACKGROUND/AWARENESS OF THE PROBLEM

The provision of adequate water supplies to households in underdeveloped rural areas remains a crucial area of concern in South Africa. In a vast and relatively dry country like South Africa, the satisfaction of basic water needs is for many people, a daily struggle (Omar & Law, 1991:1). This leads to poor living conditions and, in extreme cases, the migration of the rural population to urban centres (Arab *et al,* 1999:191). Considering the importance of clean, disease-free water in all fundamental human activities, there can be no doubt that lack of an adequate water supply acts as a major constraint to the development of rural communities. It is therefore important to design a system that will assist in providing clean, disease-free water in sufficient quantities at an affordable cost.

The rural regions of the Northern Cape are good examples of areas facing this problem. Therefore, in order to facilitate the collection of potable water, various types of water pumping technologies have been employed in the past. Photovoltaic (PV) and diesel groundwater pumping systems have been used successfully in most cases, to supply rural communities in the Northern Cape with drinkable water. Although both pumping technologies have their merits, there still exists a need to perform a thorough long-term field study of PV systems in the rural Northern Cape regions.

To date, the degree of acceptance of photovoltaic solar water pumping systems by the users is very low. There are several factors which have inhibited the widespread implementation of these systems. These include high initial cost, lack of awareness and technical expertise, lack of sufficient knowledge on the daily output of these systems (predictability) and a history of failures. A number of solar water pumping systems were installed in various areas around the world. However, most of these systems have experienced problems, mainly because these were not properly sized (Jafar, 2000:86).

As an attempt to test and assess the reliability and capabilities of the PV system, a research project was initiated at Cape Peninsula University of Technology (CPUT) in the Thermodynamics laboratory of the department of Mechanical Engineering. The project is divided into two phases. Phase 1 involves the testing, monitoring and data evaluation from the laboratory tests. Phase 2 is concerned mainly with evaluating available data from the two water pumping systems installed in the Northern Cape (PV & diesel). Data is to be transmitted from the pumping system to the microcomputer via a wireless link between the two stations (plant & base station).

1.2. PURPOSE AND SCOPE OF THE PROJECT

The purpose of this research is to monitor and evaluate two PV water pumping systems, one system is installed in the Thermodynamics laboratory in the department of Mechanical Engineering, CPUT and the other system is in Lepelsfontein, a small village in the Northern Cape. It is also the purpose of the research to show that a remote monitoring system can be used for monitoring performance and to show that the system is cost effective. Available results from the diesel water pumping system in Rooifontein will also be used and be compared with the PV results to determine the life cycle costs of two systems. Monitoring here refers to accessing data from the PV plant to the computer using a wireless link. The wireless link involves data acquisition equipment (DAE) incorporating necessary software and hardware. Then available data from the computer will be analyzed and evaluated. Data referred to here are the following parameters; flow rate, pressure, wind speed, irradiance, voltage and current generated by the panels. Evaluation involves technical, economic, institutional and social aspects of the PV pumping system. Figure 1.1 shows a line diagram of an existing PV system with the necessary data acquisition equipment. Data from the system is directly transmitted to the data logger which changes the mechanical signals from the transducers to readable electrical quantities. A power supply is provided to change AC to DC.

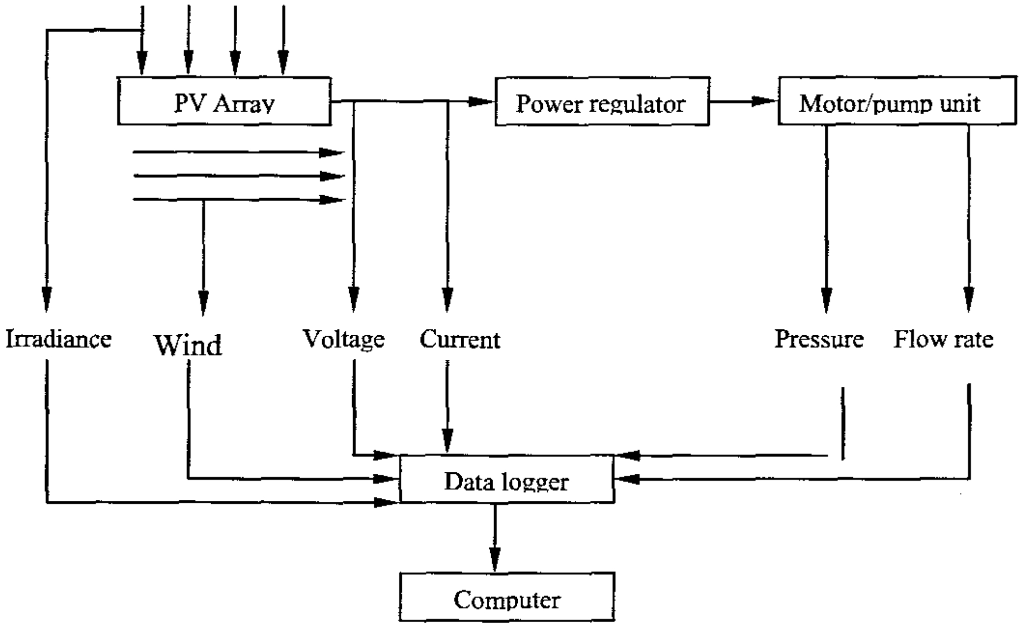


Figure 1.1: Schematic diagram of data transmission to the computer

1.3. SIGNIFICANCE OF THE PROJECT

By monitoring photovoltaic ground water pumping systems against other conventional options (such as diesel or wind pumping), technical and economic decisions regarding appropriate pumping choices suitable to local conditions, rural communities could have better access to clean and cheap water thereby improving their health and lives. One of the primary considerations needed in order to facilitate the remote monitoring of water pumping technologies, is that it is often desirable to have some form of telecommunications infrastructure already in place. However, a lack of telecommunications infrastructure is often a challenge in the setting up of remote monitoring infrastructure in underdeveloped areas. Consequently, appropriate and practical ways of side-stepping the problem of minimal telecommunication resources will have to be looked at in order to properly address these challenges. Remote monitoring can result in the reduction of costs (i.e. travel costs) in the process of collecting data, it also serves as a mechanism by which remote pumping systems can be monitored for establishing a long-term performance database as well as to manage sites remotely.

1.4. OBJECTIVES OF THE PROJECT

The project has three main objectives, namely;

1.4.1. To interface a local PV pumping system and a host computer by means of data acquisition devices at the department of Mechanical Engineering (CPUT).

1.4.2. To establish a communication link between the Lepelsfontein PV system and a local ground receiving station at the CPUT.

1.4.3. To compare PV water pumping with diesel water pumping field results and make some valid conclusions. The obtained results will assist in:

- The analysis of technical aspects of the system (determining system and sub-system efficiencies).
- The study of economic aspects (determining the true life cycle costs to establish the relative merits of each method of pumping).

1.5. REPORT STRUCTURE

The remainder of this report is structured as follows:

1.5.1. CHAPTER 2

This chapter presents a literature survey on remote monitoring systems for PV ground water pumping system. The first section defines the concept 'remote monitoring system'. It reviews the work done in this particular field as well as the problems that could be encountered.

The next section introduces various methods that can be used to transmit data from the PV plants to the receiving stations. The methods which are dealt with here are satellite transmission, telephone line transmission, direct transmission, radio & modem transmission and cell phone transmission. Section 2.3 illustrates the economic aspects of this option (PV) of water pumping. Cost comparisons are made, but more important is the illustration of the non-financial considerations that make PV the preferred choice as a power source for pumping application.

Section 2.2 gives insight into the technical aspects of the PV system. This summarizes the most important aspects related to stand-alone PV components. This includes an introduction to PV components and stand-alone systems, but also considers issues related to quality, safety and maintenance of the systems. The final section of this chapter demonstrates the importance of user involvement in all stages of the project cycle. It focuses on those applications where the success of the technology will depend not only on its own merits, but also on how well this technology has interacted with the people who daily depend on the PV equipment.

1.5.2. CHAPTER 3

Chapter 3 presents the activities that have taken place in the laboratory as well as the preliminary experiments and tests. Section 3.1 gives a brief description of the system layout as installed in the laboratory. Its subsections discuss the subsystem components which have been used in the experiments.

Section 3.2 presents an identification and description of data acquisition equipment (DAE). The DAE referred to here are a data logger, flow transmitter, pressure transmitter, anemometer, digital multimeter and a pyranometer. A brief description of each instrument is given. The preliminary results are presented in section 3.3. The focus here is on determining the pump, array, and regulator power. The results are presented in the graphical format and the results in the form of tables are shown in the appendices section. Also the efficiencies of pump, array and regulator are calculated. The results are discussed and interpreted after the presentation of results. The last section focuses on the experimental observations and the concluding remarks on laboratory work.

1.5.3. CHAPTER 4

Chapter 4 mainly focuses on fieldwork and tests. The fieldwork is carried out at two different sites, namely Lepelsfontein and Rooifontein. Section 4.1 describes the Lepelsfontein site as well as the size of the PV system used there. Section 4.2 describes the Lepelsfontein PV system. This includes the solar panels, an inverter and a pump. Section 4.3 presents the profile of the Rooifontein settlement. The last section of chapter 4 describes the configuration of cell phone telemetry.

1.5.4. CHAPTER 5

The results from the two pumping plants are presented in this chapter. The comparison between PV water pumping results and diesel water pumping results will be made. These comparisons assist in determining the life cycle costs (LCC) of the two systems from which (LCC) will be determined later in the chapter. Life cycle costing examines all the costs incurred over the lifetime of different systems, and compares them on an equal basis by converting all future costs into today's money.

1.5.5. CHAPTER 6

Chapter 6 is the concluding chapter. It presents the conclusions on the laboratory work as well as the fieldwork. Finally, the overall concluding remarks are made as to the success of the project.

Chapter 2

REVIEW OF REMOTE MONITORING FOR GROUND WATER PV PUMPING SYSTEMS (PVPS)

2.1. THE CONCEPT 'REMOTE MONITORING SYSTEM'

Photovoltaic water pumping system performance incorporating remote monitoring is an area that has not been widely researched in South Africa. Nevertheless, remote monitoring systems for ground water supply have been operating in a few African countries and elsewhere (Benghanem, 1998). In South Africa, several PV projects are underway and most of them do not incorporate data acquisition devices. The major obstacles in these systems as illustrated by Scholle (1994:1), are, advanced technological requirements and their associated costs. Scholle's data acquisition system consisted of a data logger, signal conditioning, transducers and a computer. The primary data acquisition system used for the main test period (over five months) was capable of logging a number of steady state parameters simultaneously. The secondary data acquisition unit was available for one week. It was capable of sampling two signals at a time and had a very large bandwidth. One of the problems Scholle outlined is the limitation of the signal processing units. The interface circuitry might be limited in terms of range and bandwidth. He also made an uncertainty analysis of the acquired data for each parameter and mentioned the problems encountered in his work. Scholle's data acquisition system was local to the system. Figure 2.1 overleaf shows Scholle's block diagram of the PV pumping and the primary data acquisition system (DAS).

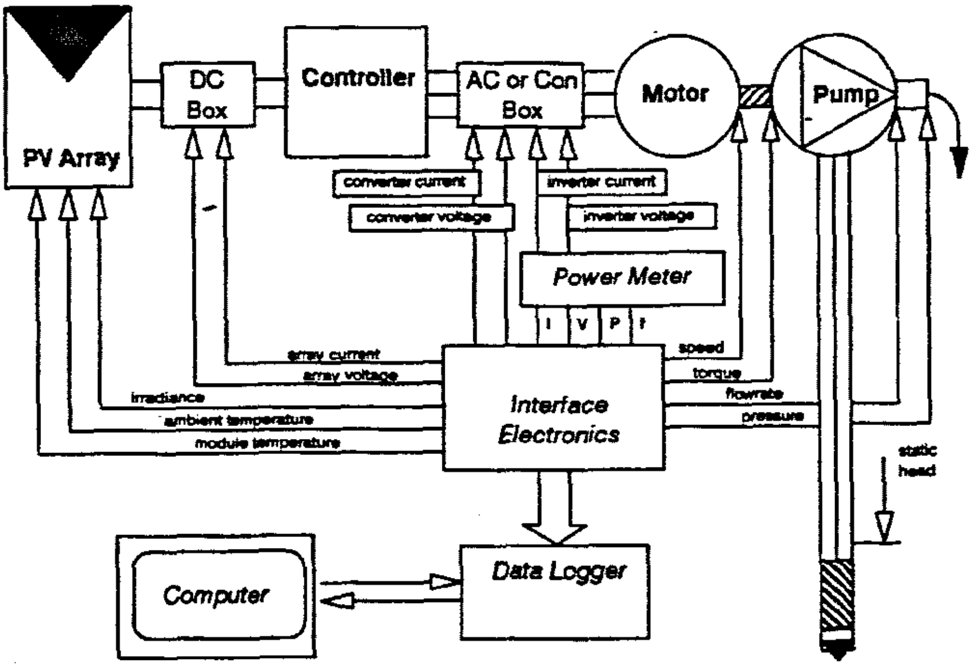


Figure 2.1: Block diagram of the PVP and the primary data acquisition ssystem (Scholle, 1994:67)

Benghanem *et al,* (1998) developed a PV water pumping system, which incorporated data acquisition equipment, and it was installed in Algeria. Due to the high cost of setting up and maintaining a large number of data acquisition systems for the PV water pumping systems, the authors developed a real time system based on a central microcomputer used as a micro-server, with a relatively low cost. They designed a universal data acquisition system for Algeria with available components and easy accessibility from a central server. They have shown three possible connections in which each can transmit data from a PV station to a microcomputer. The first connection is modem based, the second direct RS232C port connection and the third was VHF radio. Each of the three connections have pros and cons so careful selection should be made with respect to the area to be used. From the system's results they could:

- Determine component reliability
- Obtain information on performance degradation
- And evaluate the experimental design methods in the future.

Figure 2.2 shows the basic architecture of the measurement system for several stations. The configuration considered is composed of a number of micro-systems, which allow the acquisition of meteorological data and specific PV data.

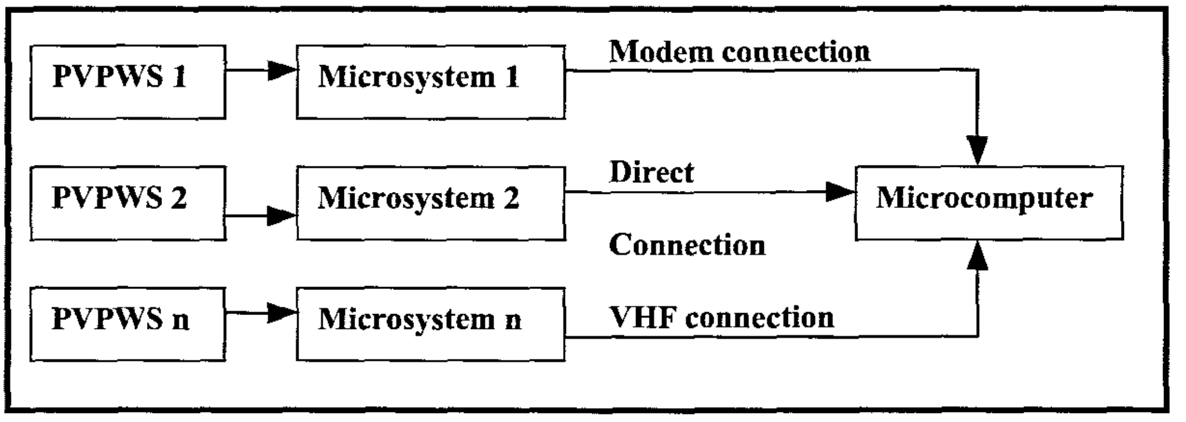


Figure 2.2: Network architecture (Benghanem *et al*, 1998:394)

This acquisition system is seen to be economical and compatible with any personal computer. This configuration also allows interested parties to access information on the Internet.

Koutrolis *et al* (2003) developed an integrated computer-based system for renewable energy source (RES). The system consisted of a set of sensors for measuring both meteorological (e.g. temperature, humidity etc.) and electrical parameters (photovoltaics, voltage and current etc.). The collected data were first conditioned using precision electronic circuits and then interfaced to a PC using a data-acquisition card. The LABVIEW program was used to further process, display and store the collected data on the PC disk. The configuration of data-acquisition architectures for RES systems is shown in figure 2.3 overleaf.

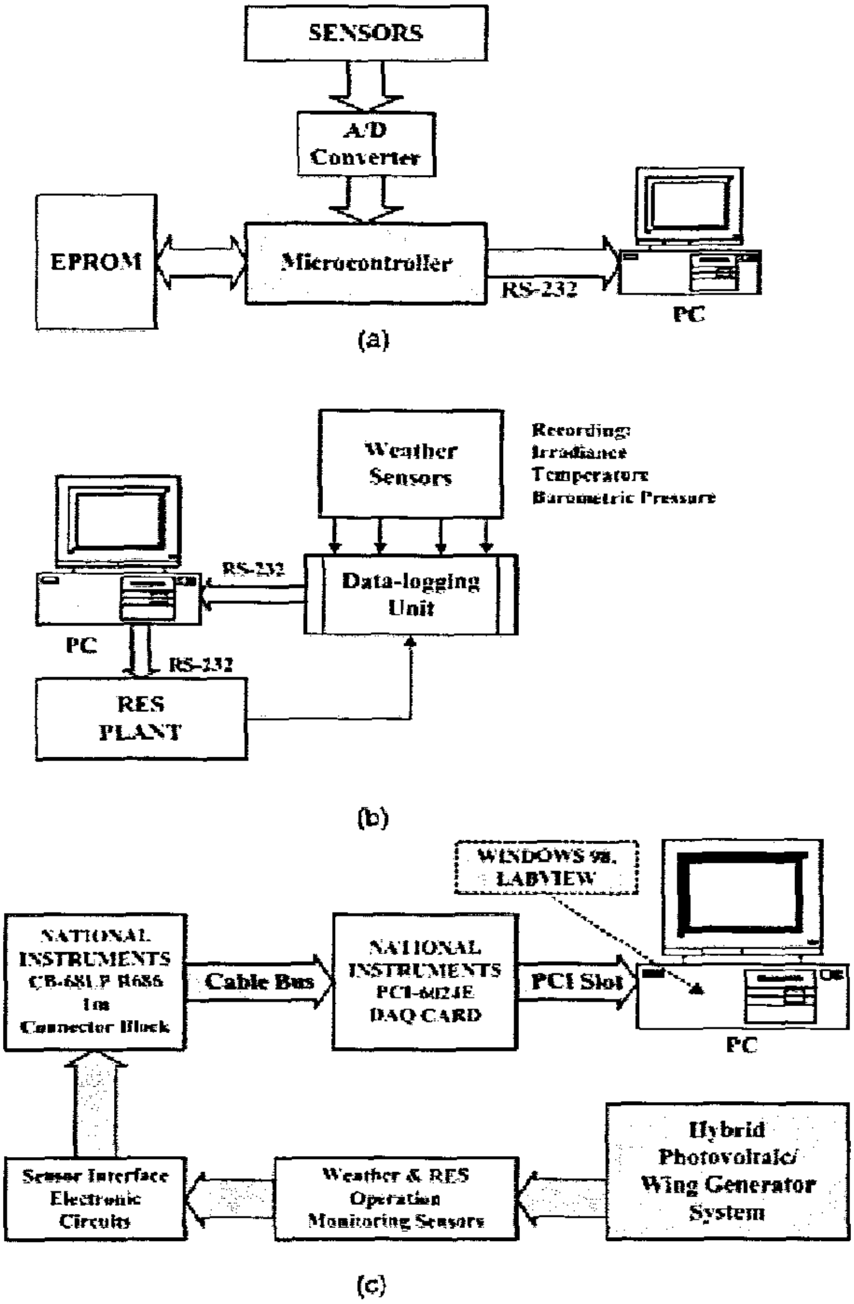


Figure 2.3: Data-acquisition architectures for RES systems (Koutrolis *et al* 2003:141)

The above architecture has the advantages of rapid development and flexibility in the case of changes, while it can be easily extended for controlling the RES system operation.

A test facility was installed by Wichert et al (2001), at the Centre for Renewable Energy Systems Technology (Australia) to quantify the potential for performance improvements of photovoltaic-diesel (PV-diesel) hybrid energy systems. The research facility is part of the cooperative program to develop improved power conditioning systems for the provision of electricity in remote areas. A customized control interface was developed using the control and data acquisition software, LabVIEW. The graphical user-interface supports the automatic or manual definition of control parameters, which allows the system designer to apply optimal control methods for the management of PV-diesel hybrid energy systems. Refer to figure 2.4 below for a configuration of PV-diesel hybrid energy systems.

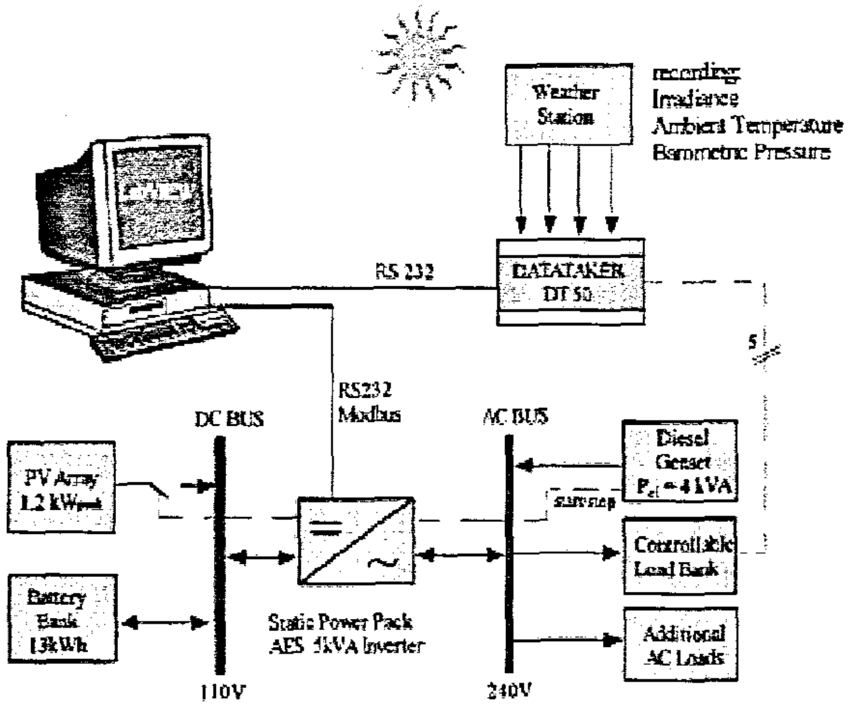


Figure 2.4: Test facility for PV-diesel hybrid energy systems (Wichert *et al* 2001:313)

The developed graphical control environment implements the following tasks:

- Continuous acquisition of weather data (5 min average data, 5 s sampling rate)
- Continuous acquisition of system performance data (5 min average data, 10 s sampling rate)
- Graphical display of actual performance and predicted operation of the test system.

Recent work shows that Algeria is one of the African countries where PV water pumping technology is used. Arab *et al* (1998) conducted a study on performance of PV water pumping systems and the aim of the work was to analyze the performance of different photovoltaic water pumping systems. They developed a simulation program to obtain generator-pump configurations for a given installation site as well as a daily load profile. The program assisted in predicting the PV pumping system performance by taking into account the different parameters of the system and its geographic location.

In the past decade, the Commission of the European Communities (CEC) has been instrumental in initiating, implementing, and coordinating the photovoltaic technology activities amongst its 12 member countries (Imamura *et al,* 1992:13). Several articles have been published on monitoring the performance of PV plants. The most common devices in use for monitoring PV plants are; modems, satellites and radios. Imamura *et al* (1992), claim that a key problem in the past has been the unreliability of continuous operation of the data acquisition systems because of their many serial elements, more complex computers, and mechanical data recording devices. One way of improving the reliability of data collection is to use parallel or redundant data acquisition devices for important parameters which one may not want to lose because of computer or data logger failure.

Another telemetry technology designed by Virtual technologies called Virtu-Well™. Wireless remote monitoring can be an option for monitoring purposes. It allows wirelessly monitoring of pumps, tank levels, water flows etc (http://www.virtualtechnologiesltd.com). Virtu-Well™ sends alarms via digital pager and email within five minutes of an event. Importantly, all systems are solar powered, for installation simplicity and superior reliability. However, they can be custom configured for AC power and requires no special software. The two disadvantages of this design are; it is only effective for distances not longer than 160 kilometers and it can only log data after every five minutes of the event.

Hamza *et al* (1995) developed a monitoring system where two pumps which were driven by two sets of solar panels (M-51 & M-53 Arco Solar modules) were monitored. For each of these pumps, solar radiation in the plane of the PV array, ambient temperature, PV array voltage and current, water discharge and water delivery pressure were monitored using a data logger. The results of pump performance showed that their performance was 10-25% less than predicted by the manufacturer's literature.

Perez *et al* (2001) investigated the capability of satellite remote sensing to monitor the performance of ground-based photovoltaic (PV) arrays. A comparison between the actual output of PV power plants and satellite-simulated output estimated at six climatically distinct locations was presented. Results showed that the satellite resource could be an effective means of simulating the performance of PV systems and of detecting potential problems with PV power plants.

2.1.1. DATA TRANSMISSION USING LOW EARTH ORBIT (LEO) SATELLITE

In remote monitoring systems for photovoltaic ground water pumping applications, a low orbit satellite is viewed as an option/alternative in communicating/linking with a ground station and a transceiver, despite some disadvantages that can make this option less viable. A satellite is basically any object that revolves around a planet in a circular or elliptical path. The path a satellite follows is an **orbit**. Satellites have been in use for several years in commercial communications. A satellite is basically used to transmit the signals from the ground station to the transceiver or vice versa. Several systems (fibre optics for example) have been designed recently to replace the satellites due to the disadvantages associated with their operation. Figure 2.5 below shows an example of a data flow diagram. It shows data transmission from a remote data collection platform in the field to a hand-held unit.

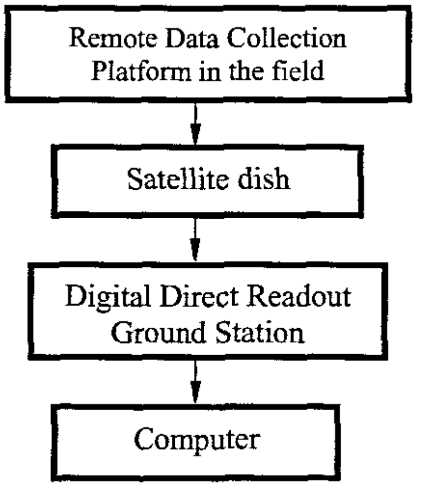


Figure 2.5: Data transmission using a satellite
(http://www.sutron.com/products/applications/HydroServicesDiagram.HTM)

A problem with these Low Earth Orbit (LEO) satellites is that they orbit the Earth in an hour or two, so they are only over a particular ground station for a few minutes. The higher the altitude of a satellite, the further it has to travel to circle the Earth and the longer it takes for one orbit. Satellite communications have lost some of their advantages over wire with the advent of fibre optics. In situations where optical fibres are available, they offer the cheapest communications solution because of their wide bandwidth. Satellites will maintain a niche in providing communications where it is too expensive to run a fibre and in mobile applications (such as ships at sea). Satellite broadcast delivery can work if the cost of the ground station can be kept lower than the cost of running and renting a line (along with its associated electronics) to the user.

2.1.2. DATA TRANSMISSION USING A TELEPHONE LINE/CELLULAR PHONE

Recent developments in mobile communication and personal computer technology have laid a new foundation for mobile computing. Performance of the data communication system as seen by an application program is a fundamental factor when communication infrastructure at the application layer is designed. Telephone/cellular phone data transmission is the most common and preferred means of transmitting information from one point to another.

The cellular phone system makes it possible to interrogate a data logger and remote telemetry unit (RTU) when no telephone line is available at the site. This is especially useful when the logging system is temporary or must be moved regularly. Cellular telephone telemetry offers an economical and convenient means of conducting remote, monitoring, and for acquiring data between two distant stations. Cellular-phone based monitoring systems offer the advantage of data acquisition and communication with remote sites via computer dial-up from any location where telephone service is available. Two-way communication also allows remote modification of data recording parameters, alert threshold values, and communication parameters as conditions change. Automatic dial-out on detection of an alert condition provides immediate notification to pre-defined pager numbers, and monthly service and airtime costs are low, making long-term monitoring and remote acquisition of data recorded on the order of hours or minutes quite cost effective (available @ http://gsa.confex.com/gsa/2002AM/finalprogram/abstract_41604.htm).

2.1.3. DATA TRANSMISSION USING A RADIO

In its broadest sense, telemetry can be defined as the and science of conveying information from one location to another. With radio telemetry, radio signals are utilized to convey that information. Radio systems are often the ideal method to pass data between remote sites and a central facility. This is especially true in remote areas not served by telephone or cellular systems. Field stations and repeater stations can be located to allow communication over long distances and rough terrain. The maximum distance between any two communicating stations is approximately 24 km and must be line of sight (unobstructed by mountains, large buildings, etc.). Longer distances and rough terrain may require intermediate repeater station(s). Hardware required for radio frequency (RF) data transmission includes antennae and radio modems. Power for the RF stations is provided by lead-acid batteries which can be charged with either solar or grid.

2.1.4. DATA TRANSMISSION USING DIRECT CONNECTION

This is the most cost effective technology of data transmission from one station to another. Direct connection is used for systems with multiple sensors and control sites within small areas. There are two types of connections viz.:

- Direct connections for distances less than 100 meters.
- Short haul modems using either two or four-wire connection, typically used for distances to three kilometers (www.sutron.com/products/telemetry/directconnect.htmw).

It is therefore evident that direct connections will not be suitable for data transmission between two distant stations.

2.2. TECHNICAL CONSIDERATIONS OF A PHOTOVOLTAIC WATER PUMPING SYSTEM (PVWPS)

From a technical point of view, photovoltaic technology is relatively simple. However, there are still some other crucial steps that must be taken at both the design and the installation stages. This section will summarize the most important aspects related to stand-alone PV systems.

There are three types of stand-alone systems depending on whether they use battery storage or auxiliary power source. The three types are:

- **PV-direct** – because it powers the load directly without using any battery. This system has the simplest configuration and is normally used either for applications that are not critical and match the availability of sunlight, such as in water pumping.
- **PV with battery** – this system includes storage that allows the load to be powered when the PV array cannot supply power directly (e.g. at night and during periods of low sunlight.
- **PV-hybrid** – includes systems that rely on other renewable energy such as wind or hydro to complement the local solar resource. This type uses batteries too, for short-term variations of sunlight conditions.

A PV system comprises three main subsystems namely; PV array, power conditioning equipment and a motor/pump unit. They are described as follows:

2.2.1. PV ARRAY

A photovoltaic module consists of a number of solar cells electrically connected to each other and mounted in a support structure or frame. Modules are designed to supply electricity at a certain voltage (commonly 12V), the current produced is directly dependant on how light strikes the modules. Although one module is often sufficient for many power needs, two or more modules can be wired together to form an array. In general, the larger the area of a module or array, the more electricity that will be produced. According to Nyman, (2000: 28), photovoltaic array with reflectors converted only 11% of the solar energy received into electrical energy.

Photovoltaic modules and arrays produce direct-current (DC) electricity. They can be connected in both series and parallel electrical arrangements to produce any required voltage and current combination. PV modules are in three main types: mono-crystalline, poly-crystalline and amorphous. Mono-crystalline panels have an efficiency ranging between 14-21% and are manufacturer guaranteed for 20 – 25 years. Poly-crystalline panels have an efficiency of about 12% and are manufacturer guaranteed for 15 – 20 years. Amorphous panels have an efficiency of about 5% and a guarantee of 5 – 10 years. Their relative costs (http://www.solarbuzz.com/ModulePrices.htm, 04/07/2005) are 3.68, 3.71 and 3.36 US dollars per peak Watt (Wp) respectively.

2.2.2. THE POWER CONDITIONING DEVICE

Matching devices are used so that systems will operate at optimum power, matching the electrical characteristics of the load and the array. Both PV arrays and electric motors operate most effectively with certain voltage and current characteristics, but it may be difficult to obtain a good match between them. For this reason it is often worthwhile to use some type of power conditioning. In most cases the use of power conditioning equipment implies a power loss (typically 5%), and additional cost. There are two types of power conditioning devices. The first is the DC/DC converter which draws power at a constant voltage for all irradiances, and then chops or boosts the voltage as required by the system. The better DC/DC converters monitor cell temperature because the Peak Power Curve moves sideways as the temperature of the cell changes. They then set the input accordingly. Overleaf (figure 2.6) is an I-V curve of a module.

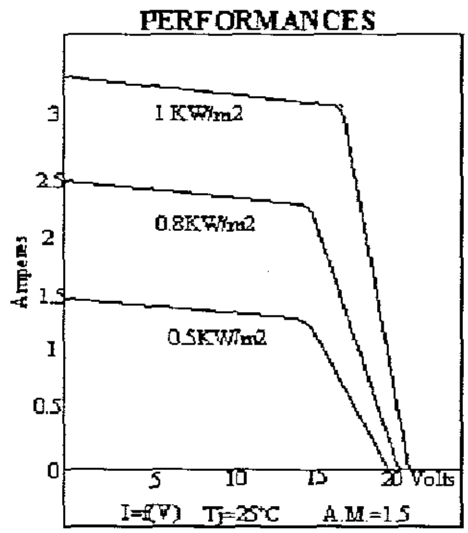


Figure 2.6: I-V curve of a module (TSP 1000 pumping manual)

The second type is the Maximum Power Point Tracker (MPPT) which monitors the power delivered by the array and adjusts the apparent impedance of the system to maximize this power. If the power increases the MPPT continues to adjust the apparent impedance in the same direction; if the power decreases it changes direction. Good DC/DC converters and MPPT deliver about 90 to 96% of the power that they receive. Another function of power conditioners is to safeguard the utility network system and its personnel from possible harm during repairs. The requirements of power conditioners generally depend on the type of system they are integrated with and the applications of that system.

For AC applications, power conditioning is often accomplished with regulators, which control output at some constant level of voltage and include an inverter that converts the direct current generated by the PV array into alternating current.

2.2.3. MOTOR/PUMP UNIT

In some cases it is feasible to utilize off-the-shelf, mass-produced motors. However, some manufacturers have developed specialized motors with an above average efficiency to minimize overall system costs. The motor/pump system operates in a different way to a conventional motor because the power supply varies as the incident solar energy changes. Most motors are designed for maximum efficiency at certain voltage/current characteristics, and performance can drop off quickly from this operating point. In a solar powered system, the motor/pump must be able to work fairly efficiently over a range of voltage and current

levels. Although these specialized motors cost more than conventional motors, this is outweighed by the cost saving in terms of the number of PV modules required.
The cost of the motor is a small fraction of the array's cost: so to minimize the cost of the whole system one would prefer a more efficient motor to a cheaper one. The motor must be reliable for a remote site. Although AC motors are cheaper and more readily available they need current inversion. This may reduce the efficiency of the system as well as its reliability by adding another component. AC motors are also less efficient than DC motors unless they use power matching with variable frequency as well as variable voltage. Until AC systems have proved their reliability and efficiency it is safer to use DC motors.

Permanent magnet DC motors should be used so that no power is wasted by an electromagnet. Even though the brushes need to be changed, brushed motors are preferable to brushless motors. This is because brushless motors are less efficient and require electronic circuits with the resulting loss in reliability. According to Gosnell, (1991:57), a DC system can be used rather than AC system because:

- The electronics for DC power maximizers are simpler and thus more reliable than for AC power maximizers.
- The efficiency of the DC motor is better because AC maximizers that track both frequency and voltage are not easily available.
- The power loss in the DC maximizers themselves is less than in AC maximizers.

Pump performance is heavily dependant on the assumptions made at the design stage regarding solar and water resource characteristics. Careful account has to be taken of the variations in solar input to the array, the static water level in the well and water demand. Failure to do this has resulted in many systems being undersized so that they fail to meet the demand, or excessively oversized, with associated additional capital cost (Hill, 1989:47).

2.3. ECONOMIC CONSIDERATIONS OF PVWPS

This section reviews economic aspects of different energy options in relation to their scale and costs. The concept of life cycle costing is introduced and its importance for photovoltaic water pumping is discussed.

2.3.1. LIFE CYCLE COSTING

The initial cost is only one element in the overall economics of a system. Some type of economic assessment is required to determine which system from a number of choices will give the best value for money in the longer run, either for the customer or for the economy as a whole. The economics of PV and other renewable energy technologies are rather different to those of conventional small power systems, in that:

- The capital cost of the equipment is relatively high, especially for larger plants.
- The running costs are low and there are no fuel costs.
- The output of the system depends on its location.
- The output of the system depends on the load pattern.
- The reliability is high.

When comparing PV with a diesel generating set, the high initial costs of the former make PV look unattractive at first sight. However, the picture often changes with an appreciation of the longer-term economic picture. This normally is achieved through the method of life cycle costing. Life cycle costing examines all the costs incurred over the lifetime of different systems, and compares them on an equal basis by converting all future costs into today's money. This method is known as a *discounted life cycle cost analysis:* the result is *levelised cost.* Life cycle costing enables one to appreciate how the various costs involved over a period of time can be simplified into a fixed annual or monthly cost. The formula for LCC is as follows (Yaron *et al,* 1994:62);

$$LCC = C_c + \sum_{n=0}^{t} \frac{Cn}{(1+r)^n} - \frac{RV}{(1+r)^t}$$

Where:

C_c = initial capital cost (capital, labour, administration cost)

C_n = operating cost (operation, and maintenance cost, fuel, tax and interest) in year n

n = time period (year)

r = discount rate

t = total life of project (years)

RV = residual value

If the annual operating costs are constant, the above formula can be simplified to:

$$LCC = C_c + \frac{C_n}{CRF} - \frac{RV}{(1+r)^t}$$

$$where\ CRF\ (capital\ recovery\ factor) = \frac{r}{1-(1+r)^{-1}}$$

Figure 2.7 below clearly shows the economics of PV compared to village diesel pump and commercial pump.

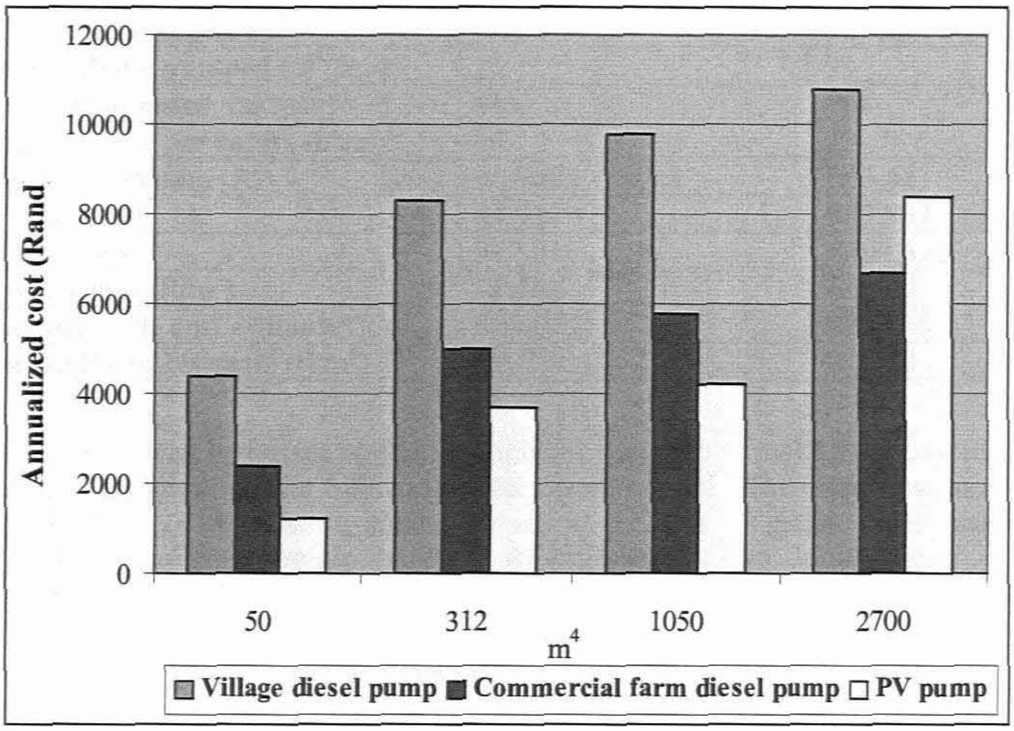


Figure 2.7: PV versus diesel pumping system (Yaron *et al,* 1994:63)

The results obtained in the figure above demonstrate the clear economic superiority of PV water pumping up to a level close to $2000m^4$/day. Moreover, in an isolated village, PV pumping is viable until levels of $3000m^4$/day (Yaron *et al,* 1994:64). Energy & Development Group, (1996), presented their results obtained from two water pumping systems, one in Kamassies, the other in Rooifontein (PV & diesel respectively) as in table 2.1. The idea here was to assess how life cycle costing can assist in demonstrating how long-term information from a pumping system can be used to determine unit water costs (R/m^3) and pumping costs (R/m^4). It is also to indicate the viability of PV water pumping compared to diesel water pumping.

Table 2.1: Summary of field PV & diesel water pumping (EDG, 1996).

Site	**Kamassies**	**Rooifontein**
Community Size(persons)	330	550
PV or Diesel	PV	Diesel
Install date	1994	1993
System size	740 Wp array	10.3 kW
Design volume (m^3/day)	10	30
Total head (m)	30	36
Total volume pumped (m^3)	8383	18720
Average volume pumped (m^3/day)	16	21
Average m^4 pumped (m^4/day)	486	764
Average volume per capita (l/cap)	49	39
Initial cost of system (R)	R66,405	R63,681
Operating costs	R1,111	R43,937
Total cost (R)	R67,516	R107,618
Unit water cost (R/m^4)	R0,268	R0,160
15 year life-cycle cost estimate (R)	R80,005	R224,253
15 year unit cost estimate (R/m^4)	R0,029	R0,052

The above results can be further presented graphically in order to make comparisons between PV and diesel systems and the following figures were created. The diesel cost in this study was R1.92/*l* (SAPIA annual report web page accessed @ http://www.mbendi.com/sapia/pubs/2002_ARep/Arepa14.htm, 26/06/2005).

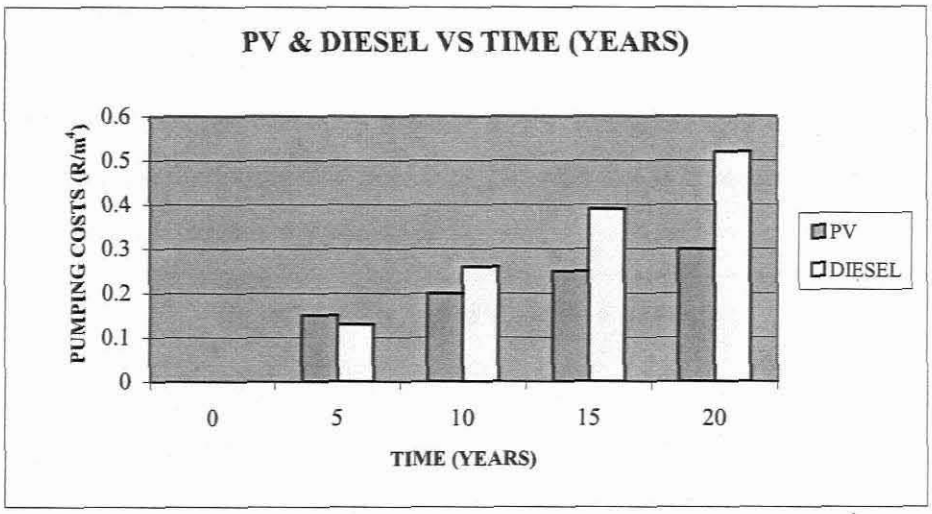


Figure 2.8: Life cycle costs (R/m^4) of PV & diesel versus time (years)

Figure 2.8 shows the energy costs in R/m^4 (m^4 = flow rate in $m^3 \times$ head in m, this gives an indication of the energy input for pumping) of PV and diesel pumping and the following conclusions can be made from the results.

- After 5 years of the project initiation, pumping costs of PV are higher than that of diesel pumping.
- As time increases beyond 5 years, the accumulative pumping costs of diesel seem to increase tremendously and in 20 years time the pumping costs of diesel will double that of PV.
- The above results show how PV can be competitive to diesel after a certain period of time.

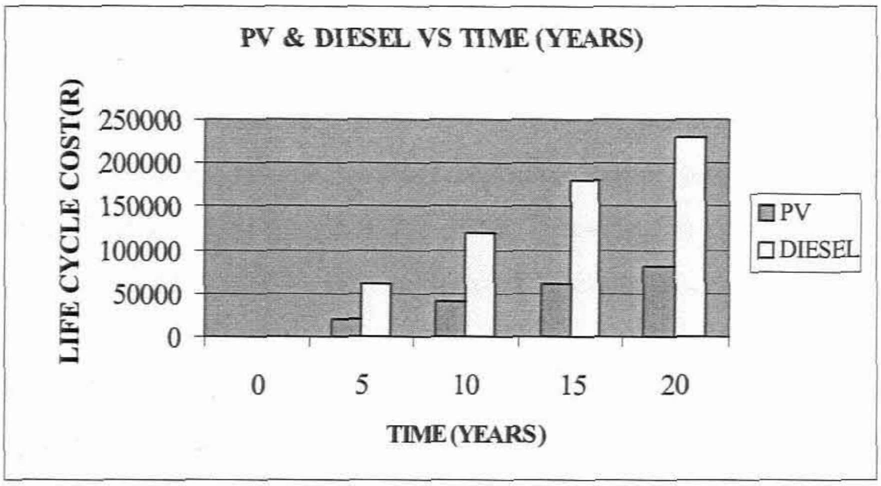


Figure 2.9: Life cycle costs (R) of PV& diesel versus time (years)

Figure 2.9 illustrates the life cycle costs in rands of PV and diesel over a period of 20 years. It shows how much diesel pumping will cost after 20 years and it is far more than PV pumping due to operating and maintenance costs (O & M).

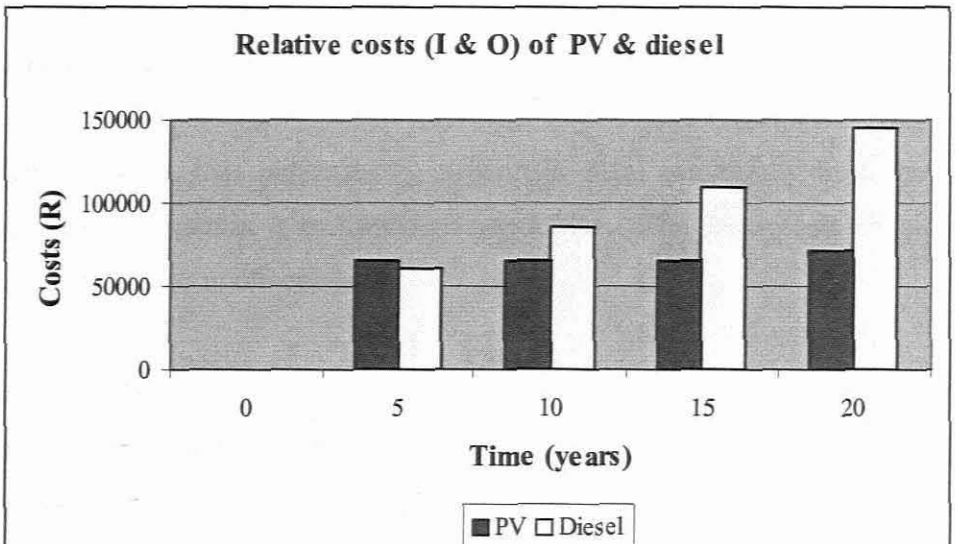


Figure 2.10: Relative costs of PV & diesel

The figure above shows the relative costs of PV versus diesel over a period of 20 years. Initial (I) costs of PV are slightly higher than that of diesel. After 10 years, the costs of diesel are far more than the costs of PV. This is due to high operating and maintenance costs of diesel pumping, therefore this makes PV more economical and viable compared to diesel pumping. A further aspect that needs consideration is the relative reliability or operating factor of PV versus diesel systems. Remote monitoring of these systems is vital as it can inform how these systems are behaving in-situ; a further benefit is the possibility of remote control and corrective action. This is to highlight that the pumping technology need not be selected on the basis of initial costs only, but on true life cycle costs (I and O & M). In areas where PV have entered into competition with diesel-driven pumps, their comparatively high initial costs are offset by the achieved savings on fuel and reduced maintenance expenditures. One aspect of this study is to make as many economic comparisons as possible using PV and diesel energy technologies to prove the most cost-effective technology under different operating conditions of load, flow rate, geographic location, etc.

2.4. SOCIAL ASPECTS OF PVPWS

PV water pumps have found wide social acceptance, particularly in villages which previously had to pump water by hand (Hill, 1989:47). However, PV pumping systems, being a new technology, need continuing institutional support to enable them to be successfully integrated into the rural communities that stand to benefit. There are three main areas where institutional support is particularly needed:

- At the planning and procurement stage
- For administering the operation
- Maintenance and spare parts.

At the planning stage, it is important to involve the local community from the outset and encourage them to organize a management committee. The local costs should be raised locally, either in cash or in direct labour.

The local organization must then be assisted to organize appropriate arrangements for distributing the water and levying charges. It is helpful to appoint a keeper or operator to watch over the system and he/she will need to be given basic training in routine maintenance and simple trouble-shooting.

With good design and the installation of the latest types of systems, system reliability could be good. However, there will inevitably be faults arising from time to time which cannot be fixed by the users. Good communication between the site and the source of support are desirable, but it has to be recognized that in many rural areas the necessary infrastructure simply is not available.

As has been stated, the point of this study is to make as many economic comparisons as possible using PV and diesel energy technologies to prove the most cost-effective technology, the next chapter presents laboratory work as well as the preliminary tests conducted on a PV rig at CPUT. The system will be briefly described as well as data acquisition equipment (DAE) in place. The available results will be presented, analysed and conclusions be made.

Chapter 3

LABORATORY WORK AND PRELIMINARY TESTS

3.1. EXISTING PV SYSTEM

The first PV water pumping system was installed in 2001. The system was installed adjacent to the Thermodynamics laboratory, in the department of Mechanical Engineering, CPUT. The system comprised three subsystems; a set of three PV modules mounted onto an adjustable structure that can be tilted at angles of 10°, 30° and 60°. The second subsystem was the DC/DC power-matching converter employed to match the maximum power points of the PV array with the I-V load line of the DC electric motor. It is an electronically controlled circuit which monitors the maximum power points of a PV system to the I-V curve of the connected load over the widest possible range.

The third subsystem was a motor/pump unit. The motor used was a 4″ permanent magnet submersible DC motor. These 4" motors have been specifically designed for permanent submersible and important operations. The pump used was the progressing cavity (Mono) type. Unlike the conventional borehole pump which uses centrifugal force as the energy to displace water, this concept uses the progressing cavity to draw water up through it. This kind of pump has the features of being capable of very high pressure and cooling by water circulation around the stator. The water was pumped from a 4000 *l* drum through a 40 mm diameter PVC pipe and discharged at a height of 4.6 m. Some distance away from the pump outlet was a BSPTF 40 mm throttling gate valve. Adjacent to the gate valve was a pressure transmitter. A digital transmitter was situated above the pressure transmitter.

The solar panel model used was PW 1000 12-24V, bi-glass series, Polycrystalline. The modules, power converter and motor/pump unit were donated by Total Energie South Africa

(TENESA). The system installed in 2002 was similar to the 2001 system except, the new modules, power regulator and a motor/pump unit. The section below will elaborate on each of the components that form the recent system. Figure 3.1 below shows the configuration of the PV system as installed adjacent to the Thermodynamics laboratory.

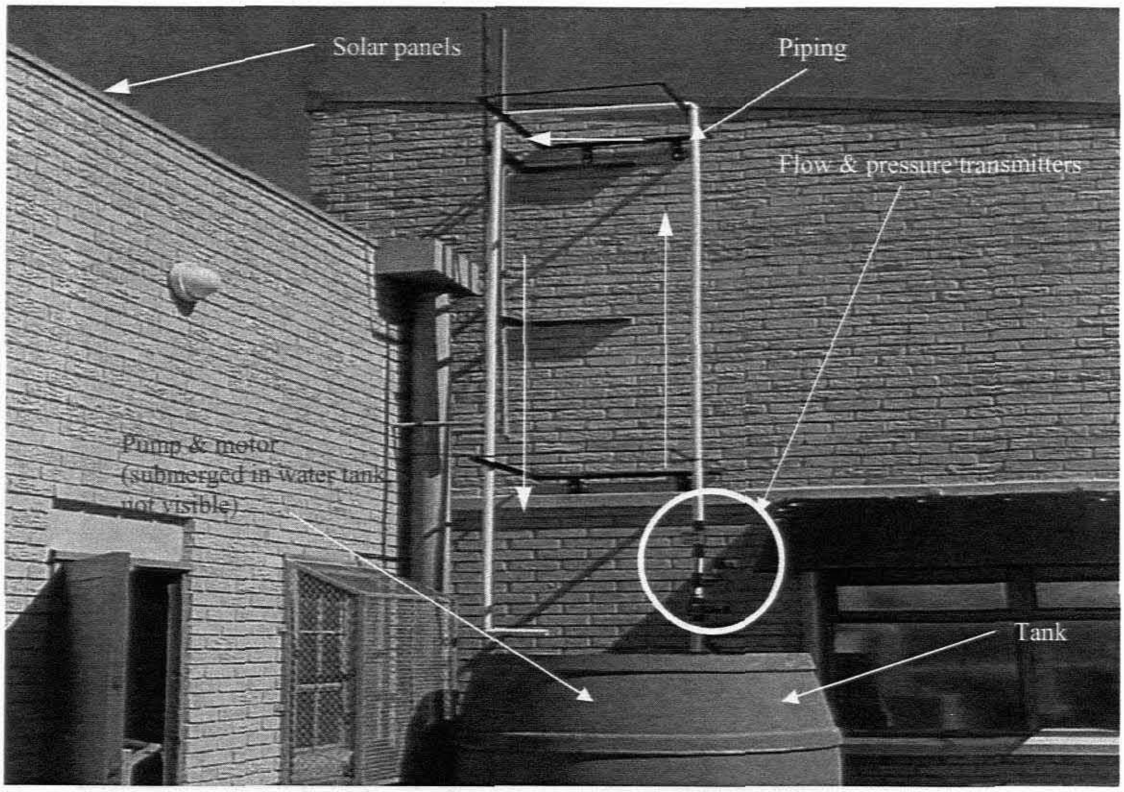


Figure 3.1: Layout of photovoltaic pumping system in the Thermodynamics laboratory

3.1.1. PV ARRAY

The modules, power regulator and motor/pump unit used for the recent installation were Allpower WaterMax equipment. The module type is Waterhog A (WA) Siemens modules 75W × 3. These modules cater for daily flow rates of between 2000 and 6838 litres at 0-80 m. 75 W modules are recommended to ensure that the flow rates indicated are in fact achieved. The specifications of the modules are seen in table 3.1 below.

Table 3.1: Specifications of WA Siemens modules

Warranty Years	Item	Watts	Peak Amps	Peak volts	Size (mm)
25	SP-75	75	4.4	17	1200×527×34

The three modules are connected in series as to give maximum voltage at maximum irradiance. They are mounted onto an adjustable structure that can be tilted at different angles as shown in figure 3.2 below. The modules are mounted in such a way that the trees and other objects cannot obstruct them.

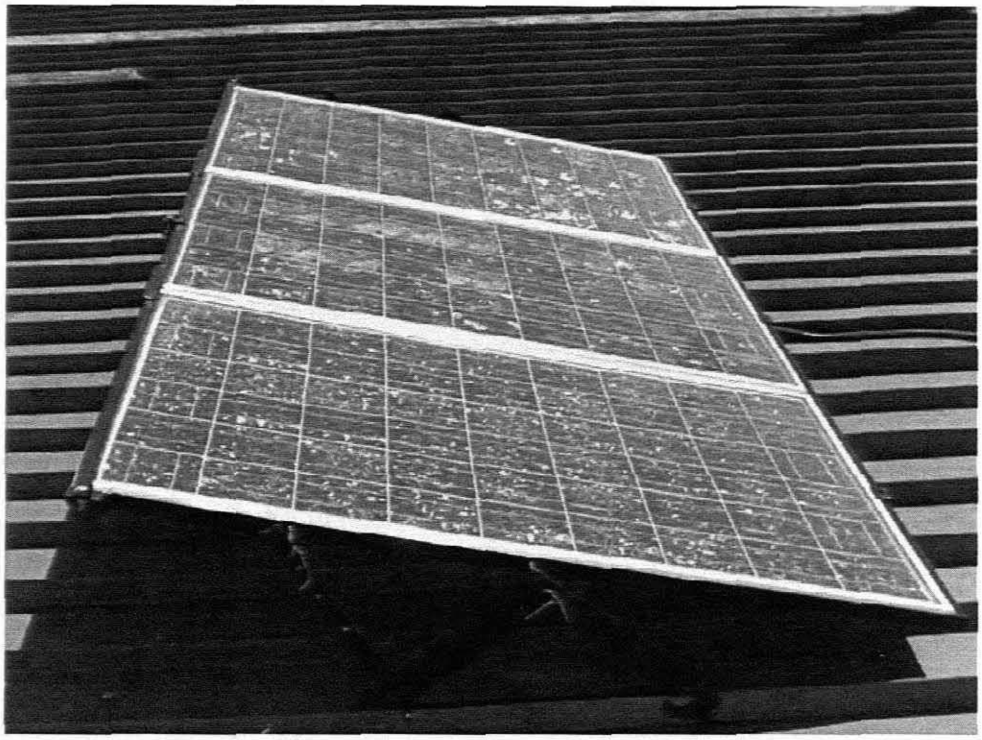


Figure 3.2: 75W × 3 WA Siemens modules

3.1.2. PUMP MASTER

A controller or current booster is an electronic device used with most solar pumps, it acts like an automatic transmission, helping the pump to start and not to stall in weak sunlight. The power controller draws power at constant voltage for all irradiances and regulates voltage as required by the system.

A PV array is a constant current type device. A 75-Watt panel is specified to deliver 4.4 amps at 17 volts. PV controllers essentially connect the PV array directly to the battery when the battery is not at a high state of charge. When this 75-Watt panel is connected directly to a battery charging at 12 volts, the PV panel still provides about the same current. Because PV output is lower, it can only deliver 53 W to the battery. This wastes 22 W of available power. In order to avoid these losses, the PV pump can be connected directly to power controller and water pumped during the day can be stored in a tank so that water can be used when there is not enough radiation to run the pump. The figure below shows the power regulator (Pump Master).

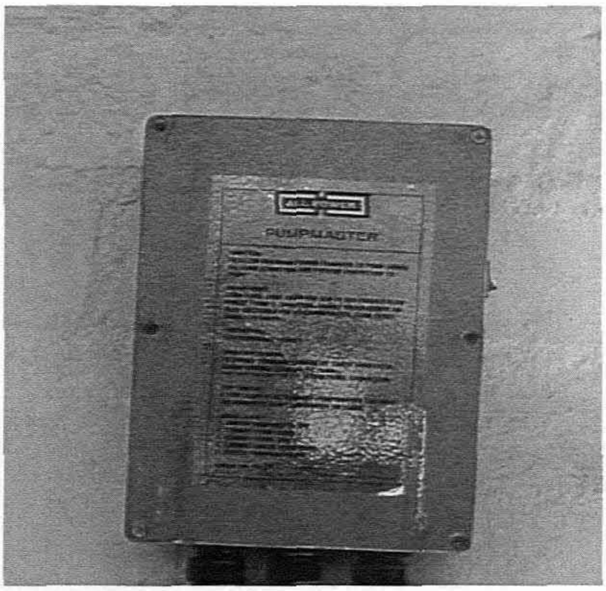


Figure 3.3: Watermax Pump Master

3.1.3. MOTOR/PUMP UNIT

The WATERMAX range of pumps are positive displacement submersible pumps constructed of high quality bronze and stainless steel, 95/113/144 mm in diameter respectively, weighing 9/12/19 kg and having a 19/25/32 mm outlet. It can be run off at variety of solar module configurations. Maximum total head depends on the solar module choice and pump selection, but can vary between 20 m to 150 m. Multiple pumps can also be installed down the same well or borehole. The pump used in this test weighs 12 kg, has an outlet of 25 mm and diameter of 114 mm. Some of the Watermax pump features are as follow;

- WaterMax pumps are serviceable
- Maintenance friendly
- Has a silent operation and is therefore environmentally friendly
- Can run on as little as 10 Watts
- Simplicity is the key feature
- Fitted with an equalizing diaphragm to compensate for submergence pressures, allowing early start-up and improving performance
- Can run dry without water in the pump chamber

- Makes use of sealed bearings obtainable at any bearing dealer and thus no oil lubrication on any components which wear with time.

The installation of the pump inside the drum is shown in figure 3.4 below. The pump is fitted inside a galvanized bracket to provide stability when in operation.

Figure 3.4: Installation of motor/pump unit

3.2. IDENTIFICATION OF DATA ACQUISITION EQUIPMENT

The purpose of data acquisition systems is to accept all the data outputs from various auxiliary sensors of photovoltaic water pumping system or other monitoring installation, displaying the data on a computer. The main point of configuring the system is to define the order and format of the data to be digitally recorded.

During data acquisition, the system should supply various modes of monitoring the real-time system performance, error and problem reporting, etc. The next section introduces data acquisition devices that have been used for the preliminary tests that have been conducted in the laboratory.

3.2.1. DATA LOGGER

Traditionally, data **acquisition** has been defined as the regular collection of data – scanning sensors, taking instantaneous measurements, and then feeding these to a recorder or computer.

Data **logging** has two possible definitions:

➢ It is considered to be making a permanent record of data that has been collected: printing or plotting it, writing it on a sheet of paper, storing it on a computer's hard disk or in electronic memory.

➢ Data logging is also perceived as the total operation of collecting data and making a permanent record of it.

Data loggers have features which provide users, with a variety of requirements and experience, a method of high quality mobile and stationary data acquisition and storage. The DATATAKER 605 used in this project is a small self-contained unit, designed primarily for remote, unattended operation. The 605 models can become a fully functional laboratory data acquisition instrument when a keyboard and monitor are attached to its built-in I/O ports.

Data can be printed out or plotted in a variety of formats. If desired the raw or analyzed data can be provided on a computer diskette, via e-mail, or on a secure Internet ftp site. The data taker 605 is a laboratory quality data acquisition instrument designed for either portable, remote, unattended operation, or as part of a laboratory set-up. Figure 3.5 below shows a DATATAKER 605 model

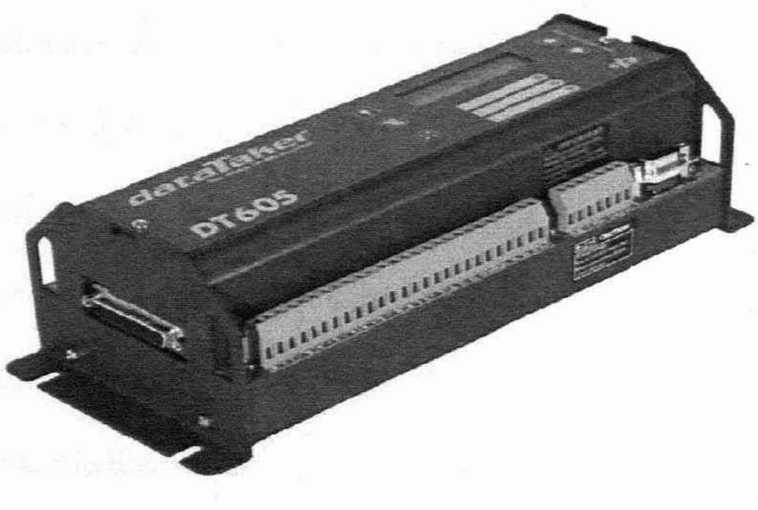


Figure 3.5: Data Taker DT605 (http://www.datataker.com/products/dt605zoom.html)

Each data logger in the data Taker range has a number of characteristics that differentiates it from other models. This section describes the characteristics of DT 605.

- 10 Analog and 7 digital channels
- Relay Multiplexer (±100 input)
- Isolated COMS Port
- Efficient switch mode supply
- Channel expansion socket

Table 3.2: Three different sources that may be used to power a data taker

Source	Range	+Terminal	-Terminal
AC	9-18Vac	AC/DC~	AC/DC~
AC	11-28Vdc	AC/DC~	Gnd
9V alkaline battery	6.2-10Vdc	Alkaline +	Bat.-
6V Gel Cell battery	5.6-8Vdc	Lead +	Bat.-

Analog inputs

- 10 differential or 30 single ended, or any mix
- Switchable attenuator that allows high voltage measurement
- Sampling rates 25 samples/sec
- Channels have 500 volt isolation while not being read
- Input impedance 1 MΩ, or >100 MΩ selectable
- Common mode range ±3.5 VDC, ±100VDC attenuators on
- Common mode rejection >90 db (110 db typical)
- Series mode line rejection >35 db

- Sensor excitation of 4.5 V, 250μA or 2.500mA each channel
- Full, half and quarter bridges, voltage or current excitation
- Multiplexer type: relay

3.2.2. DIGITAL FLOW TRANSMITTER

The flow rate also changes with respect to change in level of irradiance and therefore affecting the voltage variation. The device employed to monitor the flow rate is a digital flow transmitter with a built-in flow transducer. The paddle-wheel flow transmitter for continuous flow measurement and batch control is specifically designed for use in neutral and aggressive, solid-free liquids. The transmitter is made of a compact fitting and an electronic-module quickly and easily connected together by a bayonet. The model used for the demonstration is 8035 plastic INLINE manufactured by **Burkert Easy Fluid Control Systems.** This plastic-fitting design ensures simple installation of the transmitters into all pipes from 15 to 50 mm diameter. The transmitter component converts the measured signal and displays the actual value. The output signals are provided via a 4-pole cable plug. The flow transmitter can be installed in either horizontal or vertical pipes. The transmitter 8035 can receive an optional power supply 230/115 VAC and is also available with 9 VDC battery power supply.

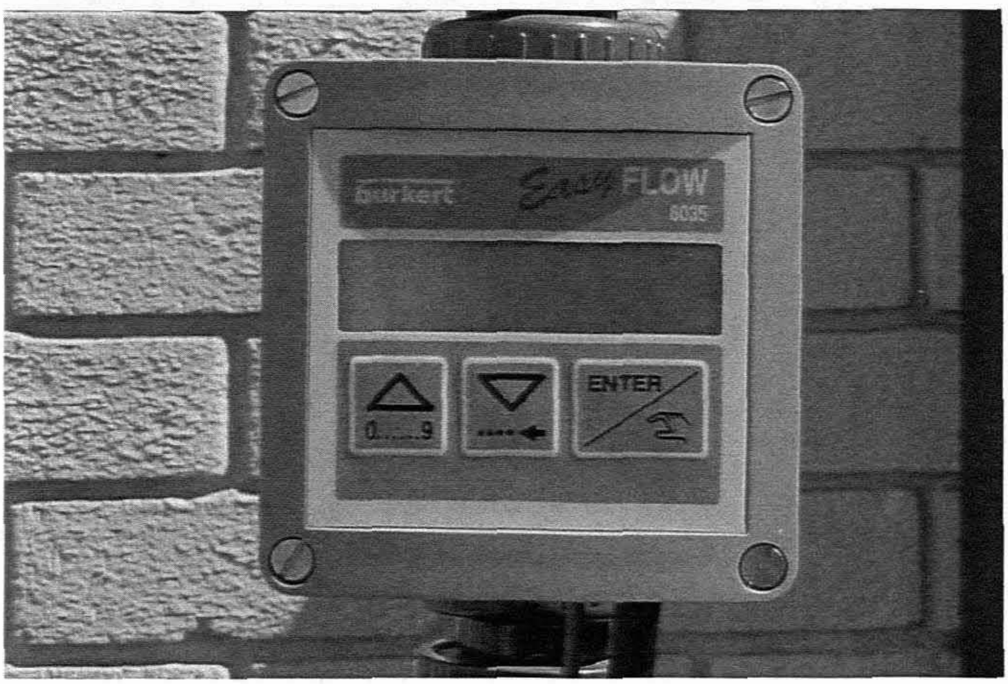


Figure 3.6: Digital flow transmitter

The operation of the transmitter is smooth, but it has to be calibrated correctly to give accurate readings.

3.2.3. DIGITAL PRESSURE TRANSMITTER

At different irradiances, voltage from the panels will vary, the pressure in the pipeline will also change due to the change in flow rate, therefore a pressure transmitter with a built-in pressure transducer is employed to convert physical signals from the system into a measurable electrical quantity to the data logger. The S10-25 bar WIKA Tronic Line with a clip-on display pressure transmitter is used for measuring pressure. It is sourced by a 10-30 VDC power supply. This type of transmitter can be used wherever a measured pressure value has to be electrically transmitted. See the appendix C3 for the model, type and specifications of this device. Then the power from the pump is given by

$$P_{pump} = water\ density \times gravitational\ acceleration \times flowrate \times Head$$
$$= \rho \times g \times Q \times (H_s + H_d) \qquad [W]$$

ρ in kg/m^3, g in m/s^2, H in m & Q in m^3/s.

Figure 3.7: Tronic Line pressure transmitter

3.2.4. ANEMOMETER

The speed of wind is another variable that needs to be monitored as it has an impact on the absorption of heat by the panels. The device used for this particular application is an anemometer. It detects the wind speed as well as the direction of wind. The working procedure of this device is the as the above devices. The figure below shows the anemometer used.

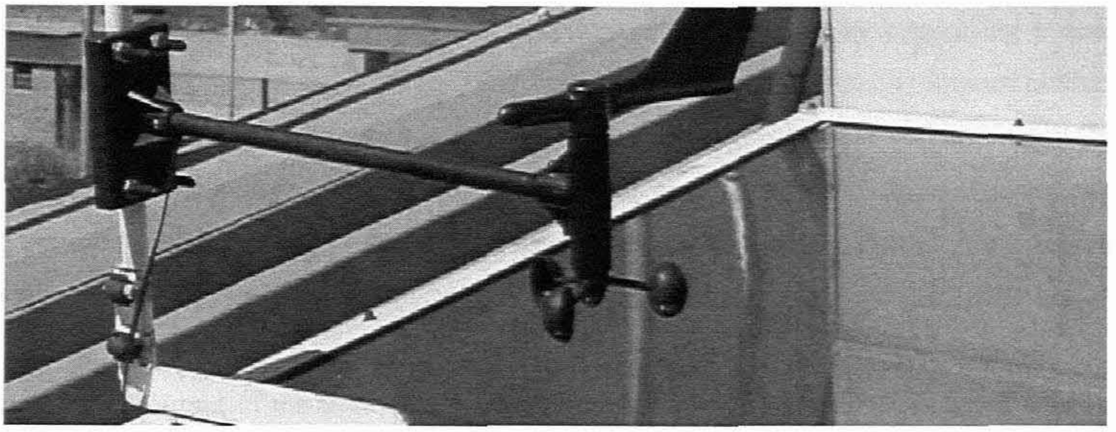


Figure 3.8: An anemometer

3.2.5. PYRANOMETER (LI-200SZ)

The LI-200SZ is an instrument for measuring solar radiation received from a whole hemisphere. It is suitable for measuring global sun plus sky radiation. Solar radiation varies significantly among geographical regions, season, and time of the day. Often, the most required measurement is the energy flux density of both direct beam and diffuse sky radiation passing through a horizontal plane of known unit area (i.e. global sun plus sky radiation).

The LI-COR pyranometer may be handheld or mounted at any required angle; provided that reflected radiation is not a significant portion of the total. The sensor and the vertical edge of the diffuser must be kept clean in order to maintain appropriate cosine correction. For operation, the cable of the LI-200SZ pyranometer sensor is terminated with the two bare leads of the coaxial cable. This allows the LI-200SZ to be used with the six current channels of the LI-1000 Data logger located on the screw down terminals to the 1000-05 terminal block, and the 1000-06 AC terminal block. The shield of coaxial cable is positive and the centre conductor is negative. This is done because the transimpedence amplifier used in LI-COR light meters requires a negative signal.

To use the LI-200SZ with the LI-1000, the calibration constant must be entered into the LI-1000 in the form of a multiplier. The multiplier (entered as al in the polynomial $Y=a0+alX+a2X^2+a3X^3+a4X^4+a5X^5$ with LI-1000 version 2.02 software) is given on the certificate of calibration. When a LI-COR Light Meter or data logger is not used, the LI-200SZ can be used with other millivolt recorders or data loggers by connecting a resistor across the leads of the coaxial cable. The value of the resistor chosen is important since it can affect the operation of the sensor. Choosing a value that is large can result in a non-linear response from the sensor. The value of the resistor used for LI-COR millivolt adapters for the pyranometer sensor is 147 Ohms. A value other than this can be chosen, but it should be a value such that the millivolt output of the sensor does not exceed 10mV per 1000W/m^2.

The millivolt output of the sensor used as described above can be calculated using Ohms law (Voltage=Current×Resistance) and multiplying the current output of the sensor in μA/1000W/m^2 (calibration constant) by the resistance, in Ohms, of the millivolt adapter. The product will give the sensor in mV/1000W/m^2. Recalibration of LI-COR radiation sensors is recommended every two years. See appendix C4 for specifications. Figure 3.9 shows a LI-200SZ pyranometer mounted on the solar panel structure.

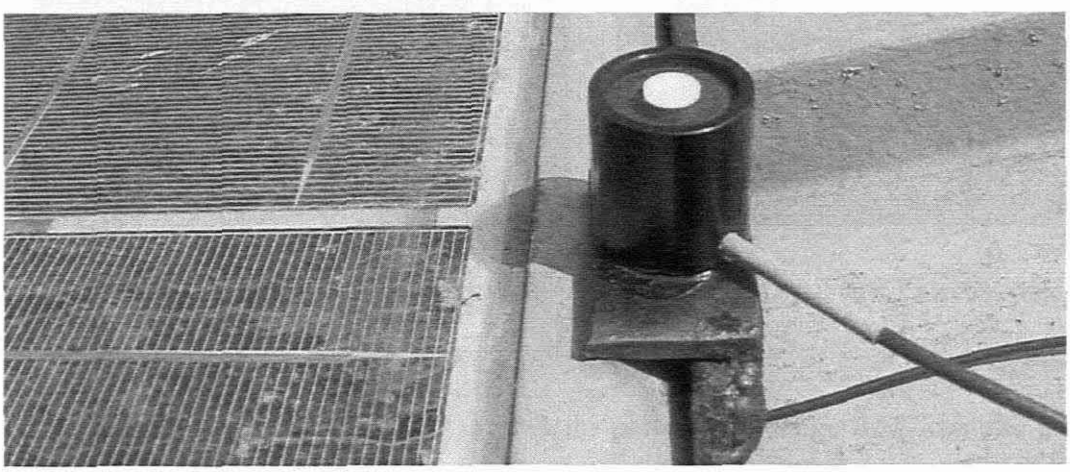


Figure 3.9: LI-200SZ (LI-COR Inc.)

3.2.6. DC POWER SUPPLY

The DC power supply will only be used for laboratory trials. For fieldwork, a battery will be used to supply power to the transducers and data logger. The output voltage is continuously adjustable between 0 rating voltage in one range by means of a coarse and fine potentiometer, the load current may have value from 0 rating current and adjusted by means of a coarse and fine potentiometer. Both outputs can accurately read on voltmeter and ammeter. Both stability and ripple are extremely good to meet the requirements of modern circuit design. The unit can be used as either constant voltage or current source. This device is employed to power a pressure transmitter, flow transmitter and a DATATAKER.

3.2.7. A DAY/NIGHT SWITCH

As an experimental trial, the datalogger was set to sample at half hour intervals. Additionally, the time window of interest is from sunrise to sunset, since this is when the PV system is operational. A locally designed day/night sensor is used to control the state of the acquisition, depending on the lighting conditions. Figure 3.10 (a) & (b) below show the internal and external pictures of a day/night switches respectively.

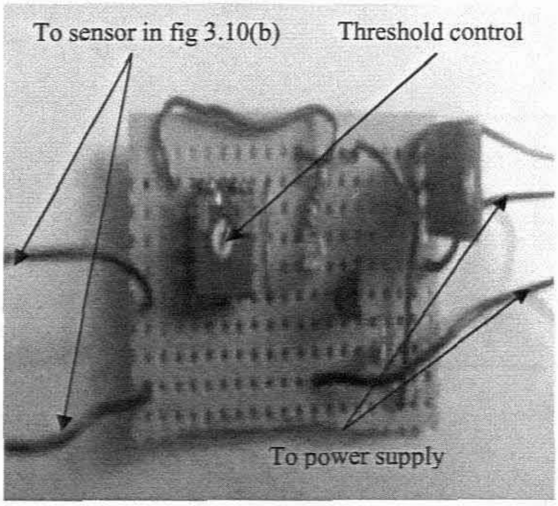


Figure 3.10 (a): Internal day/night switch

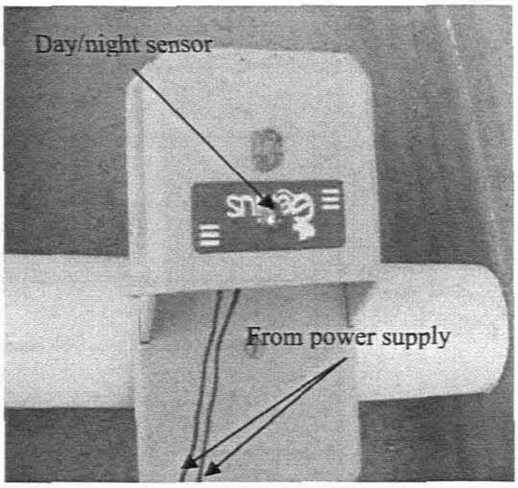


Figure 3.10 (b): External day/night switch

The diagram overleaf (figure 3.11) shows the pattern of voltage flow from the panels to the data logger and motor/pump with necessary resistors and fuses to control the amount of voltage/current to the data logger.

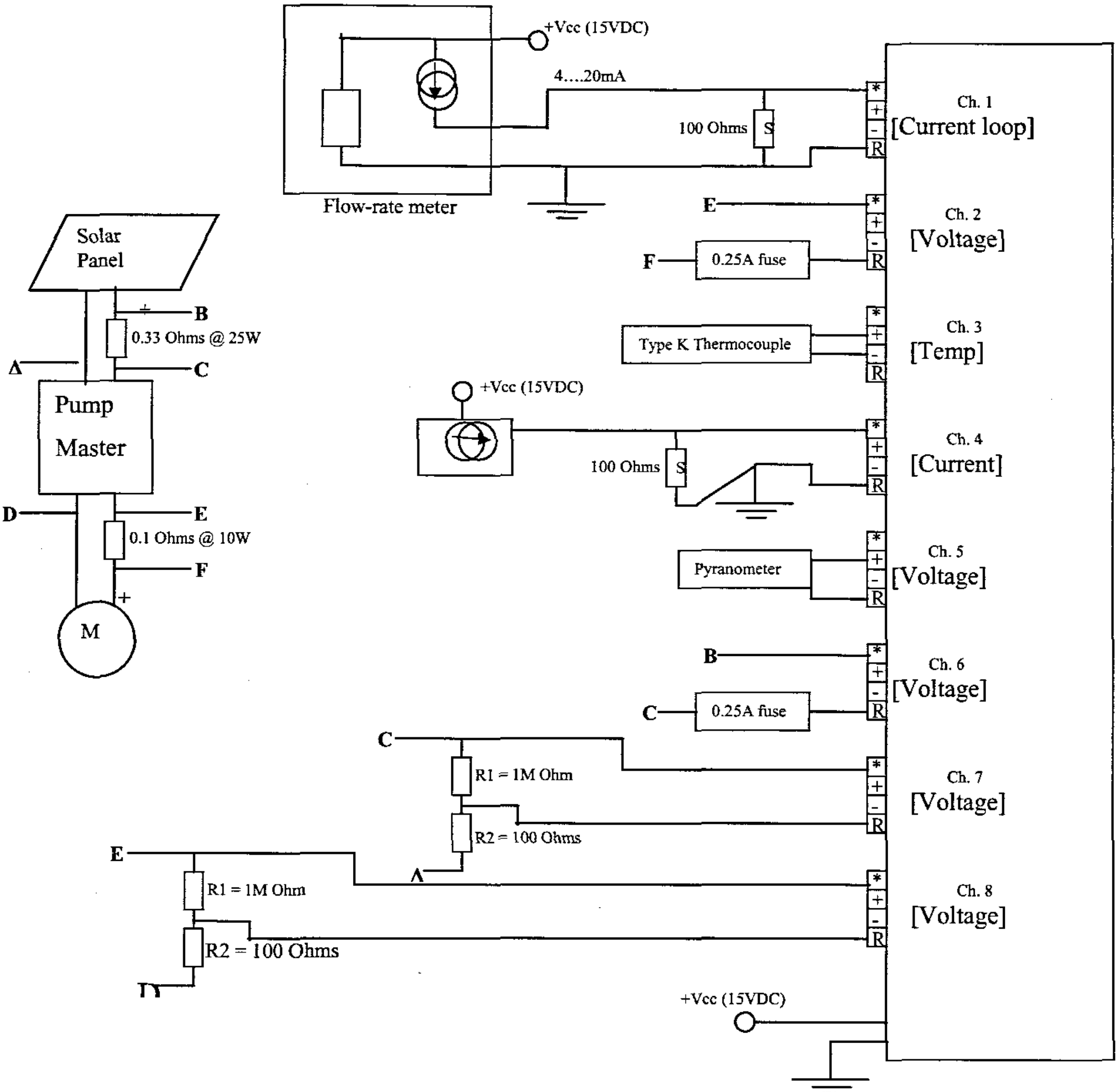


Figure 3.11: Configuration of transducers connections to the data logger

Once the data logger and Pumpmaster are in operation, they can be subjected to many conditions that they may not have been designed for. Figure 3.11 illustrates how the Pumpmaster and the data logger are protected against undesired conditions. These two devices can be protected against lightning since the panels are a good receiver of lightning. The data logger is also protected against over-voltage by using the fuse. This fuse will blow if the panels generate the threshold current that would exceed the expected current. The most effective method to avoid over-voltage damage is by use of an over-voltage crowbar (but it has not been used in this test).

3.3. PRESENTATION OF RESULTS

The results presented in this section will not be used as a basis to test the reliability of the system, but to determine the efficiencies of the system and components. The components referred to here are: solar panels, Pumpmaster and motor/pump unit. Therefore, array power refers to power generated by the panels, regulator power refers to power to run the pump and hydraulic power is power delivered by the pump at a certain head. The formulae given below will be used to calculate the above parameters.

<u>Useful equations</u>

Array input

Power efficiency of any component is given by power out divided by power in. The power into the array is the product of the irradiance and the area of the array. The area is known and so only the irradiance needs to be measured. The power out is given by the product of the array voltage and the array current.

$$P_{irradiance} = plane\ of\ array\ irradiance \times array\ area$$
$$= G_{POA} \times A \qquad [W]$$

G in W/m^2 and A in m^2

Array output

$$P_{arr} = array\ current \times array\ voltage$$
$$= I_{arr} \times V_{arr} \qquad [W]$$

I in Amps and V in Volts

Converter output

$$P_{con} = converter\ current \times converter\ voltage$$
$$= I_{con} \times V_{con} \qquad [W]$$

Power of the converter is the product of voltage from the converter and current from the converter.

Motor/pump output

$$P_{pump} = water\ density \times gravitational\ acceleration \times flowrate \times Head$$
$$= \rho \times g \times Q \times (H_s + H_d) \qquad [W]$$

The pump power output is the product of water density ρ (kg/m^3), gravitational acceleration g (m/s^2), flow rate Q (m^3/s), total head H (dynamic head + static head).

Overall Efficiency

$$\eta_{sys} = \frac{P_{pump}}{P_{irradiance}} \times 100 \qquad [\%]$$

The overall efficiency of the system is the power out of the system divided by the power into the system. In this case, power out of the system is given by pump power (P_{pump}) and power into the system is given by irradiance power.

System Efficiency

$$\eta_{subsys} = \frac{P_{pump}}{P_{arr}} \times 100 \qquad [\%]$$

System efficiency is power generated by the pump divided by power generated by the array.

Component Efficiency

$$\eta_{comp} = \frac{P_{out}}{P_{in}} \times 100 \qquad [\%]$$

System parameters

Table 3.3: Measured parameters of the PV pumping system

ABBREVIATIONS	UNITS	PARAMETERS
G_{POA}	W/m^2	Plane of array irradiance
I_{arr}	A	Array current
V_{arr}	V	Array voltage
I_{con}	A	Converter current
V_{con}	V	Converter voltage
Q	m^3/s	Flow rate
H_s	m	Static head
P	kPa	Pressure
H_d	m	Dynamic head
T_a	°C	Ambient temperature

All these parameters were interfaced to the data logger. The data logger supports eight analogue channels and four digital channels. The channels are read continuously and averages for each channel are computed for each minute. The length of the log period is set by the user. The information is recorded in the internal memory of the data logger. At the end of each test or series of tests, this data can then be transferred onto the memory of a personal computer for analysis.

The efficiencies of some of the components of the system vary with irradiance. So in order to model the operation of the components accurately it is necessary to get instantaneous readings rather than readings averaged over half an hour, for example. This is illustrated by the graph below.

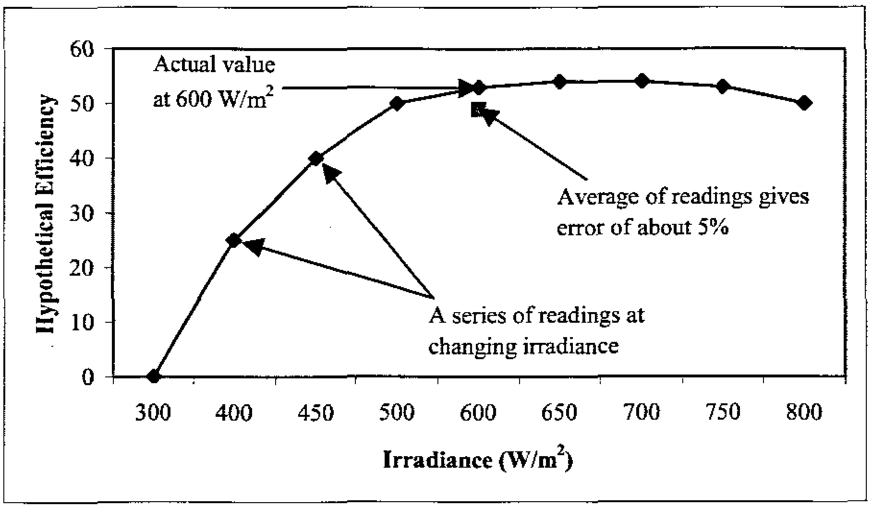


Figure 3.12: Hypothetical system efficiency versus irradiance (Gosnell, 1991:69)

The graph shows a hypothetical set of readings for efficiency versus irradiance. As can be seen if the readings are averaged a value is found which is well below the actual value of the efficiency at that time. So it can be deduced that the log period needs to be kept as short as possible to model the operation of the components accurately.

The experimental results are presented in the section. Data was captured at time intervals of 30 minutes. Relevant manufacturers' pump performance curves are presented in appendix A3 and A4.

3.3.1. TEMPERATURE VERSUS TIME

The graph below shows a relationship between ambient temperature and time. Medium temperatures are during the day and therefore would result in medium solar intensities. This is good for the solar panels to produce electrical energy, but high solar intensities have a negative impact on production of energy, as increase in the temperature of the PV modules due to solar heating lowers the PV conversion efficiency (Chandratilleke, 1986:59).

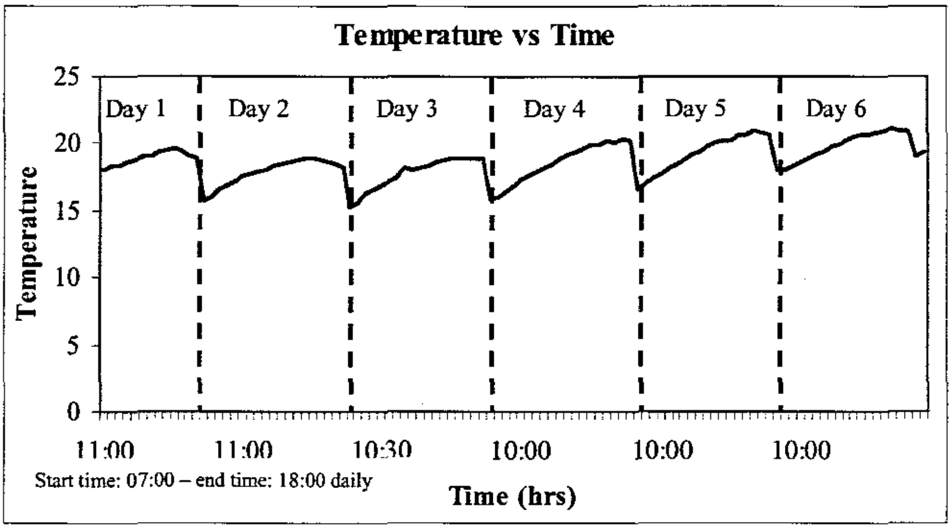


Figure 3.13: Temperature versus time (24/08/04 - 30/08/04)

3.3.2. ARRAY, CONVERTER & PUMP POWER VERSUS TIME

Figure 3.14 overleaf shows the graphical results of power generated by the panels, power to the pump/converter power and power generated by the pump over a different time of the day. The graphs show notable variations of array, converter and pump power. The relationship between array power and converter power is very close and this is because of the efficient converter. All the three powers drop drastically in the event of cloud cover and when the levels of irradiances become low. The pump power does not appear to be affected much by the small fluctuations of the array power except at night when irradiance is zero. This is because the Pumpmaster draws power at constant voltage for all irradiances and regulates voltage as required by the system. One would expect to see an increase in pump power as array power increases and a decrease in pump power as array power decreases. However, because of the Pumpmaster's operation, this is not necessarily so. The maximum array power output for this test is 120 W with a corresponding converter power of 118 W at 879 W/m^2. The efficiency of the converter with these results at this time is 97%. The maximum efficiency of 75 W module at 1000 W/m^2, with an area of 0.632m^2, is 11.9% (manufacturer).

From the obtained results, the efficiency of the array was calculated to be 16.3%. This value seems to be reasonable taking into account the fact that this experiment was conducted in winter when the levels of irradiance were quite low.

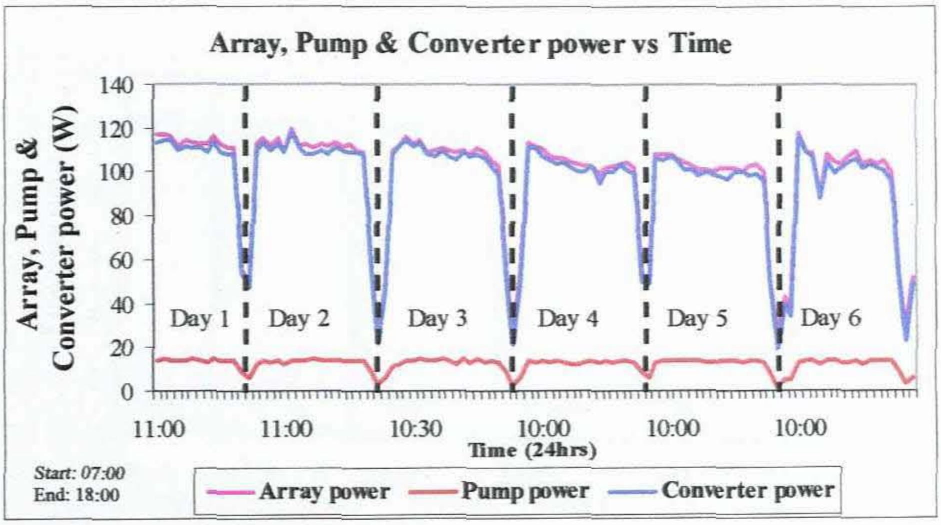


Figure 3.14: Array, pump & converter power versus time (24/08/04 - 30/08/04)

3.3.3. HEAD VERSUS TIME

The following figure shows a plot of dynamic head with respect to time of the day. Head varies with the pressure created by the pump. The higher the pressure, the more the head will increase. Here head ranges between 4.8 m and 5.5 m.

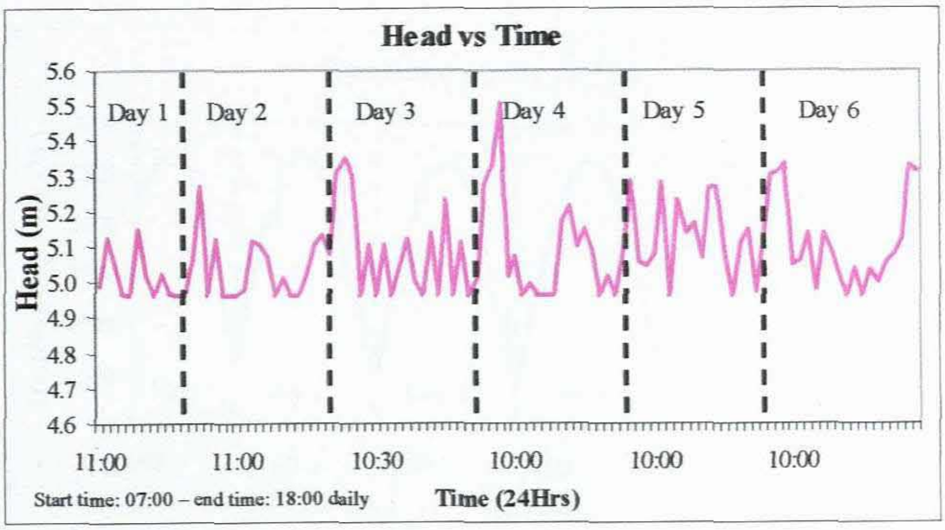


Figure 3.15: Head versus time (24/08/04 - 30/08/04)

3.3.4. FLOW RATE VERSUS TIME

The trend of flow rate versus time is increasing flow with increasing irradiance, viz flow increases from early morning to around midday, after which flow drops towards sunset. This is as expected because flow is proportional to incoming energy.

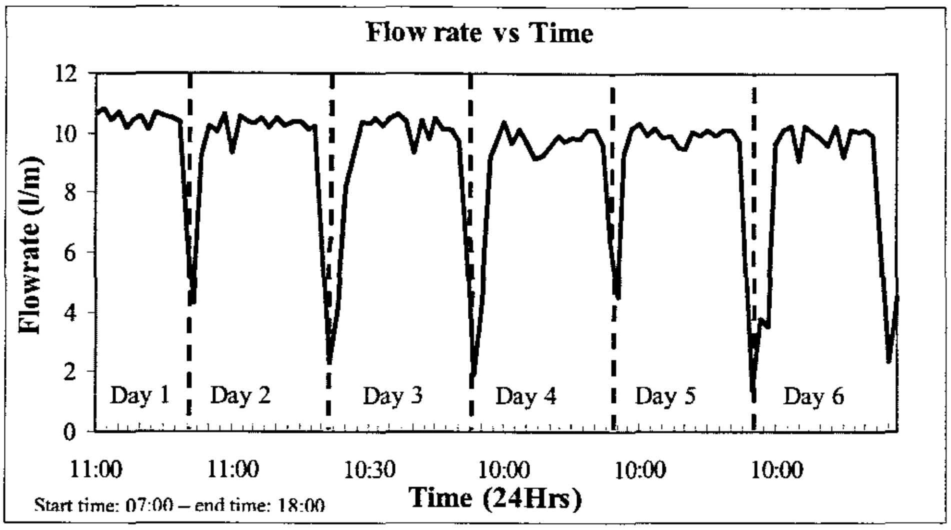


Figure 3.16: Flow rate versus time (24/08/04 - 30/08/04)

3.3.4. IRRADIANCE POWER VERSUS TIME

Irradiance power is directly proportional to the product of solar radiation (W/m^2) and the surface area of the solar panels. It means that as the irradiance increases, irradiance power will also increase while the surface area will be constant.

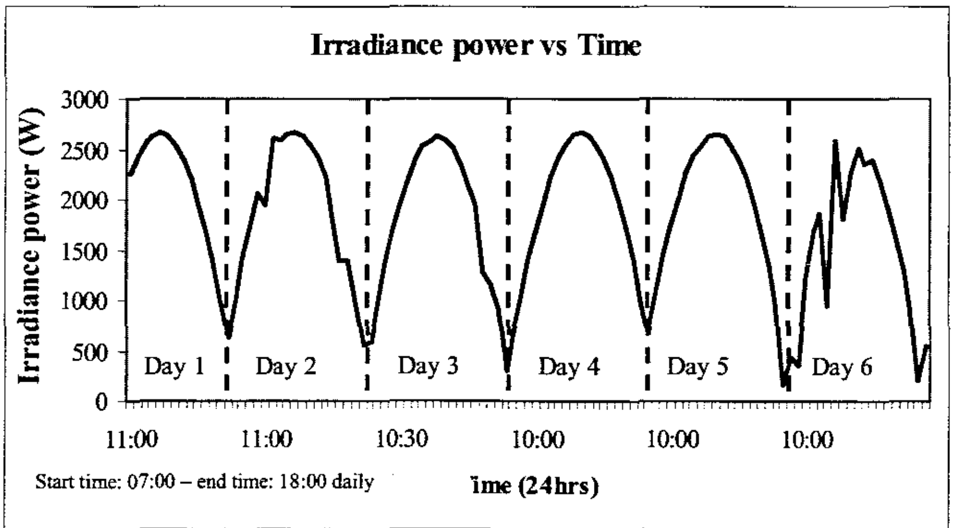


Figure 3.17: Irradiance power versus time (24/08/04 - 30/08/04)

3.3.6. ARRAY EFFICIENCY VERSUS IRRADIANCE

The array efficiency is dependant on several conditions such as solar irradiance, ambient temperature, and wind speed. The variables defining the operating condition are irradiance, cell temperature, absolute air mass, and solar angle-of-incidence on the array. The maximum peak DC power (119.5 kW) measured is considerably less than the nominal 224.4 W nameplate rating of the installed system. There are several reasons - all expected: The power production performance of the PV modules is fairly dependent on the array temperature. The higher the panel temperature, the lower the solar to electric conversion efficiency. The Siemens modules installed experienced a 0.4% drop in their nominal energy conversion efficiency for each degree centigrade which the arrays are warmer than 25°C.

The obtained maximum efficiency of 16.3% is quite reasonable and this efficiency is likely to decrease in summer due to higher operating temperature, therefore it is acceptable to conclude that the modules are efficient basing that conclusion on the manufacturer's specifications. Heliotronics (2004: 4) also reports that the solar panels can only capture about 10-20% of the energy in sunlight. Sarkar *et al* (accessed @ http//fsec.ucf.edu/ed/iasee/isree/sarkar-water.pdf, 22/06/2005) reported an array (monocrystalline) efficiency of 13%, Hamakwa (1986:415) obtained the maximum array (Amorphous) efficiency of 6-7 % and Helikson *et al* (1991:4) reported an array efficiency of 11%.

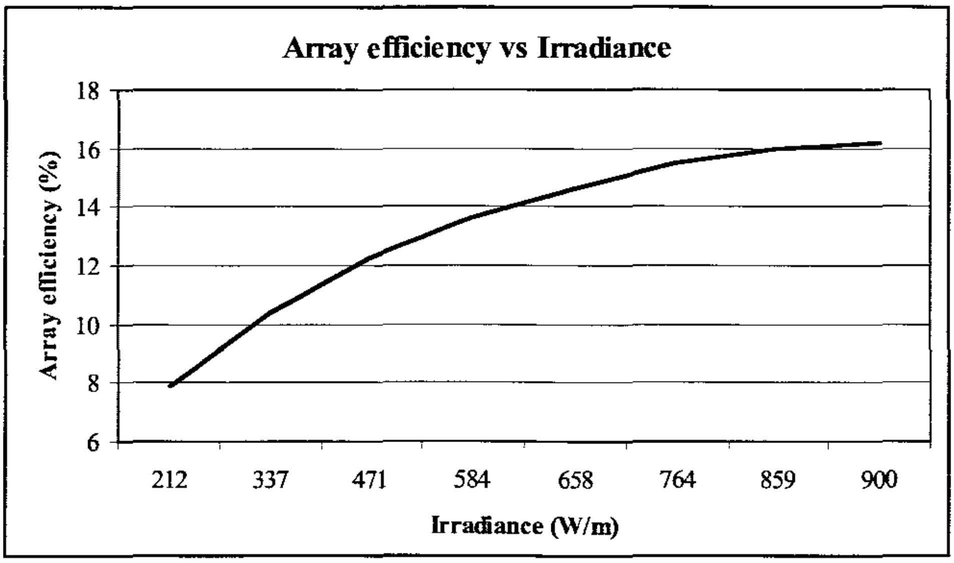


Figure 3.18: Array efficiency versus irradiance (24/08/04 - 30/08/04)

3.3.7. CONVERTER EFFICIENCY VERSUS TIME

Converter efficiency is the ratio of power generated by the solar panels and power driving the pump. The converter is one of the efficient components of the PV water pumping system. Here the average converter efficiency is 97%. Other researchers such as Helikson *et al* (1991:4) reported a converter efficiency of 96%. Sippola *et al* (2002:2) recorded converter efficiencies of 83%, 86% and 93% and Makhomo (2001:40) obtained an efficiency of 88%.

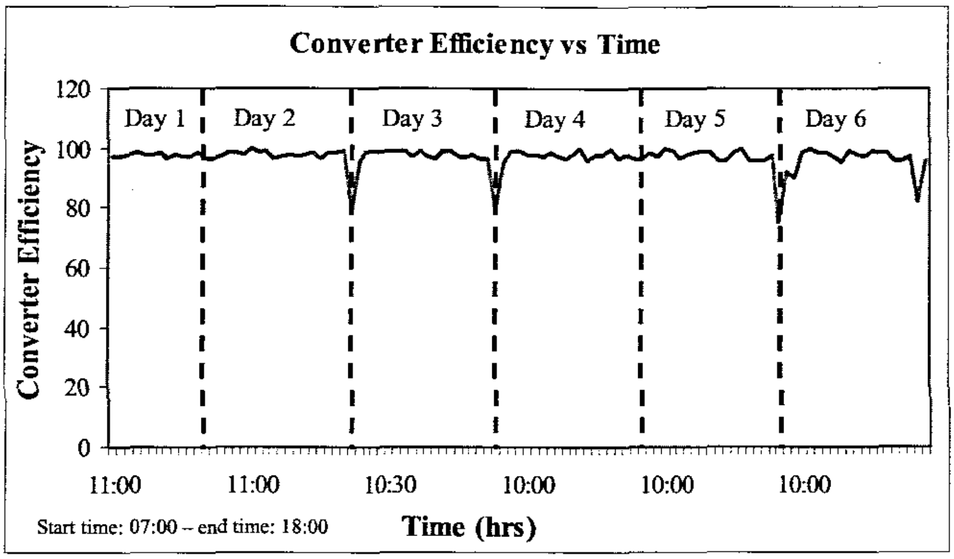


Figure 3.19: Converter efficiency versus time (24/08/04 - 30/08/04)

3.3.8. PUMP EFFICIENCY VERSUS TIME

The pump efficiency is the ratio between the hydraulic power (ρgHQ) and the electrical power (VI) of the converter. The difference between pump efficiency and system efficiency here will not be that much due to the high efficiency of the converter (97%). The value of pump efficiency reflects the efficiencies: dc-dc converter, motor and pump. The mean subsystem efficiency is 15% (motor & pump). This value is below the expected range of 25 – 45% for Mono pumps according to Hamza *et al* (1995:495). Helikson *et al* (1991) also reported a pump efficiency of 44%. If a DC motor efficiency is assumed to be 45% and mono pump efficiency of 71% according to Hadi (2003:38) then the overall motor/pump efficiency will be 32%.

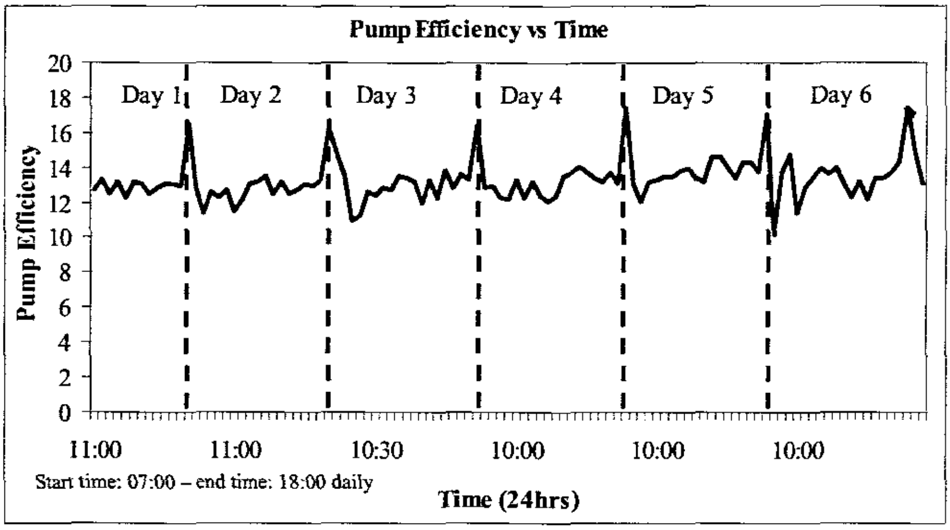


Figure 3.20: Pump efficiency versus time (24/08/04 - 30/08/04)

3.3.9. SYSTEM EFFICIENCY VERSUS TIME

System efficiency is directly proportional to power generated by the pump and inversely proportional to power generated by the panels. It is clear that system efficiency is dependent on voltage and current from the panels, system head as well as the flow rate. The maximum system efficiency obtained was 17%. The most probable cause of this is that the pump was operating at a low head (about 5m), viz at low heads efficiency is low, but increases with increasing head (see appendix A4).

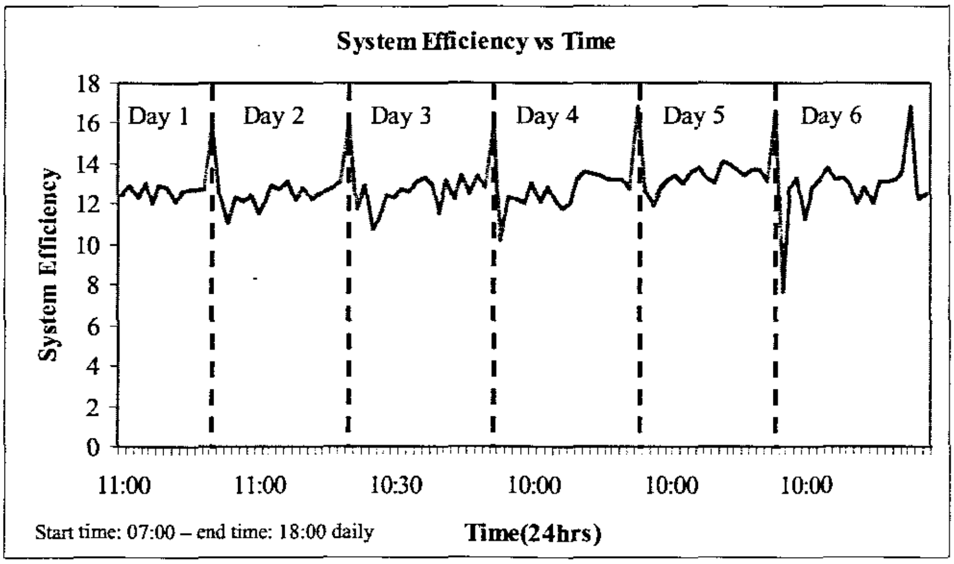


Figure 3.21: System efficiency versus time (24/08/04 - 30/08/04)

3.3.10. OVERALL EFFICIENCY VERSUS TIME

The overall efficiency of the system is determined by the hydraulic power and power from the sun (irradiance power). The graph below shows the efficiencies ranging between 0.4% and 1.8%. The average overall efficiency was obtained to be 1.47%.

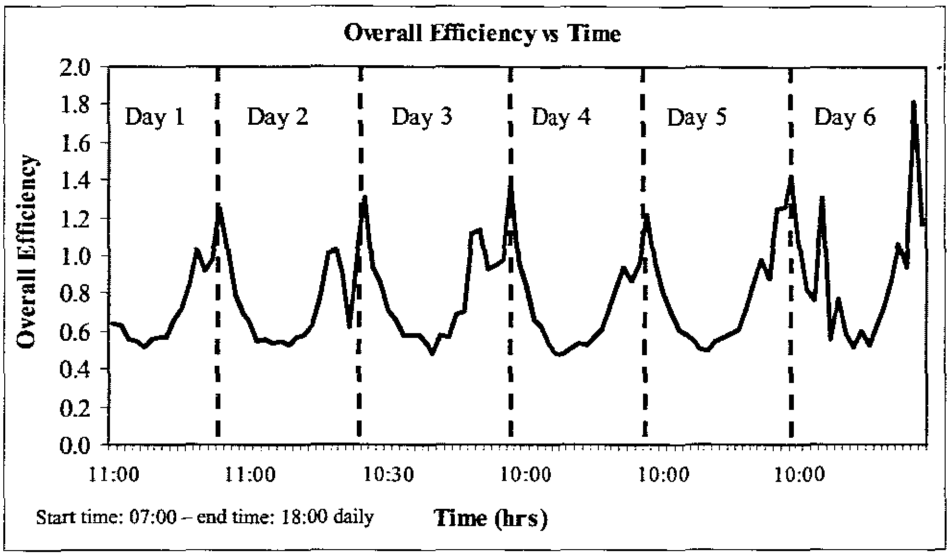


Figure 3.22: Overall efficiency versus time (24/08/04 - 30/08/04)

3.4. EXPERIMENTAL OBSERVATIONS AND CONCLUSIONS

From the above results, the mean efficiencies of the three subsystems are as follow:

- Array efficiency 16.3%
- System efficiency 15.0%
- Overall efficiency 1.47%

Some of these efficiencies are quite encouraging (especially array efficiencies) considering the fact that the tests were performed in winter when there are low levels of irradiance. There were some discrepancies in the results which might have been caused by the *operating conditions* of the whole system. These are some of the notable conditions:

- **Operating point of pump** – As mentioned in section 3.3.9, the pump is not operating at a reasonable head, with a significant loss in efficiency. If it had been operating at higher head (50m for example) as is normal in a borehole pump, pump efficiency would alter to about 35% (see appendix A4).
- **Season** – The season will also have an impact on overall results. The temperatures were very low in the Cape Peninsula on the days on which the experiments were conducted. This experiment was conducted in late August.

There are no valid judgements that can be made at this stage on these short-term results. Long-term results can enable us to perform valid assessments as to whether this system is reliable or not, so it is important to have enough data to check if the system is behaving consistently over a period of time and to obtain information about its performance over the whole range of irradiance levels. The overall experimental results are quite encouraging and the progress up to this stage is promising.

It would be important to talk of the accuracy of the data acquisition system (transducers, interface and data logger) because the accuracy for the transducers and the error sources in the components of the signal conditioning are available from data sheets. The collected data though, should be expressed on the basis of uncertainty. The reason for this is that the calibration of the data acquisition system is not based on the comparison to known values, but is compared to other measuring devices that have a particular accuracy.

However, the overall experiment was carried out quite successfully despite some problems encountered during the process. The lessons/knowledge learned out of this work will be of great importance when applying this information to the actual site. The next logical step is to develop the same experiment to the actual site.

The next chapter presents the fieldwork on two villages namely Lepelsfontein and Rooifontein. The results of the two villages will be for comparative purposes and determination of life cycle costs of the competing systems (PV and diesel pumping). More attention will be on the results that have been collected for a long time (two years for example).

Chapter 4

FIELDWORK AND TESTS

4.1. SITE DESCRIPTION (LEPELSFONTEIN)

Lepelsfontein is a small village in the Northern Cape, south west of Garies (see map in appendix F1). It has a population of roughly 450 people. The physical infrastructure comprises gravel roads, manual telephones and a pre-primary school. The water supply system in the Lepelsfontein area comprises a number of sources. The main source is groundwater from a borehole. A three-phase submersible centrifugal pump is used to pump water. There is also a diesel pump which is used as a back-up to the PV pump in the event of PV pump failure or in times of extended cloud cover. There is rainwater catchment which is collected from a large granite dome some kilometres from the settlement. Water from the dome is stored in the 11 × 25000 litre and 2 × 75 litre tanks and it is ready to be gravitated to the village for purification purposes. Figure 4.1 shows the 11 storage tanks and 2 × 75 000 litres storage tanks.

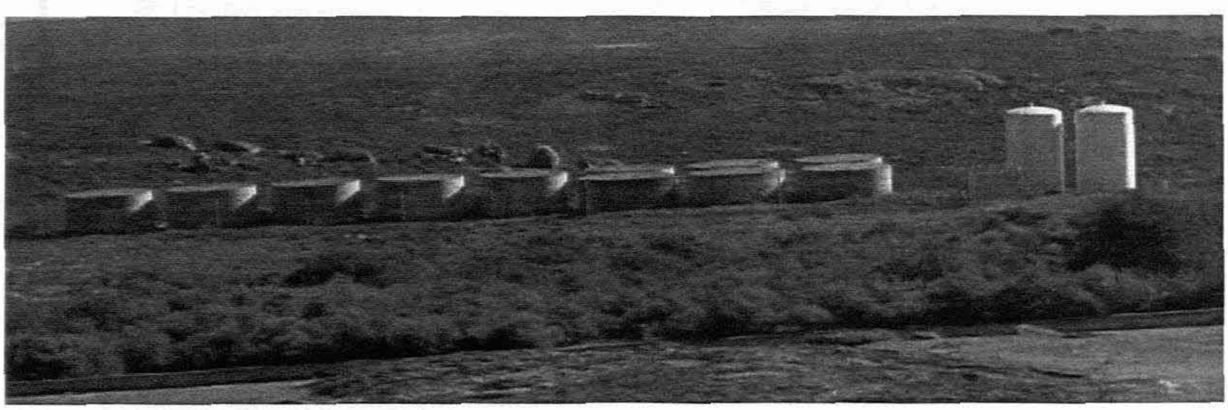


Figure 4.1: Rainwater storage tanks

The third source of water is the collection of water by means of a method termed 'misting'. It is claimed that at least 30 000 litres of water are collected in three months using this method. The latter was an experimental system, but has become non-functional due to breakage of the net and collection gutters.

The PV system is situated about 2 km to the south west of Lepelsfontein village. The PV pump operates seven days a week. A diesel pump becomes operational only when the PV pump does not work (when it is faulty or being maintained or extended cloud cover). Water is pumped to 2 storage tanks located in the village. Each storage tank has a capacity of 30 000 litres. Water from storage tanks is gravitated to a diesel pump located at about 300 m down the hill. The purifying/desalinating chemicals are added before water is pumped to the supply tanks. Water has to be desalinated as it is claimed that the sea, which is about 10 km to the south east of the settlement, affects the quality of underground water and therefore it is not readily available for consumption. A total dissolved solids content of around 1380 mg/l was measured in 2001 (Toens & Vennote, 2001: 59).

There are four supply tanks of 10 000 litres each located at about 400 m from the diesel pump house uphill. Water from the supply tank is gravitated to the village and is accessed through standpipes. Figure 4.2 below shows a line diagram of water flow from the pump to the end user.

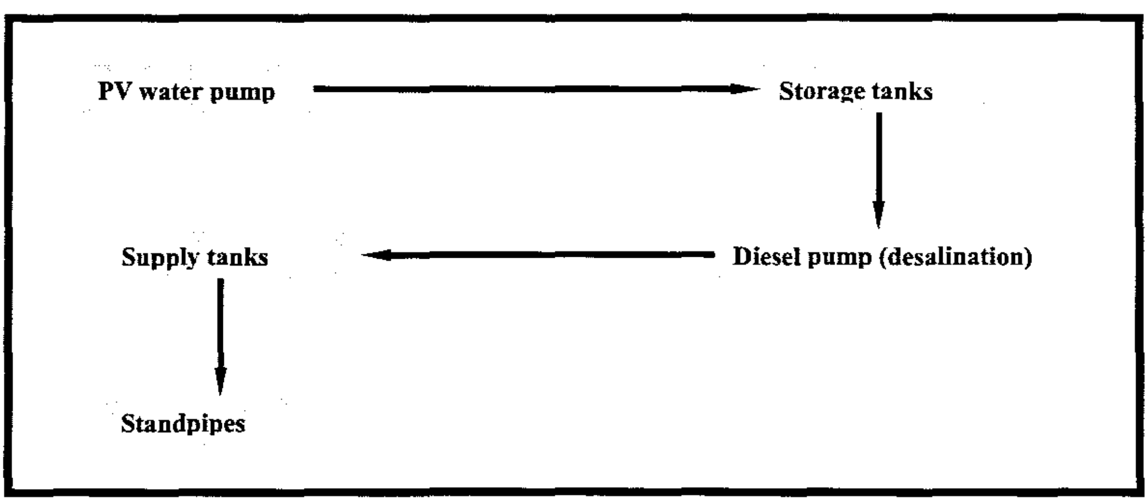


Figure 4.2: Water flow diagram from the pump to the end user

4.2. SYSTEM DESCRIPTION

The PV water pumping set-up at Lepelsfontein comprises three subsystems namely, a set of PV panels, an inverter and a three phase-centrifugal pump. Table 4.1 below illustrates comparisons between the PV system installed at CPUT and Lepelsfontein system.

Table 4.1: Comparisons between CPUT and Lepelsfontein PV systems

	CPUT	**Lepelsfontein**
Array size	225 Wp	1.72 kWp
Converter/inverter	Converter (DC/DC)	Inverter (DC/AC)
Pump	DC submersible mono pump	AC centrifugal pump

4.2.1. SOLAR PANELS

There are two sets of solar panels used to power a three phase centrifugal pump located about 10 m away from the pump. A first set of panels consists of 20 panels manufactured by Liselo Solar. The second set of panels consists of 4 Helios Power panels all connected in series. Table 4.2 below shows the specifications of the two sets of solar panels. Figure 4.3 overleaf shows the field configuration of two sets of solar panels.

Table 4.2: Specifications of Helios and Liselo solar panels at Lepelsfontein (detailed specifications in appendix B1 & B2 respectively).

Liselo Solar				
Peak Volts (V)	**Peak Amps (A)**	**Watts (W)**	**Size (cm)**	**Guarantee (years)**
17.28	4.4	75	1215(L)x540(W)x60(D)	20
Helios Power				
Peak Volts (V)	**Peak Amps (A)**	**Watts (W)**	**Size (cm)**	**Guarantee (years)**
16.66	3	55	750(L) x 524(W) x 34(D)	25

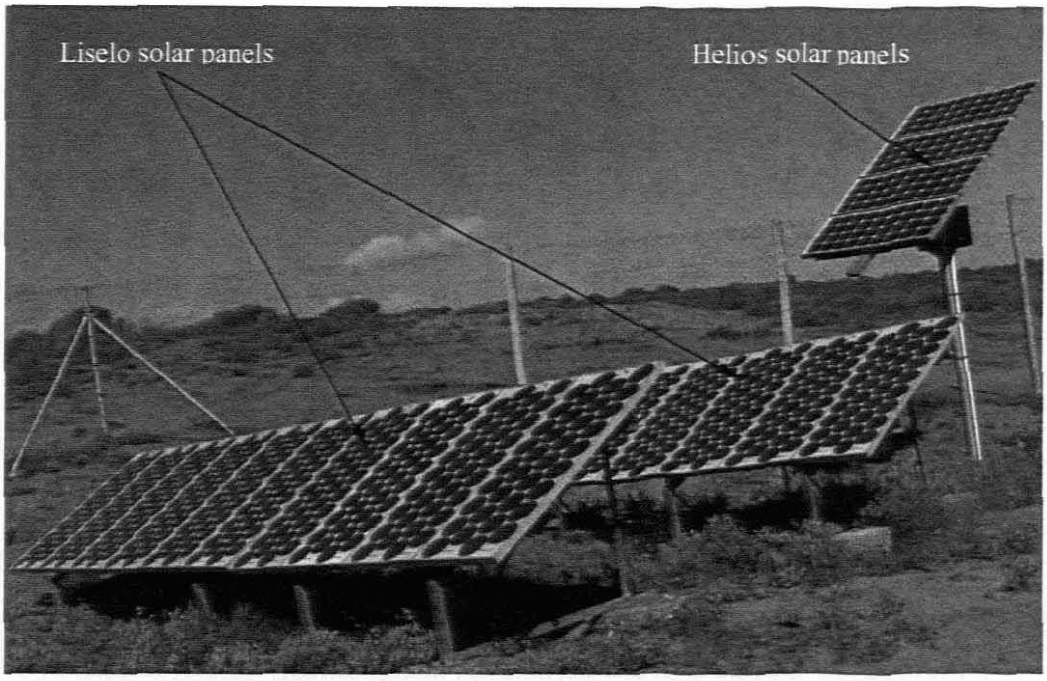


Figure 4.3: Sets of Liselo and Helios PV panels

4.2.2. THE GRUNDFOS DC/AC INVERTER

Inverters are used to transform DC power into three-phase AC power. This three-phase inverter is developed by Grundfos. The model of this inverter is Solartronic SA 1500. The specifications of the inverter are available in appendix B3.

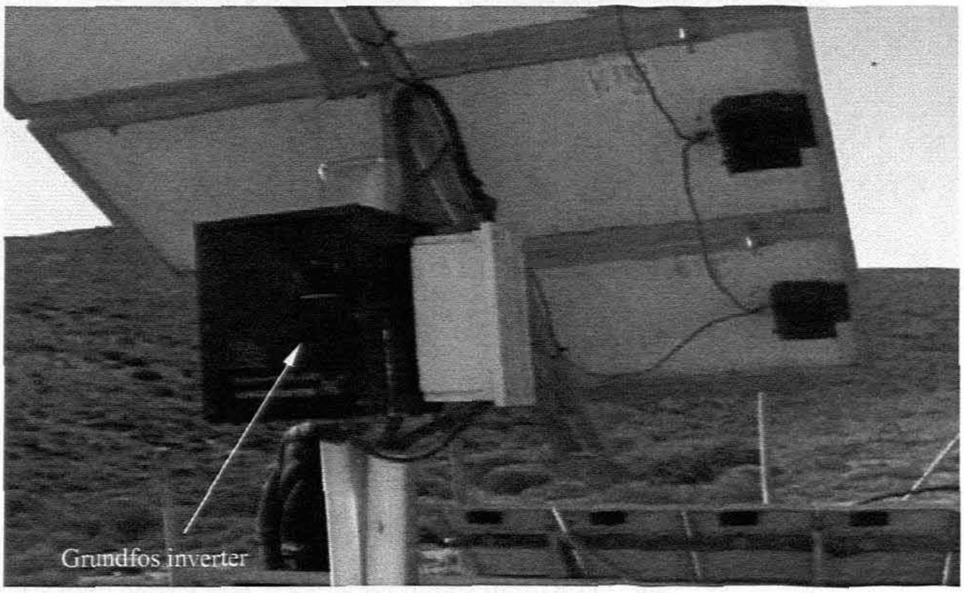


Figure 4.4: Grundfos inverter

4.2.3. PUMP

An SP2A-13 Grundfos centrifugal pump was used for pumping water. The design flow rate ranges between 0.2-2 m^3/h, total head of 52 m, maximum current 2.35 A, maximum power

0.55 kW and voltage ranging between 3×380 – 400 – 415 V. The pump curve can be seen in appendix B4.

4.3. ROOIFONTEIN

Rooifontein is located 90 km southeast of Springbok (see map in appendix F3), roughly 2 km south of Kamassies and has automatic exchange telephones, a primary school and two shops. The population is approximately 550 people in 100 households. The main forms of economic activity are limited to employment in the Provincial Roads Department, migrant labour at Kleinsee diamond mine and livestock farming.

Until the mid 1980's, the community of Rooifontein was dependant on a wind pump extracting water from the dry Buffelsrivier riverbed. Later two diesel powered water pumps were replaced in 1993 by a Lister genset installation which is currently in operation. Water is sourced from a caisson well in the dry riverbed. All the households have standpipes. The geographic location of the abstraction point is **N 30°06′57.1′′, E 018°28′73.4′′**, latitude 30.6571 and longitude 18.28734. Figures 4.5 (a) & (b) show a Rooifontein diesel engine and pump inside a borehole respectively.

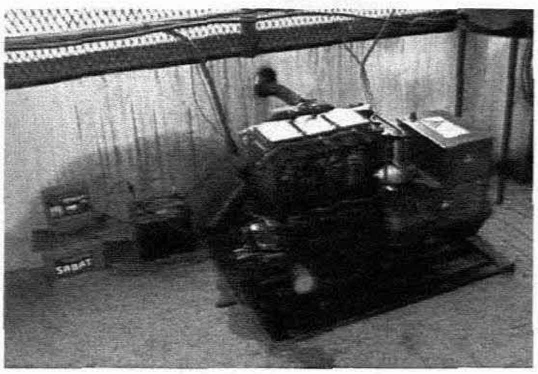


Figure 4.5(a): Diesel engine

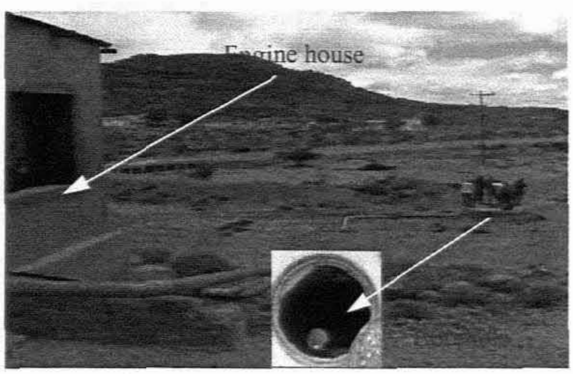


Figure 4.5(b): Pump inside borehole

4.4. TELEMETRY HARDWARE AND CONFIGURATION

Cellular phone data transmission is the most common and preferred means of transmitting information from one point to another. The cellular phone system makes it possible to interrogate a data logger and remote telemetry unit (RTU) when no telephone line is available at the site. Figure 4.6 overleaf shows the configuration of the cellular phone telemetry setup that is used in Lepelsfontein for data acquisition. The use of satellite for data transmission was initially considered but it seemed to be too costly and LEO satellite communication was found to be unreliable with a high monthly subscription. The latter will be revisited when more sites are monitored as the project develops over the next 5 years.

The information from the site will be transmitted by means of a set of modems which are in series and are interfaced to the RS232 port of a data logger. The information from the data logger is transmitted to the HF modem by means of RS232 interface. An antenna from the HF modem transmits the signals to another antenna which is connnected to the HF modem located some distance uphill. The HF modem is interfaced to a GSM by means of RS232. An antenna is ready to transmit the information to another GSM modem which is on the receiving station at CPUT. Then this GSM modem is interfaced to a computer. Information from the computer can be accessed by means of a LABVIEW program and the user sets the length of logging and transmission.

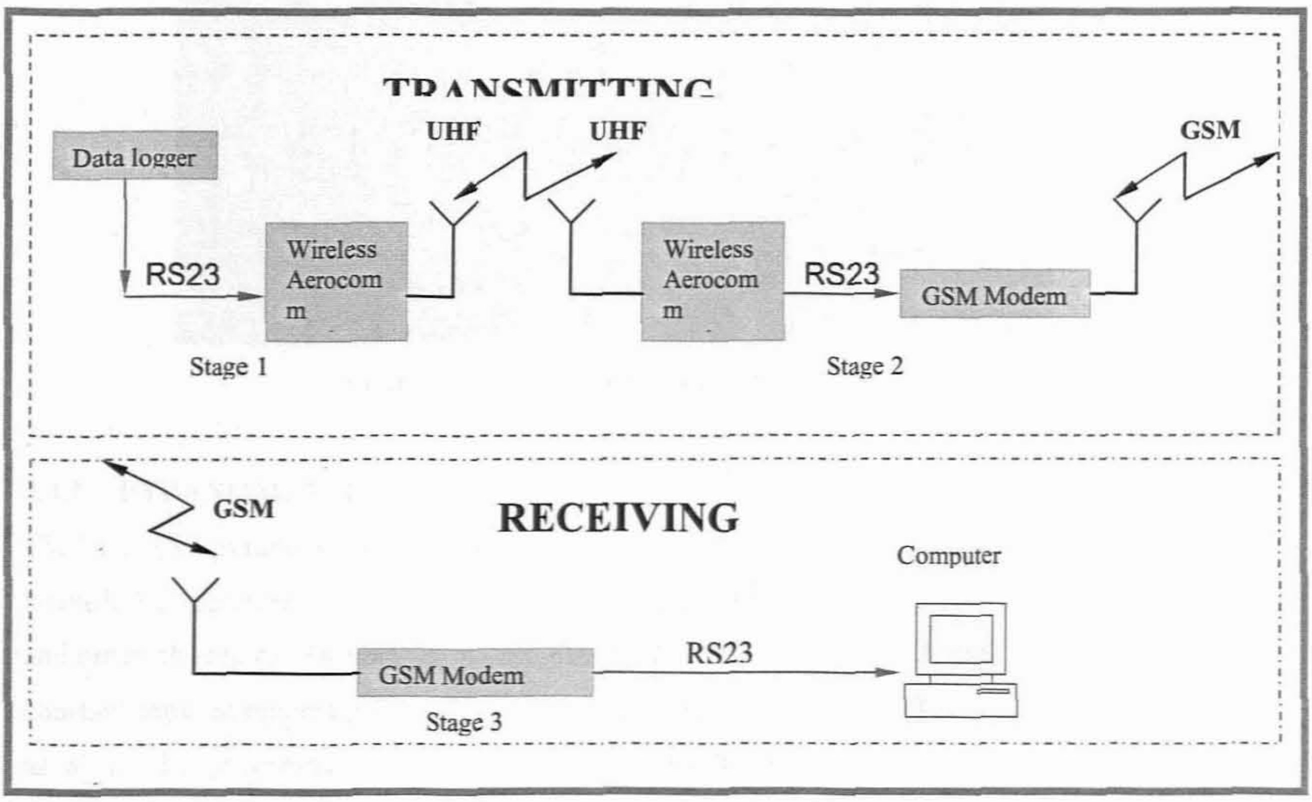


Figure 4.6: Telemetry system configuration

4.4.1. FLOW AND PRESSURE TRANSMITTERS

NOTE: *Some of the data acquisition devices used for experimental tests were also used for field tests therefore the applications and descriptions of those devices are the same. Those descriptions will be the same as in section 3.2.*

Figure 4.7 below shows the set-up of digital flow and pressure transmitters in the pipeline at Lepelsfontein PV water pumping station. The two transmitters have built-in transducers that measure and convert mechanical quantities into readable electrical quantities. The data from the two transmitters is transmitted to a data logger for storage and analysis purposes. A 12 VDC battery sources both transmitters. The flow transmitter model used in this experiment is 8032 brass INLINE manufactured by **Burkert Easy Fluid Control Systems.** The diameter of the transmitter is 50 mm and the output signal is 4 - 20 mA. The S10-25 bar WIKA Tronic Line pressure transmitter is the model used to measure pressure. The output signal of the pressure transmitter is 4 - 20 mA.

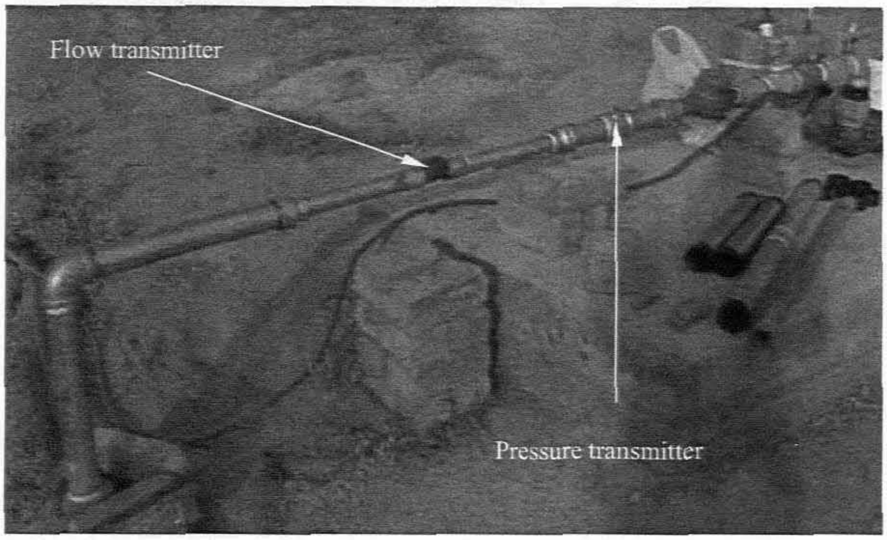


Figure 4.7: Flow and pressure transmitters

4.4.2. PYRANOMETER

The LI-200SZ pyranometer is an instrument used for measuring solar radiation received from a whole hemisphere. It is mounted onto a solar panel structure in such a way that the trees and other objects cannot obstruct it. To use the LI-200SZ with the LI-1000, the calibration constant must be entered into the LI-1000 in the form of a multiplier. The multiplier (entered as al in the polynomial $Y=a0+alX+a2X^2+a3X^3+a4X^4+a5X^5$ with LI-1000 version 2.02 software) is given on the certificate of calibration.

When a LI-COR Light Meter or data logger is not used, the LI-200SZ can be used with other millivolt recorders or data loggers by connecting a resistor across the leads of the coaxial cable. The value of the resistor chosen is important since it can affect the operation of the sensor. Choosing a value that is large can result in a non-linear response from the sensor. The value of the resistor used for LI-COR millivolt adapters for pyranometer sensor is 147

Ohms. A value other than this can be chosen, but it should be a value such that the millivolt output of the sensor does not exceed 10mV per $1000W/m^2$. The millivolt output of the sensor used as described above can be calculated using Ohms law (Voltage=Current×Resistance) and multiplying the current output of the sensor in $\mu A/1000W/m^2$ (calibration constant) by the resistance, in Ohms, of the millivolt adapter. The product will give the sensor in $mV/1000W/m^2$. Recalibration of LI-COR radiation sensors is recommended every two years. See appendix C4 for specifications.

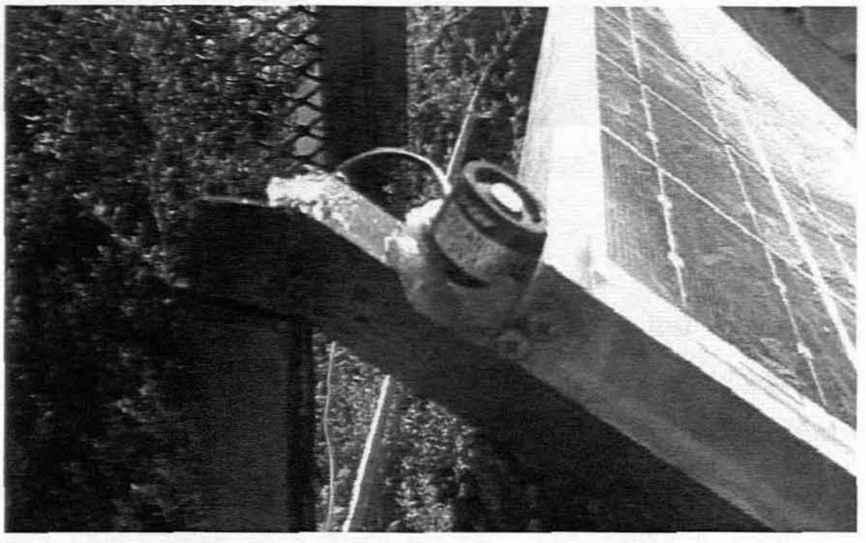


Figure 4.8: A pyranometer

4.4.3. SOLAR PANEL

A solar panel shown in figure 4.9 overleaf is used to charge a 12 VDC battery, which is used to supply voltage to flow, and pressure transmitters, data logger and an HF modem. The voltage from the solar panel is regulated by a charge controller to prevent overcharging of a battery. The specifications of this solar panel are shown in table 4.3 below.

Table 4.3: Specifications of WA Siemens module

Warranty Years	Item	Watts	Peak Amps	Peak volts	Size (mm)
25	SP-75	75	4.4	17	1200×527×34

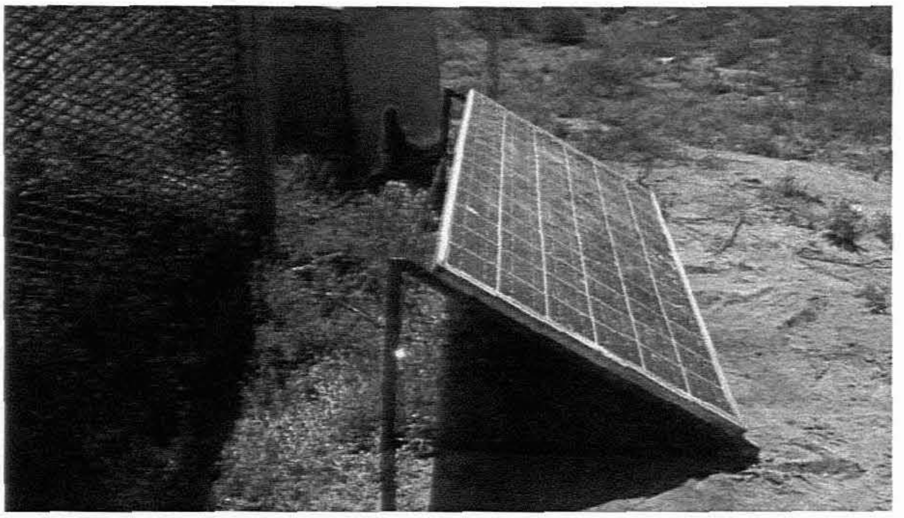


Figure 4.9: A solar panel

4.4.4. DATA LOGGER

The signals from the sensors are transferred by wire, to an instrument which conditions, amplifies, measures, scales, processes, displays and stores the sensor signals. This is the Data Acquisition instrument (data logger). It takes instantaneous measurements, stores measurements and then feeds these to a laptop or a computer, but in this case it sends data to an HF modem (Aerocomm Data Transceiver). The captured information assists in determining;

- Efficiency of the system
- Performance of the system
- Reliability of the system

The model used in this demonstration is DATATAKER 605. The specifications of this device are in appendix C1.

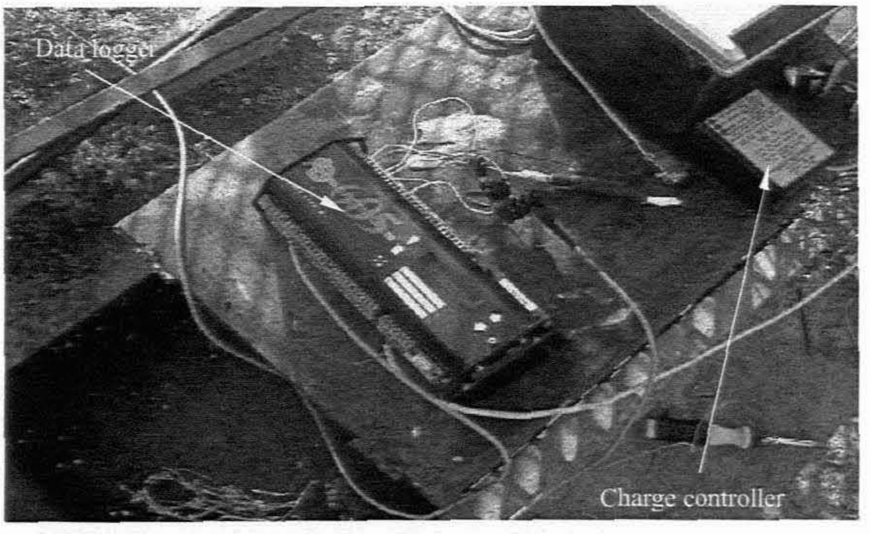


Figure 4.10: A data logger and a charge controller

4.4.5. HF MODEM (The Aerocomm Data Transceiver)

These transceivers operate in a point-to-point, point-to-multipoint or multipoint-to-multipoint architecture. Data transmission rates reach 1Mbps with a range of up to 91 meters indoors and miles line-of-sight (actual performance depends on model, antenna and environment). They contain temperature-compensating hardware and software to adapt across the -40°C to +80°C industrial range. The technology senses ambient temperature and compensates each radio according to its unique temp profile. As a result, radios operating near -40°C will maintain communication with radios operating near +80°C (http://www.aerocomm.com/). See specifications in appendix B6.

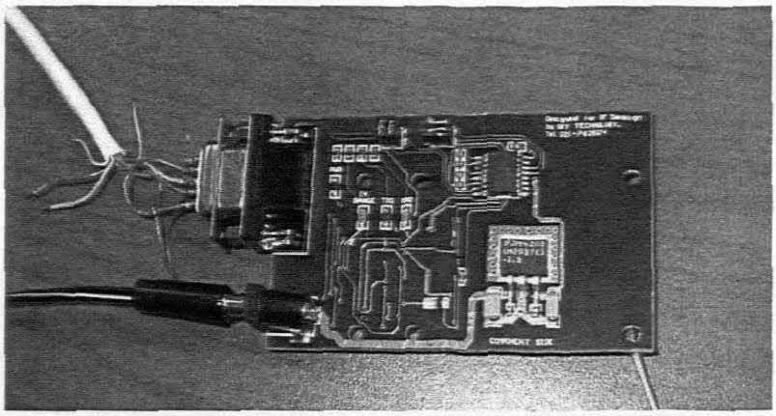


Figure 4.11: The Aerocomm Data Transceiver

4.4.6. GSM MODEM (Samba GSM/GPRS & Tango modems)

- The Falcom Samba GSM/GPRS modem is a small plug & play device, which provides a powerful state of the art technology. The embedded USB interface allows direct connections to a USB serial port of a desktop or notebook computer. The SAMBA can send to and receive data by GSM and GPRS (http://www.conigma.com/samba.htm).

Figure 4.12: The Falcom Samba GPRS/GPS modem

- The FALCOM TANGO is a plug & play Dual Band GSM/GPRS device for direct and easy connection to any terminal equipment that is able to handle attention-commands (AT) for modem control. The TANGO concept offers two RS232 interfaces, audio interface, car voltage range power supply (http://www.falcom.de/txt-produkte-tango-k.html).

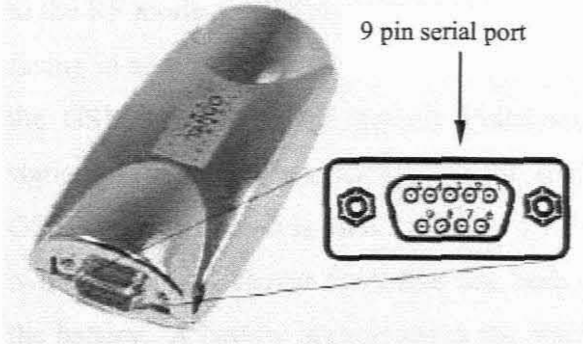


Figure 4.13(a): Tango modem

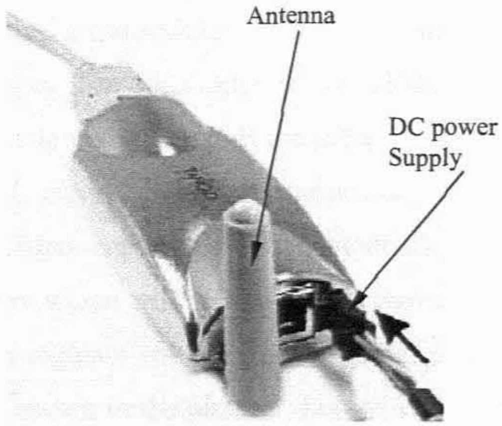


Figure 4.13(b): Tango with antenna

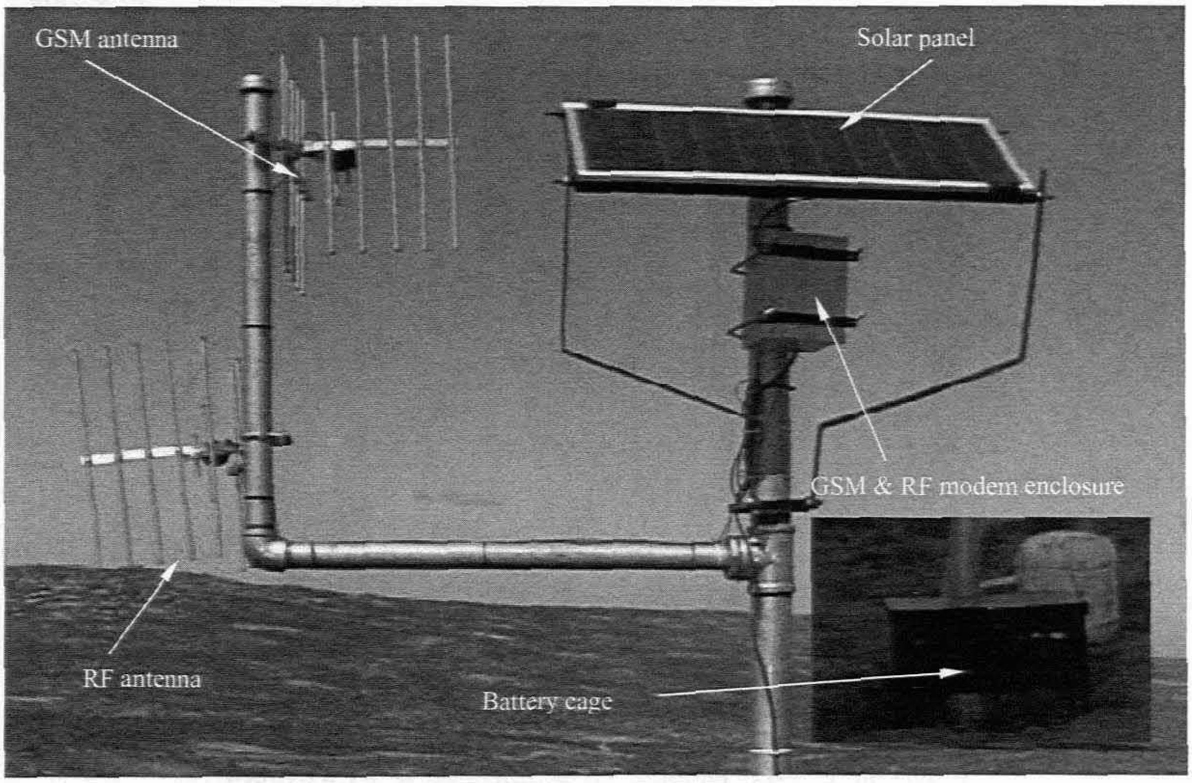


Figure 4.14: An actual telemetry set-up

Figure 4.14 shows a picture of a transmitting station located about 200 m away from the Lepelsfontein water pump station. The coordinates of the water pump station are: S 31°01′50.9′′, E017°51′50.8′′ with an elevation of 192 m. The coordinates of the transmitting station are: S 31°01′49.2′′, E 017°51′44.0′′ with an elevation of 234 m. The figure shows two antennas fixed adjacent to the solar panel. The RF antenna faces the direction of the PV station, receiving information from a transmitting RF antenna connected to the RF modem which is interfaced to the data logger. The other antenna is a GSM antenna facing in another direction to the RF antenna. This antenna is transmits the information from the GSM modem to the nearest Vodacom (GSM service provider) transmitting service station. The white box underneath the solar panel has enclosed the two modems (RF & GSM). A solar panel is used to charge a 12V battery which will in turn supply power to the two modems. A charge controller has been used to regulate voltage from the solar panel to the battery. A battery is enclosed in the black cage shown in the picture. Figure 4.15 below shows an RF antenna at the pump station and it faces in the direction of RF antenna shown in figure 4.14.

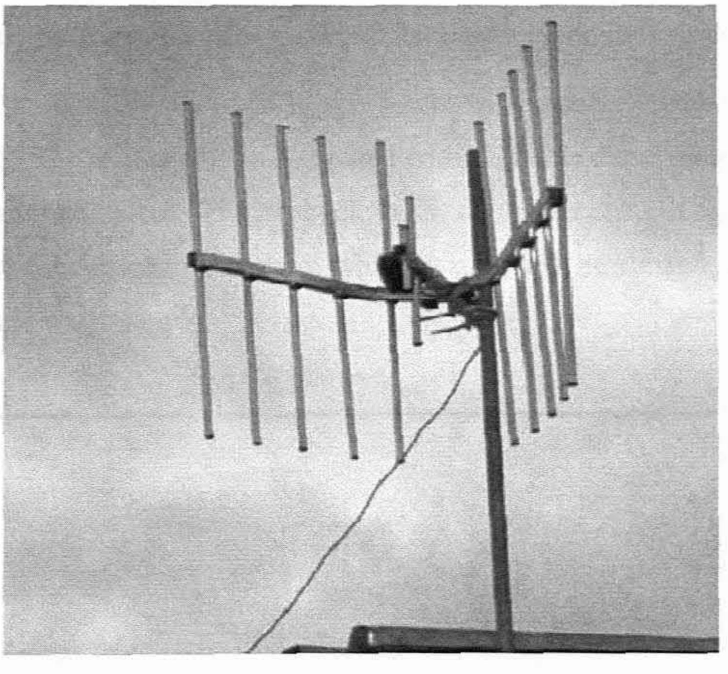


Figure 4.15: A transmitting RF antenna at the pump station

This cellular telemetry system that has been put in place seemed to be working well even though the security of the whole equipment remain a matter of concern. It is however, very unlikely that the equipment can be vandalised considering the distance between the village and the pump station. The involvement of the community in this kind of project can be significant so as to minimise the level of vandalism. Their involvement would mean that the project is their own so protection of equipment should be a priority. There are a few advantages of using the cellular telemetry and some of them are;

- Low profile, non directional antenna
- Easy to set up and low maintenance costs
- Two-way communications
- Event notification by pager, Internet, other cell phone, etc.

There are also disadvantages of using the cellular telemetry. Some of them are;

- Requires cell phone coverage area
- Monthly service fee (may vary depending on local area cell phone service provider)
- Cell phone service provides may change cell towers or communication protocol, thereby affecting communications to your remote location
- Connection may be dropped during peak cellular transmissions activities

The next chapter presents on-site (data logger results) and remotely obtained results (using the telemetry link). The results will be compared with available diesel water pumping results from the Rooifontein settlement. The life cycle costs, unit water costs of the two systems will be determined and conclusions made as to which system will be suitable and economically viable for the village water supply.

Chapter 5

FIELD RESULTS AND ANALYSIS

5.1. ON-SITE RESULTS AND DISCUSSION

Lepelsfontein comprises two different water pumping technologies namely, PV water pumping and diesel water pumping. A diesel pump has been operating for years until early 1990's when the first PV water pumping was introduced. The main reasons for substituting the diesel pump with the PV pump were regular maintenance and high cost of fuel. Now the diesel pump operates as a back-up to the PV pump. It only operates when the PV pump is faulty or if the PV pump does not operate for any other reason. Table 5.1 below shows a summary of both PV and diesel water pumping systems in Lepelsfontein and Rooifontein respectively.

Table 5.1: Summary of PV and diesel water pumping systems in Lepelsfontein and Rooifontein respectively.

	PV system (Lepelsfontein)	**Diesel system (Rooifontein)**
Installation date	09/05/2001	Mid 1993
SYSTEM DESCRIPTION		
System type:	Three phase submersible centrifugal pump	3-phase Lister TR3 10kW generator
Design output:	30 m^3/day	30.8 m^3/day
Dynamic head:	50 m	36 m
OBSERVED PERFORMANCE		
Average output to date:	3.6 m^3/day	21 m^3/day
Maintenance needs:	No reported breakdowns	Battery damaged, no other breakdowns reported ('93-'95)
FINANCIAL INFORMATION (in 2005 rands)		(in 2005 rands)
Initial cost:	R 97,000	R 45,940
15-yr life-cycle cost:	R 293,207	R 358,310
15-yr unit cost:	30 cents/m^4	8.7 cents/ m^4

Table 5.2: Data sheet of Lepelsfontein settlement.

DATA SHEET: LEPELSFONTEIN	
Description of settlement and services	**Other services**
Population: 450 persons	Few telephones
Economic activities: farming	Pre-primary school
	No electricity
Water supply: Ground water from boreholes	1 shop
	Mobile clinic (every two weeks)
	Water uses: domestic
	Storage: 4 storage tanks of 10 000 litres each
SOLAR WATER PUMP	
Technical description	
Installation date:	9/5/2001
Dynamic head:	50 m
Description:	Three-phase submersible centrifugal pump
Specifications:	1.72 kWp array (20×75Wp and 4×55Wp)
	DC/AC inverter
	Solartronic SA 1500
Design performance:	30 m^3/day
Observed performance:	3.6 m^3/day
Maximum output to date	12.1 m^3/day (May 2001)
Total output to end '04	5184 m^3
Average output to end '04:	3.6 m^3/day
Maintenance:	No maintenance recorded
Availability of data: Flow data actual - formal records available System installed recently, so limited operation and maintenance information	
Comments: As the diesel pump has mainly been used as a backup, it is difficult to compare it with pumping systems which operate full-time, and costs are likely to be higher for this system	

Borehole information

Coordinates:	S 31°01′49.2″, E 017°51′44.0″
Depth of borehole:	146 m
Pump depth:	112 m
Water level in the borehole:	35 m
Borehole yield:	4.2 l/s

The graph shown in figure 5.1 (p. 65) shows the five-year results from Rooifontein diesel pumping system (Jan '95 – Sep '01). The information provided in this report, for Rooifontein in particular, includes the following parameters; amount of rain for each month (mm), water pumped per month (kl), average water level and water consumption (l/person/day). The summary of the annual average results of Rooifontein diesel water pumping are shown in table 5.3 below. The results show an average rainfall of 1.6 cm in 1997, with corresponding average pumped volume of 918 m^3, average borehole water level of –7.47 m and the consumption of 56 l/person/day. This increase in water consumption can be caused by various reasons such as the amount of rainfall in that particular year, amount of water pumped, the level of water in the borehole or the increased population in that year (Toens & Vennote, 2001). See appendix E1 for more results.

Table 5.3: Summary of results of Rooifontein diesel water pumping (Jan '95 – Sep '01)

Rooifontein Borehole Information				
Year	**Average Annual Rainfall (cm)**	**Average Annual Water pumped (kl)**	**Average Annual Water level (m)**	**Average Annual Consumption (l/per/day)**
'95	1.3	904	-12.57	55
'96	1.5	870	-10.65	54
'97	1.6	918	-7.47	56
'98	0.3	940	-6.86	57.9
'99	1.05	843	-6.96	51.9
'00	0.96	954	-7.43	58.7
'01	1.3	1024	-8.44	63.11

The following discussions are based on figure 5.1 overleaf:

- **Volume of water pumped** – The graph shows inconsistent volume of water pumped for a three-year period with notably high volumes in summer. The maximum volume recorded is in Dec '95 and is 1480 m^3.
- **Water consumption** – The graph of water consumption (l/person/day) behaves fairly consistently for the three-year trial. One can also notice a slightly higher consumption in summer. This might be as a result of lack of rain during that period as can be seen from the graph. The population of Rooifontein at the time of data collection is not given but the average consumption of each person per day is calculated to be 55 l/per/day in '95, 54 l/per/day in '96 and 56 l/per/day in '97. In September 2001, the consumption was 63 l/per/day.
- **Rainfall** – The purpose of showing rainfall figures here is to show how water consumption behaves with respect to rainfall. It is evident from the graph that water

consumption is high in periods of no rain. The graph does not clearly show the relationship between water consumption and amount of rain.

- **Level of water in the borehole** – The level of borehole water is seen to be decreasing as time goes on. This graph behaves inconsistently for the whole trial period. One can observe that the amount of rain has a little impact on the level of water in the borehole. One might expect to see a similar trend of water level graph and the volume of water pumped, but it is not the case in this illustration. There is no observable relationship between level of water in the borehole and other parameters explained above.

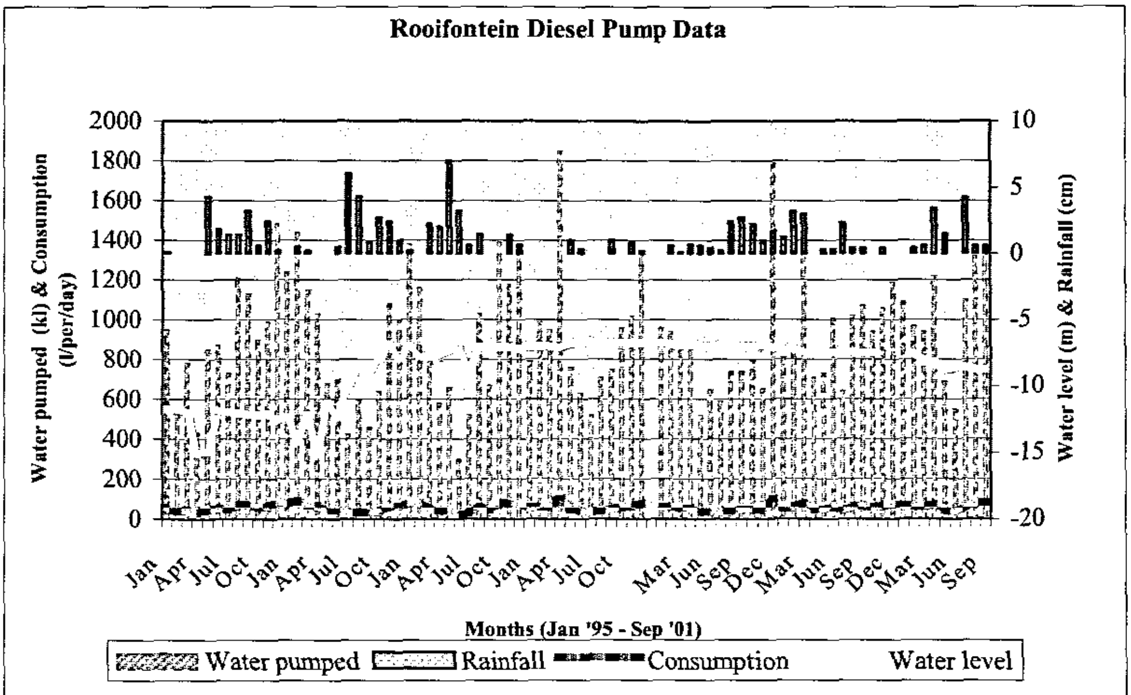


Figure 5.1: Rooifontein diesel pump data Jan '95 – Sep '01 (Toens & Vennote B.K, 2001:42)

The main difference between Lepelsfontein PV water pumping system and Rooifontein diesel water pumping system is that the output of the latter is higher than the former. This can be seen in annual average volumes from table 5.3 and 5.4. The annual average volume of water pumped in Lepelsfontein ranges between 94 and 169 m^3 while Rooifontein recorded average values ranging between 904 and 918 m^3. There are no previous records on water consumption for the Lepelsfontein system, except for real data since the monitoring system has been in place (Dec, 2004 onwards).

Table 5.4: Summary of annual results of Lepelsfontein PV water pumping (Jan '95 –Sep '01)

Lepelsfontein Borehole Information				
Year	**Average Rainfall (cm)**	**Average Water pumped (kl)**	**Average Water level (m)**	**Average Consumption (l/per/day)**
'95	2	169	-35.59	No records
'96	1.9	169	-35.99	No records
'97	1.5	94	-36.28	No records
'98	0.3	940	-32.97	No records
'99	1.4	318	-34.19	No records
'00	1.2	210	-34.92	No records
'01	2.1	196	-35.26	No records

The following discussions are based on figure 5.2 below

- **Volume of water pumped** – The maximum volume of water recorded in September '95 is 260 m^3. April and May '97 do not have records on amount of water pumped. The reason for this is not known, but one might think the readings were not recorded or the pump was not in operation.
- **Water consumption** – There are no records made in Lepelsfontein in this trial period.
- **Rainfall** – There are seven months in three years when there was no rain at all. The graph does not show any relationship between rainfall and other parameters.
- **Level of water in the borehole** – The graph of borehole water level behaves fairly consistently over this assessment period. Water level is ranging between –34 and –37 m with no sudden drop/increase observed.

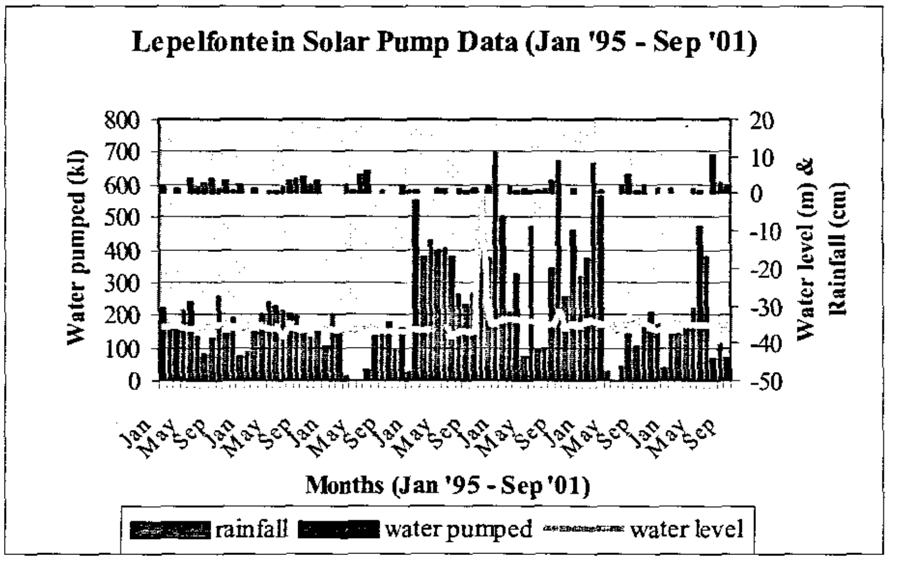


Figure 5.2: Lepelsfontein solar pump data Jan '95 – Sep '01 (Toens & Vennote B.K, 2001:58)

5.2. REMOTE MONITORING EXPERIENCES & RESULTS

To prove the reliability and validity of data from the system, acquired data was compared to data from the Aquimon database and the overlapping of data was about 97%. The difference here was that the data logger could not give accurate data when a particular variable was zero. For example, when the flow rate or solar radiation was zero, the data logger recorded a negative value which cannot be true, as flow rate cannot be negative. Despite this problem, there were no other operational problems encountered during the monitoring period.

The results presented in this section are obtained from Lepelsfontein PV water pumping system. The data logger captured the information from the 03/12/04 to 02/02/05. The results shown below are the results captured only when the pump was in operation. The results captured at night and when the pump was not in operation were omitted. The print screen shown in figure 5.3 below shows the format of results downloaded from the computer. These results were then changed to spreadsheet format to produce the graphs that follow. The first numbers (512751600) in the highlighted area represent time, the second (28.729) data logger internal temperature, the third (4.2731) flow rate in milliamps, the fourth (4.8275) pressure in milliamps, the fifth (25.483) ambient temperature, the sixth (2.8682) irradiance (multiplying factor is 200), seventh (1.1407) voltage from the solar panels (multiplying factor is 101) and the eighth (1.5571) is shunt voltage.

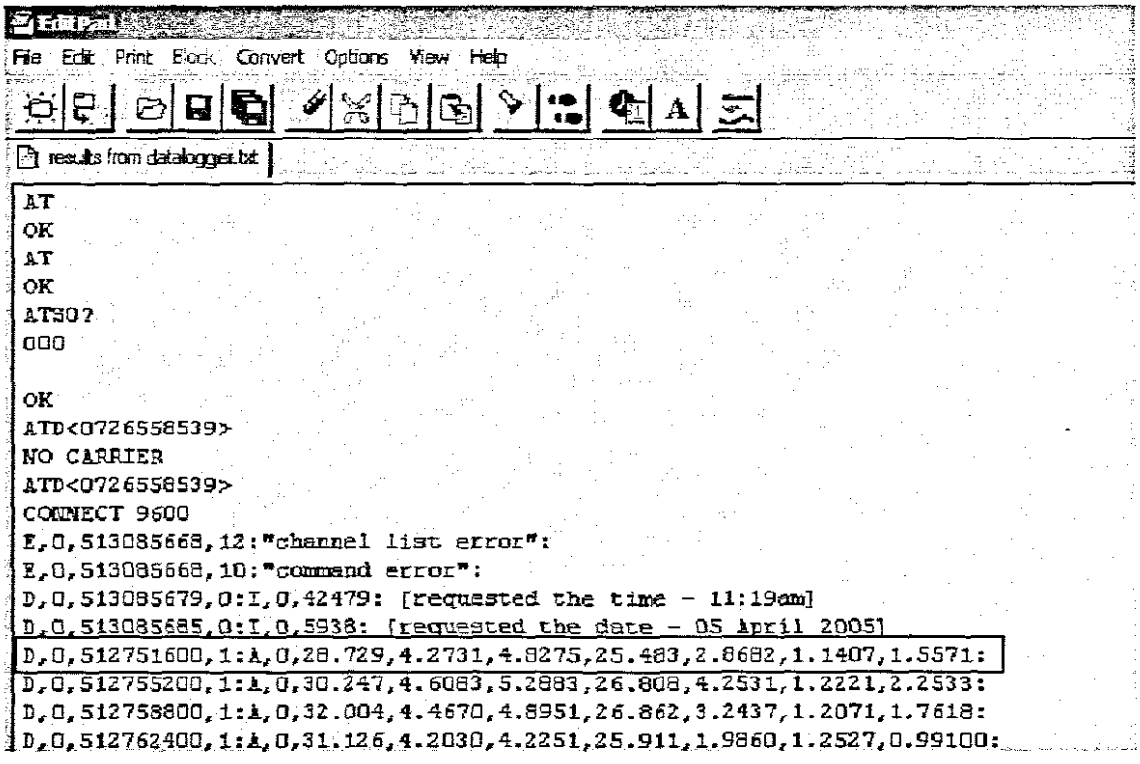


Figure 5.3: Screen print of results downloaded from the data logger

5.2.1. ARRAY & PUMP POWER VERSUS TIME

The figure below shows an array and hydraulic power with respect to time. The relationship between the two graphs is clearly seen here. The increase in array power results in increase in hydraulic power. This is because higher irradiance generates more power and that power increases the amount of water pumped.

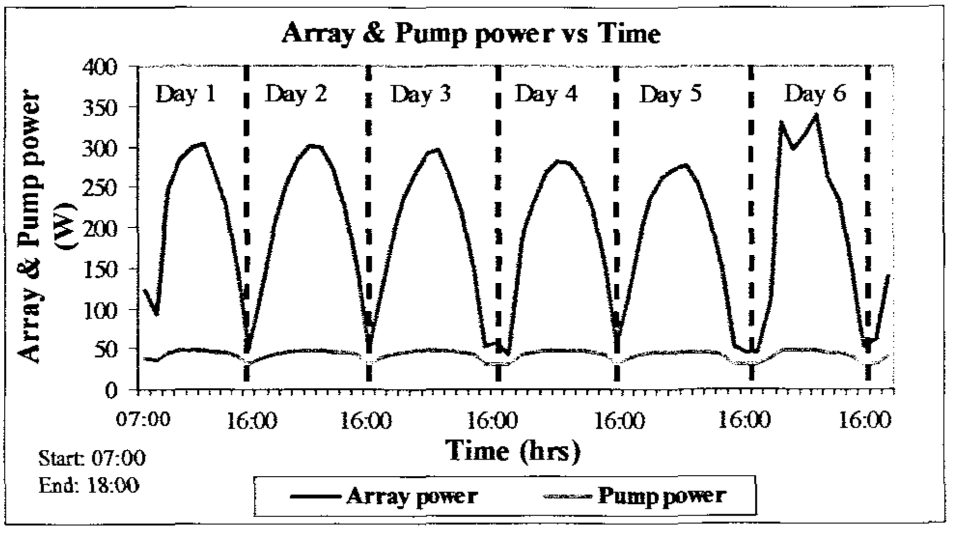


Figure 5.4: Array & pump power versus time (07/12/2004 – 13/12/2004)

5.2.2. TEMPERATURE VERSUS TIME

The following plot indicates ambient temperature over the monitoring period of six days.

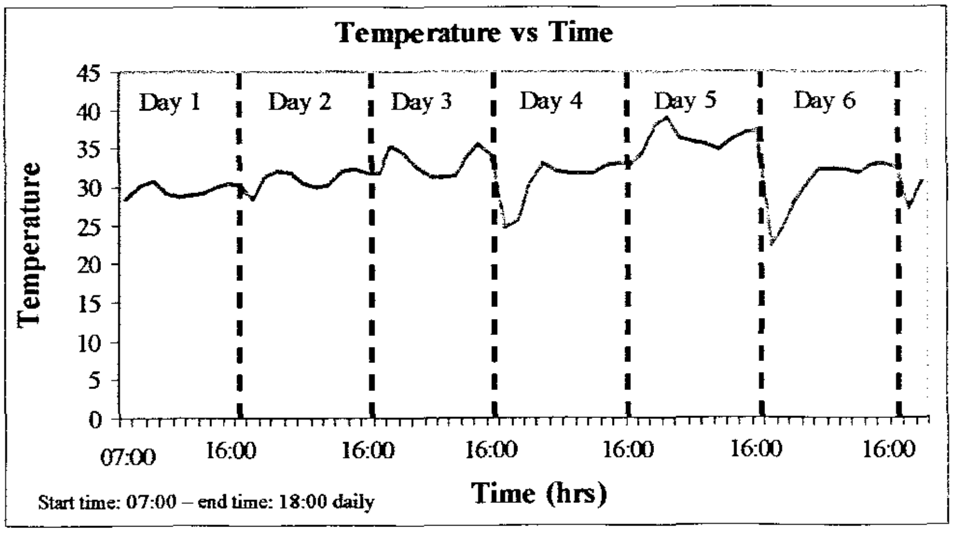


Figure 5.5: Temperature versus time (07/12/2004 – 13/12/2004)

5.2.1. ARRAY & PUMP POWER VERSUS TIME

The figure below shows an array and hydraulic power with respect to time. The relationship between the two graphs is clearly seen here. The increase in array power results in increase in hydraulic power. This is because higher irradiance generates more power and that power increases the amount of water pumped.

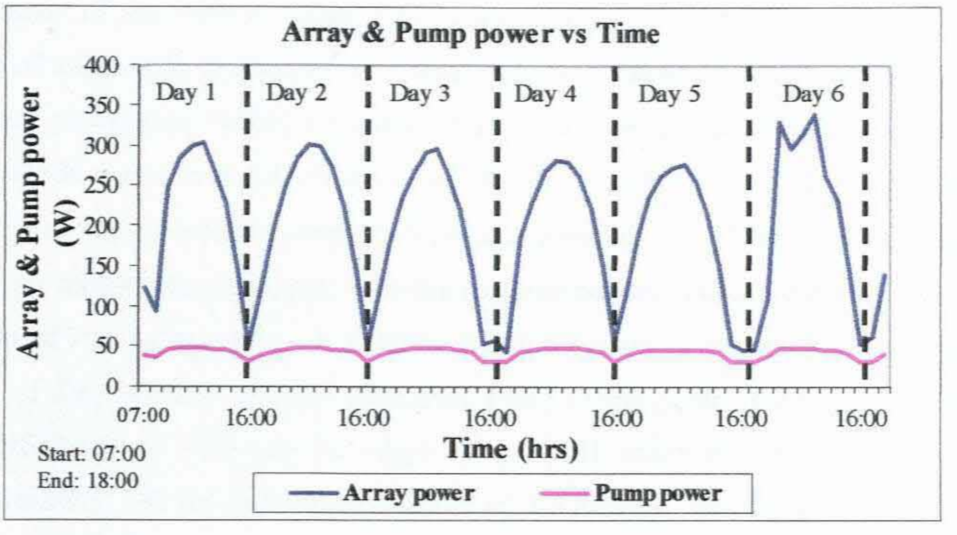


Figure 5.4: Array & pump power versus time (07/12/2004 – 13/12/2004)

5.2.2. TEMPERATURE VERSUS TIME

The following plot indicates ambient temperature over the monitoring period of six days.

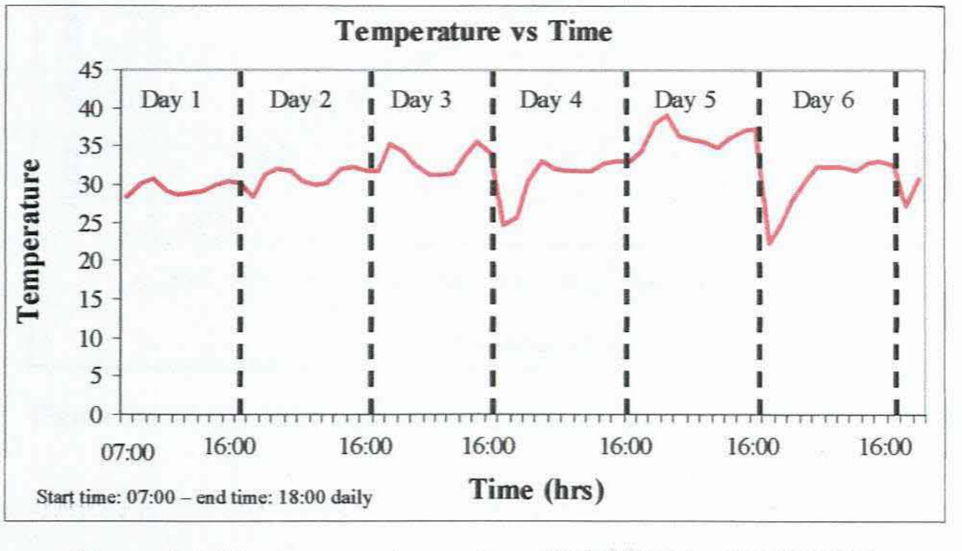


Figure 5.5: Temperature versus time (07/12/2004 – 13/12/2004)

5.2.3. ARRAY EFFICIENCY VERSUS IRRADIANCE

Efficiency of an array is the amount of solar energy the module can convert into electrical energy. Figure 5.6 below shows the efficiency of the array at different times of the trial period. The array efficiency is dependant on several factors such as; time of day, weather conditions, wind speed, and irradiance as well as the temperature of the array. The maximum array efficiency obtained was 3.9%. The obtained efficiency of 3.0% is quite low and the discrepancy of the results at high solar intensities is in part attributed to the temperature effects of solar cells at elevated cell temperatures. These high temperatures increase the irradiance power thus having a negative impact on array power generation. Another major factor which may affect the efficiency of the array, is the motor/pump efficiency. If the motor/pump draws a certain power (I×V) to pump water, even if the array can generate more power, the motor/pump will only draw the required power. This concept brings into play the question of system matching. It is either that the system is oversized or the pump itself is faulty. If the assumed optimum efficiency point of the pump is considered, the expected array efficiency of 52% can be taken, which will affect the overall system efficiency proportionately. At the operating condition of 2.6 m^3/day, the efficiency is as low as 15% (see appendix B5).

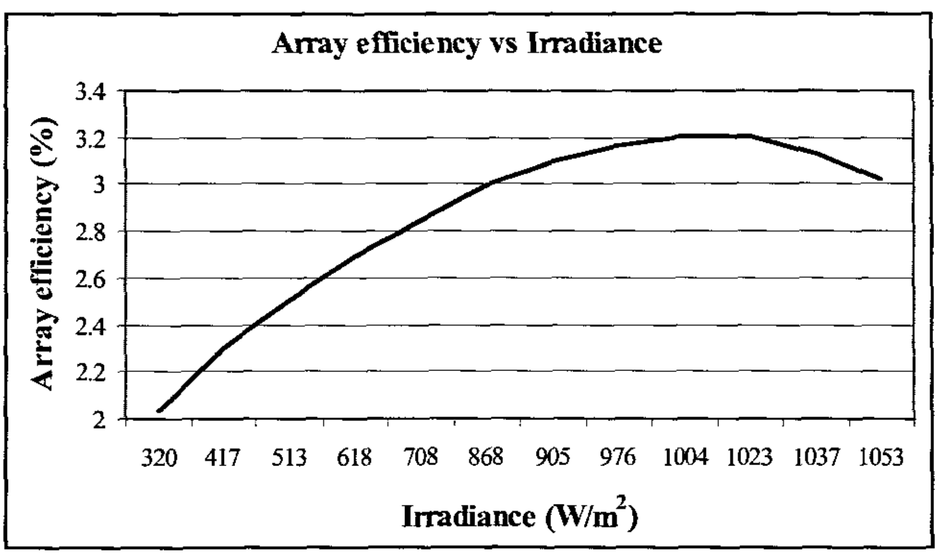


Figure 5.6: Array efficiency versus irradiance (07/12/2004 – 13/12/2004)

5.2.4. SYSTEM EFFICIENCY VERSUS TIME

System efficiency is directly proportional to power generated by the pump and inversely proportional to power generated by the panels. It is clear that system efficiency is dependent on voltage and current from the panels, system head as well as the flow rate. An average system efficiency of a 6-day trial has been calculated to be 32%. This value can be acceptable considering the fact that the pump head is 50m and Hamza *et al* (1995:495) reports a system efficiency of 30% and 36% of two villages using Grundfos centrifugal pumps. It is evident that the system efficiency increases or decreases at the same time with system head and flow.

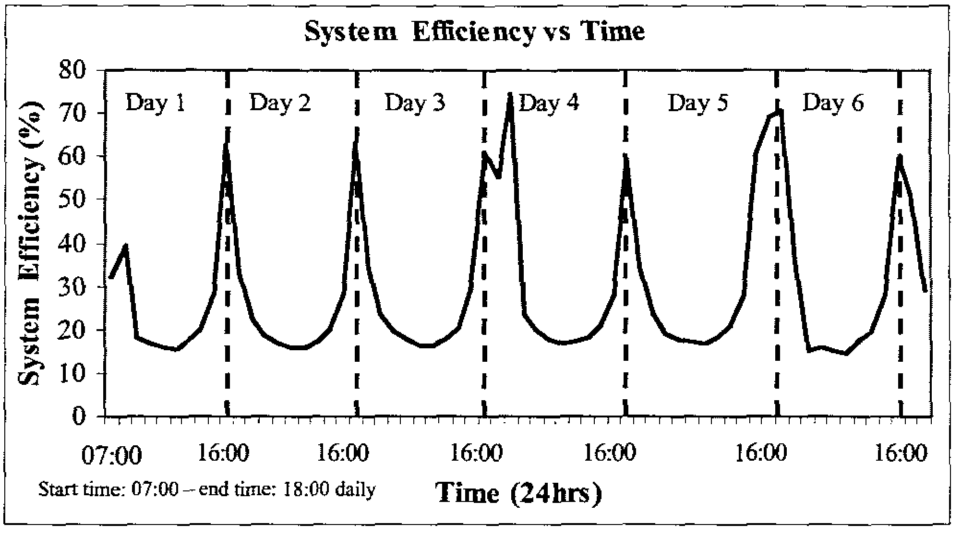


Figure 5.7: System efficiency versus time (07/12/2004 – 13/12/2004)

5.2.5. OVERALL EFFICIENCY VERSUS TIME

The overall efficiency of the system is determined by the power delivered by the pump and power from the sun (irradiance power). The graph overleaf shows the efficiencies ranging to a maximum of 3.2%, which is acceptable when one considers an overall system efficiency of 3% and 4% from the Intermediate Technology Development Group manual, (Accessed @ http://www.itdg.org/docs/technical_information_service/solar_pv_waterpumps.pdf, page 6, 24/05/2005).

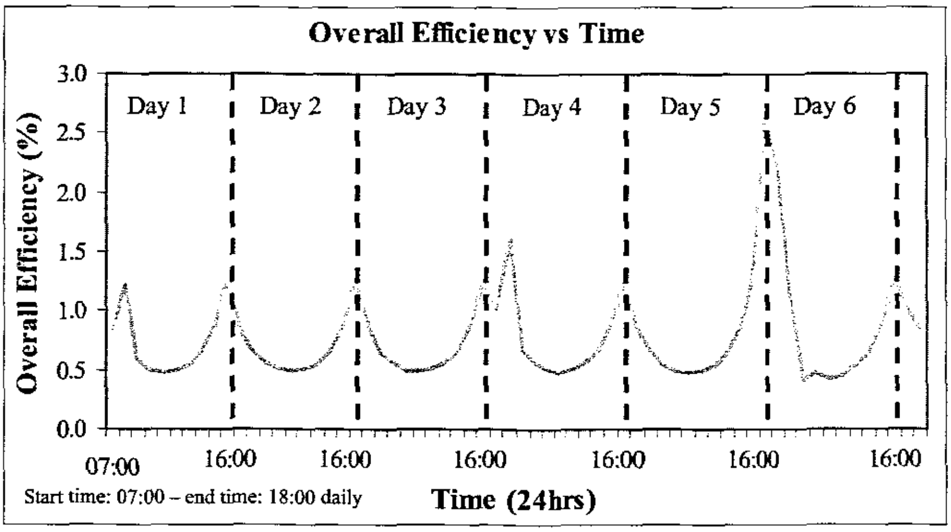


Figure 5.8: Overall efficiency versus time (07/12/2004 – 13/12/2004)

From the above results, the average efficiencies of the three subsystems are as follow:

- Array efficiency (3.0%)
- System efficiency (32.0%)
- Overall efficiency (1.3%)

If all the components were operating at their design conditions, then the following results are expected:

- Array efficiency (20%)
- System efficiency (30 – 40%)
- Overall efficiency (4%)

The efficiency of the array is quite low considering the fact that the tests were performed in summer when there are high levels of irradiance. There were some discrepancies in the results which might have been caused by the *operating conditions* of the whole system. One notable discrepancy is the efficiency of the pump. If one considers the technical specifications of the pump as well as the pumping history of this pump, it is evident that the pump was not operating according to its design specifications. It also raises a question of reliability as this pump was installed in 2001. However, there are several naturally occurring processes that can contribute to deterioration of a borehole and pumping system. Following is a list of three of the most common causes. Three common causes of deterioration - Sand, Minerals, and Bio-fouling

- Sand Production - Most wells pump some amount of sand, but over time or with an increase in the amount of sand entering the system the following may occur. Impellers can become worn to a point at which they are no longer able to lift the same amount of water as initially pumped. The sand that is pulled into the well can cause blockage in the surrounding gravel pack reducing the well's ability to pull in water. Sand pumping may also cause cavern-like formations behind the screen and/or gravel pack settling, both of which can cause failure of the well itself.

- Mineral Encrustation - Groundwater contains various levels of different minerals. The types of minerals are dependent upon the location and geology of the area where the well is located. Naturally occurring acid in groundwater keeps the minerals in solution. As the water is pumped from the well, the minerals precipitate out of the water and collect, forming a hard-scale build up on the pump, pump casing, and screen. As the scale increases, the ability of the pump to pull water into the casing and deliver it to ground level is reduced.

- Bio-fouling from Bacteria - Bacteria naturally occur in every well. The bacteria feed on iron particles in the soil and on those of the well casing and screen. If enough bacteria are present, they can form a bacterial film inside the well casing and screen, and even plug the surrounding pores of the soil. This bacterial film reduces the capacity of the borehole.

Deterioration of a system's output may be a symptom of various natural causes. Sand production, mineral encrustation, and bio-fouling due to bacteria can cause worn parts, clogged equipment and even borehole failure.

While a pump test every few years will keep tabs on the overall performance of the pump, it is also a good idea to consider having a borehole rehabilitated as necessary. How often a borehole should be rehabilitated depends on length of service of the borehole and a decrease in its specific capacity.

There are no valid judgements that can be made at this stage with regard to these short-term results. Long-term results can assist in performing valid assessments as to whether this system is reliable or not, so it is important to have enough data to check if the system behaves consistently over a period of time and to obtain information about its performance over the whole range of irradiance levels.

5.3. COST ANALYSIS

This section evaluates the cost of the PV and diesel water pumping systems. This cost is calculated over a base period of 15 years and it includes all anticipated future costs that will be incurred. Included in the analysis, is a prediction of unit and pumping costs if design conditions were achieved, i.e. flow of 20 m^3/day.

5.3.1. LIFE CYCLE COSTING

Life cycle cost analysis (LCC) gives the total cost of PV system. It includes all expenses incurred over the life of the system. There are two reasons to do an LCC analysis: to compare different power options, and to determine the most cost-effective system designs. The LCC includes the initial capital cost, the installation cost, the annual maintenance cost and replacement costs. In most cases, the operation costs of a PV system are zero since it does not require any fuel, but the remuneration of a pump caretaker will be taken as an operating cost. All the future costs are reduced to their present value by a rate which is equivalent to the opportunity cost of the capital investment. This rate is referred to as the real discount rate (dr) which can be taken to be the difference between the interest rate and the inflation rate.

The present value (PVal) is calculated as follows: $PVal = C \times \left[\frac{1}{1+dr}\right]^n$ (5.1)

Where C is the cost in terms of today's money ('05) which is being incurred n years from the present. Then, the LCC is calculated as follows: $LCC = C_{initial} + C_{install} + \sum_{n=1}^{SL} M + \sum_{n=1}^{SL} R$ (5.2)

Where $C_{initial}$ and $C_{install}$ are the initial and installation costs respectively. M and R are maintenance and replacement costs respectively. The assumptions for the LCC are that the interest and the inflation rte remain constant, that the rate of escalation is zero and that the maintenance and replacement costs have been correctly assessed. Real discount rate will be assumed to be 10% and the project lifetime to be 25 years (Cowan, 1992).

5.3.2. UNIT WATER COST

The unit water cost is useful when two water-pumping technologies are compared in terms of cost. The unit water cost takes the cost of the system and water delivered into account. The units are in cents/m^3. In order to evaluate the unit water cost the life cycle cost has to be amortised into annual amounts first. Therefore $P = LCC \times \left[\frac{(1+i)^{SL} \times i}{(1+i)^{SL} - 1}\right]$ (5.3)

Where P is the amortised annual amount, SL is the project lifetime and i is the interest rate. The real interest rate is taken to be the same as the real discount rate used equation 5.1. The unit water cost [cents/m^3] is calculated by: $Unit\ water\ cost = \frac{P}{Q_{vol:annual}}$ (5.4)

Where $Q_{vol:annual}$ is the total amount of water pumped per year in m^3. In cases where two systems are not delivering the water at the same static head the unit water cost can be stated as cents/m^4 where the unit water cost as calculated in equation 5.4 is divided by the static head (Cowan, 1992).

5.3.3. COSTS OF PV PUMPING SYSTEM

Table 5.5: PV initial costs

Lepelsfontein ('04 costs) **All costs include 14% VAT**	**Cost (R)**	**Percentage (%) of total**	**Source**
Solar panels (20 × R1,600)	36,480	34	Actual data
Solar panels (4 × R2,300)	10,488	10	Actual data
Inverter SA 1500 (1 × R8,031)	9,155.34	9	Actual data
Cables, pipes & fittings	16,518.60	16	Actual data
SP2A-15 Grundfos pump (1 × R6,196)	7,063.44	7	Actual data
Labour, installation & commissioning	8,400	8	Actual data
Supply tanks (4 × R3,700)	13,912	13	Actual data
Delivery & installation of supply tanks	4,000	4	Actual data
TOTAL	**106,017.38**	**100**	

Table 5.6: Replacement, maintenance and operating costs of PV pumping

Lepelsfontein ('04 costs)	**Cost (R)**	**Percentage (%) of total**	**Source**
Replacement costs	11,000	35	Estimated
Maintenance costs	2,805.21	9	Estimated
Operating costs	18,000	57	Estimated
TOTAL	**31,805.21**	**100**	

Since the installation of the PV system, there have been minor replacements and maintenance and they have constituted a small percentage towards the capital costs.

5.3.4. COSTS OF DIESEL PUMPING SYSTEM

Table 5.7: Replacement, maintenance and operating costs of diesel pumping

Rooifontein ('04 costs)	Cost (R)	Percentage (%) of total	Source
Replacement costs	30,780	36.3	Estimated
Maintenance costs	6,638	7.8	Actual data
Operating costs	9,600	11.3	Actual data
Fuel/yr	37,739	44.5	Actual data
TOTAL	**84,757**	**100**	

Table 5.8: Diesel set initial costs

Rooifontein ('04 costs)	Cost (R)	Percentage (%) of total	Source
Equipment	27,360	60	Actual data
Installation	8,208	18	Estimated
Prof fees	5,472	12	Estimated
Building	4,900	11	Estimated
TOTAL	**45,940**	**100**	

Table 5.9: Summary of the two water pumping life cycle costs

COSTS ('05 R)	PV SYSTEM	DIESEL SYSTEM	PV @ predicted flow
Initial costs	97,000	45,940	97,000
Operating costs (15-yrs)	184,331	213,612	184,331
15-yr life cycle cost	241,287	358,310	241,287
15-yr unit water cost (R/m^3)	15.08	3.12	2.72
15-yr energy cost (R/m^4)	0.30	0.087	0.054
20-yr life cycle cost	258,502	413,656	258,502
20-yr unit water cost (R/m^3)	12.79	2.70	2.30
20-yr energy cost (R/m^4)	0.26	0.075	0.046
25-yr life cycle cost	269,191	456,611	269,191
25-yr unit water cost (R/m^3)	11.14	2.38	11.14
25-yr energy cost (R/m^4)	0.223	0.066	0.040

While the capital costs of PV systems are two to three times higher than those of diesel systems, operating costs are typically low, as repair and maintenance are minimal and there are no fuel costs. Refer to figure 5.9 below.

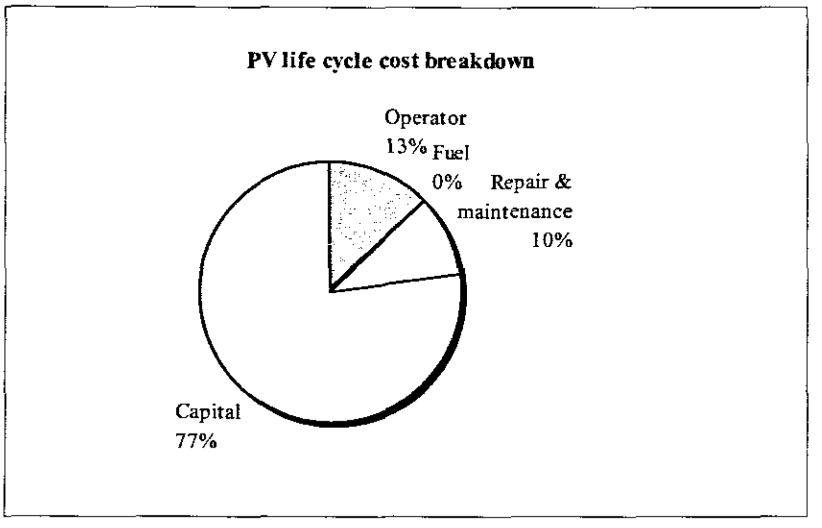


Figure 5.9: PV life cycle cost breakdown

The main problem in diesel systems is the high fuel and replacement costs as seen in figure 5.10 below. It is the high operating costs that discourage the use of diesel systems.

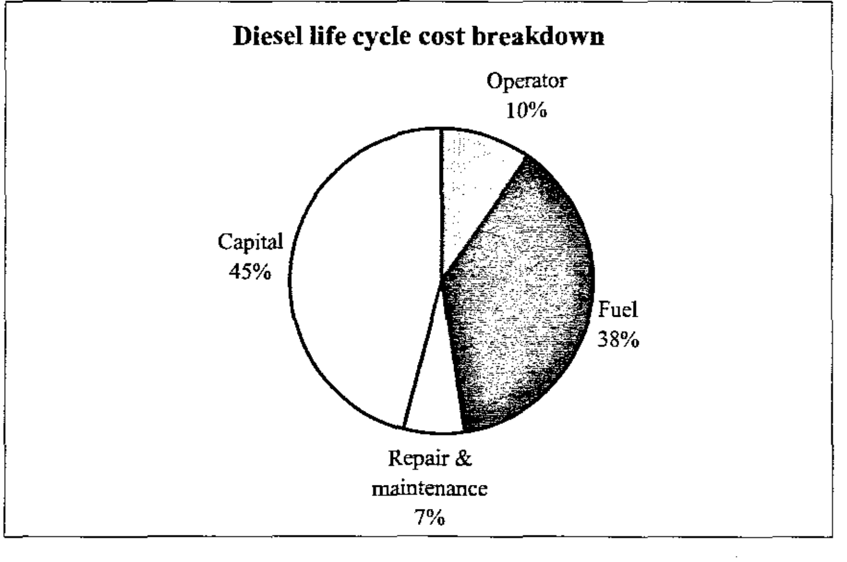


Figure 5.10: Diesel life cycle cost breakdown

Figure 5.11 below shows the relative costs of PV versus diesel over periods of 15, 20 and 25 years. Initial costs of PV are higher than that of diesel from early stages of the systems' operation. This is due to high operating and maintenance costs of diesel pumping, therefore this makes PV more economical and viable compared to diesel pumping.

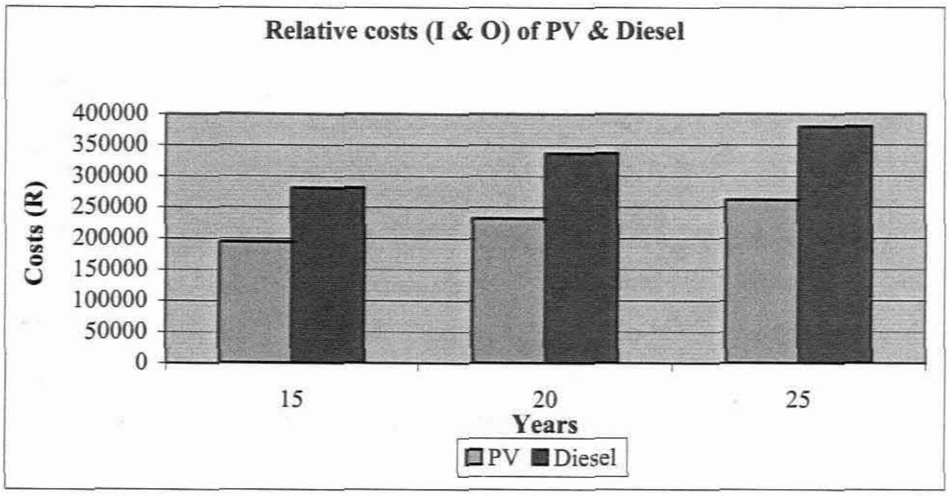


Figure 5.11: Initial & operating costs of PV & diesel

Figure 5.12 illustrates the life cycle costs in rands of PV and diesel over periods of 15, 20 and 25 years. It shows how much diesel pumping will cost after 25 years and it is far more than PV pumping due to operating and maintenance costs. Also evident are the relative costs if the PV system was to operate at design conditions, showing significantly lower costs than diesel.

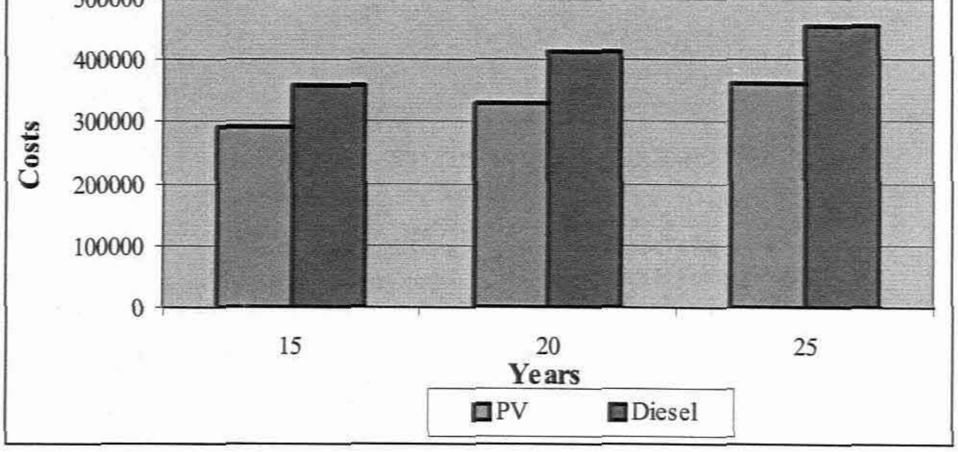


Figure 5.12: Life cycle costs of PV & diesel

It is evident from the plot below that PV initial costs are about twice higher than those of diesel system. PV enjoys low maintenance and replacement costs.

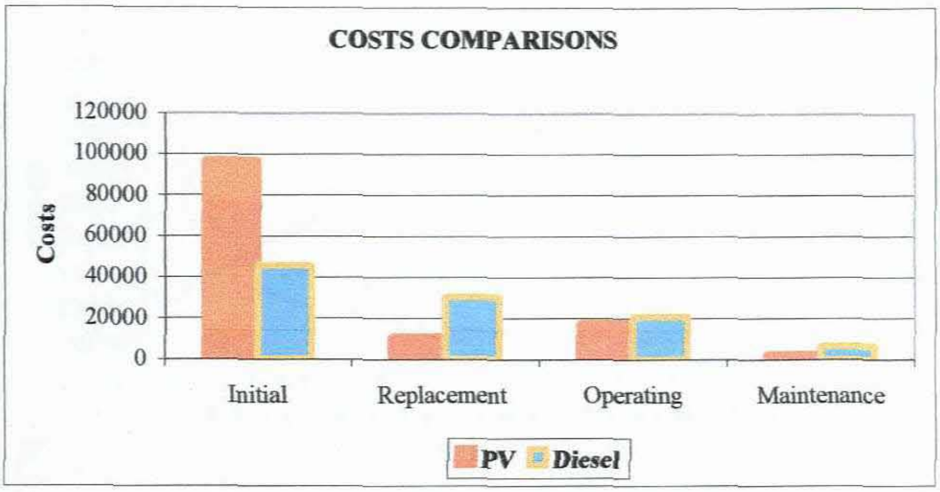


Figure 5.13: PV & diesel pumping costs comparisons

The life cycle cost analysis of the PV pumping system indicates that the average pumping costs over 25 years are likely to be below 22 cents/m^4, while pumping costs of diesel are likely to be below 7 cents/m^4 when the pump operates at 3.6m^3/day.

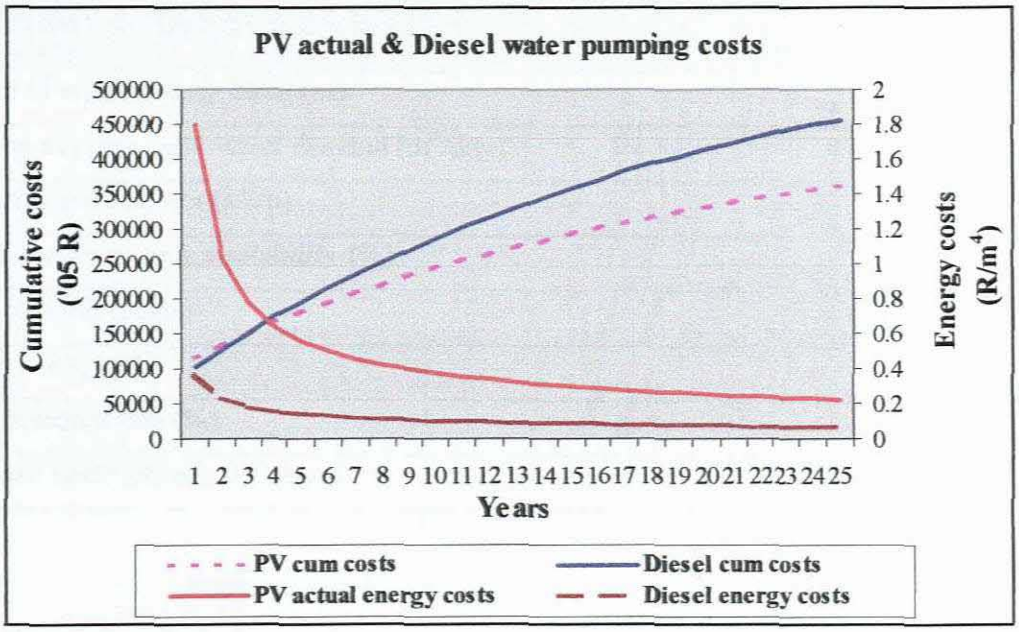


Figure 5.14: PV actual & diesel systems cumulative and energy costs

However, if the pump operated at its optimum design conditions ($20m^3$/day), then the pumping costs of PV would reduce to 4 cents/m^4, 43% less than that of diesel.

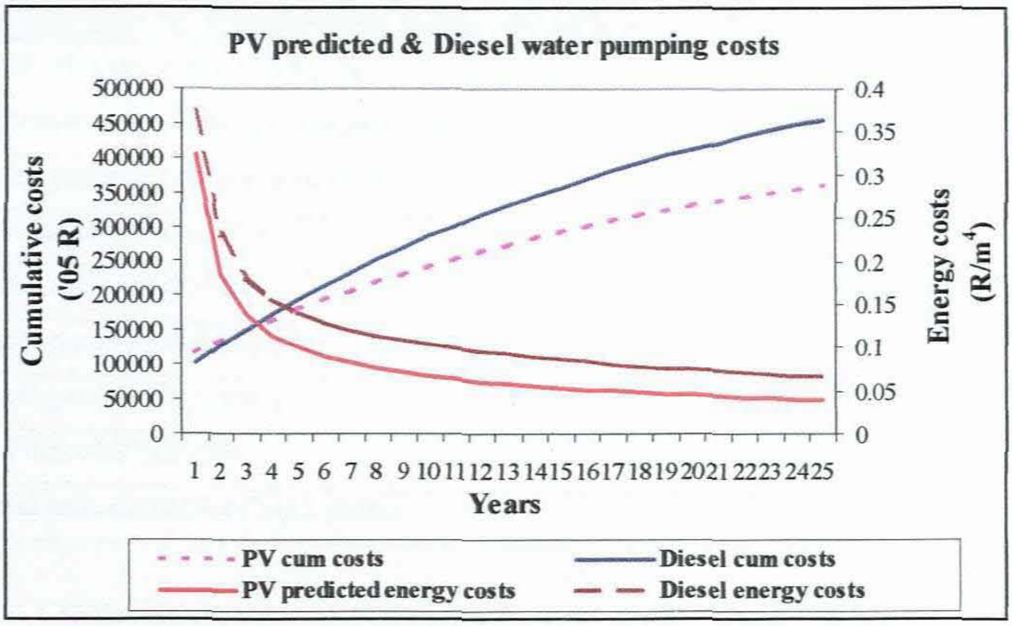


Figure 5.15: PV predicted & diesel systems cumulative and energy costs

Tables 5.10 and 5.11 show a data used for comparing PV and diesel systems.

Table 5.10: Data used for solar pumping cost comparison

PV PUMP CHARACTERISTICS	
Depth of water supply, head (m)	50
Annual average daily water demand (m^3/day)	3.6
PV array peak power (kWp)	1.7
PV pumping system availability (%)	99
PV array life (years)	25
Pump life (year)	15
Real discount rate (%)	5.2
PV unit costs (R/m^3) (15 years)	15.08

Table 5.11: Data used for diesel pumping cost comparison

DIESEL PUMP CHARACTERISTICS	
Depth of water supply, head (m)	36
Annual average daily water demand (m^3/day)	21
Diesel generator power rating (kW)	10.3
Average load factor (%)	80
Diesel fuel cost (R/litre)	3.12
Diesel pump availability (%)	97
Diesel gen-set life (years)	25
Real discount rate (%)	5.2
Diesel unit costs (R/m^3) (15 years)	3.12

5.4. COMPARATIVE ASSESSMENT OF THE TWO WATER PUMPING TECHNOLOGIES

The specific **water pumping cost** is the main criterion for an appraisal of different pumping technologies. This is the cost incurred by a pumping system, taking investment costs as well as running costs into account, to supply one cubic meter per day at a pumping head of one meter. They are expressed in R per m^4. The costs have been calculated on the basis of annuities, using a country-specific, inflation-adjusted calculatory interest rate (5.2%), and taking into account the service life of the respective component (i.e. 15 years). The specific water pumping costs depend not only on the pumping head but also on a number of other site-specific parameters, which must be accounted for. This makes it difficult to apply the results to other sites and to make generally applicable assertions regarding economic efficiency. The main parameters in question include:

- System output
- Solar irradiance
- The discount factor
- And useful life of individual system components

The objective of this section is to make a comparative life cycle analysis of the efficiency and cost of diesel and solar pumping technologies. Specifically, it aims to estimate the cost of pumping water per cubic meter using diesel and solar-power technologies over the life cycle period of the technologies, inclusive of fuel costs, costs of operations and maintenance, and other recurrent costs. A comparison of the two water-pumping options – diesel and solar-power based on current output in terms of the life cycle cost and unit-output cost was made (figures 5.9 – 5.15). Notably, the life-cycle cost of a diesel-powered pump is lower than a solar- powered pump. Annualised cost for the diesel-powered pump ranged from R33,055 to R34,992 which in contrast to the solar-powered pump was R28,626. The solar-powered pump has higher capital cost than the diesel-powered pump, but its recurrent cost declines over the economic life. The opposite was noted for the diesel-powered pump. High recurrent costs were incurred for periods requiring engine/pump replacement.

The unit-output cost for the diesel water pumping system varied from R2.83/m^3 to as much as R3.12/m^3. Figure 5.14 revealed a lower unit-output cost for diesel than the solar-powered pump. The economic analysis recorded a capital cost of R97,000 and for the PV a recurrent cost or a total life cycle cost of R364,024. Annualized cost amounted to R26,124. The economic unit cost of a solar-powered pump is R15.08/m^3. This changes to R2.72/m^3 for optimum design operation.

The maximum volume of water estimated from a 24-solar panel at full utilization is expected at 7200m^3/year depending on the location. At full capacity, unit-output cost after 25 years is estimated at R2.01/m^3 (based on 2004-05 prices) not considering wastage. Increasing the rate of utilization to its maximum would reduce unit-output cost by at least R9.13/m^3. However, operating at 75 percent utilization would result in unit-output cost of R2.67/m^3. These figures are competitive to the unit-output cost of diesel-powered pumps (R2.38/m^3 to as high as R3.12/m^3). Table 5.12 below summarizes the unit and pumping water costs of PV and diesel at different capacities and lifetimes.

Table 5.12: Summary of unit water and pumping costs at different flows for PV & diesel.

	PV				DIESEL	
Yrs	**Uwc @ 3.6m^3/day**	**Uwc @ rated flow (20m^3/day)**	**Uwc @ 75% of rated flow**	**Energy cost @ 100% flow**	**Uwc @ 21m^3/day**	**Energy cost**
15	R15.08/m^3	R2.72/m^3	R3.62/m^3	R0.054/m^4	R3.12/m^3	R0.087/m^4
20	R12.79/m^3	R2.30/m^3	R3.07/m^3	R0.046/m^4	R2.70/m^3	R0.075/m^4
25	R11.14/m^3	R2.01/m^3	R2.67/m^3	R0.040/m^4	R2.38/m^3	R0.066/m^4

From these two water-pumping technologies, the unit water cost for Lepelsfontein is about four times the unit cost of Rooifontein. These could be caused by a number of factors, including a high capital cost for Lepelsfontein, very low pump output as well as high operating costs (salary of a pump caretaker). The pumping costs for Lepelsfontein are about three times higher than those of Rooifontein. In contrast, the unit water cost is 90% that of diesel and the pumping cost is about 60% that of diesel when the design conditions for PV are assumed.

Chapter 6 is the concluding chapter. It presents the conclusions on the laboratory work as well as the fieldwork. Finally, the overall concluding remarks are made as to the success of the project.

Chapter 6

CONCLUSIONS

This chapter summarizes and concludes all the main issues emerging from the previous chapters. This chapter is structured into four sections. Section 6.1 presents general conclusions on PV and diesel water pumping. Section 6.2 summarizes the remote monitoring system. The last section (section 6.3) concludes the entire report.

6.1. PV AND DIESEL PUMPING

The findings of this study support the existing body of evidence, which indicates that PV has a place in rural water supply. The increasing number of PV water pumping systems clearly shows that the acceptance of PV technology in this sector is high. The main problem with PV pumps has been their high initial cost, but with cheaper PV modules coming onto the market and with improved system designs, this does not constitute such a barrier. The upgrading of the PV system in Lepelsfontein improved the output of the system even though the performance of the system has drastically deteriorated recently.

The introduction of PV water pumping systems in remote areas has discouraged the use of diesel water pumping. It is evident that diesel engines can deliver high flow rates even at high heads, but the costs of fuel, cost of maintenance, pollution and other obstacles make this technology less preferred. The 15-year life cycle cost indicated a unit water cost of R3.12/m^3 and an energy cost of 9 cents/m^4. The 25-year life cycle cost indicated a pumping cost of 7 cents/m^4, 43% higher than that of PV. This is because of high operating and maintenance costs of diesel and a higher pumping head of the PV system.

6.1.1. ECONOMIC ASPECTS

It is not possible to generalise about the economic viability of PV systems. Each application has to be considered on its merits, taking into account local conditions and the cost of alternatives. Although PV systems have high initial costs, they require no fuel and very little maintenance and should last many years. In many remote areas, diesel generators, the main alternative to PV generators, would be impractical due to fuel supply costs and uncertainties, plus the problems associated with maintenance and the supply of spare parts. In water pumping, PV water pumps may be cost competitive with diesel pumps for applications where the flow is low and the head is low to medium. The analysis is sensitive to the cost of diesel fuel and the life expectancy of the diesel pump. PV pumps are more likely to be viable for village water supply where social benefits are high. Even if diesel generators may appear to be cheaper on a life cycle cost comparison, it might be preferable to go for a PV system because of their operational advantages. Table 6.1 shows a summary of pumping water costs of PV and diesel over a period of 15, 20 and 25 years.

Table 6.1: Summary of PV and diesel life cycle (LCC), unit (UWC) and pumping (EC) costs

	PV					DIESEL		
Yrs	**LCC (R)**	**UWC @ 3.6m^3/day**	**UWC @ 20m^3/day**	**EC @ 3.6m^3/day**	**EC @ 20m^3/day**	**LCC (R)**	**UWC @ 21m^3/day**	**EC @ 21m^3/day**
15	293207	R15.08/m^3	R2.72/m^3	R0.302/m^4	R0.054/m^4	358310	R3.12/m^3	R0.087/m^4
20	331390	R12.79/m^3	R2.30/m^3	R0.256/m^4	R0.046/m^4	413656	R2.70/m^3	R0.075/m^4
25	361024	R11.14/m^3	R2.01/m^3	R0.223/m^4	R0.040/m^4	456611	R2.38/m^3	R0.066/m^4

6.1.2. TECHNOLOGICAL ASPECTS

Experimental experience: It would be important to talk of the accuracy of the data acquisition system (transducers, interface and data logger) because the accuracy of the transducers and the error sources in the components of the signal conditioning are available from data sheets. The collected data though, should be expressed on the basis of uncertainty. The reason for this is that the calibration of the data acquisition system is not based on the comparison to known values, but is compared to other measuring devices that have a particular accuracy. There were no serious technical problems encountered during the experiments and the experience gained from these experiments was very useful when conducting field experiments.

Field experience: The efficiencies shown in table 6.2 overleaf are a summary of experimental and field results obtained from two PV water-pumping systems (laboratory & field respectively). The average efficiency of the array was found to be 3% for a two-month monitoring period. This output is below the manufacturer's specifications. This might have been caused by several conditions such as: high solar intensities that contributed to the temperature effects of solar cells at elevated cell temperatures (increase in the temperature of the PV modules due to solar heating, lowers the PV conversion efficiency), dust that accumulates on the PV panels can also reduce the output of the panels (it should be noted that the array's structure is not projected at any height – the top part of the structure is projected at about half a meter – see figure 4.8). Bullwinkel and Hopkinson (1981) reported a 10% decrease in PV array output after 3 years of field operation due to soil accumulation on the array and degradation of system components.

It is also a possibility that the panels are gradually beginning to be less efficient considering their installation date (1991). The use of tracking PV arrays can be used to improve the performance of the panels in theory, but experience has shown that at remote sites where maintenance is difficult to provide, the extra complexity is not warranted.

The average system efficiency is calculated to be 32% for the monitoring period of two months. The results show that the pump operated at only 12% of its design volume. One cause for the pump or motor to be less effective can be overloading due to sediments in the water or tight bearings. The primary reason is attributable to the operating efficiency of the solar panels (3%).

Pump performance is heavily dependant on the assumptions made at the design stage regarding solar and water resource characteristics. Careful account has to be taken of the variations in solar input to the array, the static water level in the well and the water demand. Failure to do this can result in systems being undersized so that they fail to meet the demand, or excessively oversized, with associated additional capital cost. This system was upgraded in 2001. The pump was replaced and additional solar panels (4×55 W) were installed. Table 6.1 below shows a summary of experimental and field results.

Table 6.2: Summary of experimental and field results

	Experimental results			Field results		
	Maximum	Average	Design	Maximum	Average	Design
Array efficiency	17.3%	16.3%	20%	4%	3%	20%
System efficiency	17%	15%	32%	74%	32%	30-40%
Overall efficiency	1.8%	1.47%	6%	3.2%	1.3%	4%

6.1.3. SOCIAL ASPECTS

Experience from Lepelsfontein settlement has shown that the users now generally welcome the PV system which is in operation, provided that they be involved at an early stage in the planning process and have been given basic instruction on how to operate the system and carry out routine maintenance. No vandalism and theft have been reported to date and almost all the users know that they have to protect the system. If the community is fully involved in the development of projects like this, it is more likely that the community will take care of the installation and protect it against theft. Problems arise when a system is set down in the field by a research organization and the local people are expected to use it without any real appreciation of what is involved and without proper arrangements for follow-up. A system caretaker was appointed from the village to take care of the system's daily operation.

6.1.4. INSTITUTIONAL ASPECTS

There has been no consistent planning and project management of water supply in the Northern Cape area, partly due to many different institutions involved in this field. Implementation has thus been unplanned. The fallout of this is that there appears to have been no systematic approach in terms of system design, sizing and quality, and consequently the water supply level has sometimes been lower than expected. This is partly as a result of inadequate technical knowledge of PV systems amongst the institutions commissioning their installation, but the fact that the systems have been operating reliably to date is a reflection of the maturity of the technology and the integrity of the suppliers. The Kamiesberg municipality later came in and took control of water supply in Lepelsfontein settlement and funding the upgrading of the existing project through the Consolidated Municipal Infrastructure Programme (CMIP). Consulting engineers (Bouwer and Viljoen, Springbok, SA) did all the design work.

6.1.5. CONCLUSIONS

The technical, economic social and institutional factors associated with each application need to be carefully considered before any general conclusion can be made regarding the viability of photovoltaic water pumping. Obtaining reliable data on the performance of many PV systems is not easy and hence hampers the evaluation of the economic prospects. It is also not easy to evaluate the economic prospects, as many systems have not been in operation long enough to yield sufficient data on component lifetimes and replacement costs.

6.2. REMOTE MONITORING

The initial objective of this research was to establish a communication link between the Lepelsfontein PV system and a local ground receiving station at the Cape Peninsula University of Technology. That communication link was established and is operational. The capital and construction costs of this system were low. However, operation cost (airtime) seemed to be high, but it depended on how often and when data was downloaded from the data logger. The information provided by this system was used to;

- Determine component reliability
- Obtain information on performance degradation
- Comparatively evaluate different water pumping technologies
- And determine life cycle costs of the system.

The results from the PV station are now available and they can be downloaded at an operator's will. Long-term tests can also be performed and the results of these tests will be documented in future reports. Future work is aimed at expanding this technology to other regions of interest. An ultimate objective of this work is to develop a real time system based on a central microcomputer used as a micro-server, with a relatively low cost. A real time system will capture and measure specific data from several stations. It is important to conduct feasibility studies in order to select an appropriate communications technology for a specific village.

6.3. CONCLUDING COMMENTS

As an attempt to monitor the PV groundwater pumping systems in the remote areas of the Northern Cape Province, logical steps were followed until the final system became operational. The first step was to build a test rig to conduct laboratory assessments and preliminary tests. These experiments were done in preparation for the set up of the telemetry link required for transmission of logged PV water pump data. The preparations went quite well despite a long time taken to set up the equipment.

The next step was to construct a real time monitoring system, but prior to the construction, telemetry equipment was tested in laboratory. The installation of the system took two days. The system was tested at the base station and data was downloaded. In conclusion, the objectives of the research were achieved. This is an initial step of the on-going process of monitoring the water pumping systems in the Northern Cape.

BIBLIOGRAPHY

Ameur S, Laghrouche M & Adane: *Monitoring a greenhouse using a microcontroller-based meteorological data acquisition system,* Renewable Energy 24(2001) 19-30.

Arab A H & Chenlo F., *Performance of PV water pumping systems* International journal on Renewable Energy 18 (2) (1999) 191-204, Pergamon Press, Oxford.

Barlow R, McNelis B & Derrick A., *Solar Pumping,* An introduction and update on the Technology, Performance, Costs, and Economics, Intermediate Technology Publications and The World Bank,Washington D.C., 1993.

Benghanem M, Hadj Arab A & Mukadam K., *Data acquisition system for photovoltaic water pumps,* International journal on Renewable Energy 17 (1999) 385-396, Pergamon Press, Oxford.

Bullwinkel H.J & Hopkinson R.F: *Three-year performance study of the Mead, Nebreska, 25 kWp photovoltaic power system,* Proc. 1981 Annual Meeting American Section of the International Solar Energy Society, Vol. 4.2, pp. 1239-1243 (1981).

Burkert Easy Fluid Control Systems Manual

Chandratilleke T. T & Ho J. C: *A study of a photovoltaic array for water pumping,* Solar & Wind Technology, Vol. 3, Issue 1, pp59-71, 1986.

Cowan W.D (Ed): *RAPS design manual,* Vol 1, Energy for Development Research Centre, University of Cape Town, Cape Town, 1992.

Energy & Development Group: *Evaluation of diesel and PV water pumping systems in Namaqualand,* Noordhoek, Cape Town, September, 1996.

Gosnell R.J., *Photovoltaic water pumping: A case study in Kwazulu,* Energy for Development Research Centre, Energy Research Institute, University of Cape Town, 1991.

GTZ, 1995: *International Programme for Field Testing of Photovoltaic Water Pumps* – Final PVP Conference (27/1195 – 01/12/95). Deutsche Gesellschaft fur Technissche Zusammenarbedit (GTZ) GmbH, Eschborn.

Hadi H: *Course of Intelligent Mechanical Systems Engineering,* A Dissertation Submitted to the Faculty of Kochi University of Technology in Partial Fulfilment of the Requirement for the degree of Doctor (Philosophy), August 2003.

Hamza A.A & Taha A.Z: *Performance of submersible PV solar pumping systems under conditions in the Sudan,* Renewable Energy, Vol. 6, No. 5-6, pp. 491-495, 1995

Helikson H.J, Haman D.Z & Baird C.D: *Pumping Water for Irrigation Using Solar Energy,* Florida Cooperative Extension Service, University of Florida, 1991.

Heliotronics: *Solar Learning Lab*™ User's Guide, Inc, Hingham, 2004.

Hession P.J & Bonwick W.J: *Digital data gathering for solar energy measurement,* Solar Energy 30 (1983) 441-446, Pergamon Press, Oxford.

Hill R., *Applications of photovoltaics.* Adam Hilger, England, 1989.

Imamura M.S, Helm P, & Palz W.: *Photovoltaic System Technology,* H S Stephens & Associates, Bedford, England, 1992.

Jafar M., *A model for small-scale photovoltaic solar water pumping*, Renewable Energy 19 (1) (2000) 85-90, Elsevier Science.

Koutrolis E & Kalaitzakis K: *Development of an integrated data-acquisition system for renewable energy sources system monitoring*, Renewable Energy 28(2003) 139-152.

Lasnier F, Ang G. T, Lwin S.K & Hemasuk T,. *Photovoltaic Tests and Instrumentation,* Pumping system, Asian Institute of Technology, Thailand, 1988.

Loois G & Hemert V. B., *Stand-alone photovoltaic applications.* James & James LTD, UK, 1999.

Makhomo S.: *Installation, commissioning and preliminary testing of a photovoltaic water pumping system,* unpublished B.Tech thesis, Peninsula Technikon, South Africa, 2001.

Mukaro R, Carelse X.F & Olumekor L: *First performance analysis of a silicon-cell microcontroller-based solar radiation monitoring system,* Solar Energy Vol. 63, No. 5, pp. 313-321, 1998.

Omar I. & Law S.: *Energy Alternatives for the supply of water in Namaqualand,* Energy Research Institute, University of Cape Town, 1991.

Omar, I & Makhomo, S.: *Energy alternatives for water pumping in rural areas – Using a case study approach,* Proceedings of the 10th Domestic Use of Energy Conference, Cape Technikon, South Africa, 2002.

Omar, I & Makhomo, S.: *Remote monitoring system for Photovoltaic groundwater pumping in remote areas,* Proceedings of the 11th Domestic Use of Energy Conference, Cape Technikon, South Africa, 2003.

Oparaku O.U.: *Rural area power supply in Nigeria: A cost comparison of the photovoltaic, diesel/gasoline generator and grid utility options.* Renewable Energy 28 (2003) 2089–2098, Pergamon Press, Oxford.

Ovies S: *Personal Communication*, Lepelsfontein water pump caretaker, 2004/05.

Perez R, Kmiecik M, Herig C & Renne D.: *Remote Monitoring of PV Performance using Geostationary Satellites*, Solar Energy Vol. 71, No. 4, pp. 255–261, 2001, Pergamon Press, Oxford.

Photovoltaic Systems: Power for a new era, available @ http://www.cimat.com/buyer_guide/power.html, (06/03/03).

South African Petroleum Industry Association (SAPIA) annual report 2002, (Sapia annual report web page accessed @ http://www.mbendi.com/sapia/pubs/2002_ARep/Arepa14.htm, 26/06/2005).

Sarkar M. A. R, Obaidullah M, Mahmud Z & Martinac I: Solar PV Submersible Water Pumping for Small Scale Use in Bangladesh, Bangladesh University of Engineering & Technology, Dhaka, Bangladesh (accessed @ http//fsec.ucf.edu/ed/iasee/isree/sarkar-water.pdf, 22/06/2005)).

Scholle A.: *Evaluation of two prototype three phase photovoltaic water pumping systems,* Energy for Development Research Centre, Energy Research Institute, University of Cape Town, 1994.

Seutloali T.: *Laboratory testing and evaluation of a photovoltaic water pumping system,* unpublished B.Tech thesis, Peninsula Technikon, South Africa.

Sippola M & Sepponen R: *DC/DC Converter technology for distributed telecom and microprocessor power systems – a literature review,* Applied Electronics laboratory, Helsinki University of Technology, 2002.

System Performance Monitoring Services, available @ http://www.us.schott.com/apc/english/products/instrumentation/#data, (05/03/03).

Solar (Photovoltaic) Water Pumping Intermediate Technology Development Group, web document available @ http://www.itdg.org/docs/technical_information_service/solar_pv_waterpumps.pdf,

Toens & Vennote.: *Grondwater Monitering en Bestuur van Waterstelsels in Namaqualand,* Provinsiale Administrasie van die Provinse Noord-Kaap, Wynberg, 2001.

Virtu-Well wireless remote monitoring, web page available @ http://www.virtualtechnologiesltd.com/PDFs/Virtu-Well(TM).pdf, (06/01/04).

Wilshaw A.R, Pearsall N.M & Hill R: *Installation and operation of the first city centre PV monitoring station in the United Kingdom,* Solar Energy Vol. 59, Nos. 1-3, pp.19-26, 1997.

Witchert B, Dymond M, Lawrence W & Friese T: *Development of a test facility for photovoltaic-diesel hybrid energy systems,* Renewable Energy, 22(2001) 19-30.

Yaron G, Irving F.T & Jansson S, 1994: *Solar Energy For Rural Communities (The Case in Namibia),* Intermediate Technology Publications, University of Namibia.

APPENDICES

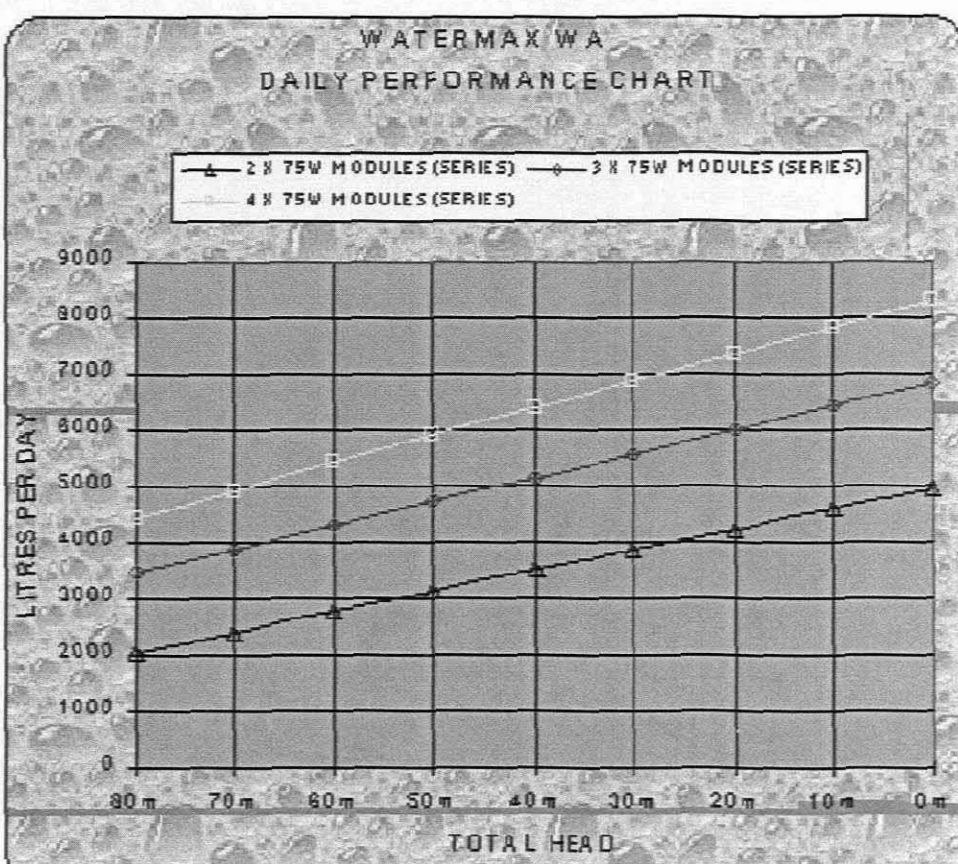
A1: Daily performance charts of watermax WA

Electrical Parameters			**SP75**		
			12V	6V	
Maximum power rating	Pmax	[Watts]	75		
Minimum power rating	Pmin	[Watts]	70		
Rated current	Imp	[Amps]	4.4	8.8	
Rated voltage	Vmp	[Volts]	17.0	8.5	
Short circuit current	Isc	[Amps]	4.8	9.6	
Open circuit voltage	Voc	[Volts]	21.7	10.9	
Physical Parameters					
Number of series cells				36	
Length			[mm] (in)	1200 (47.3)	
Width			[mm] (in)	527 (20.8)	
Depth (w/o box)			[mm] (in)	34 (1.3)	
Weight			[kg] (lbs)	7.6 (16.7)	
Warranty					
Power >= 90% of minimum power			[Years]	10	
Power >= 80% of minimum power			[Years]	25	

A2: Daily performance charts of watermax WA

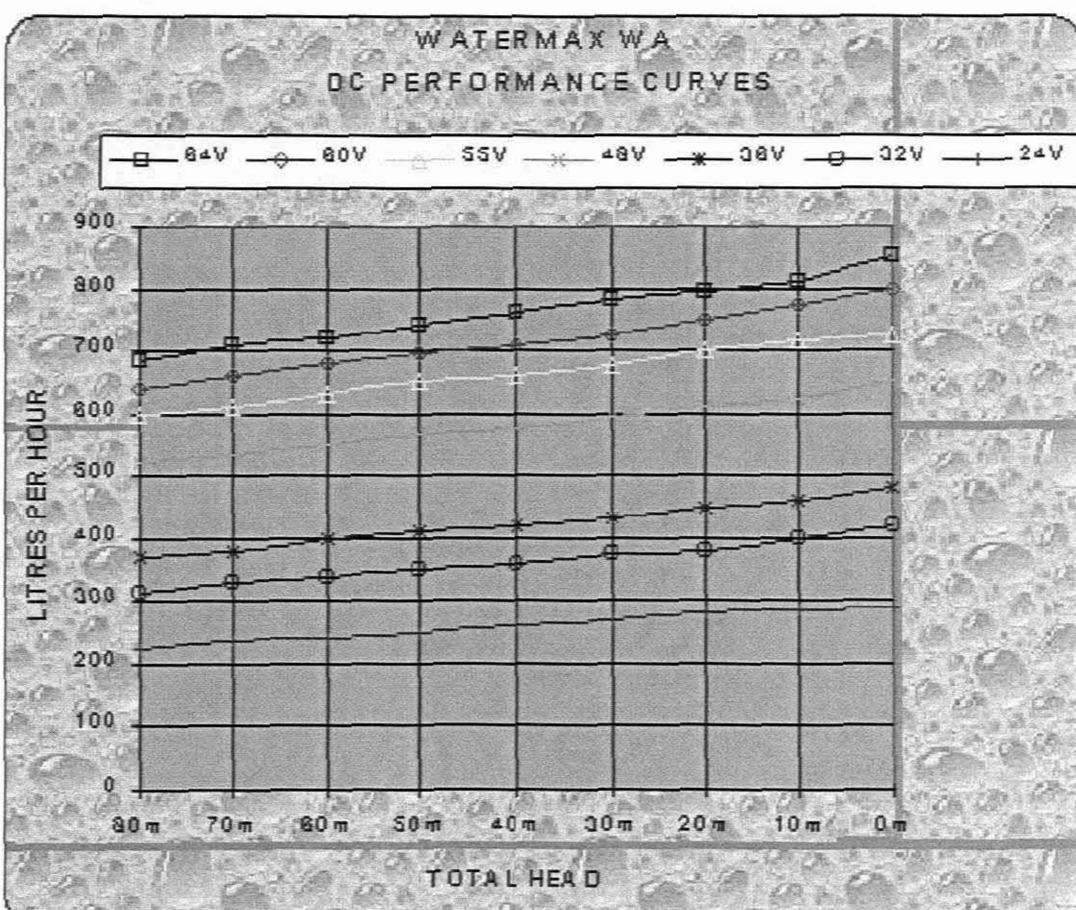
WATERMAX WA DAILY FLOWRATES						
TOTAL HEAD	2 X 60W MODULES (SERIES)	2 X 75W MODULES (SERIES)	3 X 60W MODULES (SERIES)	3 X 75W MODULES (SERIES)	4 X 60W MODULES (SERIES)	4 X 75W MODULES (SERIES)
	LITRES/ DAY	LITRES/ DAY	LITRES/ DAY	LITRES/ DAY	LITRES/ DAY	LITRES/ DAY
80m		2047	2197	3460	4017	4452
70m	1887	2412	2660	3882	4452	4933
60m	2270	2777	3123	4304	4886	5414
50m	2653	3142	3586	4726	5320	5895
40m	3036	3507	4049	5148	5754	6376
30m	3419	3872	4512	5570	6188	6857
20m	3802	4237	4975	5992	6622	7338
10m	4185	4602	5438	6414	7056	7819
0m	4570	4970	5904	6838	7490	8300

DAILY FLOWRATES ARE FOR FIXED ARRAYS ONLY
TOTAL HEAD (DAILY FLOWRATES): FROM WATER LEVEL TO POINT OF DELIVERY

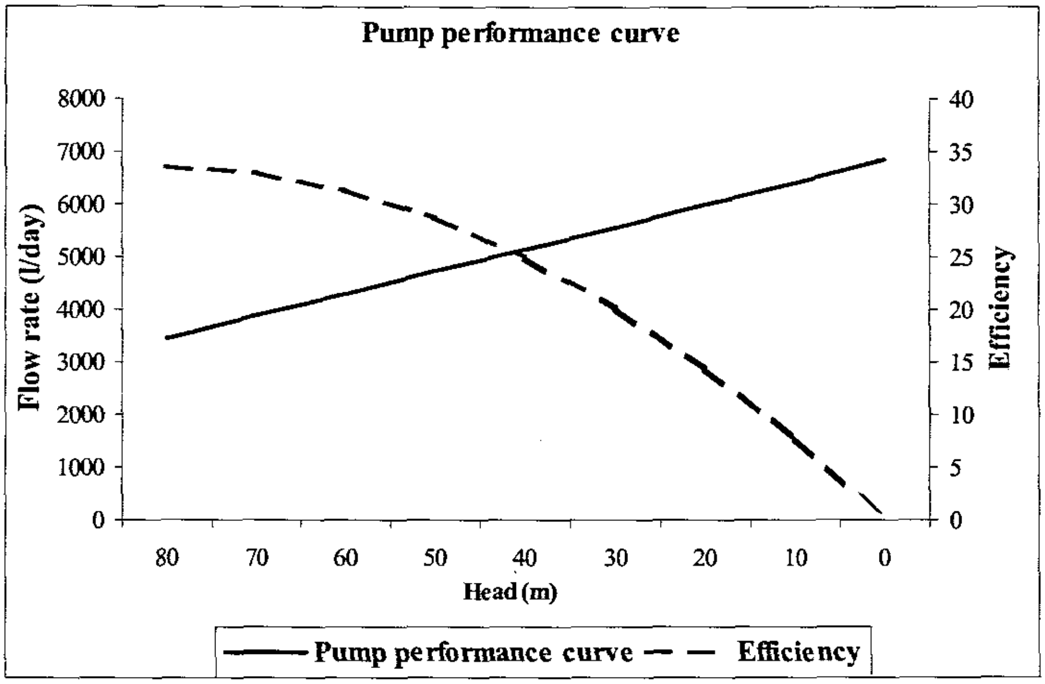


A3: DC performance charts of watermax WA pump

WATERMAX WA DC PERFORMANCE CURVES (FCC286405AS)														
	64V		60V		55V		48V		36V		32V		24V	
TOTAL HEAD	AMPS	LITRES/ HOUR	AMPS	LITRES/ HOUR	AMPS	LITRES/ HOUR	AMPS	LITRES/ HOUR	AMPS	LITRES/ HOUR	AMPS	LITRES/ HOUR	AMPS	LITRES/HOUR
80m	4.6	685	4.58	640	4.56	600	4.5	520	4.46	370	4.63	315	4.49	225
70m	4.20	710	4.20	660	4.14	610	4.11	535	4.02	380	4.07	330	4.13	236
60m	3.90	720	3.77	680	3.74	630	3.71	550	3.64	400	3.60	340	3.68	240
50m	3.55	740	3.40	695	3.35	650	3.31	565	3.24	410	3.20	350	3.23	250
40m	3.16	760	2.99	710	3.98	660	2.91	575	2.81	420	2.81	360	2.74	260
30m	2.74	780	2.56	725	2.55	675	2.54	595	2.43	430	2.39	375	2.31	270
20m	2.30	795	2.17	750	2.13	700	2.12	610	2.04	450	1.97	380	1.92	280
10m	1.89	810	1.77	775	1.72	715	1.69	625	1.62	460	1.57	400	1.47	285
0m	1.55	850	1.42	800	1.38	725	1.32	650	1.21	480	1.16	420	1.04	290
OTHER SOLAR MODULE CONFIGURATIONS ARE POSSIBLE - CONSULT MANUFACTURERS														



A4: DC performance and efficiency curve of watermax WA pump



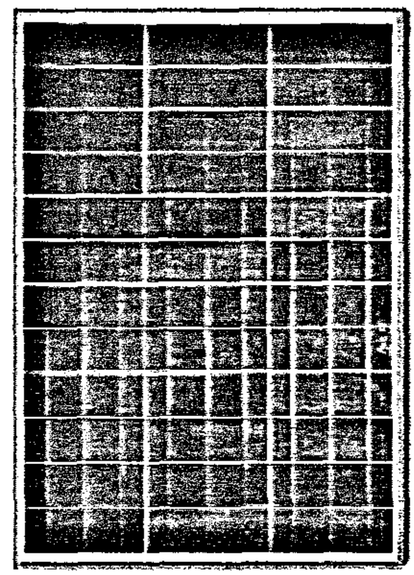
B1: Specifications of Helios PV modules

HELIOS TECHNOLOGY

H580

NEW GENERATION OF PHOTOVOLTAIC MODULES

The photovoltaic modules **H580** have been designed for the rural electrification, data survey, telecommunication and special applications. Thanks to the versatility, main characteristic of the Helios modules, they are very appreciated and used either in the developing countries or in the European markets. The recent introduction of the high efficiency cells I-Max® in monocrystalline silicon, has highly increased their performance.
At the typical battery operating voltage (12-13 Volts) the I-Max® technology, developed by Helios for the high efficiency modules, allows to obtain, differently comparing with the traditional modules, a high increase of the current (10-17%). Such characteristic makes these modules particularly suitable for stand alone systems with batteries. Made by 36 high efficiency cells I-Max® 165 x 58mm in monocrystalline silicon, these modules have been designed in order to work under the toughest operative and environmental conditions. The Helios modules have been long lasting proven of a typical average lifetime of more than 30 years.
Furthermore every single cell and module produced have been several times tested and checked throughout the manufacturing process.
Interconnections between modules are easy, practical and optimized for all configuration voltages.
Robust construction and heavy duty anodized aluminium frame design makes this module suitable secure, simple and fast to be installed in many situations.



H580 / 50W - 55W

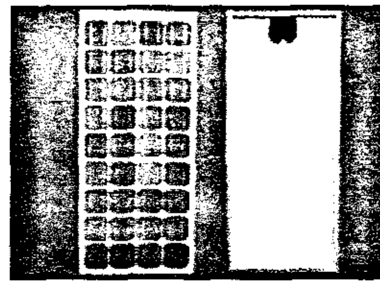
Guaranteed power ≥ 80% 25 years
Relative humidity up to 100%
Dimensions 750 x 524 x 34 ±1mm
Weight Kg. 4,60
Tolerance on technical data: ± 10%

CE

ELECTRICAL SPECIFICATIONS (at 100mW/cm², 25°C, AM 1,5)
MODULE H580

Peak Power (Wp)	**Watts**	**50**	**Watts**	**55**
Short circuit current (Isc)	Amps	3,50	Amps	3,80
Open circuit voltage (Voc)	Volts	20,80	Volts	20,90
Voltage at maximum power (Vmp)	Volts	16,66	Volts	16,67
Current at maximum power (Imp)	Amps	3,00	Amps	3,30
Typical Current at battery operating voltage (12,5V)	**Amps**	**3,15**	**Amps**	**3,4**
NOCT (Nominal operating cell temperature)	°C	43±2	°C	43±2
Change of Voc with temperature (ß)	mV/°C	-90	mV/°C	-90
Wind loading or surface pressure	N/m2 2400 (200 km/h equiv.)		N/m2 2400 (200 km/h equiv.)	
Hailstone impact resistance	24mm	at 80 km/h	24mm	at 80 km/h
Storage and operating temperature	°C	da -40 a +95	°C	from -40 to +95
Maximum system voltage	Volts	600	Volts	600

B2: Specifications of Liselo PV modules



LISELO 75W (ARX075)
MONOCRYSTALLINE PHOTOVOLTAIC
SOLAR MODULE DATASHEET

Liselo Solar Modules provide:
- Optimum solar power conversion
- High mechanical strength
- Quick, secure mounting
- Electrical continuity under extreme temperature conditions

Cell Material & Configuration : Optical Efficiency
Each module contains high quality silicon cells, in strings of cells connected in series. Individual cells are treated with a patented anti-reflective coating for enhanced optical coupling and maximum efficiency.

Module Construction : Reliability
Cells are laminated in Ethylene Vinyl Acetate (EVA), and sandwiched between high transmission, impact resistant glass, and a moisture resistant Tedlar backing. Lamination in EVA facilitates thermal expansion, provides moisture protection and ensures UV stability and electrical insulation.

Frame Construction : Mechanical Robustness
Modules have robust, extruded anodised aluminium frames, capable of withstanding wind loads of up to 200km/hour. A thin layer of silicon sealant is applied between the frame and the module, providing a further barrier against humidity, as well as a cushion against impact and thermal expansion.

Electrical Connection : Protection & Continuity
Modules are supplied with a waterproof IP65 junction box with sealed screw lid, 20mm knockout holes and compression glands for external electrical power cable feeds. Electrical connection in the junction box is directly into screw terminals on the printed circuit board containing protective bypass diodes.

Physical Mounting : Speed & Security
Modules are mounted in position via slotted holes on the frame. This provides quick, secure fixing of modules to the supporting structure.

Warranty : Continuous Operation
Modules have a typical design life of 20 years and are supplied with a 20 year limited power output warranty.

ELECTRICAL & MECHANICAL SPECIFICATIONS

Characteristic	Unit	LISELO 75W MODULE (ARX075)
Number of Cells	-	36
Cell Type		Mono 125x125mm
Module Size	mm	1215 (L) x 540 (W) x 60 (D)
Junction Box	-	Standard IP65 cover
Nominal Module Voltage	V	12
Typical Peak Power Wp	W	75.96
Voltage : Open Circuit Voc	V	21.24
Current : Short Circuit Isc	A	4.86
Voltage : Peak Power Vpp	V	17.28
Current : Peak Power Ipp	A	4.40
Module Mass	kg	8.20 (8.96 with cardboard packaging)
NOCT	°C	45
Temperature Coefficient of Voc	mV/°C	-79
Temperature Coefficient of Isc	mV/°C	1.5
Hailstone Resistance	km/h	25mm diameter @ 80km/h

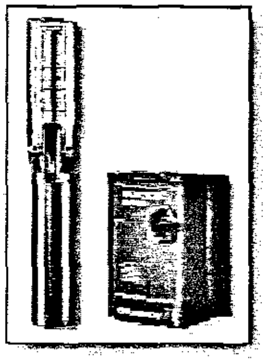
Note: All data is based on measurements made under Standard Test Conditions (STC) of insolation of 1000 Watts/m^2 (1 Sun) at a spectral distribution of AM 1.5 and a cell temperature of 25°C, and may vary by up to 10%.

LISELO (PTY) LTD
Manufacturers & Distributors of Photovoltaic Modules and Systems
57 Adriana Crescent, Gateway Industrial Park, Centurion, South Africa.
PO Box 52869, Wierda Park, 0149, South Africa.
Tel: +27 12 661-6604 Fax: +27 12 661-7165
E-Mail : info@liselosolar.co.za
ISO 9002

B3: The SA-1500 pump controller

Water Pumps

SunWize TECHNOLOGIES



Grundfos SA-1500

Grundfos

SA-1500

The Grundfos solar direct SP line of water pumps should be considered by anyone who wants to do the job right the first time. The pumps are a stainless steel centrifugal design with no diaphragms to replace and a water-cooled motor.

The Solar Pump 1500 series operates from a solar array of 7 or 8 modules in series up to 2000 watts. This series can pump water from a maximum depth of 650 feet. Common applications for this series of the Grundfos Solar Pump 1500 are campground water systems, livestock watering, irrigation, and larger community water systems.

The SA-1500 controller is a pump controller and an inverter. There are many pump control features in the controller such as maximum power point tracking, low water sensing, and float switch terminals. This controller takes the DC power from the solar array and inverts it to 65 VAC, 3 phase for the pump motors.

Accessories:

Contact your dealer for the accessories to complete your water pumping systems.

- A solar array tracker: using a tracker on a water pumping system may increase your water production up to 25%
- Submersible pump cable • Float switches • Solar modules

SOLAR PUMP 1500 PUMPS	Voltage VDC	Current	Power Wp	Flow Rate GPM	Total Vertical Lift (in feet)	Weight (lbs)	MSRP
09045029 SP1 A-28	105 to 120	14A	2000	3 to 9	328 to 656	39.9	$1,315.00
09315021 SP1.5 A-21	105 to 120	14A	2000	7 to 12	262 to 394	37	$1,290.00
09315015 SP2 A-15	105 to 120	14A	2000	7 to 20	164 to 394	34.8	$1,199.00
10315010 SP3 A-10	105 to 120	14A	2000	17 to 37	98 to 230	32.2	$1,112.00
11875005 SP8 A-5	105 to 120	14A	2000	40 to 140	7 to 92	32.9	$1,112.00
07315003 SP14 A-3	105 to 120	14A	2000	80 to 180	7 to 49	42.1	$1,224.00
CONTROLLER							
625100 SA1500 Controller	105 to 120	14A	2000			9.7	$1,558.00
CABLE TERMINATION KIT							
115099 Cable termination kit w/sock							$126.00

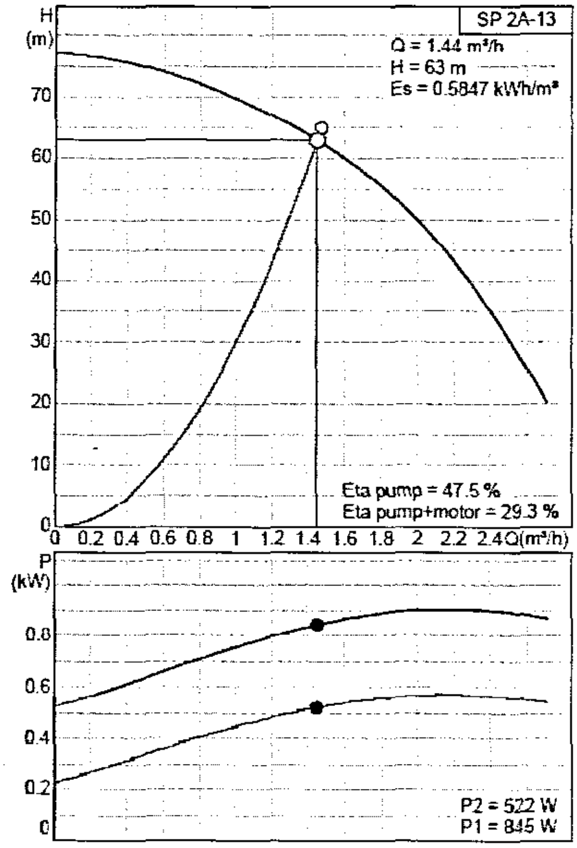
Grundfos 1500 Sizing Chart on following page

B4: Technical details of SP 2A centrifugal pump

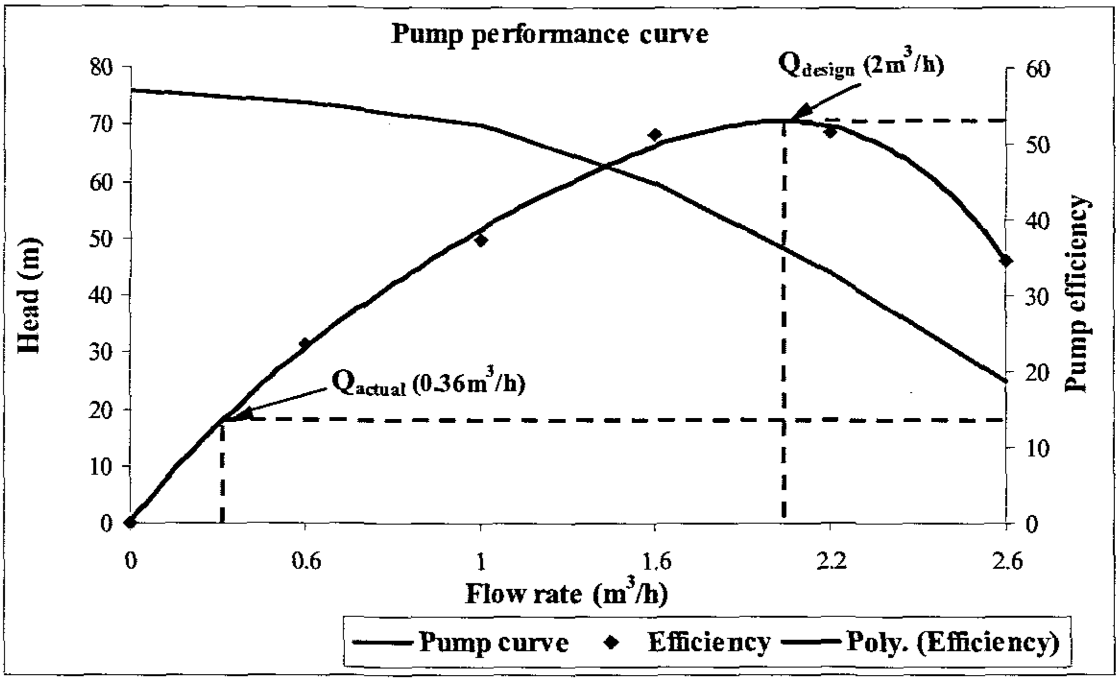
GRUNDFOS

Company name:	GRUNDFOS A/S
Created by:	Joseph Mokgwamme
Phone:	+2711 579-4800
Fax:	+2711 455-6066
Date:	23/06/2005

Description	**Value**
Product name:	SP 2A-13
Product No:	09001K13
EAN number:	5708601051302
Technical:	
Speed for pump data:	2900 rpm
Rated flow:	2 m³/h
Rated head:	52 m
Curve tolerance:	ISO 9906 Annex A
Pump No:	09000013
Stages:	13
Model:	A
Valve:	pump with built-in non-return valve
Materials:	
Material, pump:	Stainless steel 1.4301 DIN W.-Nr. 304 AISI
Material, impeller:	Stainless steel 1.4301 DIN W.-Nr. 304 AISI
Material, motor:	Stainless steel 1.4301 DIN W.-Nr. 304 AISI
Installation:	
Size, pump outlet:	Rp 1 1/4
Motor diameter:	4 inch
Liquid:	
Max liquid t at 0.15 m/sec:	40 °C
Electrical data:	
Motor type:	MS402
Applic. motor:	GRUNDFOS
P2:	0.55 kW
Mains frequency:	50 Hz
Rated voltage:	3 x 380-400-415 V
Starting method:	direct-on-line
Rated current:	2,00-2,20-2,35 A
Cos phi - power factor:	0,70-0,64-0,60
Rated speed:	2850-2860-2870 rpm
Enclosure class (IEC 34-5):	IP58
Insulation class (IEC 85):	B
Motor protec:	NONE
Thermal protec:	external
Built-in temp. transmitter:	no
Plugs mot cable:	2
Motor No:	79192003
Others:	
Net weight:	10.9 kg
Gross weight:	12.7 kg
Shipping volume:	0.012 m³



B5: An actual pump performance curve



B6: The specifications of Aerocomm (AC4486) Transceiver

Performance	**AC4486-5**	**AC4486-500** (pending)
Interface	20-pin mini connector	20-pin mini connector
Serial Data Rate	Up to 115.2 Kbps	Up to 115.2 Kbps
Power Draw (typical)	35 mA TX / 30 mA RX	TBD
Channels	Up to 2	Up to 2
Security	One-byte system ID	One-byte system ID
Radio Frequency	**AC4486-5**	**AC4486-500** (pending)
Frequency Band (software-selectable)	869.7 - 870.0 MHz (EU 5mW)	869.40 - 869.65 MHz (EU 500mW)
Modulation	FSK	FSK
Output Power (w/ 3dBi antenna)	5 mW fixed (100% duty cycle)	5 mW - 500 mW variable (10% duty cycle)
Voltage	3.3V - 5.5V	3.3V nominal +/-2%, +/-30mV
Sensitivity (@ full RF data rate)	-96 dBm	-96 dBm
Range (typical, depends on antenna and environment)	Up to 3,000 feet (914 m)	Up to 20 miles (32 km)
Environmental	**AC4486-5**	**AC4486-500** (pending)
Temperature	-40° to +80°C	-40° to +80°C
Humidity	10% - 90%	10% - 90%
Physical	**AC4486-5**	**AC4486-500** (pending)
DimDimensions	1.65 x 1.90 x 0.20 inches (4.2 x 4.8 x 0.5 cm)	1.65 x 1.90 x 0.20 inches (4.2 x 4.8 x 0.5 cm)
Weight	< 0.7 oz (< 20 g)	< 0.7 oz (< 20 g)
Antenna Connector	MMCX jack or integrated antenna	MMCX jack
Certification	**AC4486-5**	**AC4486-500** (pending)
Approvals	CE	Approvals pending.
Safety	Meets all safety and emissions requirements.	Meets all safety and emissions requirements but requires separation from the end-user to adhere to safety standards.

B7: The specifications of Samba GSM/GPRS modem

General

Tri-Band GSM/GPRS modem
E-GSM900 / DCS1800 / PCS1900 MHz
Class 4 (2W) for EGSM900
Class 1 (1W) for DCS1800 / PCS1900
Small size and low power consumption
Voice, SMS
Fax and data transmission without extra hardware
Internal 3 V SIM interface
Easy remote control by AT commands for dedicated applications
Fully type approved according to GSM phase 2+ specification
Fully shielded and ready-to-use

Electrical characteristics

Power supply: +5 V DC (trough USB port)

Physical characteristics

Dimensions: (L x W x H)
88.7 mm x 37.6 mm x 12.6 mm
Weight: 79 g
Normal range temperature: -20°C to +55°C
Restricted operation:
-25°C to -20°C and +55°C to +70°C

Interfaces

Single antenna interface
Internal SIM interface: 3 V only
USB serial link
Headset jack
Firmware upgrade:
over USB interface and SIM card

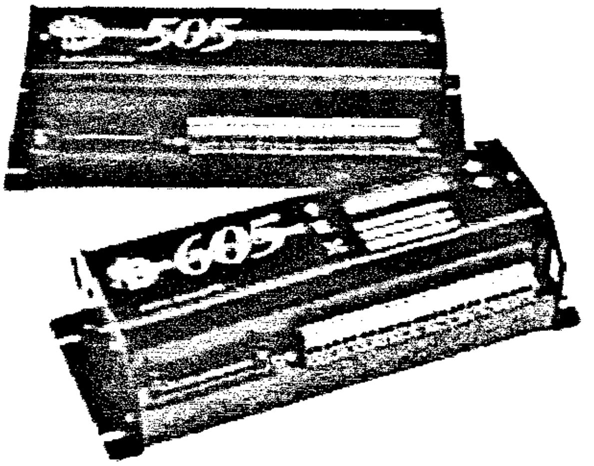
Basic features

Telephony (TCH/FS) and emergency calls; full rate, enhanced full rate, half rate and adaptive multi rate (AMR), dual tone multi frequency function (DTMF)
SMS (GSM and GPRS mode): text and PDU, point to point MT and MO, SMS broadcast
GSM circuit data features: transparent and non transparent up to 9600 bps, group 3: class 1, class 2, alternate speech and fax, MNP 2
GPRS packet data features:
data downlink transfer: max. 85.6 kbps;
data uplink transfer: max. 42.8 kbps;
coding schemes CS-1 to CS-4
WAP compliant and compliant with SMG 31
GSM supplementary services: call forwarding, call barring, multiparty, call waiting and call hold, calling line identity, advice of charge, USSD, closed user group

Other features

SM, FD, LD, MC, RC, ON, ME + SIM phone book management
Fixed dialing number, SIM toolkit class 2
SIM, network and service provider locks
Real time clock
Alarm management
UCS 2 character set management

C1: Specifications of DATA TAKER 605



The Datataker 505 and 605 are microprocessor based, battery powered data loggers which measure inputs from most sensor types. Analog input channels are relay multiplexed, providing higher voltage measurement range, greater common mode range and tolerates larger withstanding voltages than Datataker 500 and 600.

Data manipulation includes statistical functions, calculations and sensor calibration. Data is stored in battery backed RAM and removable memory cards. Alarms can be set for all channels.

The Datataker 605 has an integral display and keypad.

Suitable for scientific, industrial and public utility applications.

Analog Inputs

- 10 differential or 30 single ended, can be used in any mix.
- Expansion by external modules with 10 differential or 30 single ended analog input channels. Maximum two modules supported.
- Autocalibrating and autoranging, 4 decades.
- Resolution 15 bit plus sign, 1µV.
- Sampling rate 25 samples/second.
- Accuracy better than 0.15% of full scale.
- Linearity better than 0.05%
- Input impedance 1MΩ, or >100MΩ selectable.
- Common mode range ±100VDC.
- Input withstanding voltages for analog channels
  - Unselected channels - ±1.5KVDC for 10µS
    - ±500VDC for 50mS
    - ±100VDC continuously
  - Selected channels - ±100VDC continuously
- Common mode rejection >90db, 110db typical.
- Series mode line rejection >35db
- Sensor excitation of 5V, 250.0µA or 2.500mA each channel.
- 4, 3 and 2 wire resistance, RTD and thermistor measurement.
- Full, half and quarter bridges, voltage or current excitation.
- Relay multiplexer.

Digital Inputs

- 4 TTL/CMOS compatible digital input channels for digital state, byte, events and low speed counters 10Hz, 16 bit, presettable.
- Digital inputs share with digital output channels.
- Expansion by external modules.
- 3 high speed counters, 1KHz normally, or 1MHz optionally. 16 bit, presettable.
- Analog channels also read digital state, user definable threshold.

Ranges

Input Type	Range	Units	Resoluti
DC Voltage	±25.000	mV	1µV
	±250.00	mV	10µV
	±2500.0	mV	100µ
	±100.00	V	10mV
DC Current	±0.2500	mA	200n
Internal Shunts	±2.500	mA	1µA
	±25.00	mA	10µA
External Shunts	Any range	mA	
4-20mA Loop	0 to 100	Percent	0.01%
Resistance	10.000	Ohms	0.5mΩ
	100.00	Ohms	5mΩ
	500.0	Ohms	50mΩ
	7000.0	Ohms	500mΩ
Frequency	0.1 to 300,000.0	Hz	0.001H
Period	30,000 to 3	µSec	1µS
Temperature	-250.0 to 1800.0	Deg C	0.1%
	-420.0 to 3200.0	Deg F	0.1%
Strain Gauges	-10^4 to 10^4	ppm	1ppm
and Bridges	-10^5 to 10^5	ppm	10ppn
	-10^6 to 10^6	ppm	100ppr
Digital Bit	0 or 1	State	1
Digital Byte (4 bits)	0 to 15	State	1
Digital Average	0.00 to 1.00	State	0.01
Counter	0 to 65535	Counts	1
Phase Encoder	0 to 65535	Counts	1
Analog State	0 or 1	State	1

Temperature

- Thermocouple types B, C, D, E, G, J, K, N, R, S and T, with colc junction compensation and linearization.
- Platinum RTDs, α=0.00385 & 0.003916Ω/Ω/°C, any resista
- Nickel RTDs, α=0.005001Ω/Ω/°C, any resistance.
- Copper RTDs, α=0.0039Ω/Ω/°C, any resistance.
- Thermistors, Yellow Springs YSI 400xx series.
- Semiconductors, AD590, LM335, LM34 and LM35.

Time and Date

- Resolution 1 second, accuracy 2 seconds/day.
- Date in DD/MM/YYYY, MM/DD/YYYY, day number and decim
- Time in HH:MM:SS, seconds SSSSS and decimal hour HH.HHI
- 4 auto-incrementing internal timers (second, minute, hour ar of week) for use in sequencing, alarms, calculations, etc.
- Real time clock used for scan scheduling, date and time stam data, alarm timing and in calculations.

Digital Outputs

- 4 TTL/CMOS compatible digital output channels for switched outputs, relay control, alarm annunciation, sensor support.
- Open collector lines, rated to + 30VDC @ 200mA.
- Digital outputs share with the digital input channels.
- 3 LEDs, display backlight and beeper on the display panel.
- Expansion by external modules.

Scanning Input Channels

- 1 immediate scan schedule, can include one or more channels.
- 4 repetitive scan schedules, can include one or more channels.
- Time based scanning in increments of 1 sec, 1 min, 1 hour or 1 day.
- Event based scanning on digital or counter channel events.
- Poll based scanning initiated by host requests.
- Conditional scanning while any digital input is high.

Data Scaling

- Data read from input channels in terms of electrical units can be scaled to engineering units. All data manipulation is then performed on the scaled data.
- Up to 20 definable linear spans, declared as span co-ordinates.
- Up to 20 definable polynomials, from 1st to 5th order.
- Other forms of sensor calibration can be implemented using mathematical expressions.

Data Manipulation

- Statistical data including average, standard deviation, minimum and maximum with date and time of min and max, and integral.
- Delta, rate of delta (differential) and integral between scans.
- Histogram, with definable number of classes.
- Expression evaluation using channel data and constants, arithmetic, logical and relational operators, log, trig, and other functions.

Alarms

- Alarms for monitoring input channels for high and low alarm, inside and outside of range alarm, with definable setpoints.
- Alarms can be combined by AND, OR and XOR operators.
- Optional delay period before an out of range condition is considered a true alarm, or recovery considered a true recovery.
- Alarms can switch digital outputs & display panel LEDs, return text to the host, trigger scanning, and execute Datataker commands.

Data Storage

- Battery backed internal RAM, stores up to 13,650 readings.
- Removable memory cards, store up to 340,000 readings.
- Stack and circular buffer (overwrite) data storage modes.
- No data loss when memory cards are exchanged.
- Stored data can be returned for individual scanning schedules, and for selectable date and time periods.

Data Format

- All data in ASCII floating point, fixed point or exponential formats.
- Data format is user configurable for channel identification, data resolution, units text and delimiters.
- Selectable host computer data format with bi-directional error detection protocol.
- Compatible with spreadsheets, graphic and statistical packages, etc.
- Compatible with most computers, modems, radio, and satellite.

Programming

- All programming is by simple descriptive commands, which are entered from a host computer via the serial interface.
- Commands can be pre-recorded into a memory card, and these are automatically executed whenever a memory card is inserted.

Display and Keypad (DT605 only)

- LCD type, 2 line x 16 character, backlit, alphanumeric.
- Displays channel data, alarm status and system information.
- 5 key keypad for display selection, scrolling, backlight.
- Keypad also provide 4 user definable function keys.
- 3 LEDs, beeper and flashing backlight provide warnings for alarms.

Host Communications

- RS232, full duplex. Also supports RS423.
- 300, 1200, 2400 and 9600 baud, switch selectable.
- Bi-directional XON/XOFF protocol.
- Compatible with computers, terminals, modems, satellite ground terminals, serial printers, etc.

Network Communications

- RS485, with error correcting protocol.
- Connected via a twisted pair, maximum 1000 metres.
- Up to 32 loggers can be in a Datataker network, with one host.

Power Supply

- Voltage 9 – 18VAC or 11 – 24VDC external power.
- Mains powered from 12VAC/DC mains adaptor.
- Automatically selects low power standby (sleep) mode.
- Current draw 120mA normal power mode, 400mA when charg internal battery, <350μA low power (sleep) mode.
- Internal 1.2Ah gel cell battery, recharged by external power.
- Approximate battery life for different schedules and battery size

Sampling 10 channels every	1.2Ah Gel Cell Battery	17 Ah Alkaline Battery
Continuously	5 hours	3 days
1 minute	12 days	160 days
15 minutes	60 days	800 days
1 hour	110 days	1100 days

Mechanical Specification

- Robust modular construction using powder coated steel.
- Can be used directly, or housed in fixed or portable enclosures
- Length 270mm (10.5 inches), Width 110mm (4.3 inches).
- Height 85mm (3.3 inches) with no memory card inserted.
- Height 105mm (4.2 inches) with a memory card inserted.
- Weight 2.4Kg.
- Signal I/O connection by screw terminals.
- Operating temperature –20 to 70 °C, humidity 95%.

Accessories Included

- 110/240VAC mains/line power adaptor.
- 1.2Ah gel cell internal battery.
- RS232 communications cable for IBM™ and compatibles.
- Getting Started Manual and User's Manual.
- DeTerminal software package for IBM™ and compatibles.

Options

- Channel expansion modules with 10 differential/30 single end analog inputs, and 20 digital inputs, and 10 digital outputs.
- Portable carry case, clamshell design, waterproof (IP67, NEM
- Industrial quality steel enclosures (IP65, NEMA 5).
- 4Ah rechargable gel cell or 17Ah alkaline battery.
- 64K Datataker memory card, stores 16,000 readings.
- 256K Datataker memory card, stores 81,000 readings.
- 512K PCMCIA memory card, stores 170,000 readings.
- 1M PCMCIA memory card, stores 340,000 readings.
- PCMCIA memory card adaptor.
- Memory card readers.
- Communications cable for Apple Macintosh™.
- DeCipher Plus software package for IBM™ and compatibles.

Ordering

• Datataker with display	DT605
• Datataker without display	DT505
• Channel expansion module	CEM
• Portable carry case	PE
• Small industrial enclosure	SIE
• Large industrial enclosure	LIE
• Small industrial cabinet	SIC
• 64K Datataker memory card	MC-64
• 256K Datataker memory card	MC-256
• 512K PCMCIA memory card	MC-512P
• 1M PCMCIA memory card	MC1024P
• PCMCIA memory card adaptor	MC-ADP
• Memory Card Reader - RS232 Interface	MC-RS
• Memory Card Reader - Centronics Interface	MC-RP

C2: Specifications of flow transmitter

Digital Flow Transmitter

Type 8035

for continuous flow measurement and batch control

Plastic-INLINE

Technical data

General data

Pipe diameter	from DN 15 to DN 50 (1/2" to 2")
Measuring ranges	as from 1 l/min (DN15 pipe, 0,1 m/s flow velocity)
	as from 0.3 gpm (1/2" pipe, 0.3 fps flow velocity)
Fluid temperature	PVDF: 0 to 100°C (32 to 212°F)
	PP: 0 to 80°C (32 to 176°F)
	PVC: 0 to 60°C (32 to 140°F)
Ambient temperature	0 to 60°C (32 to 140°F)
Storage temperature	-10 to 80°C (14 to 176°F)
Pressure rating	PN 10
Max. fluid pressure	16 bar (235 psi)
Enclosure	IP 65
Measuring range	0,1 to 10 m/s (0.3 to 32.8 fps),
Accuracy	< 1% within 0,5...10 m/s (1.6 to 32.8 fps) (*)
	< 5% within 0,3...0.5 m/s (1.0 to 1.6 fps) (*)
Repeatability	0,4% of measured value (*)
Display	15 x 60 mm, 8-digit LCD-display, alphanumeric, 15 segments, 9 mm large
Fitting	PVC / PP / PVDF
Sensor holder	PVC / PP / PVDF
Paddle-wheel	PVDF
Axis and bearing	ceramic
O-rings	FPM standard
Housing	PC
Front plate foil	polyester

(*) In reference conditions (water, 20°C, ideal installation)

Specific data Flow Transmitter

Voltage supply	12...30 VDC
	Option: 115/230 VAC power supply
Output signal	4...20 mA
Load	max. 900 Ω at 30V
	max. 500 Ω at 24V
	max. 100 Ω at 15V
	max. 800 Ω with power supply 115/230 VAC
Pulse output	Open collector NPN and PNP, 0...30 V, 100 mA, protected
	Option: relay Reed closing 0,1 sec., opening depending on flow rate 0,1 sec. min. max. 34 V, 0.2 A
Relay output (option)	2 relays, freely programmable, 3 A, 230 V

Specific data Flow Switch

Voltage supply	12...30 VDC
	Option: 115/230 VAC power supply
Relay output	freely programmable, 3 A, 230 V

Specific data Batch Controller

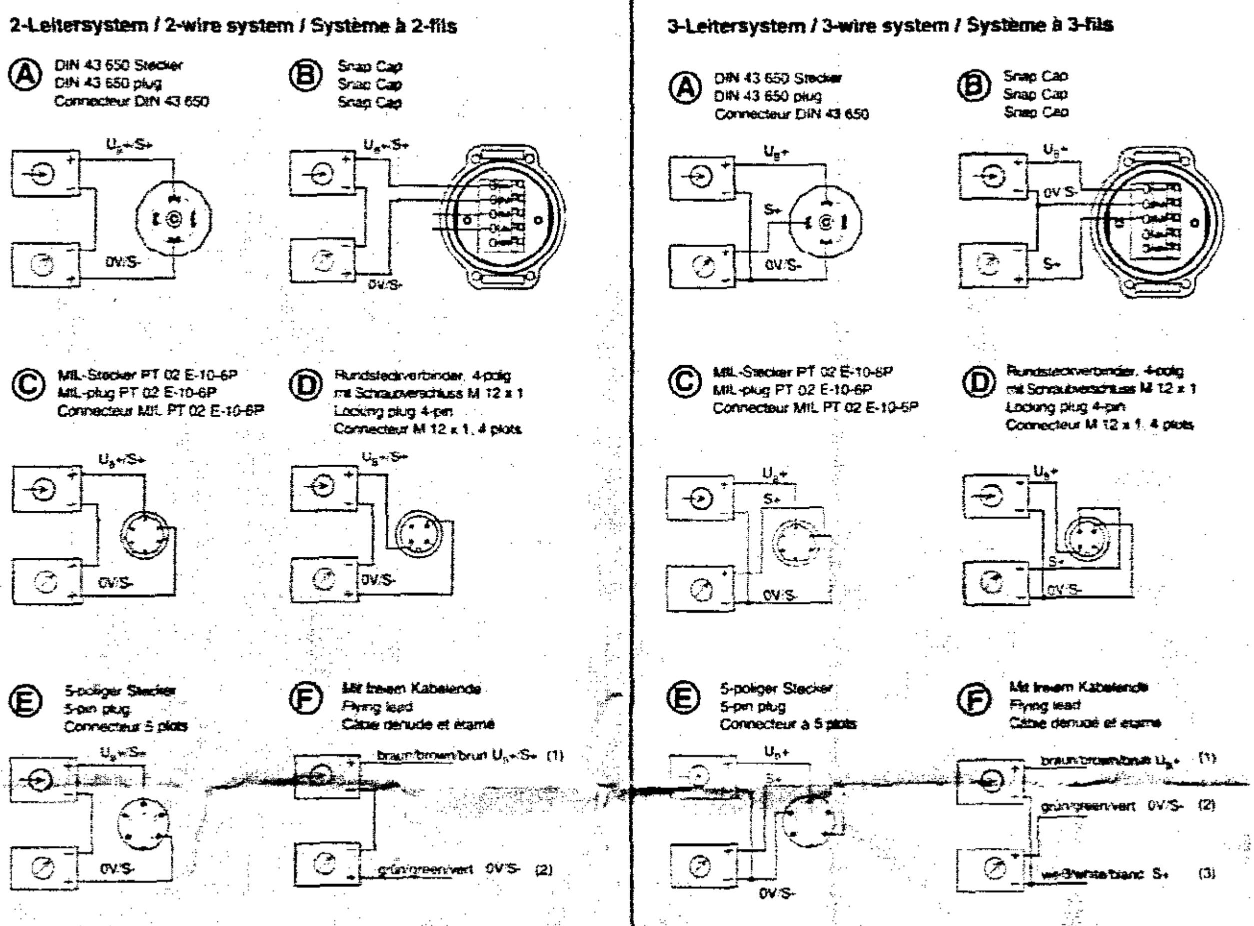
Voltage supply	12...30 VDC
	Option: 115/230 VAC power supply
Digital inputs	4 inputs, 5...30 VDC
Digital output	1 input, Open collector NPN and PNP, 0...30 V, 100 mA, protected
Relay output	2 relays, freely programmable, 3 A, 230 V

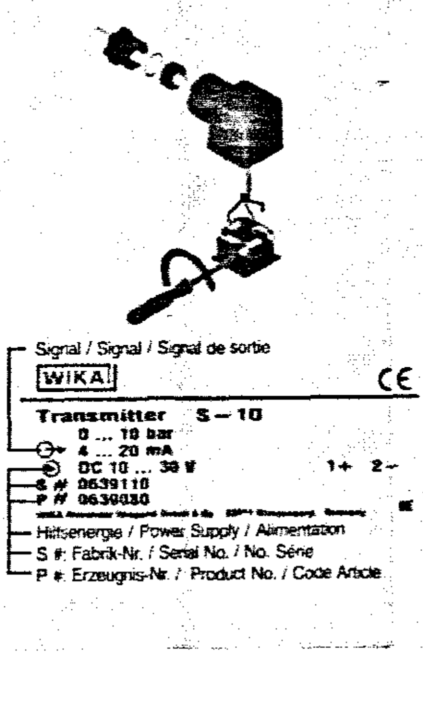
Specific data Stand Alone (Battery)

Voltage supply	9 VDC battery supply
Autonomy	3...4 years with lithium batteries
	1...2 years with standard batteries

C3: Specifications of pressure transmitter

2. Elektrischer Anschluss / Wiring / Branchement électrique

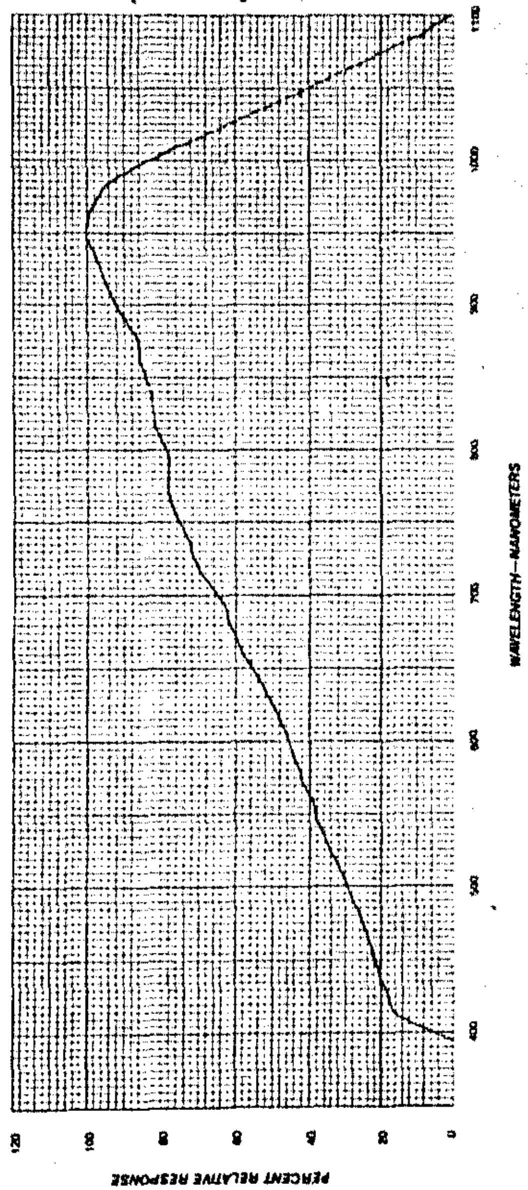




3. Zubehör / Accessories / Accessoires	Order No.
G 1/2 Einschweißadapter / weld-on adaptor / embase à souder	11 92299
G 1 Einschweißadapter / weld-on adaptor / embase à souder	11 92264
G 1/2 WIKA-Dichtung / WIKA-sealing / WIKA-joint torique	9092099
G 1/4 WIKA-Dichtung / WIKA-sealing / WIKA-joint torique	9092161
G 1/2 Kühlelement / Cooling element / Elément de refroidissement	16 04791
G 1/2 Anschlussstück mit integriertem Filtereinsatz / G 1/2 Adaptor with inset filter / G 1/2 Raccord avec filtre	9092005
G 1/2 Drossel, max. 400 bar/ Throttle, max. 400 bar / G 1/2 Raccord amortisseur, max. 400 bar	90 91262

C4: Data sheet of LI-COR pyranometer

Figure 5. LI-200SZ Spectral Response Curve.



SPECIFICATIONS

Calibration: Calibrated against an Eppley Precision Spectral Pyranometer (PSP) under natural daylight conditions. Absolute error under these conditions is ± 5% maximum, typically ± 3%.
Sensitivity: Typically 80 μA per 1000 W m^{-2}.
Linearity: Maximum deviation of 1% up to 3000 W m^{-2}.
Stability: <± 2% change over a 1 year period.
Response Time: 10 μs.
Temperature Dependence: ± 0.15% per °C maximum.
Cosine Correction: Cosine corrected up to 80° angle of incidence.
Azimuth: <± 1% error over 360° at 45° elevation.
Tilt: No error induced from orientation.
Detector: High stability silicon photovoltaic detector (blue enhanced).
Sensor Housing: Weatherproof anodized aluminum case with acrylic diffuser and stainless steel hardware.
Size: 2.38 Dia. x 2.54 cm H (0.94" x 1.0").
Weight: 28 g (1 oz.).
Accessories: 2003S Mounting and Leveling Fixture.
Cable Length: 3 meters (10 ft) standard. LI-200SZ-50: 50 ft.

Experimental results (24/08/04 - 30/08/04)

Date	Time	Flow	Irradiance	Mo Vol	Pan Vol	Press	Temp	Int temp	Pa Shnt	Mot Shnt	Hdyn	Ht	Pirr	Parr	Pcon	Ppump	Effarr	Effcon	Effsys	Effover	Effpu
8/24/2004	11:00	17.7	762	83.9	84.3	3.1	18.0	21.9	0.14	0.14	0.0	5.0	2256	117	114	14.5	5.2	97.3	12.4	0.6	12.7
8/24/2004	11:30	18.1	821	84.3	84.6	16.5	18.2	22.2	0.14	0.14	0.2	5.1	2430	117	114	15.2	4.8	97.4	12.9	0.6	13.2
8/24/2004	12:00	17.4	866	83.6	83.9	9.0	18.4	22.4	0.14	0.14	0.1	5.1	2564	117	114	14.4	4.5	98.1	12.3	0.6	12.6
8/24/2004	12:30	17.8	890	83.7	84.1	0.9	18.6	22.6	0.13	0.13	0.0	5.0	2635	112	110	14.5	4.2	98.4	13.0	0.5	13.2
8/24/2004	13:00	17.0	901	83.6	83.9	0.0	18.8	22.8	0.14	0.13	0.0	5.0	2666	114	112	13.8	4.3	97.9	12.0	0.5	12.3
8/24/2004	13:30	17.4	887	83.9	84.2	18.3	19.0	23.0	0.13	0.13	0.2	5.1	2626	114	111	14.7	4.3	97.7	12.9	0.6	13.2
8/24/2004	14:00	17.7	857	83.8	84.3	5.7	19.1	23.2	0.13	0.13	0.1	5.0	2536	113	111	14.5	4.4	98.4	12.9	0.6	13.1
8/24/2004	14:30	16.8	808	84.5	84.8	0.0	19.3	23.3	0.13	0.13	0.0	5.0	2393	113	109	13.6	4.7	96.5	12.1	0.6	12.5
8/24/2004	15:00	17.8	745	84.2	84.6	6.1	19.5	23.4	0.14	0.14	0.1	5.0	2206	116	114	14.6	5.3	98.1	12.6	0.7	12.8
8/24/2004	15:30	17.6	665	84.0	84.3	0.5	19.6	23.5	0.13	0.13	0.0	5.0	1969	112	110	14.3	5.7	97.5	12.7	0.7	13.0
8/24/2004	16:00	17.5	568	83.7	83.9	0.0	19.3	23.5	0.13	0.13	0.0	5.0	1681	111	108	14.2	6.6	97.3	12.7	0.8	13.1
8/24/2004	16:30	17.3	460	82.0	82.4	0.5	19.0	23.4	0.13	0.13	0.0	5.0	1363	111	109	14.0	8.1	98.3	12.7	1.0	12.9
8/24/2004	17:00	10.8	329	50.6	50.8	10.4	18.8	23.3	0.11	0.11	0.1	5.1	974	56	54	8.9	5.7	96.5	16.0	0.9	16.6
8/25/2004	8:30	7.2	212	34.7	43.9	30.3	15.7	20.2	0.11	0.14	0.3	5.3	628	50	48	6.2	7.9	96.6	12.4	1.0	12.9
8/25/2004	9:00	15.4	338	78.0	78.4	0.0	16.0	20.3	0.14	0.14	0.0	5.0	999	113	110	12.5	11.3	97.3	11.1	1.3	11.4
8/25/2004	9:30	17.0	471	81.5	81.9	15.8	16.5	20.6	0.14	0.14	0.2	5.1	1395	115	113	14.2	8.3	98.4	12.4	1.0	12.6
8/25/2004	10:00	16.8	585	82.9	83.1	0.0	16.9	20.9	0.13	0.13	0.0	5.0	1731	112	110	13.6	6.5	98.7	12.2	0.8	12.3
8/25/2004	10:30	17.7	698	83.0	83.4	0.0	17.2	21.2	0.14	0.14	0.0	5.0	2065	115	113	14.3	5.6	97.8	12.5	0.7	12.7
8/25/2004	11:00	15.5	658	82.0	82.3	0.0	17.5	21.4	0.13	0.13	0.0	5.0	1949	109	109	12.6	5.6	99.9	11.5	0.6	11.6
8/25/2004	11:30	17.6	879	85.9	86.2	2.0	17.7	21.7	0.14	0.14	0.0	5.0	2601	120	118	14.3	4.6	98.5	12.0	0.6	12.2
8/25/2004	12:00	17.2	871	83.3	83.6	15.5	17.9	21.9	0.13	0.13	0.2	5.1	2579	112	111	14.4	4.3	98.8	12.9	0.6	13.0
8/25/2004	12:30	17.2	896	83.5	83.7	14.1	18.1	22.1	0.13	0.13	0.1	5.1	2653	113	108	14.3	4.2	96.3	12.7	0.5	13.2
8/25/2004	13:00	17.5	901	83.4	83.6	11.2	18.3	22.3	0.13	0.13	0.1	5.1	2666	111	108	14.6	4.2	96.9	13.1	0.5	13.5
8/25/2004	13:30	17.0	885	84.1	84.4	0.0	18.4	22.5	0.13	0.13	0.0	5.0	2620	113	110	13.7	4.3	97.7	12.2	0.5	12.5
8/25/2004	14:00	17.5	858	83.4	83.8	5.2	18.5	22.7	0.13	0.13	0.1	5.0	2539	112	109	14.4	4.4	97.2	12.9	0.6	13.2
8/25/2004	14:30	17.1	812	84.1	84.2	0.0	18.7	22.8	0.14	0.13	0.0	5.0	2403	114	111	13.9	4.7	97.5	12.2	0.6	12.5
8/25/2004	15:00	17.3	751	83.8	84.1	0.0	18.9	22.9	0.13	0.13	0.0	5.0	2223	111	110	14.0	5.0	98.7	12.6	0.6	12.7
8/25/2004	15:30	17.3	624	83.6	84.0	5.9	18.9	23.0	0.13	0.13	0.1	5.0	1847	113	109	14.2	6.1	96.4	12.6	0.8	13.1
8/25/2004	16:00	16.9	471	82.7	83.0	14.4	18.7	23.1	0.13	0.13	0.1	5.1	1393	110	109	14.1	7.9	98.7	12.8	1.0	12.9
8/25/2004	16:30	17.1	471	82.1	82.5	16.7	18.6	23.0	0.13	0.13	0.2	5.1	1393	109	108	14.3	7.8	98.8	13.1	1.0	13.3
8/25/2004	17:00	10.8	333	50.4	50.7	11.3	18.5	22.9	0.11	0.11	0.1	5.1	987	56	55	8.9	5.6	99.0	16.1	0.9	16.2
8/25/2004	17:30	3.8	182	19.6	43.7	34.2	18.2	22.7	0.06	0.11	0.3	5.3	540	28	22	3.3	5.2	79.0	11.8	0.6	14.9
8/26/2004	8:30	6.9	202	33.4	43.8	38.5	15.3	19.8	0.11	0.13	0.4	5.4	598	47	45	6.1	7.9	95.4	12.9	1.0	13.5
8/26/2004	9:00	13.7	306	69.2	69.6	33.7	15.6	20.0	0.16	0.16	0.3	5.3	907	110	108	11.9	12.1	98.5	10.8	1.3	11.0
8/26/2004	9:30	15.6	457	81.7	82.0	0.0	16.3	20.3	0.14	0.14	0.0	5.0	1353	112	112	12.6	8.3	99.4	11.3	0.9	11.3
8/26/2004	10:00	17.3	568	83.1	83.5	14.4	16.6	20.6	0.14	0.14	0.1	5.1	1680	116	114	14.4	6.9	98.4	12.4	0.9	12.6
8/26/2004	10:30	17.2	663	83.9	84.0	0.0	16.9	20.9	0.13	0.13	0.0	5.0	1963	113	112	13.9	5.8	99.2	12.3	0.7	12.4
8/26/2004	11:00	17.5	744	83.7	84.0	14.5	17.2	21.2	0.14	0.14	0.1	5.1	2202	115	114	14.6	5.2	99.3	12.7	0.7	12.8

8/28/2004	16:00	16.9	564	79.4	79.6	18.4	20.9	24.7	0.13	0.13	0.2	5.1	1670	104	99	14.2	6.2	95.9	13.7	0.9	14.3
8/28/2004	16:30	16.2	452	78.3	78.5	1.4	20.8	24.7	0.13	0.12	0.0	5.0	1338	100	96	13.2	7.5	96.0	13.2	1.0	13.7
8/28/2004	17:00	10.3	332	48.5	48.7	17.1	20.7	24.7	0.11	0.10	0.2	5.1	982	52	51	8.7	5.3	97.6	16.7	0.9	17.1
8/29/2004	8:30	2.2	53	16.7	43.9	33.9	18.0	22.4	0.06	0.11	0.3	5.3	156	25	19	2.0	16.3	75.0	7.7	1.2	10.2
8/29/2004	9:00	6.3	148	30.7	43.9	34.9	18.0	22.4	0.10	0.13	0.4	5.3	439	43	40	5.5	9.8	92.2	12.7	1.3	13.8
8/29/2004	9:30	5.9	122	27.7	43.8	36.9	18.3	22.5	0.09	0.13	0.4	5.3	360	39	35	5.1	10.7	89.9	13.3	1.4	14.7
8/29/2004	10:00	16.1	419	80.7	81.1	9.0	18.6	22.6	0.15	0.14	0.1	5.1	1241	118	117	13.3	9.5	98.7	11.3	1.1	11.4
8/29/2004	10:30	16.8	570	81.4	81.8	10.2	19.0	22.8	0.13	0.13	0.1	5.1	1688	109	109	13.9	6.5	99.8	12.8	0.8	12.8
8/29/2004	11:00	17.1	632	81.2	81.4	17.6	19.2	23.0	0.13	0.13	0.2	5.1	1872	109	107	14.4	5.8	98.2	13.2	0.8	13.4
8/29/2004	11:30	15.1	315	72.2	72.5	1.7	19.3	23.2	0.12	0.12	0.0	5.0	934	89	88	12.3	9.5	98.8	13.8	1.3	13.9
8/29/2004	12:00	17.0	875	80.4	80.7	17.5	19.7	23.5	0.13	0.13	0.2	5.1	2590	108	105	14.3	4.2	97.1	13.2	0.6	13.6
8/29/2004	12:30	16.7	612	80.0	80.3	12.7	19.9	23.7	0.13	0.12	0.1	5.1	1811	105	100	13.9	5.8	95.1	13.3	0.8	14.0
8/29/2004	13:00	16.4	768	79.5	79.8	6.1	20.3	24.0	0.13	0.13	0.1	5.0	2274	104	103	13.4	4.6	99.0	13.0	0.6	13.1
8/29/2004	13:30	16.0	845	82.4	82.7	0.0	20.5	24.2	0.13	0.13	0.0	5.0	2502	107	105	12.9	4.3	97.7	12.0	0.5	12.3
8/29/2004	14:00	17.1	797	82.4	82.8	8.0	20.6	24.4	0.13	0.13	0.1	5.0	2360	110	107	14.1	4.7	97.4	12.8	0.6	13.2
8/29/2004	14:30	15.4	806	81.1	81.5	0.0	20.6	24.5	0.13	0.13	0.0	5.0	2384	104	102	12.5	4.3	98.8	12.0	0.5	12.2
8/29/2004	15:00	16.8	734	80.9	81.4	7.1	20.8	24.6	0.13	0.13	0.1	5.0	2172	105	104	13.9	4.8	98.5	13.2	0.6	13.4
8/29/2004	15:30	16.8	642	80.7	81.0	4.1	21.0	24.8	0.13	0.13	0.0	5.0	1901	104	102	13.7	5.5	98.2	13.2	0.7	13.4
8/29/2004	16:00	16.9	543	80.8	81.1	9.2	21.0	24.9	0.13	0.13	0.1	5.1	1609	106	101	14.0	6.6	95.9	13.2	0.9	13.8
8/29/2004	16:30	16.5	435	78.6	79.0	11.5	20.9	24.9	0.13	0.12	0.1	5.1	1287	101	96	13.7	7.8	95.7	13.6	1.1	14.3
8/29/2004	17:00	10.4	314	48.5	48.7	16.1	20.9	24.9	0.11	0.10	0.2	5.1	931	52	50	8.7	5.6	96.9	16.9	0.9	17.4
8/30/2004	11:00	4.0	64	19.9	43.7	36.2	19.1	23.0	0.06	0.12	0.4	5.3	190	28	23	3.4	14.8	82.4	12.3	1.8	14.9
8/30/2004	11:30	7.5	188	36.5	43.9	34.6	19.3	23.2	0.12	0.14	0.4	5.3	558	52	50	6.5	9.2	96.2	12.6	1.2	13.1
Max:		18.1	901	85.9	86.2	53.8	21.0	24.9	0.2	0.2	0.5	5.5	2666	120	118	15.2	16.3	99.9	16.9	1.8	17.5

Flow in l/m
Irradiance in W/m^2
Motor voltage in Volts
Panel voltage in Volts
Pressure in kPa
Panel shunt voltage in Volts
Total head in meters
P_{irr} irradiance power in Watts
P_{arr} array power in Watts
P_{con} converter power in Watts
P_{pump} pump power in Watts
Effa array efficiency
Effc converter efficiency
Effp pump efficiency
Effs system efficiency
Effo overall efficiency

Cost analysis to date (2001 - 2004)

Total present worth of system $= R98,940$

Recurrent Costs

Maintenance $= R970/year$

Present worth $= A \times [1-(1+i)^{-n}]/i$

$= 970 \times [1-(1+0.052)^{-4}]/0.052$

$= R3,424$

Operating Costs $= R18,000/year$

$= 18,000 \times [1-(1+0.052)^{-4}]/0.052$

Present worth $= R63,532$

Total cost $= R165,896$

Annual levelised cost $= 165,896 \times \left[\frac{(1+0.052)^4 \times 0.052}{(1+0.052)^4 - 1}\right]$

$= R46,967$

Unit water cost to date (2001-2004)

Unit water cost (UWC) to date $= \frac{\text{Total cost to date}}{\text{Total volume pumped to date}}$

$= \frac{165,896}{5,184}$

$= R32.00/m^3$

$= 3.2$ cents/l

Energy cost $= \frac{\text{unit water cost}}{\text{total head(static head + head losses + friction losses)}}$

$= \frac{32.00}{50}$

$= R0.64/m^4$

$= 64$ cents/m^4

Cost analysis for 15 years (PV)

Initial costs	$= R98,940$
Recurrent Costs	
Maintenance	$= R970/year$
Present worth	$= A \times [1-(1+i)^{-n}]/i$
	$= 970 \times [1-(1+0.052)^{-15}]/0.052$
	$= R9,934$
Operating Costs	$= R18,000/year$
	$= 18,000 \times [1-(1+0.052)^{-15}]/0.052$
Present worth	$= R194,265$
Total cost	$= R293,207$
Annual levelised cost	$= LCC \times \left[\frac{(1+i)^{SL} \times i}{(1+i)^{SL}-1}\right]$
	$= 293,207 \times \left[\frac{(1+0.052)^{15} \times 0.052}{(1+0.052)^{15}-1}\right]$
	$= R28,626$

Unit water cost for 15 years

Unit water cost (UWC)	$= \frac{\text{Annual levelised cost}}{Q_{vol:annual}}$
	$= \frac{293,207}{3.6 \times 360 \times 15}$
	$= R15.08/m^3$
	$= 1.5\ cents/l$
Energy cost	$= \frac{\text{unit water cost}}{\text{total head (static head + head losses + friction losses)}}$
	$= 15.08$
	$= R0.30/m^4$
	$= 30\ cents/m^4$

Cost analysis for 20 years

Total present worth of system $= R98,940$

Recurrent Costs

Maintenance $= R970/year$

Present worth $= A \times [1-(1+i)^{-n}]/i$

$= 970 \times [1-(1+0.052)^{-20}]/0.052$

$= R11,886$

Operating Costs $= R18,000/year$

$= 18,000 \times [1-(1+0.052)^{-20}]/0.052$

Present worth $= R220,564$

Total cost $= R327,762$

Annual levelised cost $= 331,389 \times \left[\frac{(1+0.052)^{20} \times 0.052}{(1+0.052)^{20}-1}\right]$

$= R27,045$

Unit water cost for 20 years

Unit water cost (UWC) $= \frac{\text{Annual levelised cost}}{Q_{\text{vol:annual}}}$

$= \frac{331,389}{3.6 \times 360 \times 20}$

$= R12.79/m^3$

$= 1.3$ cents/l

Energy cost $= \frac{\text{unit water cost}}{\text{total head (static head + head losses + friction losses)}}$

$= 12.79$

$= R0.25/m^4$

$= 26\ \text{cents}/m^4$

Cost analysis for 25 years

Total present worth of system $= R98,940$

Recurrent Costs

Maintenance $= R970/year$

Present worth $= A \times [1-(1+i)^{-n}]/i$

$= 970 \times [1-(1+0.052)^{-25}]/0.052$

$= R13,401$

Operating Costs $= R18,000/year$

$= 18,000 \times [1-(1+0.052)^{-25}]/0.052$

Present worth $= R248,683$

Total cost $= R361,023$

Annual levelised cost $= 361,023 \times \left[\frac{(1+0.052)^{25} \times 0.052}{(1+0.052)^{25} - 1}\right]$

$= R26,124$

Unit water cost for 25 years

Unit water cost (UWC) $= \frac{\text{Annual levelised cost}}{Q_{vol:annual}}$

$= \frac{361,023}{3.6 \times 360 \times 25}$

$= R11.14/m^3$

$= 1.1\ cents/l$

Energy cost $= \frac{\text{unit water cost}}{\text{total head (static head + head losses + friction losses)}}$

$= 11.14$

$= R0.22/m^4$

$= 22\ cents/m^4$

APPENDIX E1 (b) DIESEL PUMP LIFE CYCLE COSTS CALCULATIONS

Period of analysis (n) = **15 years**

Discount rate = **5.2%**

Capital Costs/initial costs = **R45,940**

Replacement Costs = **R30,780**

Total present worth of system = **R76,720**

Recurrent Costs

Maintenance = **R6,638/year**

Present worth

$$= A \times [1-(1+i)^{-n}]/i$$

$$= 6{,}638 \times [1-(1+0.052)^{-15}]/0.052$$

$$= R67{,}978$$

Operating Costs = **R20,859/year**

$$= 20{,}859 \times [1-(1+0.052)^{-15}]/0.052$$

Present worth = **R213,612**

Total cost = **R358,310**

Annual levelised cost

$$= LCC \times \left[\frac{(1+i)^{SL} \times i}{(1+i)^{SL}-1}\right]$$

$$= 358{,}310 \times \left[\frac{(1+0.052)^{15} \times 0.052}{(1+0.052)^{15}-1}\right]$$

$$= R34{,}992$$

Unit water cost for 15 years (diesel)

Unit water cost (UWC)

$$= \frac{\text{Annual levelised cost}}{Q_{vol:annual}}$$

$$= \frac{358{,}310}{21 \times 365 \times 15}$$

$$= R3.11/m^3$$

$$= 0.31 \text{ cents/l}$$

Energy cost

$$= \frac{\text{unit water cost}}{\text{total head (static head + head losses + friction losses)}}$$

$$= 3.11$$

$$= R0.086/m^4$$

$$= 8.6 \text{ cents}/m^4$$

Cost analysis for 20 years

Total present worth of system = R76,720

Recurrent Costs

Maintenance = R6,638/year

Present worth $= A \times [1-(1+i)^{-n}]/i$

$= 6{,}638 \times [1-(1+0.052)^{-20}]/0.052$

= R81,339

Operating Costs = R20,859/year

$= 20{,}859 \times [1-(1+0.052)^{-20}]/0.052$

Present worth = R255,597

Total cost = R413,656

Annual levelised cost $= 413{,}656 \times \left[\frac{(1+0.052)^{20} \times 0.052}{(1+0.052)^{20}-1}\right]$

= R33,753

Unit water cost for 20 years (diesel)

Unit water cost (UWC) $= \frac{\text{Annual levelised cost}}{Q_{vol:annual}}$

$= \frac{413{,}656}{21 \times 365 \times 20}$

$= R2.69/m^3$

= 0.27 cents/l

Energy cost $= \frac{\text{unit water cost}}{\text{total head (static head + head losses + friction losses)}}$

= 2.69

$= R0.075/m^4$

$= 7.5\ cents/m^4$

Cost analysis for 25 years (diesel)

Total present worth of system	$= \text{R}76{,}720$
Recurrent Costs	
Maintenance	$= \text{R}6{,}638/\text{year}$
Present worth	$= A \times [1-(1+i)^{-n}]/i$
	$= 6{,}638 \times [1-(1+0.052)^{-25}]/0.052$
	$= \text{R}91{,}709$
Operating Costs	$= \text{R}20{,}859/\text{year}$
	$= 20{,}859 \times [1-(1+0.052)^{-25}]/0.052$
Present worth	$= \text{R}288{,}182$
Total cost	$= \text{R}456{,}611$
Annual levelised cost	$= 456{,}611 \times \left[\frac{(1+0.052)^{25} \times 0.052}{(1+0.052)^{25}-1}\right]$
	$= \text{R}33{,}055$

Unit water cost for 25 years (diesel)

Unit water cost (UWC)

$$= \frac{\text{Annual levelised cost}}{Q_{\text{vol:annual}}}$$

$$= \frac{456{,}611}{21 \times 365 \times 25}$$

$$= \text{R}2.38/\text{m}^3$$

$$= 0.24 \text{ cents/l}$$

Energy cost

$$= \frac{\text{unit water cost}}{\text{total head (static head + head losses + friction losses)}}$$

$$= 2.38$$

$$= \text{R}0.066/\text{m}^4$$

$$= 6.6 \text{ cents/m}^4$$

COST ANALYSIS OF PV ACTUAL (3.6m³/day) AND DIESEL WATER PUMPING SYSTEMS (unit & water pumping costs)

Yrs	IC	O+M	PW	CC	UWC	EC	IC	O+M	PW	CC	UWC	EC
1	98940	18970	18032	116972	90.256	1.805	76720	27497	26138	102858	13.419	0.373
2	98940	18970	35173	134113	51.741	1.035	76720	27497	50984	127704	8.330	0.231
3	98940	18970	51467	150407	38.685	0.774	76720	27497	74601	151321	6.581	0.183
4	98940	18970	66955	165895	32.001	0.640	76720	27497	97052	173772	5.668	0.157
5	98940	18970	81678	180618	27.873	0.557	76720	27497	118392	195112	5.091	0.141
6	98940	18970	95673	194613	25.027	0.501	76720	27497	138678	215398	4.684	0.130
7	98940	18970	108976	207916	22.918	0.458	76720	27497	157961	234681	4.374	0.121
8	98940	18970	121622	220562	21.273	0.425	76720	27497	176291	253011	4.126	0.115
9	98940	18970	133643	232583	19.940	0.399	76720	27497	193715	270435	3.920	0.109
10	98940	18970	145069	244009	18.828	0.377	76720	27497	210277	286997	3.744	0.104
11	98940	18970	155931	254871	17.878	0.358	76720	27497	226021	302741	3.591	0.100
12	98940	18970	166255	265195	17.052	0.341	76720	27497	240987	317707	3.454	0.096
13	98940	18970	176070	275010	16.323	0.326	76720	27497	255213	331933	3.331	0.093
14	98940	18970	185399	284339	15.671	0.313	76720	27497	268736	345456	3.219	0.089
15	98940	18970	194267	293207	15.083	0.302	76720	27497	281590	358310	3.116	0.087
16	98940	18970	202697	301637	14.547	0.291	76720	27497	293809	370529	3.021	0.084
17	98940	18970	210710	309650	14.055	0.281	76720	27497	305424	382144	2.933	0.081
18	98940	18970	218327	317267	13.600	0.272	76720	27497	316465	393185	2.850	0.079
19	98940	18970	225567	324507	13.179	0.264	76720	27497	326960	403680	2.772	0.077
20	98940	18970	232450	331390	12.785	0.256	76720	27497	336936	413656	2.698	0.075
21	98940	18970	238992	337932	12.417	0.248	76720	27497	346419	423139	2.629	0.073
22	98940	18970	245211	344151	12.070	0.241	76720	27497	355434	432154	2.563	0.071
23	98940	18970	251123	350063	11.744	0.235	76720	27497	364003	440723	2.500	0.069
24	98940	18970	256742	355682	11.435	0.229	76720	27497	372148	448868	2.440	0.068
25	98940	18970	262084	361024	11.143	0.223	76720	27497	379891	456611	2.383	0.066

LEGEND:

PV actual pumping costs

Diesel pumping costs

IC: Initial costs in Rands

O+R: Operating & Replacement costs in Rands

PW: Total present worth of life cycle costs in Rands

CC: Cumulative costs in Rands

UWC: Unit water costs in R/m³

EC: Energy costs in R/m⁴

COST ANALYSIS OF PV PREDICTED (20m^3/day) AND DIESEL WATER PUMPING SYSTEMS (unit & water pumping costs)

Yrs	IC	O+M	PW	CC	UWC	EC	IC	O+M	PW	CC	UWC
1	98940	18970	18032	116972	16.024	0.325	76720	27497	26138	102858	13.419
2	98940	18970	35173	134113	9.313	0.186	76720	27497	50984	127704	8.330
3	98940	18970	51467	150407	6.963	0.139	76720	27497	74601	151321	6.581
4	98940	18970	66955	165895	5.760	0.115	76720	27497	97052	173772	5.668
5	98940	18970	81678	180618	5.017	0.100	76720	27497	118392	195112	5.091
6	98940	18970	95673	194613	4.505	0.090	76720	27497	138678	215398	4.684
7	98940	18970	108976	207916	4.125	0.083	76720	27497	157961	234681	4.374
8	98940	18970	121622	220562	3.829	0.077	76720	27497	176291	253011	4.126
9	98940	18970	133643	232583	3.589	0.072	76720	27497	193715	270435	3.920
10	98940	18970	145069	244009	3.389	0.068	76720	27497	210277	286997	3.744
11	98940	18970	155931	254871	3.218	0.064	76720	27497	226021	302741	3.591
12	98940	18970	166255	265195	3.069	0.061	76720	27497	240987	317707	3.454
13	98940	18970	176070	275010	2.938	0.059	76720	27497	255213	331933	3.331
14	98940	18970	185399	284339	2.821	0.056	76720	27497	268736	345456	3.219
15	98940	18970	194267	293207	2.715	0.054	76720	27497	281590	358310	3.116
16	98940	18970	202697	301637	2.618	0.052	76720	27497	293809	370529	3.021
17	98940	18970	210710	309650	2.530	0.051	76720	27497	305424	382144	2.933
18	98940	18970	218327	317267	2.448	0.049	76720	27497	316465	393185	2.850
19	98940	18970	225567	324507	2.372	0.047	76720	27497	326960	403680	2.772
20	98940	18970	232450	331390	2.301	0.046	76720	27497	336936	413656	2.698
21	98940	18970	238992	337932	2.235	0.045	76720	27497	346419	423139	2.629
22	98940	18970	245211	344151	2.173	0.043	76720	27497	355434	432154	2.563
23	98940	18970	251123	350063	2.114	0.042	76720	27497	364003	440723	2.500
24	98940	18970	256742	355682	2.058	0.041	76720	27497	372148	448868	2.440
25	98940	18970	262084	361024	2.006	0.040	76720	27497	379891	456611	2.383

LEGEND:

PV predicted pumping costs

Diesel pumping costs

IC: Initial costs in Rands

O+R: Operating & Replacement costs in Rands

PW: Total present worth of life cycle costs in Rands

CC: Cumulative costs in Rands

UWC: Unit water costs in R/m^3

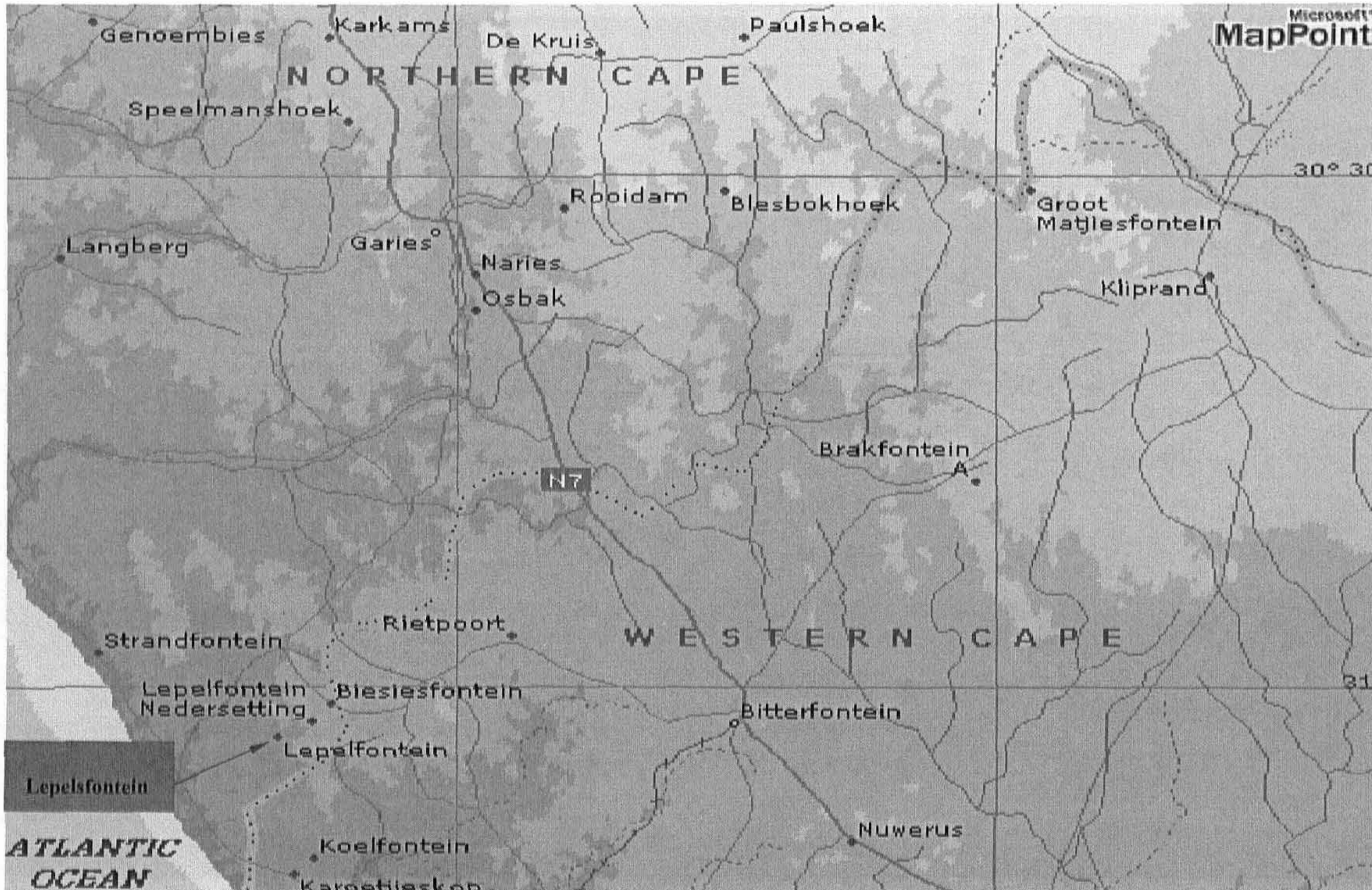
EC: Energy costs in R/m^4

Field results (07/12/2004 – 16/12/2004)

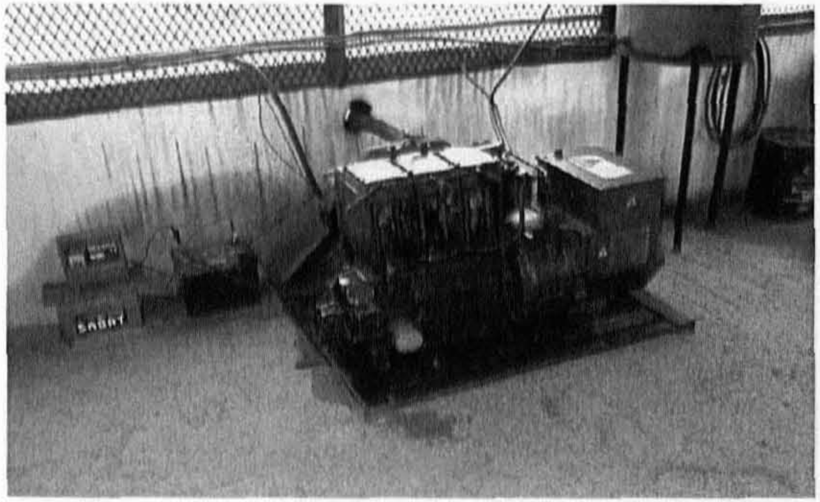
Date	Time	temp	flow	pressure	int temp	solar	Irrad	Hs	Area	p volt	Panel Vol	shunt voltage	Current	Hdy	Htot	Parr	Pinc	Ppump	Effarr	Effsys	Effover
12/7/2004	7:00:00	31.5	4.81	4.34	28.5	2.50	501	50	9.432	1.23	124.4	0.326	0.988	0.44	50.4	122.9	4724	39.7	2.602	32	0.8
12/7/2004	8:00:00	34.3	4.46	4.24	30.3	1.60	320	50	9.432	1.15	115.9	0.267	0.810	0.43	50.4	93.8	3019	36.8	3.109	39	1.2
12/7/2004	9:00:00	33.2	5.45	4.85	30.8	4.03	807	50	9.432	1.14	115.5	0.708	2.146	0.49	50.5	247.9	7610	45.0	3.257	18	0.6
12/7/2004	10:00:00	32.2	5.72	5.06	29.3	5.01	1002	50	9.432	1.16	117.5	0.799	2.420	0.52	50.5	284.4	9447	47.3	3.010	17	0.5
12/7/2004	11:00:00	30.9	5.72	5.24	28.6	5.17	1034	50	9.432	1.17	118.0	0.837	2.537	0.53	50.5	299.4	9755	47.3	3.069	16	0.5
12/7/2004	12:00:00	31.8	5.73	5.26	29.0	5.06	1012	50	9.432	1.19	119.7	0.838	2.539	0.54	50.5	303.9	9540	47.3	3.186	16	0.5
12/7/2004	13:00:00	31.8	5.65	5.11	29.1	4.53	906	50	9.432	1.17	118.3	0.745	2.257	0.52	50.5	267.1	8542	46.7	3.126	17	0.5
12/7/2004	14:00:00	29.8	5.48	4.84	30.1	3.67	735	50	9.432	1.20	120.8	0.622	1.886	0.49	50.5	227.7	6929	45.2	3.287	20	0.7
12/7/2004	15:00:00	32.3	5.09	4.32	30.5	2.57	513	50	9.432	1.19	120.2	0.407	1.234	0.44	50.4	148.3	4843	42.0	3.062	28	0.9
12/7/2004	16:00:00	34.7	3.93	3.62	30.2	1.35	270	50	9.432	1.21	122.1	0.140	0.423	0.37	50.4	51.6	2544	32.3	2.030	63	1.3
12/8/2004	7:00:00	31.1	4.74	4.27	28.5	2.44	489	50	9.432	1.28	128.8	0.303	0.919	0.44	50.4	118.3	4611	39.1	2.567	33	0.8
12/8/2004	8:00:00	34.4	5.34	4.63	31.4	3.54	708	50	9.432	1.22	123.6	0.527	1.597	0.47	50.5	197.5	6682	44.1	2.955	22	0.7
12/8/2004	9:00:00	34.7	5.66	4.83	32.1	4.42	884	50	9.432	1.18	118.9	0.695	2.106	0.49	50.5	250.4	8341	46.7	3.002	19	0.6
12/8/2004	10:00:00	35.4	5.73	5.12	31.8	4.96	993	50	9.432	1.19	120.6	0.777	2.356	0.52	50.5	284.1	9362	47.3	3.035	17	0.5
12/8/2004	11:00:00	33.1	5.77	5.16	30.4	5.16	1031	50	9.432	1.16	117.6	0.844	2.558	0.53	50.5	300.9	9727	47.6	3.094	16	0.5
12/8/2004	12:00:00	32.6	5.77	5.17	30.0	5.02	1004	50	9.432	1.18	119.1	0.826	2.503	0.53	50.5	298.1	9470	47.6	3.148	16	0.5
12/8/2004	13:00:00	32.3	5.65	5.01	30.3	4.52	905	50	9.432	1.19	120.5	0.743	2.252	0.51	50.5	271.4	8534	46.7	3.181	17	0.5
12/8/2004	14:00:00	31.6	5.48	4.74	32.1	3.68	736	50	9.432	1.19	120.5	0.617	1.869	0.48	50.5	225.2	6939	45.2	3.246	20	0.7
12/8/2004	15:00:00	34.2	5.13	4.25	32.2	2.57	514	50	9.432	1.21	122.6	0.400	1.212	0.43	50.4	148.6	4849	42.3	3.064	28	0.9
12/8/2004	16:00:00	35.5	3.93	3.60	31.9	1.35	270	50	9.432	1.19	119.7	0.140	0.426	0.37	50.4	51.0	2543	32.3	2.004	63	1.3
12/9/2004	7:00:00	34.2	4.78	4.20	31.8	2.43	485	50	9.432	1.21	122.3	0.309	0.937	0.43	50.4	114.5	4575	39.4	2.503	34	0.9
12/9/2004	8:00:00	37.8	5.21	4.65	35.3	3.53	707	50	9.432	1.18	118.7	0.504	1.527	0.47	50.5	181.2	6665	43.0	2.719	24	0.6
12/9/2004	9:00:00	37.5	5.55	4.74	34.3	4.40	880	50	9.432	1.15	115.7	0.674	2.043	0.48	50.5	236.4	8300	45.8	2.848	19	0.6
12/9/2004	10:00:00	35.8	5.70	4.74	32.6	4.98	996	50	9.432	1.12	113.5	0.777	2.355	0.48	50.5	267.2	9395	47.0	2.844	18	0.5
12/9/2004	11:00:00	34.0	5.77	4.84	31.3	5.18	1037	50	9.432	1.13	114.6	0.838	2.540	0.49	50.5	290.9	9777	47.6	2.976	16	0.5
12/9/2004	12:00:00	33.9	5.80	4.93	31.2	5.03	1006	50	9.432	1.16	117.6	0.828	2.509	0.50	50.5	295.2	9491	47.9	3.110	16	0.5
12/9/2004	13:00:00	33.8	5.73	4.83	31.5	4.52	905	50	9.432	1.17	118.5	0.738	2.236	0.49	50.5	265.1	8534	47.3	3.106	18	0.6
12/9/2004	14:00:00	32.5	5.48	4.54	33.8	3.70	740	50	9.432	1.17	118.0	0.617	1.869	0.46	50.5	220.5	6981	45.2	3.158	21	0.6
12/9/2004	15:00:00	36.6	5.24	4.03	35.5	2.62	523	50	9.432	1.20	121.3	0.402	1.219	0.41	50.4	147.9	4936	43.2	2.996	29	0.9
12/9/2004	16:00:00	39.3	3.93	3.59	34.1	1.37	275	50	9.432	1.13	114.4	0.152	0.462	0.37	50.4	52.8	2591	32.4	2.039	61	1.2
12/10/2004	6:00:00	27.1	3.92	3.90	24.7	1.69	338	50	9.432	0.89	89.9	0.215	0.652	0.40	50.4	58.7	3188	32.3	1.840	55	1.0
12/10/2004	7:00:00	28.0	3.92	3.87	25.7	1.07	215	50	9.432	1.27	128.0	0.112	0.338	0.39	50.4	43.3	2025	32.3	2.140	75	1.6
12/10/2004	8:00:00	33.3	5.31	4.51	30.6	3.47	694	50	9.432	1.17	118.4	0.516	1.565	0.46	50.5	185.4	6549	43.8	2.830	24	0.7
12/10/2004	9:00:00	35.1	5.59	4.63	33.0	4.38	876	50	9.432	1.13	113.7	0.675	2.044	0.47	50.5	232.4	8261	46.1	2.813	20	0.6

12/10/2004	10:00:00	35.2	5.73	4.75	32.0	4.93	985	50	9.432	1.14	115.6	0.761	2.306	0.48	50.5	266.7	9293	47.3	2.869	18	0.5
12/10/2004	11:00:00	34.1	5.70	4.82	31.9	5.14	1027	50	9.432	1.13	114.4	0.816	2.473	0.49	50.5	282.9	9687	47.1	2.921	17	0.5
12/10/2004	12:00:00	34.6	5.77	4.76	31.8	4.99	998	50	9.432	1.14	114.8	0.807	2.444	0.49	50.5	280.5	9411	47.6	2.981	17	0.5
12/10/2004	13:00:00	34.3	5.70	4.73	31.7	4.50	900	50	9.432	1.17	118.2	0.733	2.223	0.48	50.5	262.6	8488	47.0	3.094	18	0.6
12/10/2004	14:00:00	32.8	5.55	4.53	32.9	3.68	735	50	9.432	1.18	119.1	0.615	1.864	0.46	50.5	222.1	6937	45.8	3.202	21	0.7
12/10/2004	15:00:00	34.2	5.16	4.19	33.1	2.61	521	50	9.432	1.19	119.9	0.420	1.273	0.43	50.4	152.6	4914	42.6	3.105	28	0.9
12/10/2004	16:00:00	37.6	3.93	3.59	33.0	1.40	279	50	9.432	1.18	119.0	0.152	0.461	0.37	50.4	54.8	2632	32.4	2.083	59	1.2
12/11/2004	7:00:00	36.3	4.75	4.17	34.3	2.40	480	50	9.432	1.18	118.9	0.318	0.962	0.43	50.4	114.4	4523	39.1	2.530	34	0.9
12/11/2004	8:00:00	40.6	5.28	4.53	38.1	3.51	702	50	9.432	1.16	117.0	0.518	1.569	0.46	50.5	183.6	6622	43.6	2.772	24	0.7
12/11/2004	9:00:00	42.9	5.46	4.94	39.1	4.41	882	50	9.432	1.13	114.2	0.680	2.061	0.50	50.5	235.4	8317	45.1	2.831	19	0.5
12/11/2004	10:00:00	39.5	5.56	4.95	36.3	4.96	991	50	9.432	1.12	112.7	0.767	2.324	0.50	50.5	261.8	9351	45.9	2.800	18	0.5
12/11/2004	11:00:00	38.1	5.63	4.93	35.9	5.16	1031	50	9.432	1.09	109.7	0.819	2.483	0.50	50.5	272.5	9728	46.5	2.801	17	0.5
12/11/2004	12:00:00	38.3	5.63	4.93	35.5	5.04	1009	50	9.432	1.12	112.7	0.814	2.467	0.50	50.5	278.1	9515	46.5	2.922	17	0.5
12/11/2004	13:00:00	37.4	5.59	4.81	34.8	4.52	903	50	9.432	1.12	113.4	0.740	2.243	0.49	50.5	254.5	8520	46.2	2.987	18	0.5
12/11/2004	14:00:00	35.4	5.45	4.60	36.2	3.70	739	50	9.432	1.16	117.0	0.608	1.843	0.47	50.5	215.6	6971	45.0	3.093	21	0.6
12/11/2004	15:00:00	37.6	5.17	4.17	37.2	2.62	524	50	9.432	1.17	117.8	0.426	1.292	0.43	50.4	152.2	4944	42.6	3.078	28	0.9
12/11/2004	16:00:00	41.4	3.93	3.62	37.5	1.39	278	50	9.432	1.13	114.2	0.155	0.471	0.37	50.4	53.7	2620	32.4	2.051	60	1.2
12/12/2004	5:00:00	24.4	3.92	3.88	22.3	0.65	130	50	9.432	1.00	101.2	0.011	0.462	0.40	50.4	46.7	1226	32.3	3.812	69	2.6
12/12/2004	7:00:00	26.5	3.93	3.89	24.6	0.80	160	50	9.432	1.06	107.2	0.141	0.428	0.40	50.4	45.9	1511	32.3	3.039	70	2.1
12/12/2004	8:00:00	29.6	4.75	4.05	28.1	1.82	365	50	9.432	1.20	121.0	0.294	0.892	0.41	50.4	107.9	3442	39.1	3.135	36	1.1
12/12/2004	9:00:00	30.4	5.94	4.85	30.6	6.20	1240	50	9.432	1.10	111.3	0.979	2.968	0.49	50.5	330.5	11699	49.0	2.825	15	0.4
12/12/2004	10:00:00	34.9	5.73	5.00	32.3	5.28	1055	50	9.432	1.16	117.4	0.830	2.515	0.51	50.5	295.2	9952	47.3	2.966	16	0.5
12/12/2004	11:00:00	34.2	5.77	5.16	32.2	5.93	1187	50	9.432	1.12	113.3	0.923	2.796	0.53	50.5	316.8	11194	47.7	2.830	15	0.4
12/12/2004	12:00:00	35.0	5.98	5.02	32.2	5.90	1180	50	9.432	1.14	115.3	0.974	2.950	0.51	50.5	340.2	11125	49.4	3.058	15	0.4
12/12/2004	13:00:00	34.1	5.62	4.95	31.7	4.59	918	50	9.432	1.16	117.6	0.738	2.238	0.50	50.5	263.1	8658	46.4	3.038	18	0.5
12/12/2004	14:00:00	31.9	5.52	4.79	32.8	3.91	782	50	9.432	1.16	116.8	0.662	2.007	0.49	50.5	234.4	7373	45.6	3.179	19	0.6
12/12/2004	15:00:00	33.8	4.99	4.29	33.0	2.44	488	50	9.432	1.17	118.0	0.408	1.238	0.44	50.4	146.1	4605	41.2	3.173	28	0.9
12/12/2004	16:00:00	36.7	3.93	3.66	32.6	1.35	269	50	9.432	1.19	120.4	0.148	0.449	0.37	50.4	54.1	2538	32.4	2.131	60	1.3
12/13/2004	6:00:00	28.7	3.93	3.92	27.3	1.69	339	50	9.432	0.93	93.9	0.223	0.676	0.40	50.4	63.4	3194	32.4	1.985	51	1.0
12/13/2004	7:00:00	32.7	4.95	4.33	30.7	2.58	516	50	9.432	1.16	117.6	0.393	1.192	0.44	50.4	140.3	4869	40.9	2.880	29	0.8
12/14/2004	16:00:00	33.6	3.93	3.98	29.5	1.45	290	50	9.432	1.23	124.2	0.143	0.433	0.41	50.4	53.8	2739	32.4	1.963	60	1.2
12/15/2004	5:00:00	22.8	3.92	3.97	20.3	1.90	380	50	9.432	1.10	111.2	0.245	0.742	0.40	50.4	82.6	3584	32.3	2.304	39	0.9
12/15/2004	7:00:00	29.3	4.67	4.30	27.3	2.38	476	50	9.432	1.29	130.4	0.290	0.878	0.44	50.4	114.5	4488	38.5	2.552	34	0.9
12/15/2004	8:00:00	33.5	5.27	4.76	30.5	3.47	693	50	9.432	1.22	123.2	0.518	1.569	0.48	50.5	193.3	6540	43.5	2.956	23	0.7
12/15/2004	9:00:00	34.6	5.59	4.98	32.1	4.36	872	50	9.432	1.17	118.5	0.689	2.088	0.51	50.5	247.4	8228	46.2	3.006	19	0.6
12/15/2004	10:00:00	35.2	5.66	5.18	32.2	4.91	981	50	9.432	1.17	118.3	0.797	2.414	0.53	50.5	285.5	9254	46.8	3.085	16	0.5

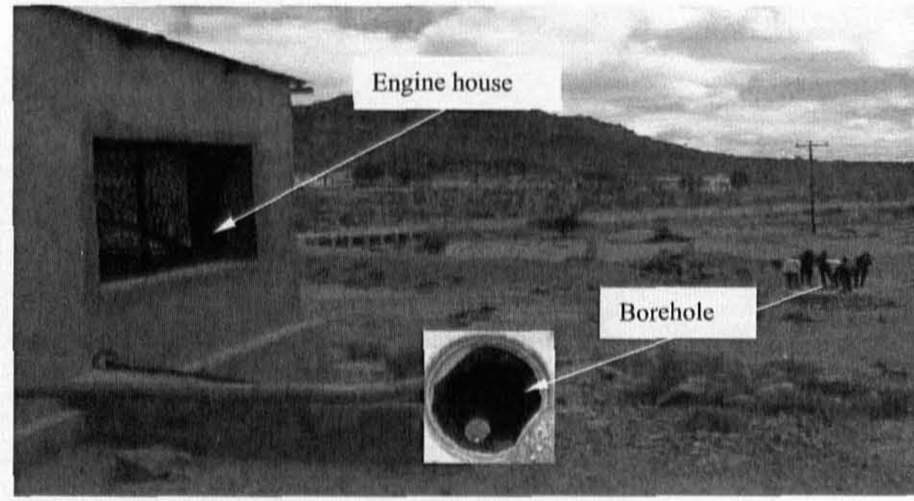
F2: Lepelsfontein Map



F3: Rooifontein Map



G1: Rooifontein diesel engine

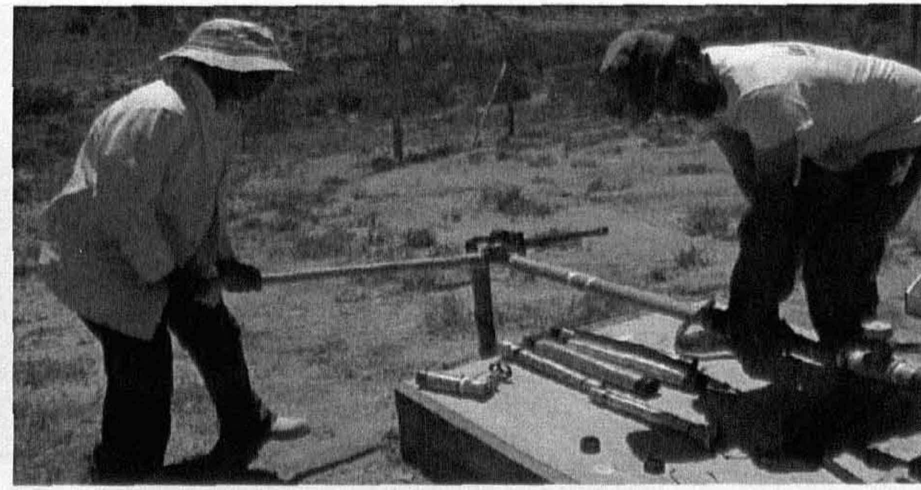


G2: Rooifontein engine house and borehole

G3: Lepelsfontein village

G4: Lepelsfontein PV system plant

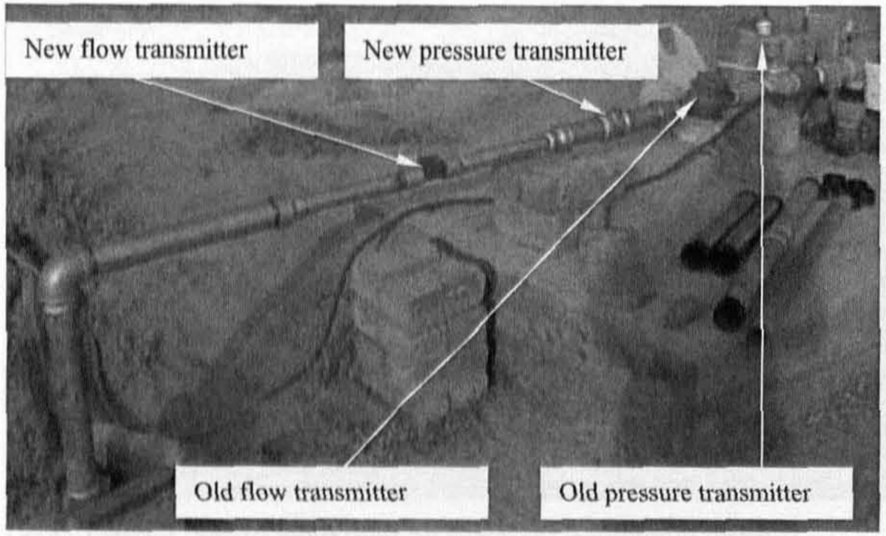
G5: Old configurations of flow & pressure transmitters



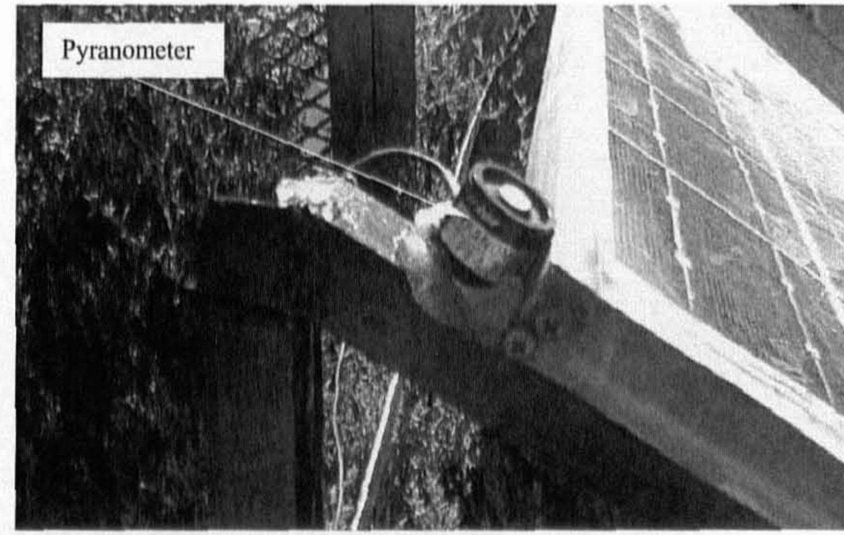
G6: Work in progress to install the new hardware

G7: Installation of data acquisition devices

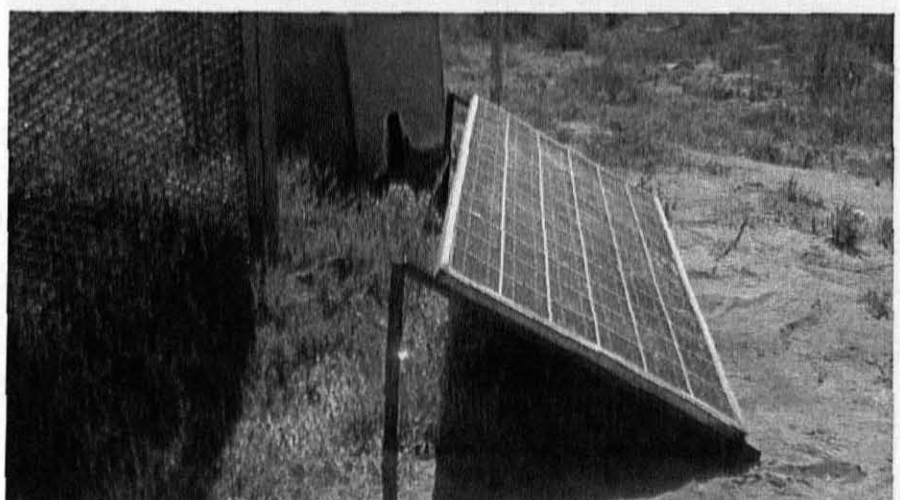
G8: The commissioning of the system



G9: Picture of hardware towards completion

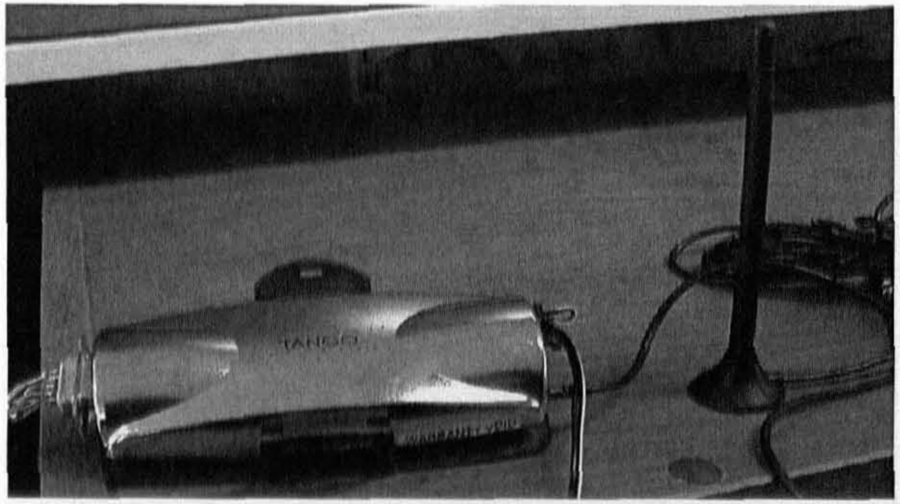


G10: The bonding of the pyranometer

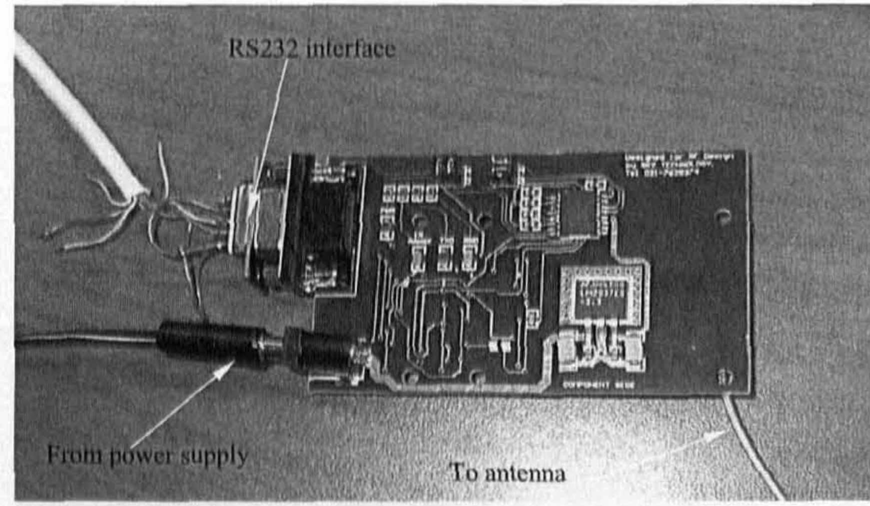


G11: The PV module charging the battery

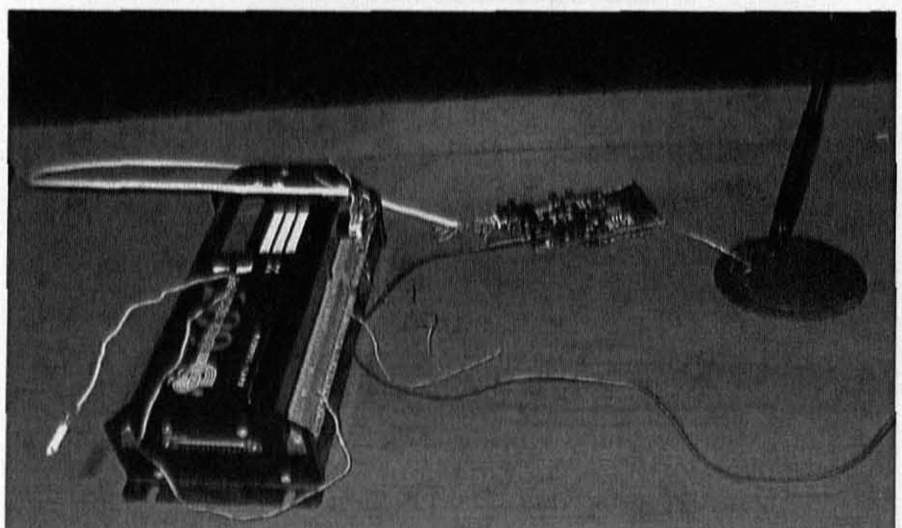
G12: Data logger, charge controller & a battery



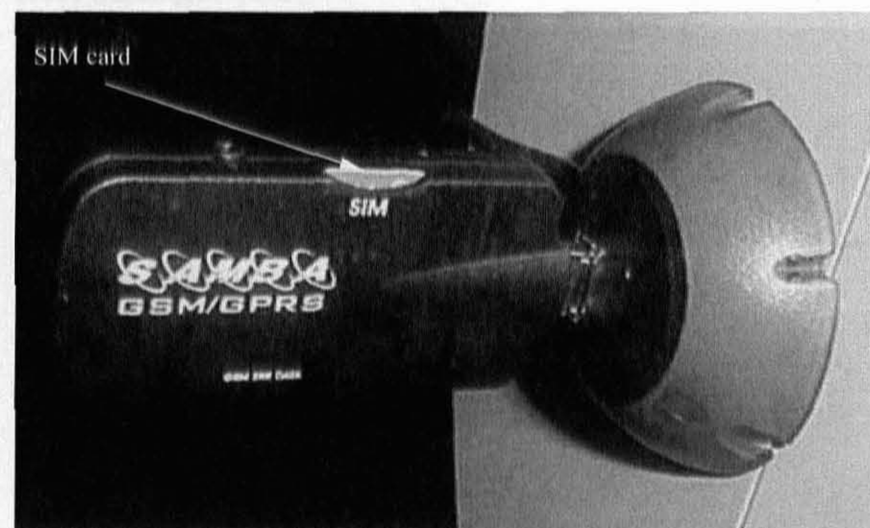
G13: Tango GSM modem with an aerial (experimental testing)



G14: Aerocomm data transceiver (experimental testing)

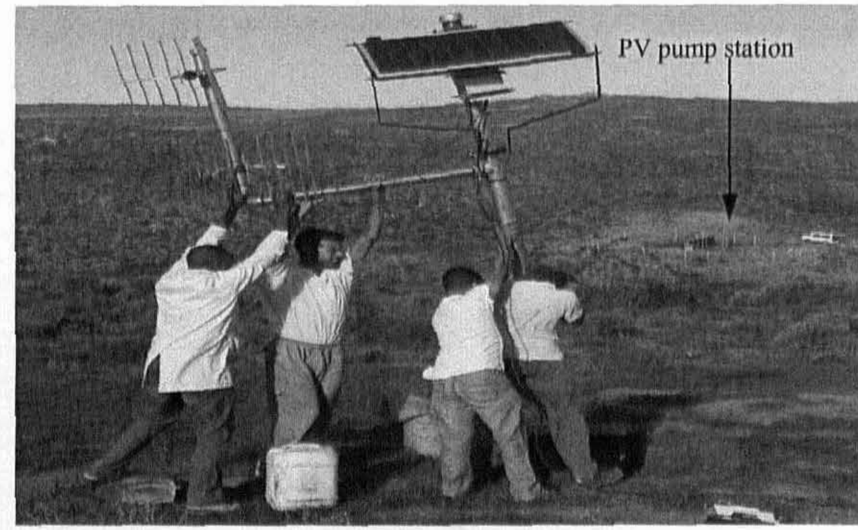


G15: A datalogger and a transceiver (experimental testing)

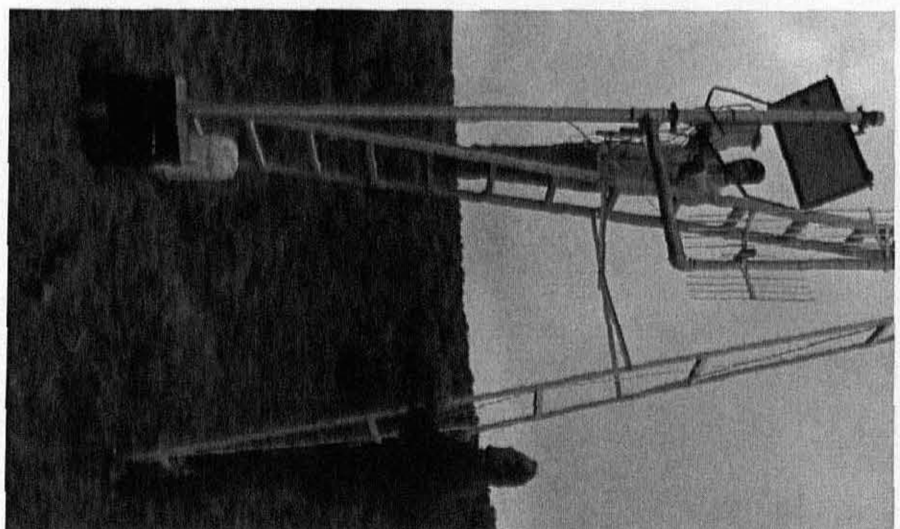


G16: The Falcom Samba GPRS/GPS modem (experimental testing)

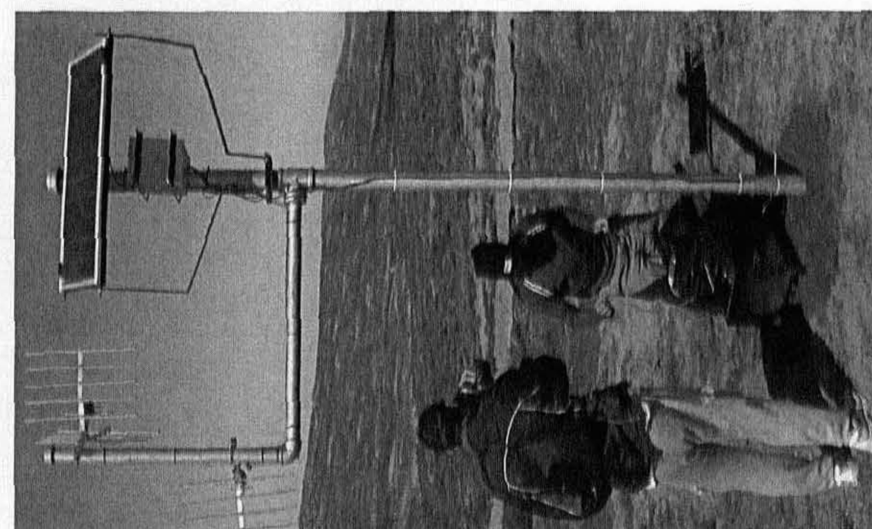
G17: Construction phase of the transmitting station



G18: Installation period



G19: Commissioning of the system



G20: Appearance of the system when it is completed