PHOTOVOLTAIC WATER PUMPING

A Case Study in Kwazulu

R J GOSNELL, BSc (Chem Eng), UCT

Energy for Development Research Centre
Energy Research Institute, University of Cape Town

January 1991

DECLARATION

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

Signed by candidate

R J GOSNELL

29th day of April, 1991

i) ABSTRACT

This is the first thorough evaluation of the viability and appropriateness of photovoltaic (PV) water pumping in South Africa. It is a case study of the operation of a PV water pumping system installed in a rural community vegetable garden in KwaZulu. The system comprised a 574 W_p array, DC power maximizer, DC motor and a Mono (positive displacement) pump. The pump delivered an average of 15 m^3/day over a static head of 12.5 metres for a Standard Solar Day of 5 kWh/m^2/d.

Three facets were considered: technical, economic and social. For the technical evaluation the operation of the whole system as well as that of each component under various conditions were monitored in the field using a data logger. The economic evaluation compared the Life Cycle Costs of PV water pumping with those of diesel, petrol and electric pumps. The social evaluation was based on three sets of interviews over a period of five years ranging from before the introduction of the pump to four years afterwards. The following are the most important conclusions.

Technical: the system Daily Energy Efficiency was 2.22%. This is low in comparison with values given in Halcrow's authoritative report of 2.35% for their average systems and 3.28% for their best systems. The reason for this was the low efficiency of the Mono Pump: 39% in comparison with 41.5% for Halcrow's average systems and 59% for their best. This was because the head of 12.5 metres at Sondela was not ideal for the Mono Pump which is designed for 45 metres. All of the low cost PV pumping systems available in South Africa, however, use positive displacement pumps and are thus inefficient at low heads. But because PV pumps are more competitive economically at low heads and low flow rates, it is important that an efficient pump for these applications is designed. Submersible centrifugal pumps should be considered.

Economics: the applicability of various assumptions to developing areas has been thoroughly evaluated. This has laid the ground work for a accurate computer program which would accurately compare the Life Cycle Costs of PV, diesel, petrol and electric pumps under a range of conditions. Connecting to the grid has many advantages and should be considered first. However, the costs of the normal tariff are affected strongly by the site and this option is out of the question for more remote sites. PV pumps are at the moment competitive with diesel pumps at only low hydraulic heads (around 40 m^4/day). However, if a PV pump which was efficient at low heads were designed and if the path of the sun were physically tracked, then PV pumps could possibly be competitive up to hydraulic heads of 1400 m^4/day.

Social: the study showed that installing pumps in community vegetable gardens can almost double the productivity of the gardeners' time. The gardeners interviewed indicated that, because of the many advantages of PV pumps, they would prefer them to diesel pumps if their amortized costs were up to twice those of the diesel pump. But few, if any, community gardens would be able to raise the capital required for a PV pump. For this reason a scheme similar to that just introduced by ESKOM could make a crucial difference to the marketability of PV pumps: ESKOM will buy and maintain the pump recovering the costs from the user at a fixed monthly rate stipulated before installation. This scheme obviates the two major barriers to the sale of PV pumps: i) high initial cost and ii) the risk of damage or loss of expensive equipment due to floods, theft or vandalism.

ii) ACKNOWLEDGEMENTS

I have been helped in many ways by many people. In particular I would like to thank the following:

Dr Anton Eberhard for his supervision of the project and for constructive criticism of draft chapters.
Bill Cowan for very thorough reading of and helpful comments on the initial drafts.
Chris Wozniak for designing and building the interface used in the monitoring system.

The Development Bank of Southern Africa for donating the PV pump to Sondela Vegetable Garden for the purpose of research.
The CSIR's Foundation for Research and Development's National Energy Programme (now under the National Energy Council) for initially funding the technical component of the research.
Anglo American's Chairman's Fund for an initial grant.
AECI for a generous travel grant when funding was short.

Mark Gandar, from the Institute of Natural Resources, for advice, encouragement and hospitality during my field work.
The Institute of Natural Resources and all the staff there for hosting me during my field work, and providing me with computer and other office facilities for many months.
Alan Cullis, from the University of Pietermaritzburg, and his team for advice and facilities to repair an ailing monitoring system - despite a very busy time schedule.

Mono Pumps Ltd for helping to install some of the monitoring equipment, for installing some protection against theft free of charge, and for patience in waiting for the results.

Sampson and Purity Ngubane and their family for hosting me for a total of 13 months while I was working on site. Thank you for your patience in teaching me Zulu and especially for accepting me into your family.
Jim and Marian Rankin and their family for hosting me for a total of seven months. Thank you for accommodation and encouragement.

The members of Sondela garden for bearing with the series of interviews and for accepting some inconvenience occasioned by the technical component of the research.
Mrs Princess Mdluli, the chairperson, for answering many questions about the garden, and for her hospitality and patience with my Zulu.
Chiefs Mdluli and Mlaba for permission to research and live in their respective wards.

In particular I would like to thank my parents for patience, encouragement and financial support during difficult times.

iii) TABLE OF CONTENTS

iv) LIST OF FIGURES

v) LIST OF TABLES

---

vi) NOTATION

The following two tables define the symbols used. The first table defines the main symbols; the second the subscripts used to specify the components or conditions which the parameter relates to. For explanations of some of the parameters used here see the glossary.

Symbol	Description	Units
DEE	Daily Energy Efficiency	%
E	Energy	kJ or kWh
g	Gravitational acceleration	9.81 m/s^2
G	Solar irradiance	W/m^2
H	Head to which water is pumped	metres
i	Electric Current	Amps
I	Insolation	kWh/m^2
PE	Power Efficiency	%
P	Power	Watts
Q	Water flow rate	m3/hr
r	Radius (eg of pulley)	m
rho	Density	kg/m3
s	Rotational speed	rpm
tau	Torque	N.m
T	Temperature	oC
V	Voltage	Volts
VOL	Volume of water pumped	m^3

Many of the above symbols are used with the following subscripts or qualifiers.

Subscripts	Adaptation to above definition
a	From the array - V_a is the array voltage
amb	Ambient - T_{amb} is ambient temperature
c	Critical - eg I_c is the "Critical Insolation"
d	Dynamic - H_d is the dynamic or friction head
hyd	Hydraulic - P_{hyd} is the power the pump delivers
m	To the motor - i_m is the current to the motor
max	Maximum - normally at the array Peak Power Curve
sc	At short circuit - i_{sc} is the array short circuit current
tr	Of the transmission - PE_{tr} is the transmission power efficiency
oc	At open circuit - V_{oc} is the array open circuit voltage
p	From or of the pump - r_p is the radius of the pump pulley
pm	Of the power maximizer - PE_{pm} is the maximizer power efficiency
ppc	Of tracking - DEE_{ppc} efficiency of the maximizer
ppc	Of tracking - DEE_{ppc} is the Daily Energy Efficiency of tracking
s	Static - H_s is the static head
sub	Of the subsystem - PE_{sub} is the subsystem Power Efficiency
sys	Of the whole system - PE_{sys} is the system Power Efficiency
'	Value at desired conditions. These are estimations arrived at by extrapolation or interpolation. For example, V_a is the actual measurement of array voltage at measured values of T_a and G. V_a' is the expected array voltage at specified values of T_a and G.

vii) GLOSSARY OF TECHNICAL TERMS AND ABBREVIATIONS

---

a) Abbreviations

AERL:	Australian Energy Research Laboratory
BOS:	Balance of System
BP Ltd:	British Petroleum Ltd
CPI:	Consumer Price Index
LCC:	Life Cycle Costs
MPPT:	Maximum Power Point Tracker
PDF:	Peak Demand Factor
PPC:	Peak Power Curve
PV:	Photovoltaic

b) Technical Terms

Amorphous Cell:	A **photovoltaic cell** in which the **semiconductor** (normally **doped** silicon) is in a non-crystalline form. These cells cost less to produce than **single crystal** and **polycrystalline** cells but are also less efficient.
Array, photovoltaic:	A number of **photovoltaic panels** connected together electrically.
Balance of System Costs:	The sum of all the costs apart from those of the major components. (The major components include the **array**, **power maximizer**, motor, and pump).
Bypass diode:	A diode used to allow electrical current to bypass a weak or damaged **photovoltaic panel** or string of photovoltaic panels.
Centrifugal pump:	A type of pump in which the water is fed to the centre of a rotating impeller and is thrown outward by the impeller. See also **positive displacement pump**.
Daily Energy Efficiency:	The ratio of the energy out of a component (or system) to the energy into that component (or system) for a whole day. The Daily Energy Efficiency is the time average of the **Power Efficiency** for the day. Daily Energy Efficiencies should be quoted for a **Standard Solar Day** of a particular **insolation**.

Insolation:	The sun energy per unit area falling on a surface. Commonly used units are kWh/(m^2.day). This is the time average of the **irradiance**.
Inverter:	An electrical device which converts Direct Current to Alternating Current.
Irradiance:	The sun power per unit area falling on a surface. Commonly used units are kW/(m^2.day). When unqualified this term implies **global irradiance**. See also **insolation**.
Life Cycle Costs:	The sum of the **Net Present Values** of all the costs of a project for the whole of the project life.
Maximum Power Point Tracker:	An electronic device which ensures that the array is operating at its **Peak Power Curve**. This term is normally applied to a device which is "intelligent", constantly searching for the Peak Power Curve.
Maximizer:	See **power maximizer**
Mismatch:	Conflicting electrical characteristics between **photovoltaic cells** in a **panel** or between panels in an **array**. Mismatch results in a loss of efficiency of the array or panel and may result in damaging **hot spots**. The effect of mismatch can be reduced by the use of **bypass diodes**.
Mono pump:	The brand name for a make of **progressive cavity pump**. This is a type of **positive displacement pump**. A Mono pump was used in the PV pumping system at Sondela.
Net Present Value:	The Net Present Value of an expense made at some time during a project is found by discounting that expense using the **discount rate**. It is the equivalent value of that expense at the beginning of the project.
Panel, photovoltaic:	A number of **photovoltaic cells** connected together in series and assembled on a panel.
Peak Demand Factor:	The ratio of the highest monthly irrigation requirement in the year to the average monthly irrigation requirement for that year.
Peak Power Curve:	The set of current/voltage operating points at which a **photovoltaic panel** (or **array**) delivers the maximum amount of power it is able to at all **irradiances**.
Peak watt rating:	The amount of power a **photovoltaic array, panel,** or **cell** produces at an **irradiance** of 1 kW/m^2.

Photovoltaic cell:	A **semiconductor** device which is able to convert the power of the sun into electrical power. It normally consists of two layers of doped silicon wafers placed together creating a "P-N" junction. A number of cells can then be connected in series to make a **photovoltaic panel.**
Polycrystalline cell:	A **photovoltaic cell** in which the **semiconductor** wafers consist of a number of crystals formed randomly from the raw material (normally doped silicon). These are cheaper than **single crystal cells** but also less efficient.
Positive Displacement Pumps:	A category of pumps including most pumps excepting **centrifugal pumps.** This category includes Mono **progressive cavity pumps,** piston pumps and diaphragm pumps. Positive displacement pumps tend to operate more efficiently at high heads.
Power conditioning:	Any device or system which helps to match the electrical characteristics of the **array** to those of the **subsystem.**
Power efficiency:	The ratio of the power out of a component (or system) to the power into that component (or system). Power efficiencies should be quoted at a specific **irradiance** or power. See also **Daily Energy Efficiency.**
Power maximizer:	An electronic device which uses some method to ensure that the array operates close to its **Peak Power Curve.** This is a general term which includes **Maximum Power Point Trackers** and **DC/DC converters.**
Progressive Cavity Pump:	A type of **positive displacement pump** which uses the "Archimedes screw principle". It consists of a rotor and stator configured in such a way that when the rotor turns the cavity containing the water moves forwards.
Pyranometer:	An instrument which measures **global irradiance.** This is a general term including semiconductor devices and **thermopile solarimeters.**
Semiconductor:	A material which may act both as a conductor of electricity or an insulator. Semiconductors are used widely in transistors, diodes and photovoltaic cells. They can be created by **doping** silicon with boron

	(creating an n-type semiconductor which has more electrons than are required to complete the crystal structure) or with phosphorous (creating a p-type semiconductor with fewer electrons than are required to complete the crystal structure).
Single Crystal Cell:	A photovoltaic cell created from semiconductor wafers which are cut from a large single crystal grown from the raw material (usually doped silicon). These cells are more efficient than **polycrystalline** and **amorphous** cells, but are also more expensive to produce.
Solarimeter:	See **thermopile solarimeter**.
Sondela garden:	The community vegetable garden where the photovoltaic pump used as a case study for this thesis was installed.
Standard Solar Day:	A theoretical day during which the **irradiance** follows a sine curve with time.
Static Head:	The difference in height between the water source and outlet of the delivery pipe from the pump: i.e the resistance to water flow solely due to the height to which the water is pumped. See also **dynamic head** and **total head.**
Subsystem:	All the components of a photovoltaic pumping system except for the **array**. The subsystem normally includes some **power conditioning**, the motor, transmission and pump.
System:	The system comprises the **subsystem** and the **array**.
Thermopile Solarimeter:	An accurate instrument used for measuring **global irradiance**. It works on the differential effect of irradiance on various metals (using the Moll-Gorczynski design). See also **pyranometer**.
Total Head:	The sum of the **static head** and the **dynamic head.**
Tracking Efficiency:	The ratio of the power produced by an photovoltaic **array** to the power it would produce if it was operating at its **Peak Power Curve**.
Tracking, Physical:	The movement of the plane of the **array** with time so that the sun's rays are always perpendicular to the array.
Watt Peak (Wp):	The units used to denote **Peak Watt Rating**.

CHAPTER 1

INTRODUCTION

The structure of this chapter is as follows:

a) Section 1.1 outlines the purpose, scope and structure of the report;
b) Section 1.2 examines briefly the need for this work by discussing the advantages and disadvantages of photovoltaics against other possible sources of power and methods of pumping;
c) And finally, Section 1.3 discusses the technical peculiarities of photovoltaic water pumping for those not acquainted with the field.

1.1 Purpose, Scope and Structure

Photovoltaic water pumping is a very new field. The first major study in the world was done by Halcrow and Partners in 1982. This report and subsequent literature indicated that photovoltaic (PV) water pumps were already competitive with alternative methods in other countries for certain applications, and that they were becoming progressively more competitive as the price of PV panels continued to drop.

However, no thorough study on the suitability of PV water pumping in South Africa has yet been published despite the fact that this country would seem particularly suited to it for the following reasons:

a) in most parts of the country there are high levels of insolation (sun energy);
b) many areas in the country are too remote for the existing ESKOM grid to be extended economically;
c) About two thirds of South Africans do not yet have access to electricity (Dingley, 1990);
d) PV pumps require little maintenance which is an important advantage for developing areas where maintenance skills for mechanical equipment are not common;
e) Diesel prices are high because of the international embargo on oil to South Africa;

So this report aimed to fill this gap by examining whether PV pumps are yet suitable in South Africa. However, the viability of a particular pumping technology depends very much on many factors: for example levels of technical expertise, access to finance, and remoteness from the ESKOM grid. So it was necessary to narrow the focus of the report further to consider only a particular type of community. The communities chosen for consideration were poor communities in remote rural settings.

The method used for research was a thorough examination of a case study. In keeping with the focus of the report, the site chosen for the case study was a community vegetable garden in a rural ward of KwaZulu. Examining a case study is more realistic than either laboratory trials or computer simulation studies because fewer assumptions are made. This method also makes it more likely that potential but unexpected problems will be discovered. It is also possible to gauge the attitudes of the target community to the various advantages and disadvantages of the technology against alternatives.

The study was divided into three aspects: the technical evaluation, the economic evaluation and the social evaluation. All these three aspects need to be examined if the suitability of a new technology to a particular type of community is to be evaluated.

These three aspects were dealt with as follows:

a) Technical Evaluation: The technical evaluation had three focuses - i) monitoring the efficiencies of the whole system and each of its components; ii) modelling the interaction between various components and examining its effect on system efficiency; and iii) the efficiency and suitability of alternative components.

   The aim was to describe the operation of a PV pump in enough detail to provide much needed information on the efficiencies of PV pumps in South Africa, to examine possible methods of improving the efficiency, and to identify areas of further research. A data logger monitoring system was used to record the data. The technical evaluation is covered in Chapter 3.

b) Economic evaluation: The purpose of the economic evaluation was to compare the long term costs of PV water pumping with those of other methods of pumping. The only other pumps considered were diesel, petrol, and electric pumps connected to the ESKOM grid. (Hydraulic ram pumps, wind pumps, hand pumps and animal driven pumps were not considered).

   A sophisticated computer model was used to compute the Life Cycle Costs of each method of pumping. The assumptions used in the computer were model were examined thoroughly in order to ensure the results were accurate and reliable. A sensitivity analysis was used to determine the effect of changing various parameters including the water demand, head, insolation, distance from the grid etc. The economic evaluation is covered in Chapter 4.

c) Social Evaluation: no matter how cheap or efficient a technology is, it will not sell if it is not suitable to the needs of a community. For this reason the social evaluation is of paramount importance - it is the social factors which determine the relative importance of the various technical and economic factors.

   The social evaluation was based on three sets of interviews done over a period of 5 years from before the introduction of the pump to 5 years after its introduction. It covers: a social profile of the area and the gardeners; the effect of the introduction of the pump on the garden; problems encountered with PV pumping; the comparative suitability of PV and diesel pumping; and the problem of the high initial cost of PV pumps. The social evaluation is covered in Chapter 5.

The conclusions of each chapter are given at the end of that chapter - there is no separate chapter with conclusions. However the executive summary draws together the main conclusions.

It was necessary to put this report into context by reviewing the literature on PV water pumping. The literature review examines technical, economic and social factors, and is contained in Chapter 2. An extensive bibliography can be found in Chapter 6.

The appendices contain back-up information for the argument in the main body. The sections in the appendices map directly onto the main body so that relevant information can be found quickly and easily.

1.2 The Relevance of PV Water Pumping

The relevance of research on PV water pumping can only be evaluated in the context of alternative methods available for achieving the same result. For this reason the following are considered.

a) Photovoltaic power versus conventional sources of power.
b) PV water pumping versus other uses for PV panels.
c) Alternative methods of water pumping.

a) Photovoltaic power versus conventional power

Photovoltaic power has many advantages over conventional sources of power, including the following:

i) Most importantly they use renewable energy. Fossil fuels have formed the basis of the explosion in industrial activity in the past two centuries. However, fossil fuels are effectively not renewable - they were deposited over the past 600 million years, but have been used up increasingly rapidly over the past 200 years. For example, petroleum began to be extracted in significant amounts in 1880. Since then consumption has approximately doubled every 10 years with the result that the same amount was used in the 10 years between 1959 and 1969 as in the 102 years from 1857 to 1959 (Hubbert, 1971).

Fossil fuels are themselves a form of stored solar energy. About 0.02% of the solar energy impinging on the earth is converted to carbohydrates in organic matter by photosynthesis. A minute fraction of this 0.02% is then deposited in oxygen deficient peat bogs and is converted over millennia into fossil fuels (Hubbert, 1971). So the recent explosion in industrial activity has been based on the use of that minute fraction of solar energy that happened to be converted to fossil fuels. However, it would be more elegant and sustainable to use the solar power directly, as solar power contributes 99.98% of the earth's total energy budget (Hubbert, 1971). This can be done through photovoltaics. With more research the use of this renewable energy source may be made more economical and more practical.

ii) They are environmentally sound. The use of fossil fuels contributes to both acid rain and the green house effect. Nuclear energy has the inherent risk of radiation and the problem of dealing successfully with radioactive wastes from the power plants.

iii) PV panels are light and easily transportable. They are thus able to provide small amounts of electricity cheaply in remote places. Extending the grid to these places would be expensive. Provision of electricity in these places could promote agriculture, education and improved working conditions.

iv) They require no fuel and are self-starting. This makes them ideal for remote areas where access to fuel may be difficult, and for applications such as repeater stations for telecommunications for which diesel generators would be impractical because of the need to start and stop the engine.

v) The require little maintenance and so are ideal for communities which have little technical expertise.

vi) The price of PV panels is decreasing while that of fossil fuels will inevitably increase as reserves are depleted and as the global energy demand increases.

For all these reasons PV power could possibly make an important contribution to energy supply; and research into its present long term costs, suitability and efficiency is important.

b) PV water pumping vs other applications for PV panels

Water pumping is one of the uses most suited to PV power for two reasons. Firstly, the storage of the energy from the panels is cheap. If PV panels are used for domestic energy for a household, a large proportion of the cost of the system is battery storage of electricity. This is because while the sun's energy is only available during the day, much of the electrical energy is required at night for lighting and TV. Thus batteries which are expensive and unreliable must be used. In contrast, water for irrigation is mostly used during the day. And energy can be stored more cheaply as pumped water in a reservoir than it can be in batteries.

Secondly, the variation in demand for irrigation water is closely matched to the variation in irradiance (sun power): when it is overcast or raining no water is pumped because of the low irradiance; but little water is needed because the evapotranspiration from the plants is low. In contrast, the need for household electricity remains almost constant despite the amount of sunshine and so more storage of energy is required to cope with overcast periods.

c) PV water pumping versus other methods of pumping using renewable energy

The suitability of PV water pumping is compared with that of diesel and electric pumps in this report in detail. However, there are pumps which use renewable energy which could also be considered: wind pumps, hand pumps etc. Their likely suitability is commented on briefly below.

Wind pumps: these have been used very successfully by commercial farmers. However, the power available from the wind is proportional to the cube of the wind speed: so the suitability of wind pumps depends strongly on the site. Wind pumps are also unlikely to be suitable in areas where there are long periods of time without wind. Wiseman (1986) also notes that the average time between break-downs for wind pumps installed by the Transkei government is 3 months: partly because of lack of maintenance skills locally and partly because responsibility for maintaining the wind pumps is not normally transferred to the local communities. So wind pumps are unlikely to be suitable to communities with low levels of technical expertise.

Hand pumps: these are suitable only for low water demands. For higher water demands, the cost of using and number of pumps (and possibly of sinking a number of boreholes) may well make this option too expensive. Also, for a community vegetable garden it is easier to share the expenses of a diesel or PV pump fairly than it is to share the work of hand pumping fairly. Unequal effort spent on water pumping may cause friction between members of a community garden.

Solar thermodynamic pumps: instead of using PV panels to convert sunlight to electricity, these pumps are driven by engines which work off the concentrated heat of the sun. Thermodynamic cycle engines which have received particular attention are the Rankine (Girardier and Vergnet) and the Stirling (Beale, 1979). Neither the Stirling nor the Rankine have been used on a commercial scale for water pumping. However, prototypes of both systems have been successfully tested in the field. They have the potential to compete favourably with photovoltaic systems, both in terms of system efficiency and system cost (Banks: pers. comm., 1991).

Hydraulic ram pumps: these pumps use the momentum of the water in a river to pump a portion of the water up a head. They are robust and can be made cheaply. However, they can only be used if the ratio of the drop available in the river to the head that the water must be pumped to is within the correct range. A minimum drop of 1 metre is required which rules out their use in many slow falling rivers.

Rain water harvesting: rainwater can be collected from surfaces such as roads and mountain sides and stored fairly cheaply in dams or reservoirs. However, the amount of storage required depends on the annual variation in rainfall and that of the irrigation requirements. Rain water harvesting is impractical in some areas because there is almost no rain during the winter when most of the irrigation is required.

1.3 Introducing the technical peculiarities of photovoltaic water pumping

The principles of conventional water pumping are well known; but the use of photovoltaic (PV) panels to power water pumping introduces considerations which are not well known. This section explains these technical peculiarities and the considerations that influence the choice and matching of components for a PV water pump.

1.3.1 Converting Light to Electricity: PV cells

The most common photovoltaic device is the single crystal cell which is made of two layers of silicon each doped with an impurity. The layer on which the sun shines is doped with phosphorus creating a n-type semi-conductor; the other with boron producing a p-type. The two layers are bonded creating a p-n junction as is used in transistors.

The n layer has "free electrons". Each silicon atom has four valence electrons and expects to bond with an atom which also has four. However the phosphorus atom has five valence electrons, and so there are free electrons which are not bonded. The crystal is nevertheless still neutral.

Similarly, in the p layer there are spaces for extra electrons which the boron atoms have created as they have only three valence electrons. These spaces are called "electron holes".

Thus when these two layers are bonded a "depletion zone" forms at the interface: the free electrons from the n layer flow into the p layer filling the "holes" leaving a zone relatively free from free electrons or electron holes. A potential difference is built up across the junction.

At any given time some valence electrons have enough energy to overcome their bonds to the nuclei and are thus mobile. The electric field sweeps these mobile electrons across the junction (in the opposite direction to the flow of "free electrons" described above) and an equilibrium is established.

If this cell were placed in the dark and connected into an electrical circuit, no current would flow because of the equilibrium. However, in sunlight the photons of light liberate a large number of electrons from their bonds. Most of these are swept out of the depletion zone before they recombine with the nuclei, and they form the current of the PV cell.

Figure 1.1 below shows a schematic of the operation of a PV cell.

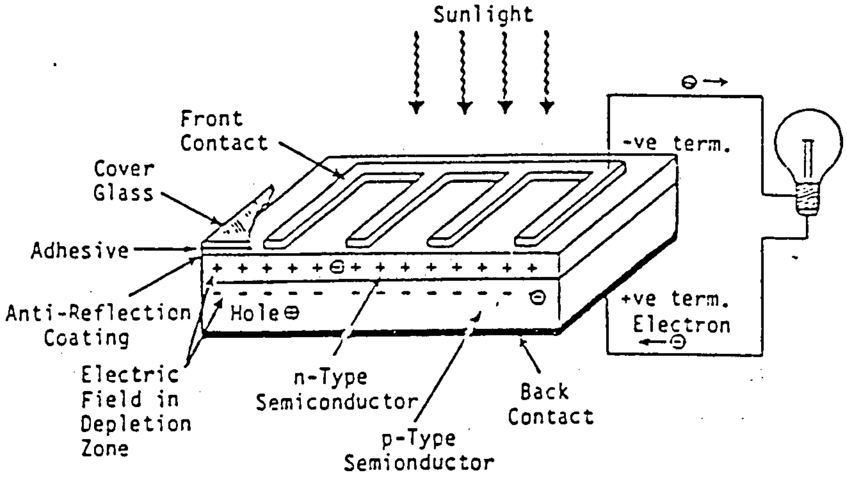


Figure 1.1: Schematic of a Photovoltaic Cell
Source: SERI, 1985, p2

A number of cells is then connected in series and assembled on a panel. These panels can then be connected in series or parallel to form a PV array. Figure 1.2 shows the array of 16 panels which was first installed at Sondela garden.

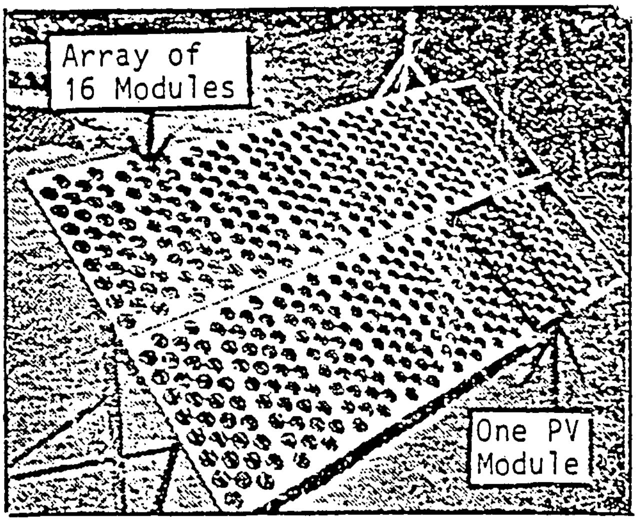


Figure 1.2: The Array of 16 Photovoltaic Panels at Sondela

1.3.2 The Peculiarities of Solar Energy

The amount of solar energy at any time cannot be controlled or predicted. Unlike diesel, solar energy itself cannot be stored and used at will - it must be converted to other forms of energy when available and stored if necessary in these forms (for example as electricity in batteries or as pumped water).

A user must decide how much down time can be tolerated for a particular use. The more essential the use the more the PV array and the storage must be oversized to cope with freak conditions. Weather data averaged over previous years is then used to size the system. Back up by a diesel machine is another method of ensuring reliability.

To be able to harness as much of the available energy as possible it is important to understand what happens to the constant flux of solar energy striking the outer atmosphere. This is shown below.

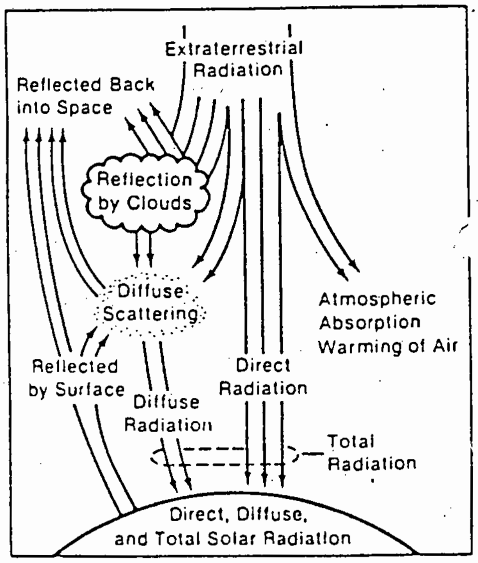


Figure 1.3: The Effect of the Atmosphere on Extraterrestrial Solar Radiation
Source: SERI, 1984a, p6.

The diagram illustrates the distinction between direct radiation and diffuse radiation - diffuse radiation reaches the earth after reflection or scattering. The combination of direct and diffuse radiation is termed global or total radiation. An object in the shade, for example, receives only diffuse radiation.

For a sunny day the graph of the level of global radiation against time approximates a sine curve. Figure 1.3 illustrates this and shows how much humidity can reduce the amount of solar energy available by comparing typical graphs for an arid and a humid site.

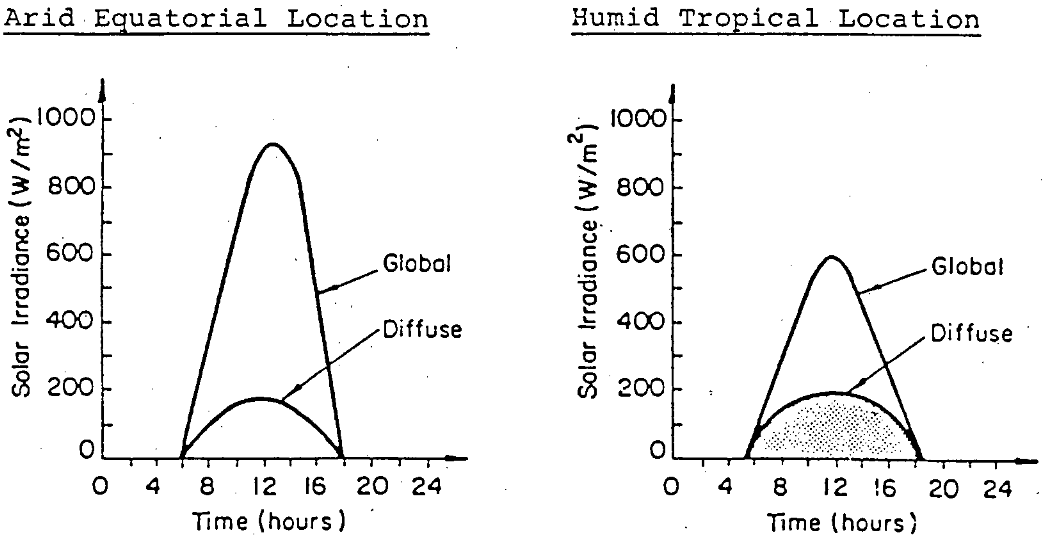


Figure 1.4: Solar Irradiance versus Time for Two Sites
Source: Halcrow, 1984, p5.

At a favourable place the solar irradiance may peak at 1 kW/m². The power delivered at this particular irradiance is called the "peak watt rating" of the array. So a 600 W_p array will deliver 600 W at an irradiance of 1 kW/m² at its Nominal Operating Cell Temperature (normally 25 or 28 °C).

1.3.3 Selection of Components for a PV Pumping System

A PV pump includes the PV array, possibly a power matching device and electrical storage, a motor, pump and possibly storage of the pumped water. Some of the possible configurations of these components are shown in Figure 1.5 below.

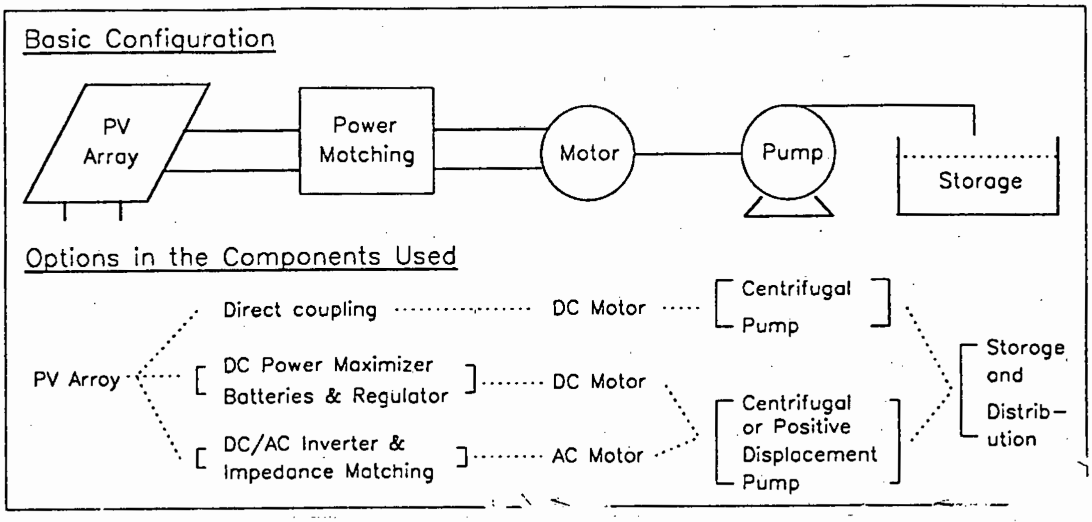


Figure 1.5: Possible Configurations of a PV Pumping System

The PV array produces direct current. So a DC motor is necessary unless a DC to AC inverter is used. The array may be directly coupled with the motor or a power matching device may be used. The need for power matching is discussed below. If the array is directly coupled to the motor a centrifugal pump should be used - otherwise either type of pump is suitable. The choices which need to be made for each component are discussed in turn below.

a) The PV Array: Tracking or Fixed?

A tracking array is kept normal to the sun's rays at all times so that as much solar energy as possible may be absorbed. About 20% more radiation is absorbed than if the array were fixed (Potgieter, 1988). Equipment for tracking used to be expensive and was normally only justified for concentrator cells. (For these cells it is essential as the concentrating mirrors or lenses must track the sun to focus the light on the cells.) But passive tracking devices are now available that are likely to be cost effective for many applications.

If the PV array is fixed it should face due North for a site in the southern hemisphere and should normally be at an angle from the horizontal equal to the latitude of the site.

b) The Need for Component Matching and Power Conditioning:

At a particular irradiance the power delivered by a PV panel may range from zero to the maximum possible at that irradiance. The power delivered depends on the voltage required by the device the array is powering. This is shown in Figure 1.6 below.

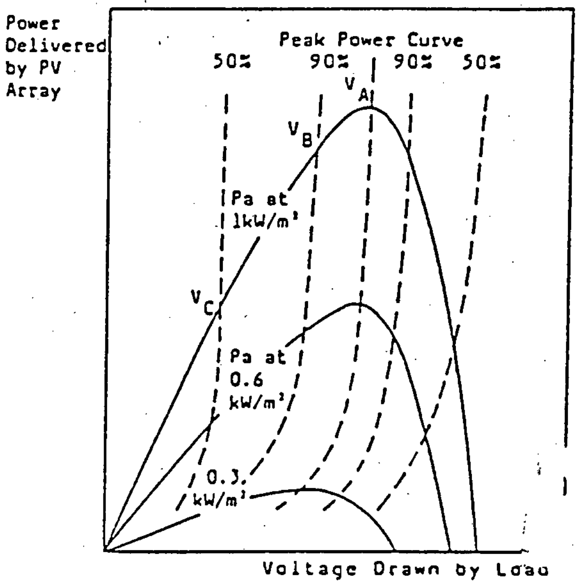


Figure 1.6: The Need for Power Matching
Source: Adapted from Appelbaum and Bany, 1979, p439.

The Peak Power Curve is the locus of the maximum power the array can deliver at each irradiance. The graph also shows loci for 90% and 50% of the maximum power. For example, if the irradiance is 1 kW/m² the array would deliver its maximum power for that irradiance if the device it operated required a voltage V_A, but 90% or 50% its maximum power if V_B or V_C were required.

So to maximize its efficiency the array must be made to operate as close to its Peak Power Curve as possible: either by carefully matching the components of the subsystem powered or by electronic power conditioning.

The figure below shows typical current versus voltage curves at various irradiances. These curves are interrelated with the power curves because P=Vi. The current at short circuit, i_{sc}, and voltage at open circuit, V_{oc}, (which are often quoted by manufactures) are shown on the graph.

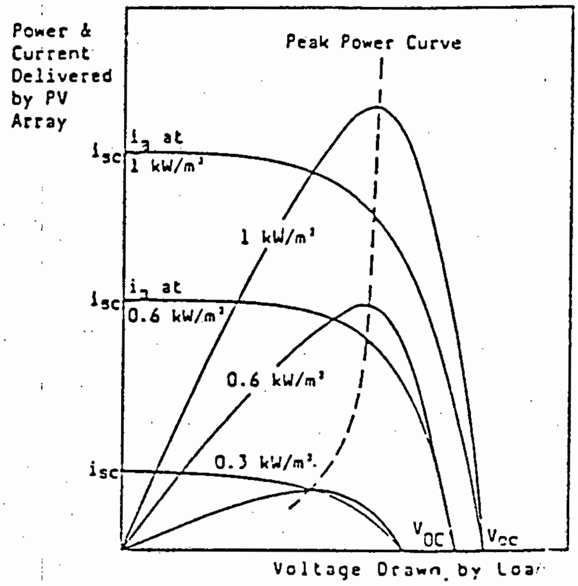


Figure 1.7: The Relationships Among Power, Voltage and Current Delivered by the PV Array

Typical demand graphs for three subsystems are shown in Figure 1.8 below.

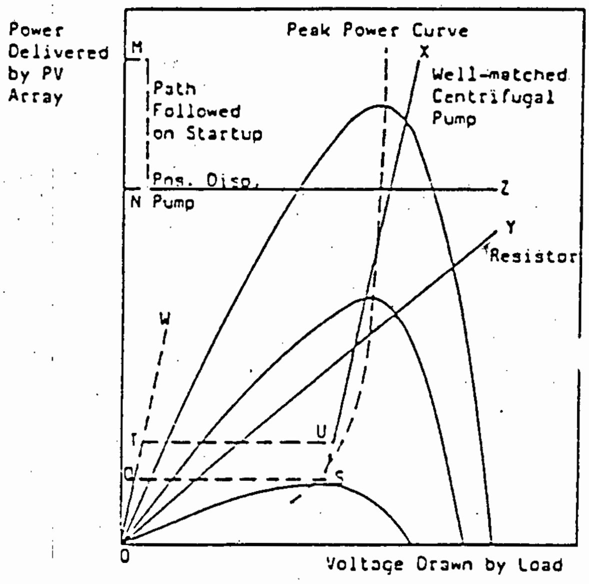


Figure 1.8: Demand Graphs for Three Subsystem
Source: Roger, 1982, p 299.

The demand graph for a simple resistance is a straight ascending line such as OY - as R=V/i and R is constant. Thus a simple resistance is not matched well to a PV array: its demand graph cuts the Peak Power Curve in only one place and at all other irradiances the array will be delivering less power than it could.

Similarly a DC motor driving a positive displacement pump is not well matched. The current the motor draws is constant, because the pump torque is constant at a constant head. So the demand graph is a horizontal line such as NZ which does not follow the Peak Power Curve closely. On start-up, a high current is required to overcome the starting torque - this represented on the graph by point M.

The third demand graph shown is for a well-matched centrifugal pump driven by a DC motor. As the irradiance increases the current drawn rises sharply along the line OW until the starting torque is equalled at point T. During this time the array is inefficient; but as soon as the pump begins to turn the voltage increases rapidly along line TU and from then onwards the demand graph follows the Peak Power Curve closely. The system will follow path XSQO when the irradiance is decreasing because the running torque is lower than the starting torque.

If the subsystem is not well matched power conditioning is essential. The figure below shows how this operates for a positive displacement pump which has a demand of NZ as well as for a badly matched centrifugal pump represented by the other demand curve.

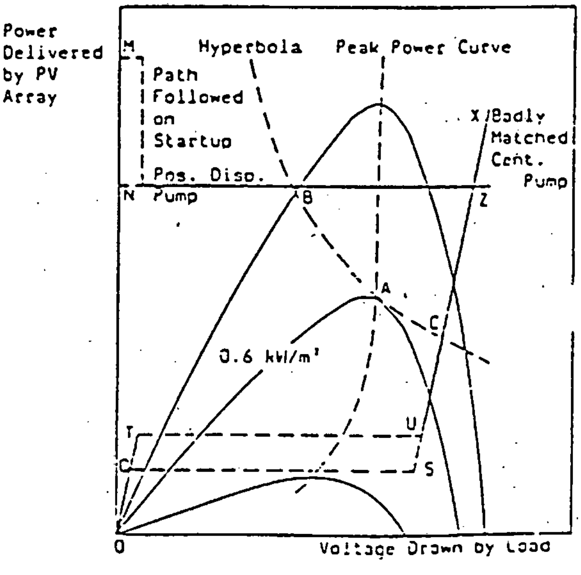


Figure 1.9: The Way Power Conditioning Works
Source: Roger, 1982, p 304.

At an irradiance of 0.6 kW/m² an ideal power conditioning device would draw power at point A (on the Peak Power Curve) and deliver it as the subsystem requires i.e. point B for the positive displacement pump or point C for the centrifugal pump. In practise some power is lost and the hyperbola (which is a constant power curve) is not followed exactly.

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 subsystem. The better DC/DC converters monitor cell temperature because the Peak Power Curve moves sideways as the temperature of the cells changes. They then set the input voltage accordingly.

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 subsystem to maximize this power. If the power is increasing the MPPT continues to adjust the apparent impedance in the same direction; if the power decreases it changes direction. Good DC/DC converters and MPPTs deliver about 90 to 96% of the power that they receive.

If an AC motor is used an inverter is required. A well-matched inverter has a demand curve which follows the Peak Power Curve closely - see curve A in Figure 1.10 below. But most inverters are inefficient - the average efficiency is around 85% (Buresch, 1983, p172) - so that although the array delivers nearly its peak power, power is wasted inside the inverter. The efficiency of most inverters drops markedly as the load they are under drops: at 50% capacity a typical inverter is 60% efficient (Morris, 1988).

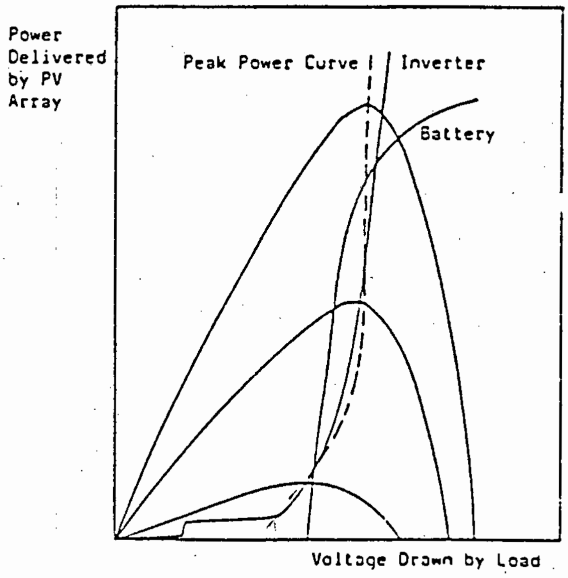


Figure 1.10: Demand Graphs for an AC Inverter and for a Battery
Source: Buresch, 1983, p156.

Curve B in Figure 1.6 shows that batteries are also well matched to PV arrays. The voltage the battery draws increases slightly as its level of charge increases but it remains close to the Peak Power Curve. Nevertheless, for a PV pump energy should be stored as pumped water rather than in batteries as batteries have low efficiencies of about 70 to 80% (Buresch, 1983, p143). They are also expensive, have short lifetimes and require regular maintenance.

c) Choosing a Motor: DC or AC?

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 also be reliable for a remote site.

Although AC motors are cheaper and more readily available they need voltage 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. Work is currently being done on the use of AC systems. 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 (about once every two years) 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.

d) What Type of Pump: Centrifugal or Positive Displacement?

The cost of the pump is a small fraction of that of the array: so high efficiency and reliability outweigh low cost in choosing the pump.

Because both positive displacement and centrifugal pumps have strong and weak points, the choice between them can be only made for a particular situation given the available alternatives.

A well-matched centrifugal pump requires no power conditioning. This reduces the number of components and consequently the loss in reliability and efficiency associated with each additional component. However the efficiency of the pump drops considerably when it operates away from its design head and speed. (This may outweigh the small increase in efficiency resulting from dispensing with power conditioning). In their favour, these pumps have low starting torques and so will turn at even low irradiances. They also tend to be better suited than positive displacement pumps to low heads. Self-priming or preferably submerged types should be chosen.

Positive displacement pumps require power conditioning as explained in part b) of this subsection. But their efficiency is more consistent throughout the range of speeds. There are two common types of positive displacement pumps. The piston and cylinder type should be used only for heads higher than 15m as friction is then small compared with the work accomplished. The second type is the progressive cavity pump made by Mono Pumps which works on the Archimedes screw principle. This is a very reliable pump which can be built to have a low starting torque.

e) Thrift in the Use of Water:

The purpose of an irrigation pump is to get enough water to the roots of the plants, not just to efficiently lift a quantity of water up a certain height. The efficiency of water distribution is as important in reducing the costs as the efficiency of the pump. The head that the distribution system requires represents energy wasted and it should be minimized. Table 1.1 below gives the heads required and efficiencies of four distribution methods.

Table 1.1: The Efficiency of Four Water Distribution Methods

Distribution Method	Application Efficiency	Head (m)	Suitable for Solar Pumps
Open Channels	50-60%	0.5-1	Yes
Sprinklers	70%	10-20	No
Trickle Irrigation	85%	1-2	Yes
Flood Irrigation	40-50%	0.5	No[1]

1. Flood irrigation is considered unsuitable unless there is water storage because it entails high demand peaks.

Source: Halcrow, 1984, p30.

More efficient than all the above is the application of water by hand directly onto the plants from a network of taps in the garden.

Increasing the water retention of the soil by mulching and deep trenching may also increase the cost-effectiveness of the PV pump considerably.

CHAPTER 2

LITERATURE REVIEW

The basics of PV technology are covered in Chapter 1. This chapter reviews recent literature and summarizes the following:

1) efficiencies reported and expected for PV water pumping (Section 2.1);
2) its suitability to underdeveloped areas (Section 2.2);
3) its present and future economic feasibility (Section 2.3).

2.1 Technical - Efficiencies

2.1.1 The Range of Efficiencies for the Whole System

The efficiency of a PV pump changes with the irradiance. Thus in order that comparisons of efficiencies be valid it is vital to make some distinctions. Each efficiency must specify both of the following:

a) The components it includes:

The system efficiency comprises those of the array, power conditioning, motor, transmission and pump. It is the ratio of the hydraulic energy/power delivered by the pump to the energy/power of the incident sunlight.

Whereas, the subsystem efficiency includes those of all components except the array. It is the ratio of the hydraulic energy/power delivered by the pump to the energy/power of the electricity delivered by the array.

b) The basis - either of energy or power:

The Power Efficiency is the ratio of the power out to power in, and must be quoted at an irradiance (e.g. 0.7 kW/m^2).

Whereas, the Daily Energy Efficiency is the time average of the power efficiencies for a day, or the ratio of energy out to energy in for that day. So that energy efficiencies may be compared, Halcrow (1983) has defined a "standard solar day". On a standard solar day the irradiance follows a sine curve with time, and the peak of the sine curve is set so that the insolation (the area under the curve) is that which is required. For example, for a standard solar day of 5 kWh/m^2 the irradiance follows a sine curve with time peaking at 0.708 kW/m^2.

The most telling efficiency is the Daily Energy Efficiency. For example, a pump which has a high efficiency at high irradiance levels might easily have a low efficiency at lower irradiances. Quoting the Power Efficiency at a particular irradiance does not tell how much water would be delivered on an average day. It might well be misleading.

A further caution is that results found by computer models, laboratory tests and field trials are not exactly comparable and so the method of research must be noted.

The most extensive study on PV pumping to date is by Halcrow (1983). Sixty two companies throughout the world were asked to tender to certain specifications resulting in designs for 64 systems. The twelve best systems, four in each of three categories, were tested under controlled conditions for five months. A PV array simulator provided the electricity so that the "irradiance" could be controlled and the results would be comparable. Motor efficiencies were determined by laboratory tests, and from these pump efficiencies were calculated.

Table 2.1 below, compiled from Halcrow's results, is used as a basis of comparison for all the results reported in this section.

Table 2.1: System and Subsystem Efficiencies: Averages for 12 PV Pump Systems

Category and Size of System	System Effs (%)[1]		Subsystem Efficiencies (%)[2]			
	Daily Energy[3]		Daily Energy[3]		Peak Power[4]	
	Ave	Good	Ave	Good	Ave	Good
1. 220 W_p array, 60 m^3/day at 2m head (120 m^4/day)	1.9	2.3	25	30	30	40
2. 700 W_p array, 60 m^3/day at 7m head (420 m^4/day)	2.5	3.4	28	40	40	60
3. 730 W_p array, 20 m^3/day at 20m head (400 m^4/day)	2.4	3.8	32	42	35	45

Notes:
1. Sun to water efficiency: see explanation at the beginning of this subsection.
2. Electricity to water efficiency: see explanation at the beginning of this subsection.
3. For a "standard solar day": 5 kWh/m^2 with peak at 0.708 kW/m^2.
4. Measured at 0.708 kW/m^2.

Source: Halcrow, 1984, p26 and Halcrow, 1983, p5.26.

Category 1 is for the smallest systems and Category 3 for the largest. It can be seen that system daily energy efficiencies for average systems range from 1.9% to 2.5% with the best systems giving 2.3 to 3.8%. The daily energy efficiencies for average subsystems range from 25 to 32% with the best systems giving 30 to 40%. It can be calculated from these results that the PV arrays were on average operating at 8.4% efficiency. This is lower than figures given for PV efficiencies in the next subsection (2.1.2) partly because the arrays were operating away from their Peak Power Curve.

A comparison of columns 4 and 6 above emphasizes the importance of distinguishing between daily energy efficiencies and power efficiencies. For example, a subsystem which has a Power Efficiency of 60% at 0.708 kW/m^2 has a Daily Energy Efficiency of only 40% for a standard solar day (5 kWh/m^2).

<u>Other reports:</u> Roger (1982) computed a system Power Efficiency of 6% at 0.6 kW/m^2. He was using a computer model to examine the operation of a direct-coupled centrifugal pump with a DC motor. (The DC motors usually have permanent magnets and this is to be assumed unless otherwise stated). The array power of 900 W_p puts it in category 3 above.

Unfortunately, he did not mention the array efficiency he was using, so it is difficult to compare. If he used an array efficiency of 8.4% (the average found in Halcrow's study) then the Power Efficiency of his subsystem at 0.6 kW/m^2 is 71% - which is excellent. Halcrow gives 35% as average and 45% as good (at 0.708 kW/m^2). However, if he used an array efficiency of 15% (cf Buresch,1983: p38), then the Power Efficiency of his subsystem is 40% - good but not excellent.

Field data for a system in Botswana are given by Maseng and Jacobs (1984). The system includes an electronic regulator, batteries, a DC motor and Mono pump (positive displacement). It fits most closely into category 1 above with an array size of 360 W_p and a hydraulic head of 260 m^4/day. However, it has a high head of 75m and low output rather than a low head (2m) and high output.

They measured a Daily Energy Efficiency for the subsystem of 24%. This figure is an average for the day measured and not at a "standard solar day", but still the value given by Halcrow of 25% for an "average" pump is a good standard of comparison. Maseng gives a peak Power Efficiency of 38%, but does not give the irradiance. However this compares with 30% for an average subsystem and 40% for a good one in Table 2.1.

A system worth special note is that examined by Pulfrey et al (1987) - it is very similar to the system at Sondela garden which is the case study for this thesis. Both systems include a Mono progressive cavity pump, DC motor and DC/DC converter. The sizes of the systems are similar: Pulfrey's system is sized at 800 W_p, 15 m^3/day and 35m head compared with 655 W_p, 27 m^3/day in summer, and 13m head at Sondela. This places both systems in category 3 above.

However, Pulfrey's tests are in the laboratory compared with field trials at Sondela. Pulfrey also uses an expensive custom designed motor with a very high efficiency of 82-88%, whereas a standard motor is used in the Sondela system.

Pulfrey measured the Daily Energy Efficiency of his system for a standard solar day as 3.3% (cf 2.4% average and 3.8% for a good system - Table 2.1). However, the subsystem Daily Energy Efficiency can be calculated from the array efficiency of 7.7% quoted by Pulfrey. This gives 42% which is the same as that obtained by Halcrow for the best system in this category.

So the potential efficiency of Pulfrey's system depends on the comparative efficiencies of the panels used in the two studies. If the lower array efficiency measured by Pulfrey was due to the use of less efficient PV panels then the system is as efficient as the best system tested by Halcrow. If, however, the lower array efficiency is because the DC/DC converter was not keeping the PV array operating as close to its Peak Power Curve as the array in Halcrow's study, then Pulfrey's system does not rate as well - but is still one of the better examined in the literature.

2.1.2 Component Efficiencies

a) Photovoltaic Panels

Because there are numerous types of PV cells, the reader must distinguish between them when comparing efficiencies. For this reason, a brief explanation of the method of production is given before quoting the efficiency of a particular type of PV cell or panel. Table 2.2, p 29, summarizes the results for those conversant with cell types.

In 1983 Buresch claimed that the maximum theoretical efficiency of silicon PV cells is 25% (p38). By 1987, efficiencies of 28% in the laboratory were being obtained for concentrator cells (Moore et al, 1987:p8). Efficiencies of 30% are expected to be achieved in the next few years using concentration (Sinclair, 1988:p46). However, the highest reported commercial efficiency reported was 19% (Arvizu, 1987,p131) and that for amorphous silicon cells was 6-7% (Hamakawa, 1986).

It has therefore been necessary to revise estimates of maximum theoretical efficiency. The literature available has as yet not provided this estimate. The diagram below illustrates the energy losses involved for a crystalline silicon cell. . The band-gap energy of silicon determines that only 44% of the incident light can be absorbed. The diagram shows what happens to this 44%. 16% of the incident energy is lost due to voltage and carrier recombination. This is the only unavoidable loss making the theoretical limit of efficiency 28%. Other losses are due to reflection, and series resistance.

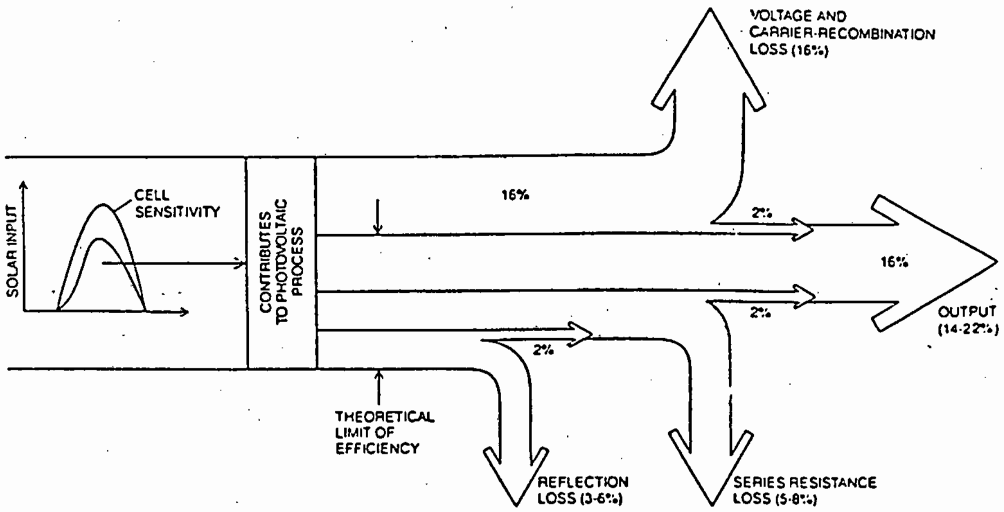


Figure 2.1: Energy flow in a crystalline-silicon solar cell
Source: Hamakawa, 1987:p80.

There have been three main avenues of research in the drive to produce cost-effective PV cells. Firstly, different production techniques have been used to reduce the cost of producing a silicon cell. This has resulted in the development of polycrystalline and amorphous thin film cells. Secondly researchers tried to increase the amount of irradiance absorbed by using materials with different band-gap energies as well as cascade cells. Thirdly the efficiency has been improved and the cost reduced through concentrating the light on the cell. These three avenues are discussed in turn below.

Production techniques used to reduce costs

The single crystal cell is made by growing a ingot from molten silicon which is then sliced into wafers. However, because of the thickness of the saws approximately half of the ingot is wasted. This is the oldest method and although its share of the world market is falling it still held about 48% of it in 1987 (Strategies Unlimited, 1987). It has obtained the highest efficiency of all types of cells - with a laboratory efficiencies of 21%, and commercial efficiencies of up to 19% being reported. (See Table 2.2, p 29 for references for this and all figures quoted below).

To avoid wastage of the crystal, techniques of drawing up a ribbon or sheet single crystal from the molten silicon were developed. These ribbon cells are not yet commercially competitive but will soon become so. Laboratory efficiencies of 17% have been reported.

Growing a single crystal is time consuming and needs very exacting conditions. Polycrystalline cells are cheaper to grow and require less refined silicon but they have lower efficiencies. The molten silicon is either cast in a brick and sliced into wafers or it is grown in ribbons as described above. Laboratory efficiencies of 15 to 19% have been reported and 8-10% for commercially produced panels. Their share of the world market has grown from around 2% to around 20% during the 1980s.

A new and promising type of cell is the amorphous silicon cell. Here the silicon is deposited onto a base in a thin film from the vapour phase. The resulting film is amorphous (not crystalline) and this has two important effects. Firstly its ability to absorb light is two orders of magnitude greater than crystalline silicon and consequently the films can be about 0.5 micron thick as opposed to 100-300 microns for the crystalline wafers. (1 micron of amorphous cell absorbs 90% of the usable solar energy). This results in a great material saving and considerable cost reductions.

Secondly, however, the efficiency of the cell is reduced: laboratory efficiencies of 12% have been obtained, and Sinclair (1988) notes that the efficiency these cells seems to be limited to around 12-14%. Commercial efficiencies of 6-7% have been obtained. Despite their low efficiencies these cells have become second only to single crystal cells in the world market due to their cost of production, growing from around 3% of the market to about 38% during the 1980's.

Amorphous silicon has been marketed mainly for small-scale consumer appliances (watches etc.), as opposed to bigger panels. These films are also very adaptable and can be formed on roof tiles, stick-on plastic rolls, etc.

The use of materials other than silicon

The second avenue of research has involved examining the use of different materials with different band-gap energies in order to increase the maximum amount of radiation which can be absorbed. Figure 2.2 below shows how of the maximum theoretical efficiency of a PV cell is determined by the band-gap of the material it is made from. Although these estimates are outdated, they show that materials such as gallium arsenide (GaAs) and cadmium telluride (CdTe) have a maximum theoretical efficiency 5% higher than that of silicon.

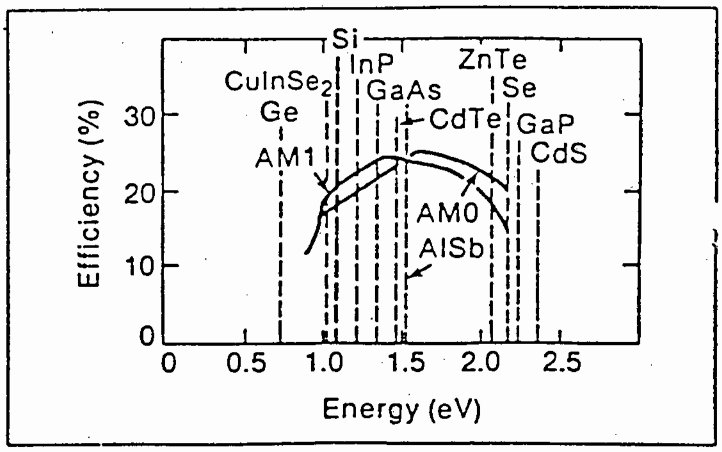


Figure 2.2: Maximum Theoretical Efficiency of PV cells versus Band-gap of the constituent material
Source: SERI, 1984a, p27. Cited by Sinclair, 1988.

The highest efficiency reported for single crystal cells without concentration is for GaAs - that is 23.7%. The other materials mentioned have mostly been used with thin film cells and so their laboratory efficiencies have been much the same as that of amorphous silicon - around 12%.

However, a further innovation using these materials has great potential - the cascade cell. This cell uses two or more thin cells of different materials with the lower cells being able to absorb light of lower and lower frequencies. This enables a greater efficiency to be obtained than would be possible if only one material was used.

The maximum theoretical efficiency for cascade cells has been estimated as 37% - compared with 28% for single crystal cells. However, because of the extra material costs mainly amorphous thin film cells are used to construct cascade cells and the highest laboratory efficiency obtained so far is 17%.

Concentrator cells

The third main avenue of research has been in the use of concentrator cells. Most cells improve in efficiency when subjected to concentrated light. A cell efficiency may improve by 5% when the intensity of the light on it is increased from 1 sun to 100 suns (where 1 sun = 1 kW/m^2). Because a smaller area of cell is required per unit of energy output, very high quality cells are used in concentrator cells.

Lenses and mirrors concentrate light on the cells and thus they are able to use only direct beam radiation. For this reason they also need to track the sun and so are practical only for large-scale centralized systems (100 kW or more). They also require cooling.

Concentrator cell efficiencies of 26-28% have been attained in the laboratory using GaAs and single crystal silicon cells - (cf 20-23% for the same type of cells without concentration).

Table 2.2 summarizes efficiencies reported in the literature for different type of cells.

Table 2.2: PV Cell Efficiency by Type

Cell Type	Max Theor. Eff. (%)	Laboratory Eff. (%)	Commercial Eff. (%)
Single Crystal Si	28.0 (1)	20.8 (11)	15-19 (12,13)
Polycrystalline Si		15.3 (14)	8-10 (3)
Ribbon Si Cell		16.6 (11)	
Single Crystal GaAs		23.7 (2)	
Thin film cells (aSi,CuInSe,CdTe)		9-13 (3,6,7,10)	5-7 (3,7)
Cascade cells	36,6	10-17 (2,3,9,10)	
Concentrator cells			
GaAs at 750 suns		26.1 (15)	
Si at 110 suns		28.2 (5)	

References for the table (given in brackets):

1. Hamakawa, 1987
2. SERI, 1986
3. Hamakawa, 1986
4. Moore et al, 1985
5. Moore et al, 1987
6. SERI, 1984b
7. Zweibel, 1986
8. Krantz, 1986
9. Int. S.E. Report, 1986

10 Strategies Unlimited., 1987
11 Eberhard, 1987
12 Prince, 1987
13 Arvizu, 1987
14 Shirasawa et al, 1987
15 Gee et al, 1987

Source: Condensed from Sinclair, 1988:p44.

b) Power conditioning methods

Here we look at efficiencies recently measured for methods of power conditioning: direct coupling, maximum power point trackers (MPPTs), DC/DC converters, and batteries. See Chapter 1 for an explanation of the need for power conditioning or matching.

Direct coupling versus MPPT: Hsiao and Blevins (1984) compared the efficiency of direct-coupling with that of MPPT's using a centrifugal pump and DC motor. His computer study found that for the best matched systems the efficiency of direct coupling was 79% at a 2m static head, and 63% at a 5m static head. MPPT's, on the other hand, have efficiencies of around 86%.

DC/DC Converters: Table 2.3 below gives the efficiencies measured by Pulfrey (1987) in his laboratory study on a Mono pump system with DC/DC converter.

Table 2.3: DC/DC Converter Power Efficiencies

Head (m)	Eff. at 500 W/m^2	Eff. at 1000 W/m^2
25	94%	98%
35	96%	99%
55	88%	94%

Source: Calculated from Pulfrey, 1987: p261.

At heads of 25m and 35m the Power Efficiency of the converter is 94% to 99% (between 0.5 and 1 kW/m^2) whereas at 55m it is 88% to 94%.

The necessity of the DC/DC converter for the above system was evaluated by testing the system performance without it. Although the system operated slightly better at very high irradiances of 0.8 kW/m^2 and above, it did not work below 0.65 kW/m^2. So, during a standard solar day it would not work for the 75% of the time during which the irradiance is below 0.65 kW/m^2. Further, because the starting torque of the pump is normally 1.5 to 4 times the running torque, the system would not start till the irradiance is around 0.85 kW/m^2 or higher - a level which is not reached on many days. The converter is obviously essential to this system.

This converter uses a 2000 micro Farad capacitor to overcome the starting torque of the pump. Because it is vital to use the energy at low irradiances, this is a very useful yet cheap innovation.

Payne (1986) measured the efficiency of a DC/DC converter which his company, Mono Pumps Ltd., had developed. The same model of converter is being used in the Sondela system. The Power Efficiency of the converter ranged from 82% to 100% at all irradiances. The average head was 50m. The Daily Energy Efficiency of the converter for the day on which the data was measured was 89%. These figures indicate a similar efficiency to that of the converter used by Pulfrey et al.

AC Inversion: Obloch (1987) reports that an inverter developed by the company he works for, AEG, has an efficiency of 96% at 3 kVA and 95% at 1 kVA. He reports that the inverter "keeps the solargenerator [PV array] in the maximum power point". However, the device monitors operation of the pump only once every 10 minutes and this may be inadequate if there are moving clouds in the sky.

Batteries: Buresch (1983, p146) gives the usual watt-hour efficiency of new lead acid batteries as 85%.

In summary: In order to accurately determine the efficiency of a power conditioning method one must compare the energy delivered to the motor to the energy the array would give if it were operating at its Peak Power Curve continuously. If efficiencies were determined in this way for each method one would be able to compare the methods. However, of the literature studied only Hsiao and Blevins (1984) do this calculation.

Reported efficiencies for DC/DC converters compare the energy delivered to the motor to the energy delivered by the array - but this does not indicate how much efficiency loss there may be due to the array not following the Peak Power Curve exactly. However, the daily energy efficiencies reported for converters are around 90%.

c) Motors

Halcrow (1983) measured in a laboratory efficiencies of 75 to 82% for the best brushed DC motors of the twelve systems they studied. (Mostly a range power efficiencies under differing conditions of load and power is quoted for motors and pumps). He estimated that cost-effective improvements could increase the efficiency to between 85 and 90%.

Halcrow reported efficiencies of 67 to 72% for brushless DC motors. He notes a little scope for improvement.

Waddington and Herlevich (1982) measured 70 to 76% and 74 to 82% for two Honeywell DC motors in laboratory tests.

Pulfrey et al (1987) measured efficiencies of 74 to 88% at 25 and 35m heads and 65 to 82% at a 55m head for their highly efficient custom-designed DC motor.

For AC motors, efficiencies at full load range from 59 to 74% for sizes ranging from 0.25 kW to 1.1 kW according to manufacturer's specifications (Payne, 1986).

d) Transmission systems

Efficiency loss through a V-belt is negligible for the small power used in most PV systems.

However, the gearing ratio affects markedly the efficiency of the system. For example, Hsiao and Blevins (1984) noted an increase from 33 to 63% of the Daily Energy Efficiency of direct-coupling when the gearing ratio was changed from 1.2 to 1.4.

e) Pumps

From 1979 to 1982 the efficiency of the pumps used in PV systems improved markedly: from 46 to 69% for the best single-stage centrifugal pumps, and from 50 to 60% for the best multi-stage centrifugal pumps (Halcrow, 1983). These are presumed to be power efficiencies. Halcrow estimates the limits for cost-effective improvements to be 72 to 75%.

Pulfrey et al tested their Mono pump in a laboratory and found a range of power efficiencies from 45 to 55% for heads of 25 and 35m, and 26 to 53% for a 55m head.

2.1.3 Summary

Table 2.4 below gives the range of reported efficiencies for the different parts of the PV system.

Table 2.4: Reported Efficiencies for the Components of a PV System

Component(s)	Efficiency	Type of Efficiency
Complete system	1.9 to 3.8%	Daily Energy Eff.
Subsystem (system excl. array)	24 to 40%	Daily Energy Eff.
Best Comm. single crystal Si PV panels	15 to 19%	Daily Energy Eff.
Best Comm. amorphous silicon panels	5 to 7%	Daily Energy Eff.
Power conditioning units	64 to 89%	Daily Energy Eff.
DC permanent magnet motors	65 to 88%	Power Efficiency
AC three phase motors	59 to 74%	Power Efficiency
Centrifugal and pos. displacement pumps	42 to 69%	Power Efficiency

2.2 Sociological Considerations - the Suitability of PV Pumps

Few writers consider the suitability of PV pumps in any detail. Mostly they simply comment that they are reliable and simple to use and thus suited to third world countries. Then they go on to consider their technology and economics.

Eskenazi (1986) details the two main barriers to implementing PV systems in the third world as: the lack of institutional support and long-term financing; and the absence of an established infrastructure to support training, maintenance and repair.

Reliability is one of the most important criteria in deciding whether a technology is suited to a third world community. The reliabilities of PV pumps are compared to that of diesel pumps in Subsection 2.2.1 below.

Smith (1985) warns that no matter how suited PV pumps may be to a third world community, unless the technology is introduced in the right way, it may harm rather than help the community. Introducing the technology correctly requires careful consideration of the channels of power in the community as well as good communication with the intended users. Subsection 2.2.2 gives two examples of the results of bad introduction methods.

2.2.1 Comparing the Reliability of PV and Diesel Pumps

The reliability of a pumping system is affected greatly by many things: the quality of maintenance services, financial position of the owners, accessibility of the site, weather and water conditions, and the level of involvement of the community in maintenance. In short, the success of a technology depends heavily on sociological factors. These factors must be borne in mind when evaluating the significance of the statistical data given below.

PV Pumps: Photovoltaic panels have low maintenance requirements because they have no moving parts or high temperature working fluids.

McNelis (1987) reports that in Mali, where over 80 pumps have been installed, component failure has "almost always been due to pump, motor or power-conditioning problems" - rarely the PV array. He adds that recent installations by the more experienced manufacturers have been much more reliable since 1982 when submersible units began to replace surface-mounted units for use in boreholes. There are also no longer problems with the electronics for DC and AC motors.

One problem not fully solved in Mali is that of pumps running while dry - but proper consideration of the borehole's delivery potential could easily solve this problem.

In New Mexico, 96 out of 111 PV pumps (87%) were found to be in working order by Schaeffer (1985). This study was based on a mailed questionnaire. 40% of the systems had worked without problems and 72% of the owners reported the pumps satisfied their expectations. Problems which were reported included: lack of reliability of AC inverters and charge controllers, battery malfunction due to lack of maintenance, difficulty in overcoming starting torque and poor matching of components in direct-coupled systems.

Diesel Pumps: After an extensive study of rural water supply in Lesotho, Feachem et al (1978) concluded: "We do not consider diesel pumps appropriate for water supplies to small communities like Lesotho's villages. The only rural communities for which they might be suitable would be those adjacent to missions or other institutions with the financial, technical and manpower resources to take full responsibility for their operation and maintenance."

For example, of four diesel pumps in one district, only one was working - and this one did not provide water for two weeks in each month while money for diesel was collected. There had been only one case of successful repair.

2.2.2 The Importance of the Method of Introduction of a Technology

One of the most thorough studies of the effects of a PV pump on a community is that of the Tangaye water pump and flour mill in Burkina Faso. The system comprised a water pump, a hammer mill, and a refrigerator and lighted buildings for a clinic. The project was studied before the introduction of the system in 1979 (Hemmings, 1978), and then for six years after its introduction (Roberts, 1980, 1981, 1982; Martz and Roberts, 1985).

Smith (1985) provided a critical review of these reports noting that the PV pump had not affected the community in the way intended. The purpose of introducing the system was to free the time of the women from water carrying and the grinding of grain and to encourage the use of this time in financially rewarding activities. USAID was concerned about the empowerment of women and wanted the existing women's cooperative to manage the scheme.

However, with time the village headman became the chairperson of the management committee of the system and all the women on the committee were replaced by men. No women worked for the cash wages at the hammer mill. The man who operated the project lived in the buildings which were lighted by the array for the purpose of providing a night clinic. And he used the refrigerator (which was earmarked for preserving medicines) to cool drinks for a bar which he ran. Even the water pump did not benefit all the villagers but mostly those who live closest to it - the headman and his people.

So, because the channels of power were not considered closely enough, the effect of the system on the community was not that intended. And it is arguable whether the net effect of the pump is positive or negative.

The second example emphasizes the importance of consulting the users of the technology. US NASA introduced four identical PV systems to four villages in Gabon at a cost of $1.5 million. The systems included: 1) a dispensary with refrigeration, ventilation and lighting; 2) school lighting and VCR equipment; 3) street lighting; and 4) water pumping.

The lack of consideration of the local politics and sociology of the villages and lack of consultation lead to a "comedy of errors": there were reports of "electrified dispensaries complete with refrigerator and vaccines but no staff, and the refrigerators switched off; schools with VCRs but no tapes; ... street lighting installed just before the highway department rerouted the village road; new wells and pumps sitting idle because villagers do not like well water when alternatives are abundant; factional fights within villages because one faction's leader received a light while another's did not..." (Smith, 1985).

2.3 Economics - Comparing the Cost of PV and Diesel Pumping

2.3.1 Past and Future Costs of PV Panels

a) International Prices:

The cost of PV panels at the moment forms about 55% of the cost of a PV pump. For this reason their price affects the cost of PV pumping greatly.

In 1958 the price of PV panels was 2000 $\$/W_p$ (Hoffman, 1985). Since then prices have dropped dramatically and are continuing to drop. In the eight years to 1987 the panel price halved - dropping from 10 to 5 $\$/W_p$. And it is expected that it will halve again by 1995 (ISEIR, 1987).

However, early predictions were ambitious and have not been fulfilled. Figure 2.3 below gives a projection made by the U.S. Department of Energy in 1980. The prices of crystalline cells were expected to drop from 30 $\$/W_p$ in 1975 to 2.50 $\$/W_p$ in 1980, bottoming out at 0.50 $\$/W_p$ in 1990 - all 1980 US$. To aid comparison prices have been converted to 1988 $ where possible, and unless otherwise specified 1988 $ should be assumed. In 1988 $'s the above prices are: 42 $\$/W_p$ in 1975, 3.50 $\$/W_p$ in 1980 and 0.70 $\$/W_p$ in 1990.

Curve C is the projection for amorphous thin film cells. If mass production had been possible by 1984, this curve would have moved down to curve B. So the price of thin film cells was expected to reach 0.25 $\$/W_p$ by 1990 (i.e. 0.35 1988$\$/W_p$). Expectations have been lowered with 2-3.5 $\$/W_p$ predicted in 1995 and prices below 1 $\$/W_p$ after the year 2000.

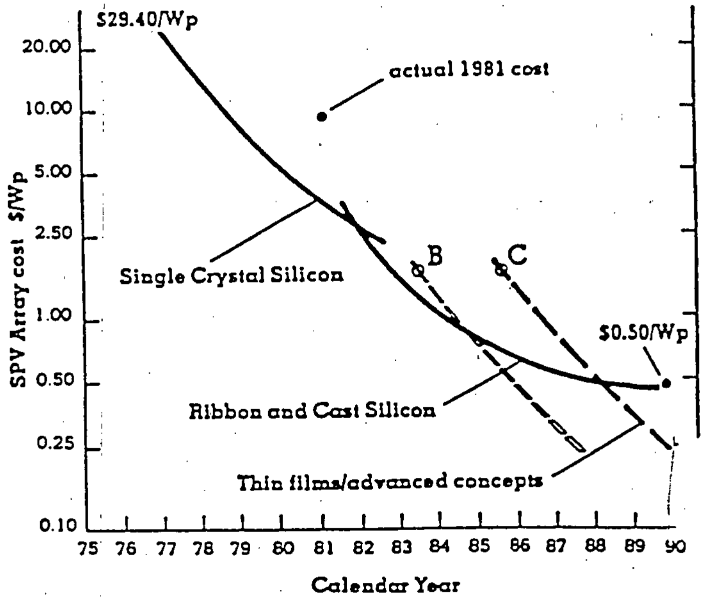


Figure 2.3: Projected PV Panel Prices in 1980 US Dollars
Source: Kiss (1982) p63. From US Department of Energy
Note: 1988$ = 1.40 * 1980$ (IFS, 1988)

Table 2.5 below gives reported and projected prices for all types of PV panels from 1958-2000. The meaning of some of the prices is unclear as some authors do not specify whether they are for cell, panel or system costs (Sinclair, 1988). Mostly it can be assumed that the panel price is meant. Further some do not specify the year of the $ they are using - so the original sources are included for reference. The prices that have asterisks are projected prices.

Table 2.5: Prices of PV Panels: 1958-2000

Year	US D.O.E.[1] (1988 US$)	Starr & Palz[2] (1988 US$)	Sinclair[3] (Unspec. US$)	Sinclair's Sources
1958			2000	Hoffman (1985)
1959			1000	Kiss (1982)
1974			50	Hamakawa (1986)
1975	42	42		
1979			10	Kiss (1982)
1980	3.50*	12.70		
1985		4.20-5.35*	3-6	Hamakawa (1986)
1987			4.5-5.5	ISEIR (1987)
1990	0.35*	1.40-2.80*	2.5-5.0*	ISEIR (1987)
1995		1.00-2.80*	2.0-3.5*	ISEIR (1987)
2000		0.70-2.80*		

* Projected Price

1. US Dept of Energy in 1980, cited in Kiss, 1982, p63. See Fig. 2.4 above. 1988$ = 1.40 * 1980$ (IFS, 1988).
2. Starr and Palz (1983), cited in Halcrow, 1983, p5.35. 1988$ = 1.40 * 1980$ (IFS, 1988).
3. Sinclair, 1988, p60. The year of the $ is unspecified and can only be deduced from the date of the source report - see column 4.

The projections in columns 1, 2 and 3 were made in 1980, 1983 and 1987 respectively. Note how the projections are becoming less ambitious: the three projections for 1990 are 0.35 $\$/W_p$, 1.4-2.8 $\$/W_p$, and 2.5-5.0 $\$/W_p$. Maycock predicts that after the year 2000 the price of concentrator cells will drop below 1.00 $\$/W_p$ (cited in ISEIR, 1987).

Table 2.6 below shows how the price of panels varies with their type. The prices of most cells were about 5 $\$/W_p$ in 1987 but it is expected that in 1995 the concentrator and amorphous silicon panels will have the edge at 2 $\$/W_p$ with the other types lagging at around 3.5 $\$/W_p$.

Table 2.6: Comparative Prices for Types of PV Panel (1987-1995)

Cell Type	1987 (1987$)	Projected 1990 (1987$)	Projected 1995 (1987$)
Single Crystal	5-50	4-00	3-50
Polycrystalline	5-50	3-50	3-00
Ribbon Cell	7-50	5-00	3-50
Concentrator	5-00	3-00	2-00
Amorphous Si	5-00	2-50	2-00

Source: Sinclair, 1988, pp 60 & 62.

Comparative prices of electricity

Maycock (cited in Sinclair, 1988) asserts that the likelihood of PV power being used much for grid power is "very low". However, he notes that if the 1990 and 1995 estimates are realized then the market for photovoltaics will be very large as they will compete with "10 million small diesel or gasoline generators world-wide".

Hamakawa however believes the prospects for photovoltaics are even brighter. The figure below shows his estimate of the "economic domains" of different sources of power. (He must have used solar radiation data for a real or imaginary site to convert the cost of panels from a watt peak basis to one of kWh. He would also have incorporated the balance of system costs required to establish a PV power plant from the panels.)

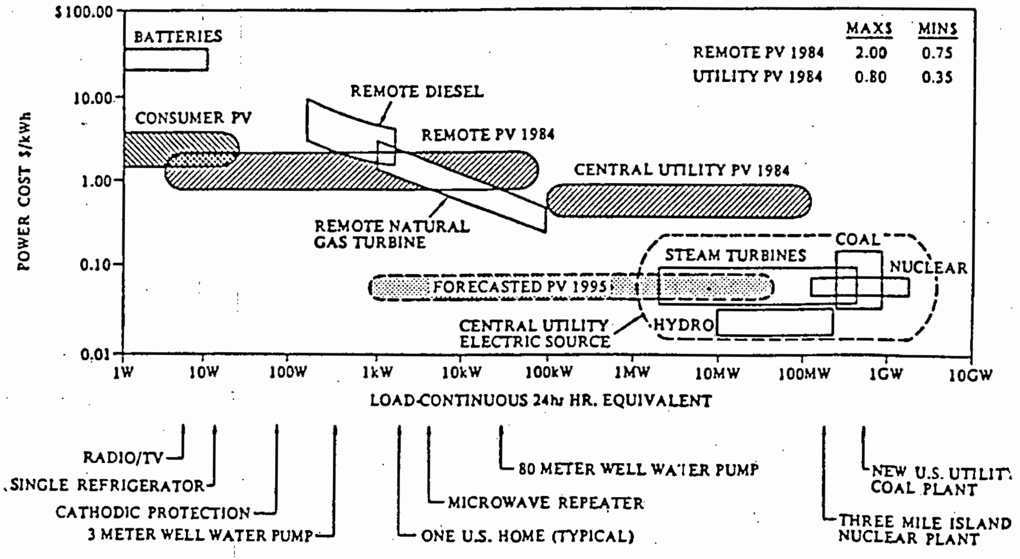


Figure 2.4: Economic Domains of Various Sources of Electricity
Source: Hamakawa, 1986 (cited in Sinclair, 1988)

The diagram shows that photovoltaics for consumer appliances are already an order of magnitude cheaper than batteries. The market for this use is large and will ensure funding for further research. Moreover PV was in 1984 already cheaper than diesel and natural gasoline for power requirements lower than 3 kW. Hamakawa contends that in 1995 PV will be competitive with fossil and nuclear fuels for use in power stations rated less than 50 MW. The diagram indicates that the cost of electricity from PV will then be about 7 USc/kWh.

b) Prices in South Africa:

The picture changes considerably when considering PV viability in South Africa - largely because of our present low exchange rate. Table 2.7 compares panel prices reported in the literature with those quoted by local suppliers. The local Rand price is about 4 times the $ price. Some of this is accounted for by the exchange rate: the rest must be due to transport, import duties and the delay in new prices arriving here.

Table 2.7: The Exchange Rate's Effect on S.A. PV Panel Prices

Date	US Panel Price (\$/W_p)	Exchange Rate (\$/R)	Equiv. SA Price (R)	Local Suppliers' Price (R/W_p)
1982		0.86		13.6
1983	7-10	0.89	7.9-11.2	11.1
1984		0.63		11.3
1985	4	0.45	8.90	15.6
1986	4-8	0.38	10.5-21.1	22.1
1987	5(ave.)	0.47	10.60	19.4

Source: Sinclair, 1988, p.63.

Diesel Generation

Williams (1986) calculated the cost of electricity from diesel gensets to be 83 to 170 SA c/kWh (1988). He collected field-data on the usage of 10 gensets on farms. The Life Cycle Costs of the sets and the unit cost of water were then calculated using the assumptions detailed in the footnote[1].

The cost of electricity from diesel generators is about ten times that of grid electricity, which in 1986 was 9.1 c/kWh (1988).

---

1) A diesel price of 69c/l (1988), an engine replacement age of 15000 hours, operation and maintenance of R375/5000 engine hours (1988) (labour assumed free), and a discount rate of 5% a year.

PV Generation

As noted above the Rand price of PV panels is about four times the dollar price reported in the literature. So the unit cost of electricity in South Africa can be estimated by reading off figures from Figure 2.4, multiplying by 1.06 to get the 1988 US$ cost and again by 4 to get the cost in South Africa. Thus the unit cost of PV electricity was about 370-640 SAc/kWh in 1984 (4.5 times the cost of electricity from diesel gensets). If Hamakawa's prediction holds it will be 19-37 SAc/kWh in 1995 (one-fifth of the cost of diesel from gensets). (All these prices are 1988 SAc).

2.3.2 Past and Future Costs of Water Pumping - PV versus Diesel

In this subsection both US and SA prices have been brought to the year 1988.

a) Internationally:

The most thorough study to date of water pumping alternatives was done by Halcrow (1983). He used mathematical models on a computer to calculate the unit costs of pumped water for PV, diesel, wind, kerosene, hand, and animal pumps. The unit costs of water were calculated from the Life Cycle Costs, which is the sum of the capital, replacement, operating and maintenance costs for the life of the project all discounted to their present value. A sensitivity analysis was then done.

Cost and efficiency data for PV pumping were obtained from his detailed study of 12 PV pumps (1983). He used world market data for the costs of other types of pumps. The operating and maintenance costs of diesel pumps were established through questionnaires in Bangladesh, Kenya and Thailand and through interviews with experts.

Past and Future Costs: The costs of PV pumping are falling rapidly. Table 2.8 on the next page gives Halcrow's prediction in 1983 of the future costs of PV pumping.

Table 2.8: Cost of PV Pumps from 1982 to 1998: Internationally

Time	PV System[1] (1988$/$W_p$)	BOS[2] Costs	Panel Costs	Pump & Motor
Actual (mid 1982)	20.6-22.5	34%	56%	10%
Target (1987)	10.5-11.7	30%	55%	15%
Potential (1993-1998)	6.9- 8.1	50%	33%	17%

1. Costs include foundations, array support, shipping, transport, labour, piping. The range is for pumps with hydraulic heads from 120 m^4/day to 420 m^4/day. 1988$ = 1.20 * 1982$ (IFS, 1990).
2. Balance of System Costs = All costs excepts those of the PV panels, pump and motor. The last three columns of the table give percentages of the total system cost.

Source: Halcrow, 1983, p8.9 (Adapted)

The 1982 costs in the table were calculated from those of the 12 pumps they examined. At that stage array costs were 12 $/$W_p$ [1]. The "target costs" assumed PV panel costs had dropped to 6 $/$W_p$ and that subsystem costs had dropped to those estimated by manufacturers for mass production (more than 1000 units). It was estimated these costs would be achieved in 1987. This is an accurate prediction: panel costs were in fact 4.5 to 5.5 $/$W_p$ in 1987 (ISEIR, 1987), and more than 3000 pumps had been installed world-wide (McNelis, 1987). The "potential costs" assumed the PV panel costs had further reduced to 2.4 $/$W_p$ and this is expected to be achieved between 1993 and 1998 (Halcrow, 1983).

Note from the table that the target costs and potential costs are about 50% and 35% of the 1982 costs respectively. These percentages are used to estimate 1987 and 1995 costs in the tables below.

Also, note that the cost of panels is a large part of the total costs - 55% in 1987. However, as panel costs drop this percentage will drop to 33%. Conversely, the balance of system costs which at the moment comprise 30% of the total costs will increase in importance to 50%. Pump and motor costs now comprise about 15% of the total cost.

---

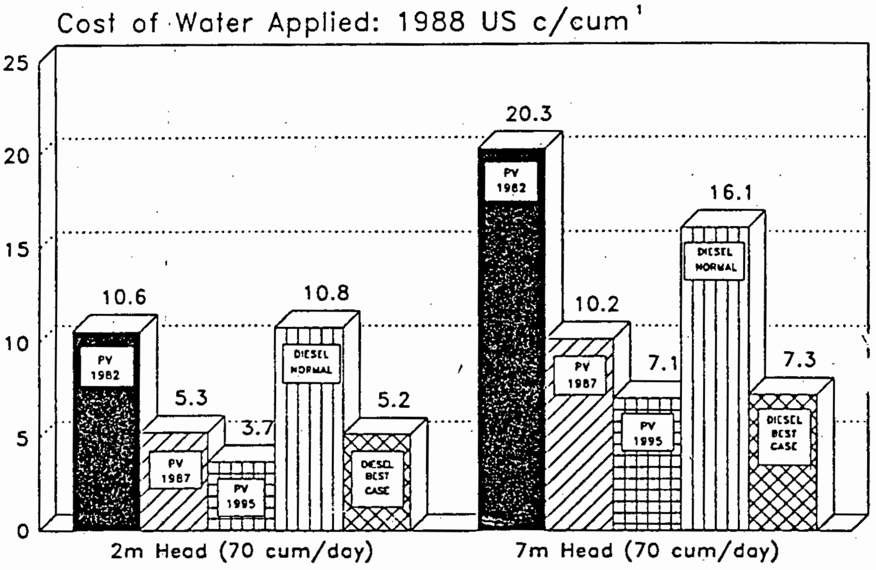
1) 1988 US$

Comparing PV and Diesel: Two sets of assumptions were used for diesel pumps - the "normal" and the "best case". Halcrow found that manufacturer's data overrate the performance of diesel pumps. This is because most engines need to be derated to get a longer engine life. They are also mostly run not at their optimum speed and not well-tuned. So the assumptions for diesel engines are as follows:

a) "Normal case" - combined engine and pump efficiency of 6%, an engine lifetime of 3700 hours (with a maximum of 7.5 years), and a diesel price of 48 c/l [1];
b) "Best case" - combined engine and pump efficiency of 9%, an engine lifetime of 5000 hours (with a maximum of 10 years), and a diesel price of 96 c/l.

The "normal case" is probably average for diesel pumps in developing areas while the "best case" is the best likely in these areas.

The unit costs of pumped water for PV and diesel pumps are compared in the bar chart, Figure 2.5 below.



Note: See Tables 2.11 to 2.13, pp 49-53, for assumptions used.
1. The unit cost of water applied to the garden: i.e accounts for inefficiency in the distribution system. 1988$ = 1.20 * 1982$ (IFS, 1990).
2. The costs for the 1987 and 1995 cases were calculated from the 1982 case by multiplying by 0.5 for 1987 and 0.35 for 1995. See Table 2.8, p43.
Source: Halcrow, 1983, pp. 8.17, 8.18, and 9.9.

Figure 2.5: Unit Cost of Pumped Water Internationally: PV vs Diesel

---

[1] 1988 USc

It can be seen the assumptions used in calculating the cost of water from a diesel pump make a large difference: the "normal" case is about twice that of the "best case". For our uses the "normal" case gives the best estimate - poorer communities in South Africa have little expertise in maintaining and tuning diesel pumps so the lower efficiency is more likely. Moreover, gardening cooperatives are not eligible for farmers' concession on diesel and so buy it at the consumer price which is between 81 and 87 c/l (ERi, 1988) - so the assumption of 96 c/l for the normal case is more accurate.

For PV pumps the most accurate estimate of present costs is the "target case" (1987) - as noted above the conditions on which the prediction was made have been fulfilled.

The chart shows that the unit cost of water from a PV pump in 1987 was about half that from a "normal" diesel pump for a head of 2 to 7 meters. In about 1995, the cost of water from a PV pump is expected to be between one-third and a half of that from a diesel pump at these heads.

However, if the diesel pump is well run and the diesel price around 48 c/l the 1987 PV pump would be competitive at a head of 2m but would be more expensive for a 7m head.

The World Bank estimates that unit costs of water for irrigation of 12 c/m^3 (1988 USc) and below are economical. This is based world prices of food and agricultural inputs and so can only be used as a guide - local prices and conditions will be decisive. But still, it seems that at heads much above 7m water lifting for irrigation is unlikely to be economical.

Table 2.9 below gives a breakdown of the costs of pumping for a 7m head.

Table 2.9: Breakdown of Life Cycle Costs of PV and Diesel Pumps (1988 US$)

System (no storage incl.)	Unit Water Cost c/m^3	Life Cycle Costs $	Capital Cost $	PW of re-placements $	Running Costs $/year	Maint. $/year	Lifetime (yrs)	
							Power	Pump
PV actual (1982)	20.3	52 500	39700 (76%)	10500 (20%)	0 (0%)	210 (4%)	15	6.9[2]
PV target (1987)[1]	(10.2)	(26 200)						
PV potent. (1995)[1]	(7.1)	(18 400)						
Diesel normal	16.1	41 400	3600 (9%)	4200 (10%)	2700 (68%)	530 (13%)	4.0	10
Diesel best case	7.3	19 000	3600 (19%)	3100 (16%)	900 (49%)	290 (16%)	5.5	10

1. Calculated from 1982 "PV actual" costs by multiplying by 0.50 and 0.35 respectively.
2. The same for the electric motor

Note: The percentages in brackets represent the fraction which that component is of the Life Cycle Costs. These percentages were calculated from the numbers in the table.
Assumptions: For irrigating 2 hectares, head = 7 metres, average water demand = 70 m^3/day, Average Daily Insolation for Worst Month = 5.8 kWh/m^2.day, Peak monthly demand factor = 1.76, Discount rate = 10%, Project length = 30 years.
Source: Halcrow, 1983, p8.18.

The table emphasizes how misleading it is to use the capital cost to choose between a PV and a diesel pump: although the capital cost of a PV pump was over ten times that of a "normal" diesel pump in 1982 ($39700 compared with $3600), the Life Cycle Costs of both pumps were similar. This is because the Life Cycle Cost of the PV pump consists almost entirely of capital equipment (76% for the initial capital cost and 20% for replacements); whereas the initial capital cost of the diesel pump forms only 9-19% of its Life Cycle Cost.

The largest part of the Life Cycle Cost for the diesel pump is the running cost which accounts for 49-68% - so the price of diesel and the pump's efficiency have the largest bearing on the cost of diesel pumping. This is why there is such a large discrepancy between the "normal" diesel pump and the "best case".

Sensitivity analysis: From Halcrow's sensitivity analysis the following four quantities are the most important to us:

1. Insolation: the cost of pumped water from a PV pump is about inversely proportional to the average daily insolation during the "worst month". Reducing this insolation to half from the baseline case increases the cost of water by a factor of 2.45 (p8.25). This emphasizes the importance of a suitable site for PV pumping.

2. The diesel price: Table 2.9 on p46 shows that the running cost is 50-68% of the Life Cycle Cost of a diesel pump. So for example if the diesel price doubled the cost of water would increase 1.50-1.68 times.

3. The static head: Figure 2.6 below shows that the increase in water cost is steady with increasing head - the graphs are almost straight lines. The cost of water from PV pumps increases slightly faster than that from diesel pumps because diesel pumps are normally oversized for small irrigated areas.

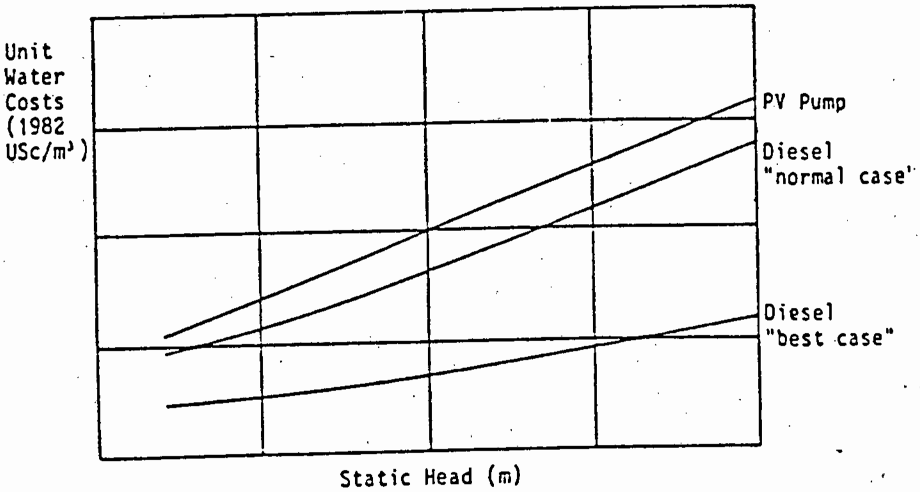


Figure 2.6: The Effect of the Static Head on Unit Water Costs
Source: Halcrow, 1983, p8.28.

4. The Peak Demand Factor: The Peak Demand Factor (PDF) is the ratio of the highest monthly irrigation requirement in the year to the average monthly irrigation requirement. Figure 2.7 below shows that diesel pumps are favoured by increasing PDF. The PV pump needs to be sized for the worst month and consequently during other months the excess power is wasted. On the other hand the amount of diesel bought can be varied with the need for irrigation.

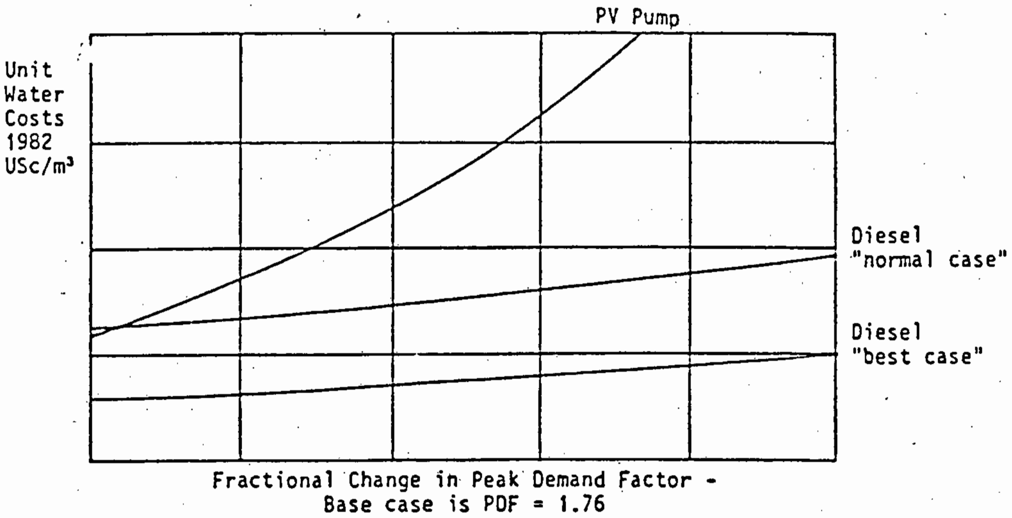


Figure 2.7: The Effect of the Peak Demand Factor on Unit Water Costs
Base Case: Peak Monthly Demand Factor of 1.76.
Source: Halcrow, 1983, p8.28.

Choosing Between PV and Diesel: Based on the above sensitivity analysis, Halcrow drew a decision chart for choosing between PV and diesel pumps (1984, p10). This chart was based on 1982 prices. The chart recommends that one considers PV over diesel for the following cases (where I_c is the daily insolation for the worst month):

a) if I_c is less than 4 kWh/m^2.d, only for very low hydraulic heads. (The hydraulic head is the product of the volume of water pumped a day and the static head);

b) if I_c is between 4 and 5 kWh/m^2.d, for hydraulic heads less than 75 m^4/d (e.g. 15 m^3/day over a head of 5m);

c) if I_c is greater than 5 kWh/m^2.d, for hydraulic heads less than 100 m^4/d.

Otherwise the decision chart recommends that a diesel pump is preferred for the short term and photovoltaics reconsidered later. Because their prices have been rapidly falling, PV pumps would now be competitive at higher hydraulic heads than those given above.

b) In South Africa

The most comprehensive comparison in South Africa of water pumping technologies has been done by Wiseman (1987). He used computer models which include the replacement, operating and maintenance costs.

Table 2.10 below gives his results as well figures extrapolated from Halcrow's calculations for comparison. To calculate the cost of water pumped by PV systems, Wiseman used the cost of the PV pump at Sondela (which is my case study). He based the costs of water from diesel on manufacturers' data. The assumptions he used are given in Tables 2.11 to 2.13, and will be discussed fully later.

Table 2.10: Unit Costs of Pumped Water in South Africa in 1986

Power Source[1]	Unit Cost of Pumped Water at a 30m Head (1988 SAc/m^3)[2] 5 m^3/day	10 m^3/day	30 m^3/day	Halcrow Extrapolated[3]
PV	3.24	2.80	2.48	1.32 (1982 costs)
PV costs * 0.5	1.95	1.56	1.29	0.66 (1987 target)
Diesel	1.71	1.20	0.86	0.34-0.84[4]

1. System includes installation and the below ground main for the borehole. It excludes borehole drilling and casing, the reservoir and water reticulation.
2. 1988 SAc = 1.25 * 1985 SAc (IFS, 1990).
3. Extrapolated from the costs for heads of 2m and 7m to a 30m head using a straight line graph (see Figure 2.5, p44). An exchange rate of 2.00 R/$ was used.
4. 0.84 c/m^3 is for Halcrow's "normal" case; 0.34 c/m^3 for the "best case".

Source: Wiseman, 1987, p113

Wiseman's results lead to different conclusions to Halcrow's. Let us use the 30 m^3/day column for example: according to Wiseman the cost of water from a PV pump is three times that from a diesel pump (R 2.48 per m^3 as opposed to R 0.86 per m^3). Even if the prices of PV pumps were to halve with falling panel costs, the water from PV pumps would still be more expensive than that from diesel pumps at R 1.29 per m^3.

In contrast, Halcrow predicted that in 1987 PV pumps would have a distinct advantage over diesel pumps under "normal" conditions in developing areas. PV pumps would lift water at 0.66 c/m^3 compared with 0.84 c/m^3 for diesel pumps. (The PV system used by Wiseman was bought in 1987 so Halcrow's 1987 prediction gives the best comparison). Only under the best conditions would water from diesel pumps cost 0.34 c/m^3 and thus be much cheaper.

Comparing the assumptions used by Wiseman and Halcrow clarifies this discrepancy. Firstly, the assumptions about diesel pumps are given below.

Table 2.11: Comparison of Assumptions on Diesel Pumps: Halcrow vs Wiseman

Assumption	Halcrow (1983) "Normal Case"	"Best Case"	Wiseman (1987)
Diesel pump eff.[1]	6%	9%	20%
Diesel Price (1988c)	48 USc/l	96 USc/l	63 SAc/l
Engine Lifetime	3700 hr	5000 hr	10000 hr
Pump Lifetime	40000 hr	40000 hr	10000 hr
Annual Maintenance	15% cap. cost	8% cap. cost	5% cap. cost

1. Energy delivered to the water divided by the calorific energy of diesel.

Source: Halcrow, 1983, p 8.6, 8.8, 8.18 and Wiseman, 1987, p 120.

Running costs make up the largest part of the Life Cycle Cost of diesel pumps (about 50% for Halcrow's best case). The diesel pump's efficiency and the diesel price are thus the most important assumptions as they bear directly on the running costs.

Wiseman based his estimate of efficiency of 20% on manufacturers' information. Halcrow, however, states that manufacturer's quotes are unrealistically high even for developed areas, and that the best efficiency likely in developing areas is 9% with 6% being normal. If we accept Halcrow's assumptions for a "normal" situation then Wiseman's running costs would be 3.3 times greater on account of the decreased efficiency.

Wiseman also used the price of diesel for farmers which is 63 c/l [1]. However, small farmers in developing areas would pay the price for consumers which ranges between 81 and 87 c/l (ERi, 1988). So for small farmers the running cost would be multiplied further by 1.35.

With the 3.3 times for the decreased efficiency, the running cost would in fact be 4.5 times that estimated by Wiseman. As the running cost contributes 50% of the unit water costs, it can be calculated that the unit water costs would in fact be 2.75 times Wiseman's figures.

There is a further discrepancy between the assumptions used for the annual maintenance costs: Wiseman used 5% of the capital cost whereas Halcrow used 15%. As Halcrow's study was in much greater depth, his estimate is likely to be more accurate. So, if Wiseman's maintenance costs were in fact three times higher, the unit costs would be multiplied by 1.32 (as the maintenance costs form 16% of the unit costs).

With the factor of 2.75 that accounts for the lower efficiency and increased diesel price, this indicates that the real unit costs of diesel pumping is likely to be 3.6 times those calculated by Wiseman.

The effect of the discrepancies between the assumed lifetimes of the engines and those of the pumps will approximately balance each other and so these differences are ignored.

---

1) 1988 SAc/l

So the unit cost of water from the average diesel engine in South Africa's developing areas is likely to be about 3.6 times that calculated by Wiseman. If we use the ratio between the costs for Halcrow's "normal" case and his "best case" as a guide, the "best case" in South Africa would be about 1.5 times Wiseman's figures. For easy comparison the bar chart in Figure 2.8 on page 52 showing Wiseman's diesel costs times 1.5 and 3.6 has been created.

Secondly we compare the assumptions about PV pumps, which are given below.

Table 2.12: Comparison of Assumptions on PV pumps: Halcrow versus Wiseman

Assumption	Halcrow (1983)	Wiseman (1987)
Daily Insolation[1]	5.8 kWh/m^2.d	2.9 kWh/m^2.d
Subsystem Energy Efficiency[2]	40%	30%
Array lifetime	15 years	20 years
Pump lifetime	6.7 years	20 years
Annual Maintenance Costs	0.4% Cap. Cost	1% Cap. Cost

1. Ave Daily Insolation for the critical month - the month with the lowest daily insolation.
2. Energy delivered to water in an average day divided by electrical energy delivered by the array during that day.

Source: Halcrow, 1983, pp 8.6 and 8.18, and Wiseman, 1987, p121.

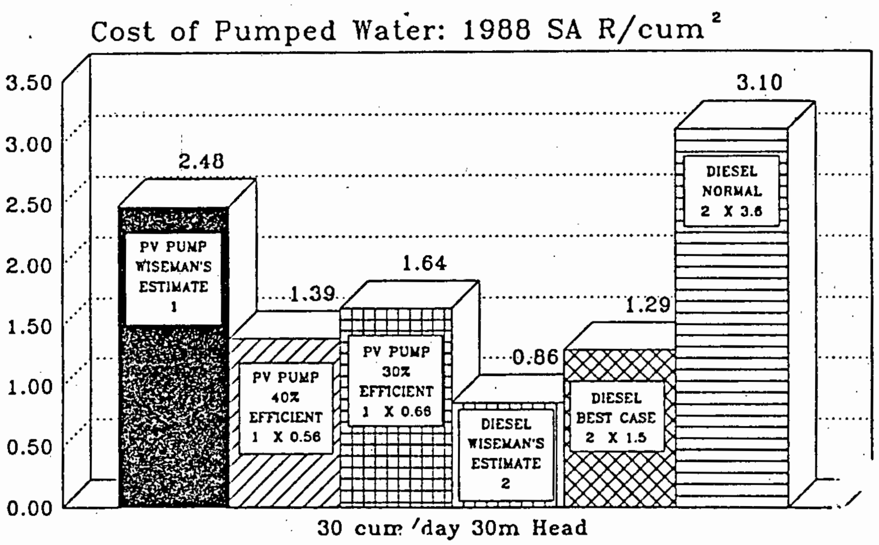
The initial capital cost and the replacements together make up 96% of the unit water costs from PV pumps (see Table 2.9, p46): and the cost of the array makes up over half of this cost (Table 2.8, p43). So the most critical assumptions are the daily insolation and the subsystem energy efficiency (which determine the size of array needed) and the array lifetime (which determines the frequency of replacement).

Wiseman assumes an average daily insolation for June (which is the month with lowest insolation) of 2.9 kWh/m^2.d. This is exactly half that assumed by Halcrow. Wiseman's figure is taken from the conservative design calculations for the PV pump at Sondela, which is near Durban. In fact the average daily insolation in Durban in June is 4.4 kWh/m^2.day (NBRI, 1978). As the unit water cost is approximately inversely proportional to the critical daily insolation, the unit costs for an well-sized PV pump would be about 0.66 those calculated by Wiseman.

For the subsystem daily energy efficiency, Halcrow's study shows that for a 20m head 32% is average whereas 42% is good for a head of 20m (see Table 2.1). So Wiseman's assumption of 30% represents an average pump and Halcrow's of 40% a good pump. Considering the advances in technology since the estimates of 32% and 42% were made, 40% may be a more reasonable assumption. If this were so, the unit water cost would be multiplied further by 0.85 (Halcrow, 1983, p8.25).

If the factor of 0.66 that accounts for the higher insolation is taken into account, the unit water costs would be 0.56 or 0.66 times those calculated by Wiseman depending on whether the subsystem efficiency was 40% or 30% respectively. For comparison bars for Wiseman's PV costs times 0.56 and 0.66 have been added to Figure 2.8 on the next page.

(None of the other assumptions have much affect. Wiseman assumes an array life of 20 years which is probably reasonable nowadays. The effect of the pump lifetime and maintenance costs is negligible.)



1. System includes installation and the below ground main for the borehole. It excludes borehole drilling and casing, the reservoir and water reticulation.
2. 1988 SAc = 1.25 * 1985 SAc (IFS, 1990).

Source: Adapted from Table 2.10, p49.

Figure 2.8: Unit Costs of Pumped Water in South Africa in 1986 - The Effect of Different Assumptions

So after looking at the assumptions and adjusting the figures to more realistic assumptions, the picture changes considerably. The chart shows that water from a "normal" diesel pump is about 2 times more expensive than that from either an average or an efficient PV pump. The "best case" diesel pump, however, undercuts even the efficient PV pump at 30 m³/day. (However, although not shown on this chart, even the less efficient PV pump undercuts the "best case" diesel at a flow rate of 5 m³/day).

These are however the present PV pump prices. Their cost is likely to fall further in the near future and so they may soon undercut even the "best case" diesel pumps at the higher flow rates.

For completeness, the other less critical assumptions used by Halcrow and Wiseman are given below.

Table 2.13: Comparison of Remaining Assumptions: Halcrow versus Wiseman

Quantity	Halcrow (1983)	Wiseman (1987)
Discount Rate	10%	5%
Project Lifetime	30 years	20 years

Sources: Halcrow, 1983, p8.18 and Wiseman, 1987, pp 109 & 119.

CHAPTER 3

TECHNICAL EVALUATION

3.1 Introduction

Photovoltaic pumping is a very new field. The first major study on PV pumping world-wide was in 1982 (Halcrow). No research on PV pumping has been published in South Africa.

The project thus aimed to examine the operation of one local PV pump thoroughly, to determine its efficiency and so to be able to compare it with pumps available elsewhere in the world. Further, the project aimed to model the operation of the system and each of its components under a range of conditions. This would make it possible to identify areas of research to improve the efficiency of the system.

There were three main focuses in the examination: a) the efficiencies of the system and of each component, b) the matching of the components and c) the suitability of alternative components. These are described in turn below.

a) Efficiencies: manufacturers' specifications are often given at ideal conditions and so cannot be relied on to calculate the actual efficiency of the system. For example the efficiency of a PV module decreases with cell temperature. And the efficiency of a string of modules in an array will be lower than that of the individual modules because of mismatch between the modules. So the module efficiency quoted by the manufacturer at 25 °C cannot be used directly to predict the likely efficiency of an array of modules at a realistic array temperature or 40 or 50 °C. The project aimed to determine realistic estimates of efficiency.

   A second example: Motors are run in industry at a set input voltage and for this reason all data available is at this nominal voltage. This is inadequate because the input voltage to a motor in a PV pump varies with the irradiance. The project aimed to fill this gap by examining the operation of the motor over the full range of input voltages.

It is also possible that the system would not operate as efficiently in the field as in controlled laboratory conditions. For this reason the tests were done on a pump installed in a remote area so that the results would be realistic for actual installations.

b) The matching of components: It is possible for a component to be efficient on its own, but operate inefficiently when coupled in the system. For example the array operates inefficiently if the subsystem makes it operate away from its Peak Power Curve. So the project aimed to determine the position of the Peak Power Curve and so how well different strategies for tracking it work.

A second factor which affects matching is the motor/pump pulley ratio. This affects the efficiencies of the power maximizer, the motor as well as the array. The project aimed to determine the best trade-off between the efficiencies of these components.

c) The suitability of alternative components: The efficiency of the system can be improved by better selection of components. Where practical the project aimed to compare alternatives. Two motors and two power maximizers were compared. It was impractical to test alternative pumps in the field but specifications for some centrifugal pumps are used to compare their operation to the Mono pump installed with the system tested.

The organization of the rest of the chapter is as follows. First the details of the PV pump which was examined (Section 3.2) and of the monitoring system (Section 3.3) are given. The experimental method and method by which the data was analysed are described in Section 3.4. The results are discussed in Section 3.5. This section attempts to answer the questions outlined above. Finally the conclusions are summarized in Section 3.6.

3.2 Description of the PV Pump Tested and the Site

The System Configuration

The PV pump chosen for examination was selected from tenders made by all the firms marketing PV pumps in mid-1986. The main selection criteria were efficiency, simplicity and robustness. Simplicity and robustness are important because of the shortage of technical skills for maintenance in remote rural areas.

The pump selected was tendered by Mono Pumps Africa Ltd and comprised an array of 14 panels, a power maximizer, a DC motor and a Mono progressive cavity pump. The important features of the system are shown below:

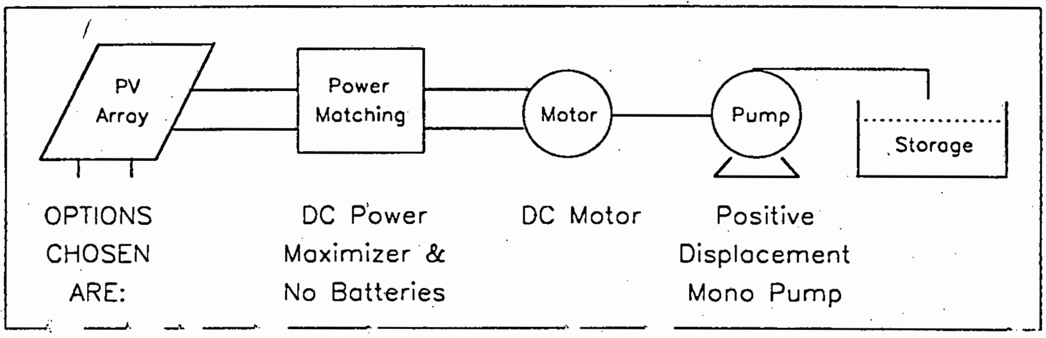


Figure 3.1: The Components Used in the Pump Tested

The important things to note about the choice are: a) a DC rather than an AC system is used; b) energy is stored as pumped water rather than by batteries; and c) a positive displacement pump rather than a centrifugal pump was chosen. The reasons for the choices are given below.

A DC system was chosen rather than an AC one because:

a) The electronics for DC power maximizers were simpler and thus more reliable than for AC power maximizers.
b) The efficiency of the DC motor was better because AC maximizers were not easily available that tracked both frequency and voltage.
c) The power loss in the DC maximizers themselves is less than in AC maximizers.

d) The importance of efficiency, simplicity and robustness outweighed two drawbacks of the DC system: i) the higher cost of DC motors and ii) the need to change the brushes in the DC motor (after about 2000 hours pumping or every 2 years).

Since this pump was commissioned much work has been done on using AC maximizers and they have the potential to give as good if not better system efficiencies than DC maximizers. If they prove as efficient and reliable as DC maximizers they would be preferable (because AC motors are cheaper and they do not have brushes).

Why no batteries? Batteries were not used in the system because they are inefficient, unreliable and costly. Instead energy was stored as pumped water in the reservoir which provided for cloudy days. Batteries do help in matching the array to the subsystem - but this was done for the system by the maximizer.

Why a positive displacement pump? The Mono pump was chosen because of the efficiency of positive displacement pumps over the full range of speeds and because of its robustness. The load characteristics of a positive displacement pump are not as well matched to the array characteristics as those of a centrifugal pump. But this is unimportant if a power maximizer is used. The suitability of various types of pumps is discussed fully in Subsection 3.5.5.

Component Makes and Specifications

The table below gives the major specifications for each of the components. Full specification sheets are given in Appendix 3.2.

Table 3.1: Component Specifications for the PV Pump Tested

Component	Make	Specifications
Array	M.Setek MSP-103 Modules	Peak Power Rating: 574 W_p (14 modules of 41 W_p) Configuration: 2 strings of 7 modules. Module Efficiency: 12% at 25 °C. Optimum conditions: V_{max} = 107 V, i_{max} = 5.4 A.
Power Maximizer	Miltek	Max Power: 1 kW Max V_{oc}: 160 V (Nine 41 W_p panels is series) Tracking Method: Array voltage set to constant Current Protection: Maximum of 15 A Overspeed Protection: Not included Quoted efficiency: 98%
DC Motor	Honeywell	Maximum Ratings: 1 kW, 1900 rpm, 9.3 A Optimum Efficiency: 83% Type: Brushed permanent magnet
Transmission	V-belt drive	Pump pulley diameter: 220 mm Motor pulley diameter: 126 mm Gear Ratio: 1.74
Pump	Mono SW4L Pump (Progressive Cavity type)	Maximum Ratings: 4 m^3/h, 1500 rpm, 75 m head Min Starting Torque: 4.5 Nm Optimum Efficiency: 66%

Details of the Site of the Pump

The pump was installed in Sondela Community Vegetable Garden near Durban in Natal. The details of the site are as follows:

Table 3.2: Details of the Site of the Pump

Quantity	Value
Size of garden:	1 hectare
Water Usage:	Expected 17 m^3/day in winter
Static head:	12.5 meters
Delivery Dist:	260 meters
Pipe diameter:	65 mm
Water source:	Umsunduze River
Location:	Nyavu Ward near Cato Ridge, Natal
Latitude:	29° 30′ South
Insolation:	Winter - 4.5 kWh/m^2/d Summer - 5.5 kWh/m^2/d

3.3 Description of the System Used to Monitor the Pump

This section deals with the following:

a) A general description of the monitoring system;
b) What parameters were measured and why;
c) What instruments were used to measure these parameters and their accuracies; and
d) A description of the interface and the data logger.

General Description

The following figure gives an outline of the monitoring system used.

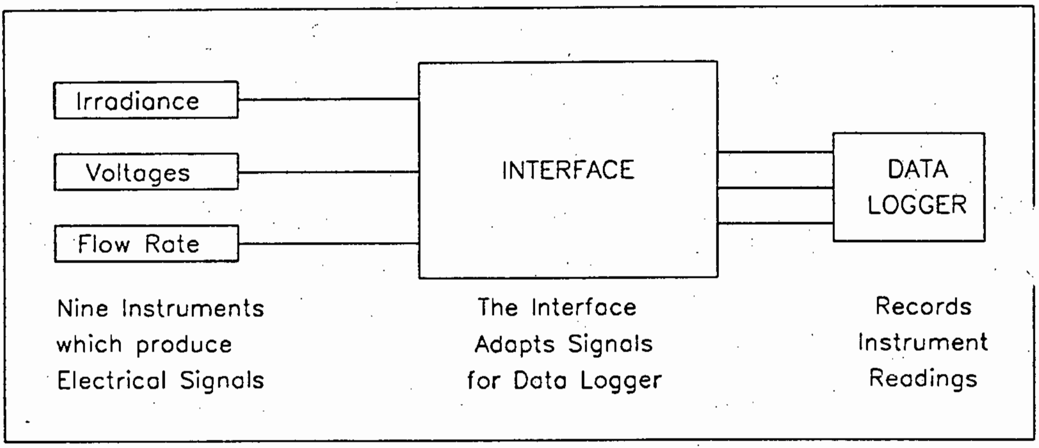


Figure 3.2: Outline of the Monitoring System Used

The system consists of three sections: 1) the nine instruments which measure the important parameters giving out electrical signals; 2) the interface which modifies those signals to give acceptable inputs to the logger; and 3) the data logger which records the values of all the channels at the end of every log period.

The monitoring system was installed on site and powered by batteries charged by two PV panels.

3.3.1 The Parameters Chosen for Measurement

Parameters were chosen so that the efficiency of each component could be monitored. But the data logger has only eight analogue channels. Only the signal for pump speed was digital and so this meant that in total nine channels could be logged at any one time.

In order to fully model the performance of each component it is necessary to log at least twelve parameters, ten of them analogue. However, some parameters can be calculated accurately from others and so it is possible to exclude these without losing accuracy. The choice of which parameters to monitor using the data logger sytem and how to measure the others is discussed below in relation to the components they are concerned with.

a) Monitoring the Array

The 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.

So the efficiency of the array can be calculated if irradiance, array voltage and array current are monitored. But the array efficiency is also affected by array temperature, which is in turn affected by the ambient temperature. So in order to model the changes in efficiency with array temperature it is necessary to monitor these two. So all these five parameters were chosen to be monitored by the data logger system: irradiance, array voltage, array current, array temperature and ambient temperature.

b) The Power Maximizer

The power into the maximizer is the same as that out of the array - and so was discussed above. There will be a similar situation for all components below so only the power out of each component is discussed.

The power out of the maximizer is given by the product of motor voltage and motor current. These two parameters were also chosen to be monitored by the data logger system.

Because the power maximizer is a switching device the power into and out of the maximizer may have an AC component. If so, the product of the average voltage and average current would not give accurate figures for average power - there may be a power factor involved. For this reason electronic circuits were designed to measure the instantaneous power into and out of the maximizer. It was, however, found that there was no AC component to these powers and so only the circuit for array power was used in the data logger system to backup the measurements of array voltage and array current.

c) The Motor

The power out of the motor is given by the product of torque and speed. However, the motor's operation is completely described by only two of the parameters. This means that if only the current and voltage to the motor are measured it is possible to predict the exact operating point of the motor and so its torque and speed.

Measurements for torque in the field would be expensive and far less accurate than those done in a laboratory using calibrated equipment. So motor torque and speed were not monitored by the data logger system in the field; instead the motor was tested in a laboratory to find correlations for torque and speed in terms of voltage and current.

d) The Transmission

The power out of the transmission is the product of pump speed and pump torque. It is not necessary to measure pump torque as this is given by the product of the motor torque and motor/pump pulley ratio between the pump and motor. But the pump speed cannot be calculate in the same way from motor speed as there may be some creepage in the V-belt. So the pump speed was monitored by the data logger system.

e) The Pump

The power out of the pump is given by the following formula:

$$P_p = \text{rho}.g.H.Q.$$

The density of water (rho) and the acceleration of gravity are effectively constants. It is however necessary to measure the total head (H) and the water flow rate (Q).

The total head consists of the static head and the dynamic or friction head. The static head changes with river level. However, if the river level is measured daily then just one measurement for static head is sufficient. The dynamic head depends on the length and diameter of the delivery pipe and the flow rate. So it is necessary to measure the dimensions of the delivery pipe and the dynamic head can then be calculated from the flow rate.

The flow rate changes continuously and so should ideally must be monitored by the data logger system. This was tried but unfortunately the flow meter did not work. The system for measuring flow rate is described below.

3.3.2 Instruments Used and Their Accuracies

The following two tables give a list of the parameters measured and the instruments used. The first table is for those parameters which were monitored by the data logger system. The second table is for those that were measured in some other way.

Table 3.3: The Parameters Measured and Instruments Used - Data Logger System

Parameter Measured	Instrument Used	Calibrated Against	Accuracy
Solar Irradiance	Kipp & Zonen Thermopile	Weather Bureau Standard	1%
Ambient Temperature	LM35D Sensor	Mercury Thermometer	1%
Array Temperature	LM35D Sensor	" "	1%
Array Voltage	Voltage Division	Multimeter	1%
Array Current	Current Shunt	"	2%
Array Power	Integrator	"	2%
Motor Voltage	Voltage Division	"	2%
Motor Current	Current Shunt	"	2%
Pump Speed	Inductive Proximity Sensor (Pepperl and Fuch NJ5)	Digital Tachometer	1%

All the instruments used in the field were calibrated against more accurate standards. The instruments used for calibration are given in the above table. Also given is an estimate of the maximum error of the readings of the instruments used in the field.

The following are the parameters not monitored by the logger system.

Table 3.4: Additional Measurements for Calculating Efficiencies

Parameter Measured	Method of Measurement
Motor Torque	SABS Laboratory test
Motor Speed	SABS Laboratory test
Static Head	Dumpy Level
Dynamic Head	Dimensions of Delivery Pipe
Water Flow Rate	235 l drum and stopwatch
Water Used	Kent PSM 5 Flow Meter

The instruments used and their estimated accuracies are discussed more fully below. They have been put under headings of the parameters they measure.

a) Solar Irradiance

Two instruments were available for measuring irradiance: the Kipp and Zonen thermopile and the Licor pyranometer. I decided that the accuracy of the Licor pyranometer was not adequate based on Cowan's comparison of the two (1989). There are three main sources of Licor error: tilt angle, spectral distribution and drift in calibration.

Error due to tilt angle: Cowan measured discrepancies between the Licor and Kipp & Zonen measurements of 11.5% at an angle of incidence of the sun's rays of 70°. Most of this error is attribute to the Licor as the Kipp & Zonen's measurements agreed well with weather station measurements. Further Coulson (1975) notes that the error for Kipp and Zonen instruments is typically less than 1% at 70° (cited Cowan, 1989).

Error due to spectral distribution: the Licor specifications note that at low solar elevations its readings "show significant error because of altered spectral distribution with changes in atmospheric transmission". This is because the spectral response of the Licor is narrow: it falls away outside the range 800 to 1000 nm. In comparison the response of the Kipp and Zonen is almost flat between 300 and 2500 nm. The ideal response would be flat between 280 and 2800 nm.

Error due to drift in calibration: the Licor specifications note that the calibration may drift by as much as 2% per year. The Licor pyranometer available was four years old giving a possible calibration error of 8%.

For these reasons it was decided that only the Kipp and Zonen provided the required accuracy. The instrument was calibrated by the Weather Bureau in Pretoria just before the tests were started. The accuracy of its measurement is likely to be better than 1%. The resolution of the data logger was also about 1%. So the accuracy of readings was better than 2%.

b) Ambient and Array Temperature

Ambient and array temperatures were measured using LM35D integrated circuit temperature sensors. It is claimed that their maximum error is less than 0.5 °C and their linearity better than 0.25 °C over the full range. As they were both calibrated against a mercury thermometer their absolute accuracy was unimportant. The linearity gives a maximum error of less than 1%.

In order to ensure accurate readings the sensor for array temperature was held tight against the array by a spring, and heat conducting paste was used to improve heat transfer. The temperature of ten cells in the array was measured and a cell chosen which gave an average.

c) Voltages, Currents and Powers

The voltages which were to be measured had a top range of 120 V. Voltage division was used to produce a manageable signal from these high voltages. The currents were measured using 10 A to 50 mV current shunts. And the power was measured by using a multiplier chip to find the product of the current and voltage signals. These signals were then conditioned by the interface.

The accuracy of these measurements depended on the amount of drift in the interface during the tests. Unfortunately due to the quality of the construction of the interface this was not negligible. Each channel was calibrated against a multimeter on each day of the tests and manual checks were done during the tests.

From the standard deviation of the discrepancies between manual readings and the logged readings the accuracy of these channels was estimated as better than 0.5% for array voltage and better than 2% for the other channels. (See Appendix 3.4.4 for details).

d) Motor Speed and Torque

The motor torque and speed were measured using the motor test bed at the SABS Rotating Machines Department in Pretoria. These instruments are of very high quality and are calibrated regularly. The correlation coefficients for all correlations used were better than 0.9998 - which confirms the accuracy of both the data and of the equations used to model motor behaviour.

e) Pump Speed

The pump speed was initially measured using the Pepperl and Fuch NJ5 Inductive Proximity Sensor. This sensor was mounted on the pump so that on every revolution a metal protrusion passed within 2 mm of the sensor - which generated a current pulse in the sensor.

Unfortunately, the measurements from the proximity sensor were found to be unreliable at low speeds. Even when the pump was moving very slowly or stopped the sensor nevertheless indicated very high speeds .

It is possible that this interference was caused by the Miltek power maximizer. In order to chop the voltage from the array this device switches the array voltage on and off at a high frequency. During this process it may generate oscillating magnetic fields which could be picked up by the proximity sensor.

Because the amount of interference changed with irradiance it was impractical to try to adapt the reading from the proximity sensor by using some correlation. Instead a correlation for pump speed was found in terms of motor and current voltage - using a similar correlation to that for motor speed.

To find this correlation the pump speed was measured using a digital tachometer while the motor current and voltage were logged. This was done over the full range of the pump speeds. The resultant correlation gave a correlation coefficient of 0.9985.

f) Water Flow Rate

Initially a Weber Flow Captor type 4113.30 was used to measure water flow rate. However this was washed away in the 1987 Natal floods. Another was bought but it did not work satisfactorily in the field - the signal wandered badly and bore no relationship to the flow rate. Due to lack of time this instrument was abandoned.

Instead a correlation was found for flow rate in terms of pump speed. For a positive displacement pump the flow is proportional to pump speed and so a linear correlation was expected.

To establish the correlation the flow rate and pump speed were measured over their full range. The pump speed was measured by a digital tachometer. The flow rate was calculated from the time taken to fill a 235 litre drum. The times ranged from 4 to 12 minutes which meant that the error in measurement using a stopwatch was negligible.

The resulting correlation was linear and gave an acceptable correlation coefficient of 0.9947.

g) Static and Dynamic Head

The static head was measured using a dumpy level - twice in order to check the accuracy. The discrepancy between the two readings was 5 mm (0.06% error).

The following equation was used to calculate the friction head from the flow rate once the dimensions of the delivery pipe had been found. The derivation of this equation (from the Blasius equation for the range of flows expected) is given in Appendix 3.3.

$$H_d = 4.659 * 10^{-10} * Q^{1.75} * d^{-4.75} * l$$

where d is diameter (m) and l is length (m) and Q is flow rate (m³/hr)

The friction due to elbows and couplings in the delivery pipe was accounted for by increasing the value for the pipe length by a specific number of diameters per fitting (for example, 35 diameters per 90°elbow) (Coulson, 1977).

h) Water Used

The volume of water used by the gardeners does not affect the efficiency of the pump. But it does affect its size. So it is important to measure this to aid accurate sizing of PV pumps. The water used was measured using a Kent Flow meter. This meter gave a manual reading and was read at least every week from March to September 1987. The results from these readings are discussed in Chapters 4 and 5 on Economics and Sociology.

3.3.3 Description of the Interface and Data Logger

a) The Interface

The interface was built by the Energy Research Institute to adapt the instrument signals to readings acceptable to the data logger. The interface was powered off two 12 V batteries which were charged by PV panels.

Most of the signals from the instruments were analogue readings; only that from the proximity sensor was in current pulses and so a digital signal.

The analogue signals were either in Volts or millivolts. These were amplified by the interface to give signals of 0 to 2 V which were suitable for input to the data logger. On all these boards the amount of amplification could be set by a potentiometer. On the boards that amplified millivolt signals it was also possible to set the zero as any small error would be amplified greatly.

For the digital channel a Smith's trigger was used to ensure that erroneous readings were not caused by noise on the signal. The Smith's trigger ignores all changes in the signal until a set trigger level is reached at which stage it changes the output instantaneously from off to on or vice versa.

b) The Data Logger

An MC Systems 120-02 Data Logger was used. This supports eight analogue channels and four digital channels.

The channels are read continuously and averages for each channel are computed for each minute. The user can then set output programs for recording this information. The output programs specify whether the average or the maximum or minimum of a channel during the log period is recorded. The length of the log period is also set by the user.

The information is recorded on an EPROM memory chip. At the end of each test or series of tests this data can then be transferred from the memory chip onto a personal computer for analysis.

3.4 Experimental Method and the Data Analysis

There were four series of tests concentrating on different components of the system. These are discussed separately below. But similar principles were used for all the field tests and these are discussed briefly first.

Choosing the Log Period

The operation of all the components of the system varies 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.

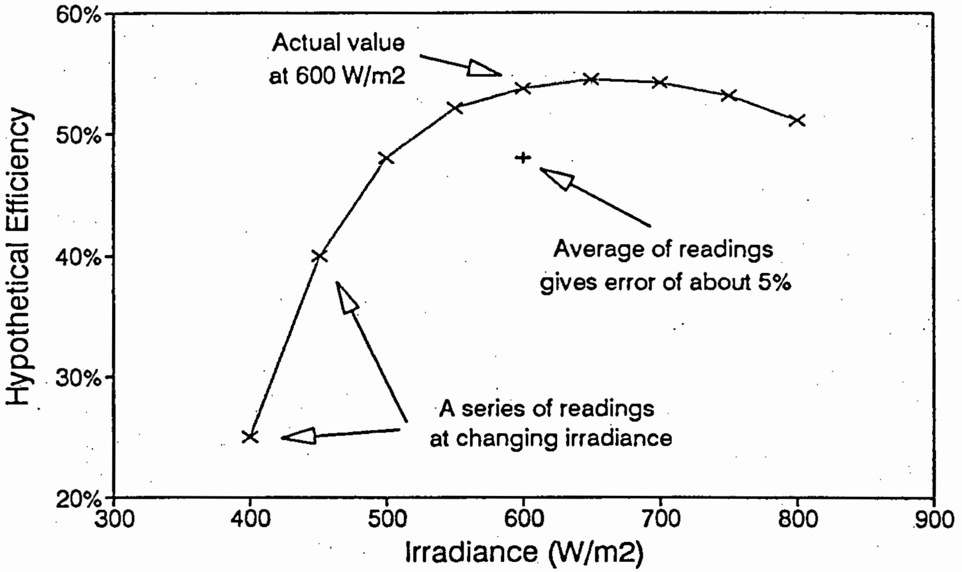


Figure 3.3: The Need for Instantaneous Readings

The graph shows a hypothetical set of readings for an 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 irradiance. So the log period needs to be kept as short as possible to model the operation of the components accurately.

The shortest log period possible on the data logger is one minute and this was used. For a cloudless day the change in irradiance during one minute is so small that it will cause no distortion of the readings. So all the tests were done on cloudless days.

Adjusting Readings to Standard Conditions

Most of the tests involved comparing different components or conditions. To ensure comparability, the components or conditions were swapped as quickly as possible so that the change in irradiance between tests was as small as possible.

However, there was always some discrepancy in the irradiance and array temperature for tests that were being compared. So it was necessary to find correlations to adjust the data to standard conditions. Finding these correlations was one of the main functions of the data analysis.

Checks on the Reliability of the Readings

On each day of the tests each channel was checked against constant battery signals. These checks provided "fine tuning" for the calibration of the channel for that day and ensured that the effect of any drift in the interface electronics was minimized.

Throughout the test the channels were checked manually against accurate instruments. The discrepancies between the manual and logged readings gave an idea of the reliability of the channels on that day.

Tables giving the standard deviation of the discrepancies and correlation coefficients for the "fine tuning" calibrations are given in Appendix 3.4. But for all the data used the discrepancies were small - about 1% or below with the worst giving 2% error.

Focuses of the Four Series of Tests

The operation of the major components was examined separately. So there were four series of tests which examined the following:

a) The operation of the array. And the effect of shading and the use of diodes on array efficiency.
b) The operation of the Honeywell DC motor installed with the system; and in comparison that of a the Baldor DC motor.
c) The operation of the Miltek power maximizer installed with the system; and in comparison one designed by the Australian Energy Research Laboratories (AERL).

d) The operation of the whole system as installed over half a day. This gave data on the operation of the system and each of its components under undisturbed conditions. In particular this data was used for data on the Mono Pump and the transmission.

Each series of tests is dealt with separately in the following four subsections.

3.4.1 Modelling the Operation of the Array and the Effect of Diodes and Shading

The results from the experiments described below are given in Subsection 3.5.2.

a) Experimental Method

The purpose of the measurements was to be able to produce curves such as the following for the array.

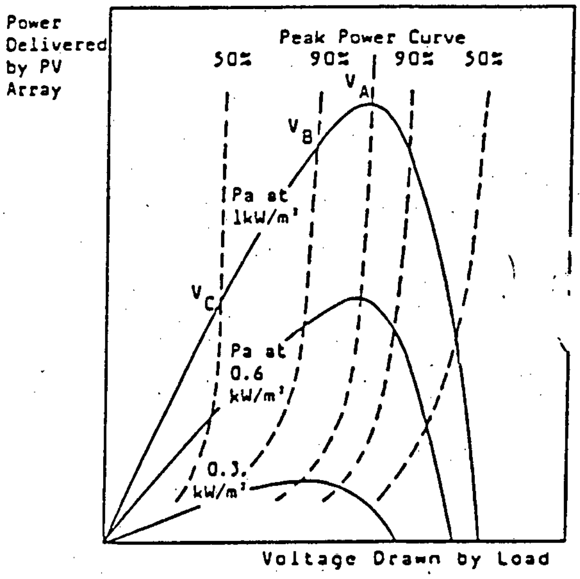


Figure 3.4: Power from Array vs Array Voltage

From similar curves it is possible to find the Peak Power Curve (PPC) of the array as well as its efficiency at different voltages, irradiances, and array temperatures.

Description of Test Method

Four irradiances were chosen (200, 400, 600 and 800 W/m^2) and the performance of the array was recorded over the full range of array voltages as close to these irradiances as possible. At each irradiance the performance of the array was measured at ten voltages from 0 Volts to the open circuit voltage. The readings were concentrated about the expected position of the PPC.

To get the array to operate at the intended voltage and for it to be stable for the full time during which its performance was logged it was necessary to provide a stable load which could be set by the experimenter. This was done using resistances. At each irradiance the operation of the array was to be measured at ten voltages. The values of the required load were calculated for each of these points.

As a large amount of power needed to be dissipated it would have been expensive to buy resistors or variable resistors to simulate these loads. So six 900 W heaters in various series and parallel combinations were used to dissipate most of the power. Then various combinations of 10 W resistors were used to get exactly the load required.

The experiments were done on four cloudless days. When the the irradiance reached one of the levels required, the performance of the array was logged for two minutes at each of the array voltages decided on. Only records for the second minute were used as during part of the first minute the readings were still reaching steady state.

The Conditions at which the Test was Done

The test described above was done both with and without a covering security wire mesh fence, and with and without diodes. This is because I had noted that if only one or two cells on the array were completed shaded the pump stopped working even on a sunny day. This indicated that shading had a marked effect on the efficiency of the array.

However two of the panels in the array had been stoned and the gardeners suggested putting a fence over the array to protect it. I wanted to quantify the decrease in array power due to the shading in order to work out the real cost of this method of protection. I also wanted to test whether the use of diodes would decrease the effect of shading by bypassing cells which were shaded.

So the test described above was done under the following four conditions (at each irradiance):

a) With no diodes and no fence;
b) With no diodes and the fence in;
c) With diodes in and no fence;
d) With diodes in and the fence in.

The fence and diodes were arranged so that it took about one minute to install or remove them. So it was possible to test the conditions consecutively at most irradiances and so ensure the comparability of the data.

A Closer Examination of Shading and Diodes

The above tests gave the bulk of the data needed to model the operation of the array at various voltages, irradiances and temperatures. It remained to examine closely the effect of shading and the use of diodes. Small rectangles made out of cardboard were used to simulate the effects of different amounts of shading. Two sizes of cardboard shade were used: the smallest was supposed to show the effect of something small and opaque (such as a bird dropping) and the largest blocked out a whole cell (possibly demonstrating the effect of a cell with a hot spot).

Four conditions of shading were tested. They included shading various numbers of PV modules with either the large or small shades. This was done with the diodes both in and out.

b) Method of Data Analysis

The aim of the data analysis was to model the performance of the array under various conditions of irradiance and temperature. Of particular importance is the modelling of the area around the Peak Power Curve.

Adjusting to Standard Conditions

The first step was to find correlations for array voltage and array current in terms of irradiance and array temperature. The conditions of irradiance and array temperature at which the data was read could not be controlled. So to compare data read at slightly different irradiance and temperature it was necessary to be able to adjust the data to standard conditions.

Wang (1987) proposed that the effect of irradiance and array temperature on array current and voltage could be modelled by measuring their effect on the open circuit voltage and short circuit current. Correlations found here could then be used for any array voltage or current (to adapt them from reference conditions).

This method was adopted by with more sophisticated correlations as those Wang used were simplistic. The correlations I used were based on the following two graphs.

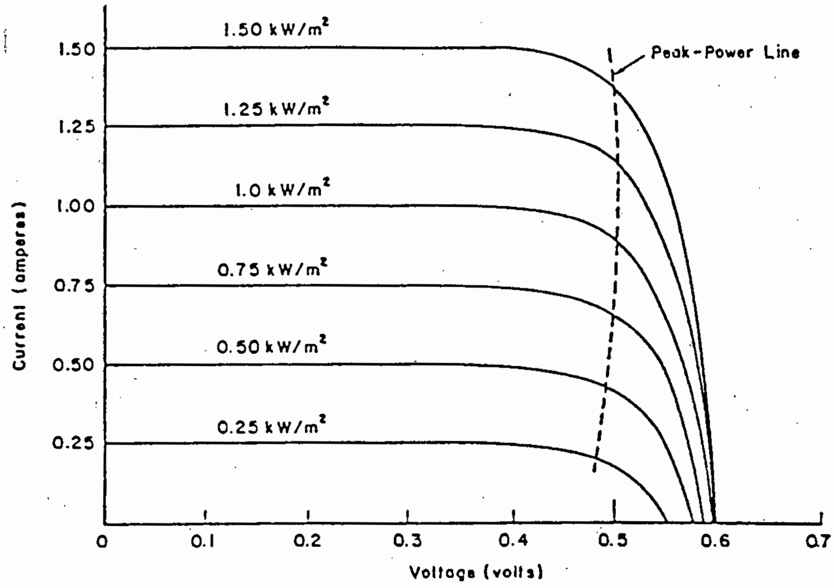


Figure 3.5: The Effects of Irradiance on Open Circuit Voltage and Short Circuit Current
Source: Lasnier, 1988, p65.

The short circuit current (i_{sc}) is strongly dependent on irradiance and proportional to it (as indicated by the y-intercepts). The open circuit voltage (V_{oc}) is proportional to the logarithm of irradiance and the dependence is weak (see x-intercepts).

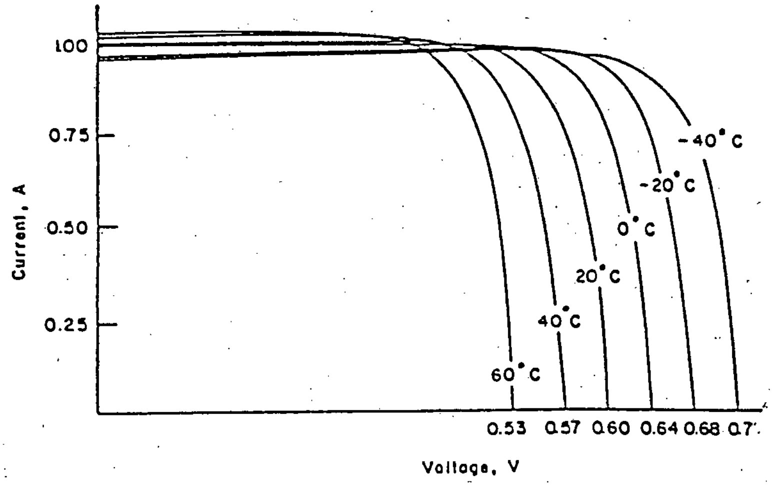


Figure 3.6: The Effects of Array Temperature on Short Circuit Current
Source: Lasnier, 1988, p 65.

Both i_{sc} and V_{oc} are proportional to array temperature. While i_{sc} increases fractionally with increasing temperature, V_{oc} decreases markedly.

So two equations were created to get the adjusted values V_a' and i_a' at standard conditions of array temperature and irradiance ($T_a'$and G') from read values V_a and i_a at actual values T_a and G:

$$V_a' = V_a + a.DEL(Ta) + b.DEL(\ln(G))$$

$$i_a' = i_a + c.DEL(Ta) + d.DEL(G)$$

where: a, b, c and d are constants found by regression;
DEL(G) = G' - G, and similarly for T_a and ln(G)

Experimental data for i_{sc} and V_{oc} were used to find the coefficients of these correlations. Two correlations were necessary for i_a: one for when the fence was installed and one for without it. The resultant correlations are:

$$V_a' = V_a - 0.43\ DEL(T_a) + 6.034\ DEL(\ln(G))$$

$$i_a' = i_a + 0.001\ DEL(T_a) + 0.006877\ G; \quad \text{with no fence}$$

$$i_a' = i_a + 0.001\ DEL(T_a) + 0.006571\ G; \quad \text{with the fence}$$

The standard conditions (T_a' and G') were chosen for each test so that the adjustments were kept as small as possible. Thus any error in the correlations would hardly affect the accuracy of the results.

Finding the Maximum Power Point

The second step was to find the maximum power point at each irradiance and for each condition (of shading and diodes). The adjusted array power ($P_a'=V_a'*i_a'$) was calculated for each test from values V_a' and i_a' at standard conditions. From these values of P_a' a correlation which modelled the performance of the array near to the PPC was found for each condition. The following graph shows both the experimental values and the correlation used to model the curve for one of the tests.

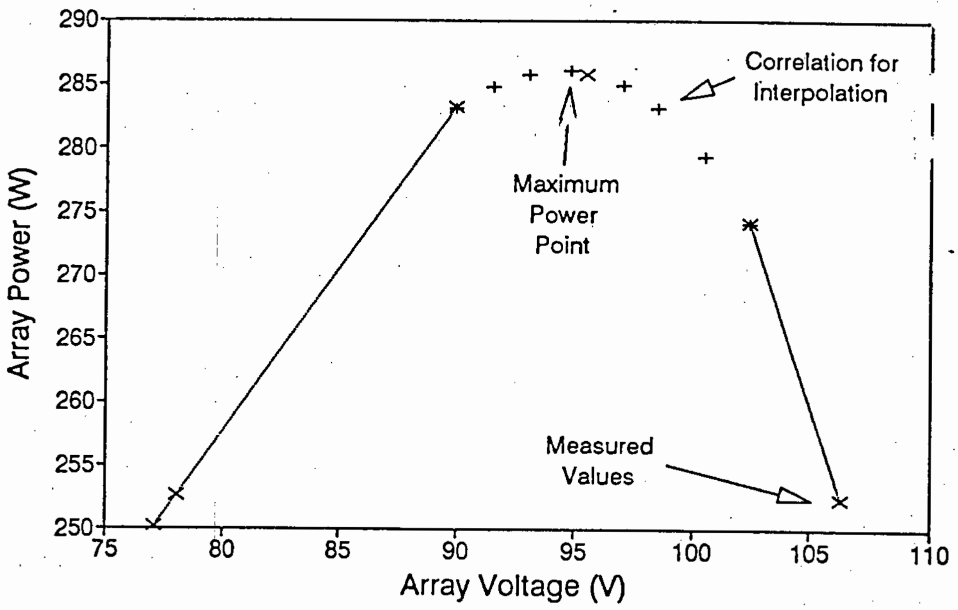


Figure 3.7: Interpolation to find Vmax and Pmax

A cubic equation was found to give adequate accuracy in modelling this small area close to the Maximum Power Point. This was then differentiated and solved to give the location of the Maximum Power Point for each test.

The Maximum Power Points could then be connected to find the location of the Peak Power Curve (PPC); and to find how it is affected by temperature and irradiance. The cubic correlations described above modelled the operation of the array near the PPC - and so enabled the efficiency of various tracking methods to be calculated. All these results are discussed in Subsection 3.5.2.

3.4.2 Comparison of Honeywell and Baldor DC Motors

The second test done was an examination of the operation of two motors. The test aimed:

a) to get data for the Honeywell and Baldor motors at all voltages so that their performance in a PV pump system could be compared; and
b) to find correlations for motor speed and torque in terms of current and voltage. These could then be used to calculate the speed and torque from the information logged by the data logger monitoring system (see Subsection 3.3).

The Honeywell is the motor installed with the PV pump examined at Sondela. It is a brushed permanent magnet DC motor. The Baldor is a similar motor but a different make which Mono Pumps had used and wanted compared.

a) Experimental Method

The experiments were done on the motor test bed at the SABS laboratories in Pretoria. The instruments there give immediate read outs of all the important parameters: voltage, current, speed and torque.

The readings were taken at six different voltages: from 15 to 90 V. At each of these voltages, readings for all four parameters were taken at six currents ranging from 1 to 11 A. This was done for both the motors. These readings were noted down manually and entered into a Quattro spread-sheet for analysis.

b) Method of Data Analysis

There were four aims of the data analysis:

a) to model the operation of the motor at constant voltage;
b) to model its operation at constant current;
c) to find correlations for speed and torque in terms of voltage and current; and
d) to find the power required by each motor to overcome starting torque.

Constant voltage: With the experimental set up used, it was impossible to set the voltage to exactly that required. Voltages that were within 1 V of the desired setting were accepted and the readings were recorded at this voltage. So from here it was necessary to use regression analysis to find out what the readings would have been at exactly the right voltage.

Constant current: When coupled to a positive displacement pump the DC motor draws an almost constant current. For this reason graphs at constant current are more informative than those at constant voltage. While most of the readings were close to round figures, they needed to be adjusted to be exactly at the currents required. Seven currents from 1 to 11 Amps were used.

Regression analysis was used to predict what the readings would have been at the voltage or current required. The variables used to correlate each reading were:

V_m = $f(s_m, tau_m, tau_m^2)$ where s_m is speed and tau_m is torque
s_m = $f(V_m, tau_m, tau_m^2)$ where V_m is voltage
i_m = $f(tau_m, V_m, V_m^2)$ where i_m is current
(The torque readings were not adjusted - no correlation was needed)

Voltage is proportional to speed: so it is not necessary to include the square of speed as a variable in its correlation. Although voltage should be independent of torque there may be a small, possibly non-linear dependence on it. For this reason both torque and its square were used for safety. Similar reasoning was used for the other parameters.

All the readings were graphed to visualize the applicability of the correlations used. The following is an example:

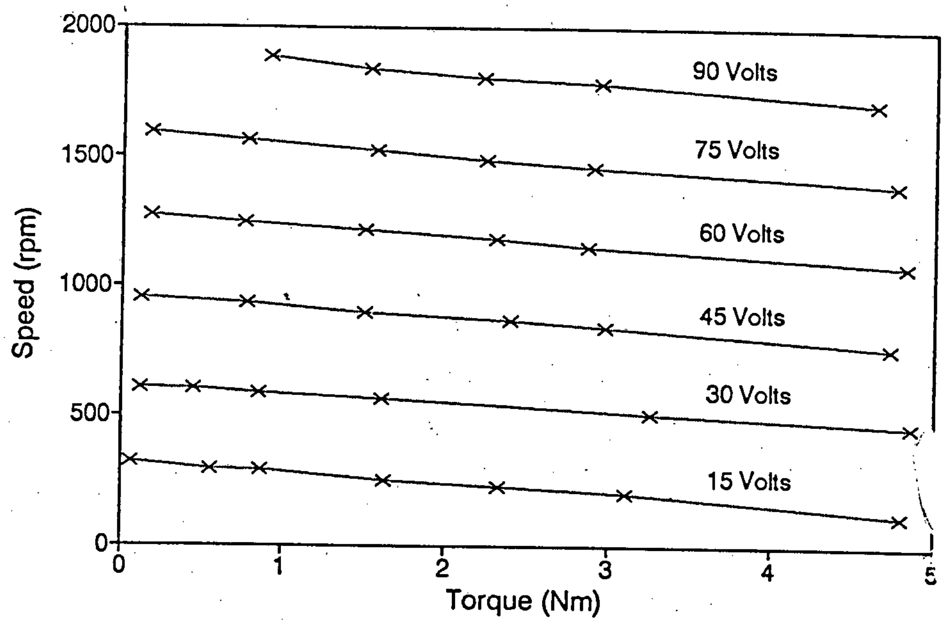


Figure 3.8: Raw Data: Speed versus Torque at all Voltages

This shows that Speed does have a small (seemingly linear) dependence on Torque, but that it has a much stronger dependence on Voltage (as expected). So it is necessary to include the Torque terms in the correlation.

The coefficients for the correlations were found by regression analysis. The correlations were then used to make the adjustments necessary to model motor operation at constant voltage and constant current.

Correlations for Motor Speed and Torque

These were simply found by regression analysis on the raw data. They are:

$\text{tau}_m = 0.4558\, i_m - 0.00244\, V_m + 1.02\text{E-}5\, V_m^2 - 0.229$

$s_m = 21.05\, V_m - 42.88\, \text{tau}_m + 0.4865\, \text{tau}_m^2$

where the units for V_m, i_m, tau_m, and s_m are Volts, Amps, Nm, and rpm respectively.

The correlation coefficients for both these correlations are above 0.9998.

The power required for start-up

An important point to establish accurately is the power required by each motor to overcome starting torque. However the start-up condition was not measured in the laboratory. The following equations show how this point can be accurately calculated.

If one starts with the starting torque to be overcome. Then:

$$i_m = f(tau_m)$$
$$V_m = f(s_m, tau_m, tau_m^2) \text{ where } s_m = 0$$
$$P_m = i_m * V_m$$

The performance of the motors is discussed in Subsection 3.5.4. The above method is used to find the power for start-up for the graph given there which compares the operation of the two motors.

Further details and graphs on the data processing are given in Appendix 3.4.2.

3.4.3 Comparison of Two Power Maximizers

The third series of tests was a comparison of the operation of the Miltek power maximizer which was installed with the Sondela system and a maximizer designed by the Australian Energy Research Laboratories (AERL) which was supplied for comparison by Mono Pumps. A third maximizer, the Pump Mate Autotrack supplied by BP, was also tested. Unfortunately the data on this maximizer was not sufficiently accurate to be used.

There were three aspects to this series of tests:

a) Comparing the operation of the maximizers over the full range of the irradiances;
b) Examining the effect of the pulley ratio; and
c) Examining start-up conditions.

The operation at all irradiances: On two sunny days the operation of the maximizers was compared at all irradiances. At any particular irradiance one maximizer was first monitored for five to ten minutes. Then the other was tested. They were swapped quickly to ensure similar conditions.

Pulley ratio: As noted previously the gear ratio between the motor and the pump affects the efficiencies of the motor, the power maximizer, and the array. For this reason the operation of the maximizers was monitored with two sizes of pulleys: the 126 mm which was installed with the system, and a 151 mm pulley which would enable the maximizers to track the array Peak Power Curve more effectively. So for all irradiances each maximizer was tested with both motor pulleys.

Start-up: the operation of the maximizers at start-up is very important. So their operation was monitored on three cloudless mornings. The Miltek maximizer with the normal (126 mm) pulley was tested intially. The AERL was tested with both pulleys as its specifications required the use of the 151 mm pulley to increase tracking effectiveness.

3.4.4 Monitoring the Performance of the Whole System

The fourth test was the monitoring of the performance of the whole system over half a day. The purpose of this was to:

a) Provide data on the operation of the system and its components under undisturbed conditions - during all the other tests special conditions were created to examine a component in detail;
b) Provide data on the operation of the Mono pump and the transmission which were not monitored separately as were the other components;
c) Provide data from which the Daily Energy Efficiencies of the system and its components could be computed.

Experimental Method

The experimental method was simple as the pumping system was left to operate normally. It was necessary to monitor its performance for only half a day as this gave the full range of irradiances.

The readings to provide the correlations for pump speed and for flow rate were taken on this day (see Subsection 3.3). This ensures that the data for the efficiency of the Mono pump itself is accurate for this day.

Graphing the Operation of the System

To graph the operation of any component it was necessary to reduce the bulk of data to give its operations at ten irradiances. Irradiances from 100 to 900 W/m^2 in steps of one hundred were used with an extra peak irradiance of 950 W/m^2. Records were selected which were as close as possible to these irradiances and which were read under stable conditions. All records at a particular irradiance were then averaged. The averaging of a number of records increased the reliability of the data.

Computing the Daily Energy Efficiencies

The data found above is instantaneous: it provides a snap shot of the operation of the system at a particular irradiance. The snapshots provide useful detailed information by which one can identify weak points in the operation of the components and so identify areas for further investigation.

But the snapshots may show that this PV pump is more efficient than another at low irradiances but less efficient at higher irradiances. In this case which pump would deliver more water? How much more water? Would one pump be better for a site with low insolation and the other better if the insolation is higher?

These questions illustrate the importance of Daily Energy Efficiencies and Standard Solar Days. A customer does not want to know the efficiency of the pump at, for example, 800 W/m². Rather he or she wants to know how much water the pump will deliver if it is installed at a particular site. This can be calculated from the Daily Energy Efficiency which is the <u>average</u> efficiency for a whole day.

To find the average efficiency of the pump for a location it is necessary to find an average irradiance profile. The most common practice is to assume that this profile follows a sine curve. A day for which the irradiance follows a sine curve is called a Standard Solar Day.

The insolation on the Standard Solar Day can be varied by changing the peak irradiance of the sine curve. The computations described below were done for insolations ranging from 4.5 kWh/m²/d (equivalent to Durban in the winter) to 7 kWh/m²/d (equivalent to Windhoek in the summer).

The following graph shows the irradiance profiles used for each of the Standard Solar Days.

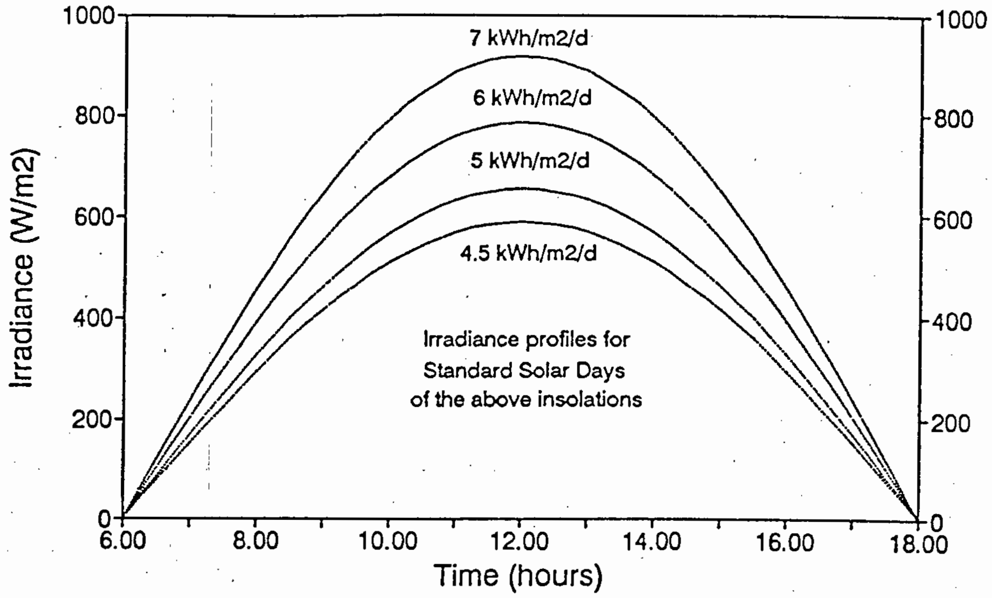


Figure 3.9: The Irradiance Profile for a Standard Solar Day

The Daily Energy Efficiencies for each of the components were computed using a Quattro Spreadsheet. The first column had the times from sunrise to sunset in 15 minute intervals. The irradiance at each time was then calculated using the sine curve profiles shown above. From the irradiances the power delivered by the array was calculated using a correlation found previously. In the next column was the efficiency of the power maximizer calculated from a correlation in terms of array power.

And so on down the system: the operation of each component was calculated using a correlation in terms of the inputs to that component. (A table of the correlations and equations used is given in Appendix 3.4.4.)

The resulting spreadsheet gave the power into and out of each component at each time during the day. The energy into and out of each component for the whole day was then computed using Simpson's rule. And the Daily Energy Efficiencies of each component were calculated from these values for energy.

3.5 Results and Discussion

As noted at the beginning of this chapter there are three focuses for the technical examination: a) the efficiencies of the system and each of its components; b) the matching of the components; and c) the suitability of alternative components. These questions are dealt with as follows:

a) Efficiency: This section starts with an overview of the operation of the system in Subsection 3.5.1. The efficiencies of the system, subsystem and components are given, but more detailed discussion is left to Subsections 3.5.2 to 3.5.5. These subsections deal in turn with the array, the power maximizer, the motor, and finally the pump and transmission.

b) Component Matching: The position of the Peak Power Curve and thus the efficiency of different methods of tracking is discussed in Subsection 3.5.2 on the array.

The second factor examined, the motor/pump pulley ratio, affects the efficiencies of the array, the motor and the maximizer and so is discussed in each of the subsections relating to those components. The best trade-off between these various effects is discussed in the subsection on the maximizer (3.5.3).

c) Alternative Components: The alternative power maximizer made by AERL is compared with the Miltek in Subsection 3.5.3. The alternative Baldor motor is compared with the Honeywell motor in Subsection 3.5.4. And the suitability of centrifugal pumps for photovoltaic applications at low heads is compared to that of the Mono Pump used in Subsection 3.5.5.

3.5.1 The Performance of the Whole System - Power and Energy Efficiencies

This subsection provides an overview of the operation of the system. It deals with the following topics:

- a) How efficient is each component of the system and how does its efficiency vary over the day? What are the resultant system and subsystem efficiencies?
- b) How efficient is each component if its efficiency is averaged for a whole day? So how much of the energy coming into the pump goes into pumped water - and where does the rest go?
- c) How does this PV pump compare with those studied elsewhere in the world? And do the components match up to manufacturer's specifications?
- d) How do the system's components interact with one another? What briefly is the function of each component? This is illustrated by a series of graphs.

These questions are dealt with in turn below. For more detail on each component see Subsections 3.5.2 and onwards.

a) Component Efficiencies and the Effect of Irradiance

The data discussed below was collected on a cloudless day from before sunrise to just after mid-day (see Subsection 3.4.4). All the original components were used and the system was not disturbed. The following graph shows the conditions for the day of the test: irradiance, ambient temperature and array temperature.

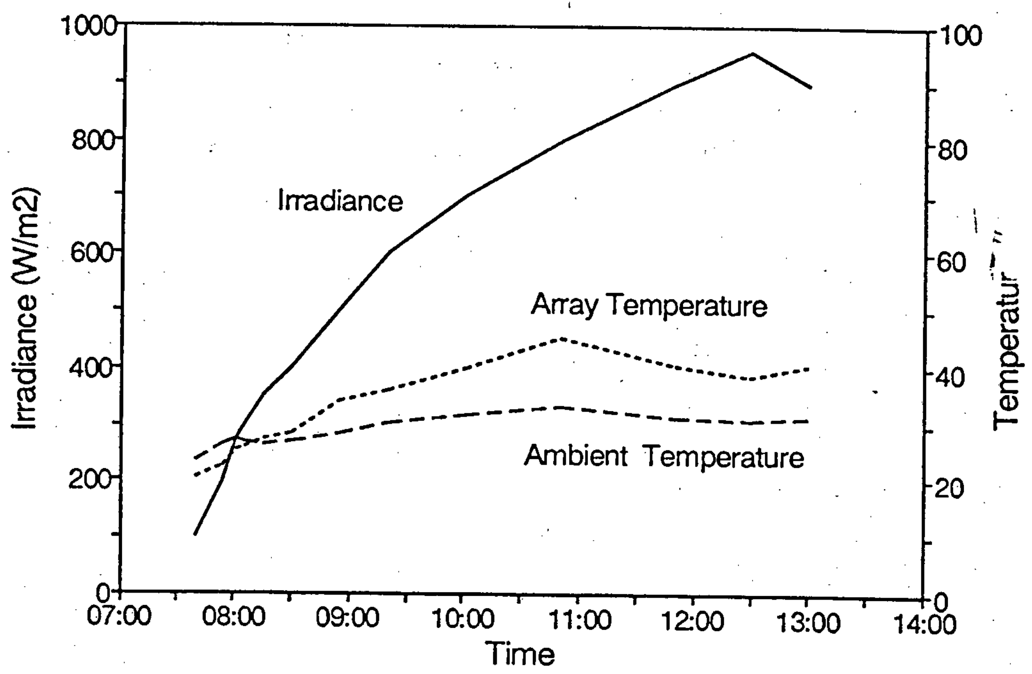


Figure 3.10: Irradiance and Temperature versus Time

It can be seen that the irradiance did follow a curve which might be modelled by a sine curve (the profile for a Standard Solar Day). Also the difference between the array and ambient temperatures increases linearly with increasing irradiance (until it is 12 °C at 1000 W/m^2).

The variation of the Power Efficiencies of the major components with irradiance is shown below.

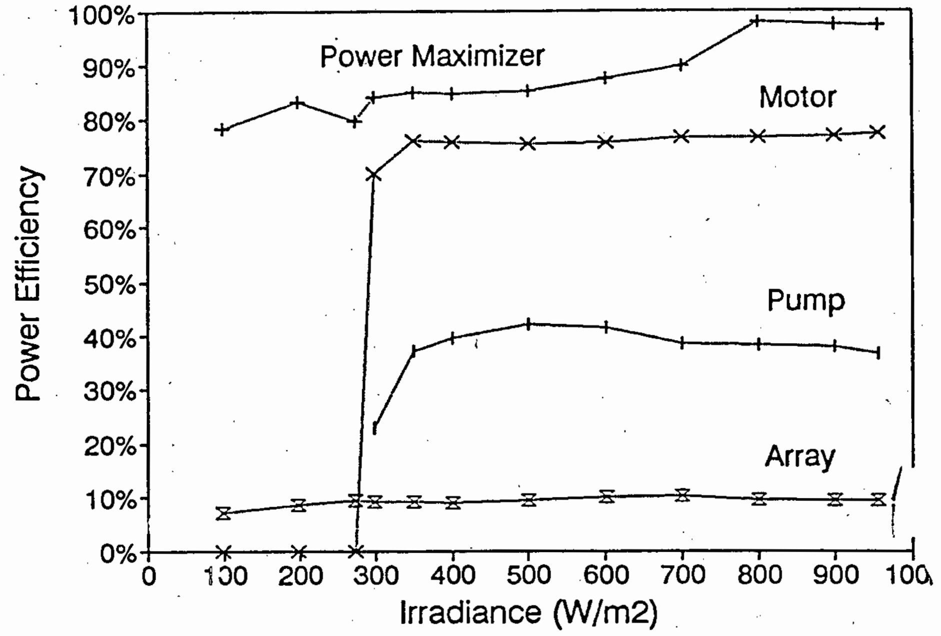


Figure 3.11: Component Power Efficiencies versus Irradiance

The array efficiency climbs steadily from 7.1% at 100 W/m^2 to 10.3% at 700 W/m^2 and then drops slightly with increasing array temperature. Although the scale of the figure does not emphasize this point, the increase in efficiency is significant (1.45 times).

The maximizer efficiency climbs steadily from 78% at 100 W/m^2 to 90% at 700 W/m^2. It then begins to operate in "straight-through" mode (no longer chopping the array voltage) with a constant efficiency of 97.3%.

The efficiency of the motor is zero before start-up (which occurs at 270 W/m^2). It then shoots up to an almost constant 76% efficiency.

The efficiency of the transmission is constant at 93%. (It is not shown on the graph). The efficiency of the pump rises quickly from 23% on start-up to around 40% where it settles.

The subsystem efficiency is the combined efficiency of all the components except the array. How it varies with irradiance is shown below:

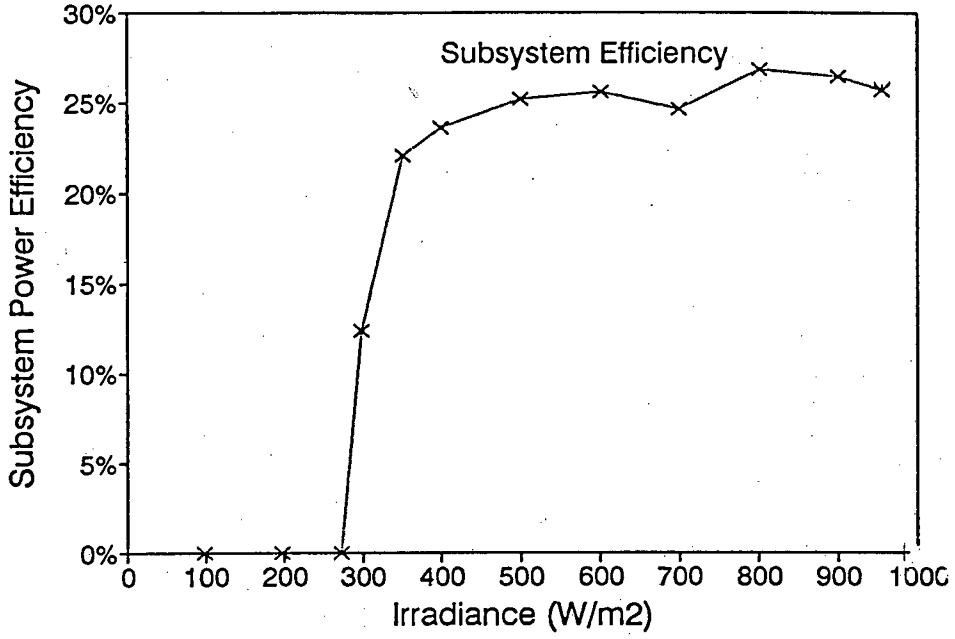


Figure 3.12: Subsystem Efficiency versus Irradiance

On start-up the subsystem efficiency shoots up to 22% and then rises more slowly to 27% at 800 W/m². From here it drops slightly to 26% at 950 W/m².

The whole system comprises the subsystem plus the array. Its efficiency is shown below.

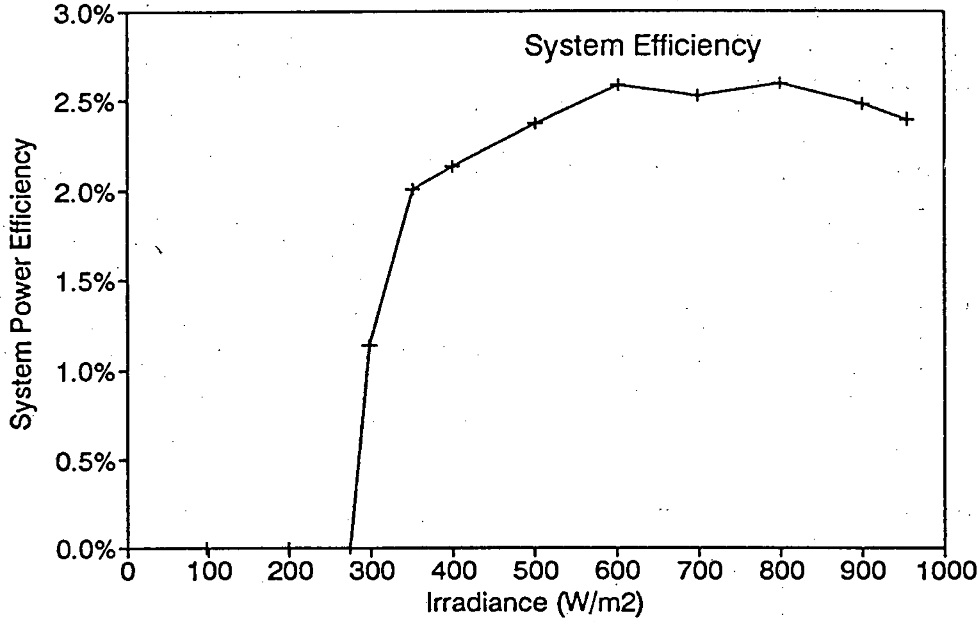


Figure 3.13: System Efficiency versus Irradiance

The system efficiency shoots up to 2% on start-up and then rises rapidly to 2.6% at 600 W/m^2. Above 800 W/m^2 it drops slightly to 2.4%. This is a combined effect of the dropping array efficiency caused by a high array temperature and a slightly falling pump efficiency.

b) Average Daily Efficiencies

The above graphs give snapshots of the efficiency of each of the components over the full range of irradiances. But the system's performance can only be compared to others if its average performance over a whole day can be computed. Average efficiencies were computed for all the components for Standard Solar Days from 4.5 to 7 kWh/m^2/d. The following table gives these values for a Standard Solar Day of 5 kWh/m^2/d.

Table 3.5: Component Daily Energy Efficiencies: 5 kWh/m2/d

Component	Efficiency
Whole System	2.22%
Subsystem	24.4%
Array	9.13%
Power Maximizer	86.8%
Motor	76.8%
Transmission	93.0%
Pump	39.3%

These figures are compared to manufacturers' specifications and values given in the literature in part c) below. But first it is useful to visualize the effect of the efficiencies of the various components by showing what happens to the sun's energy which falls on the array and how much of it eventually goes into pumped water. This is shown in the pie chart below.

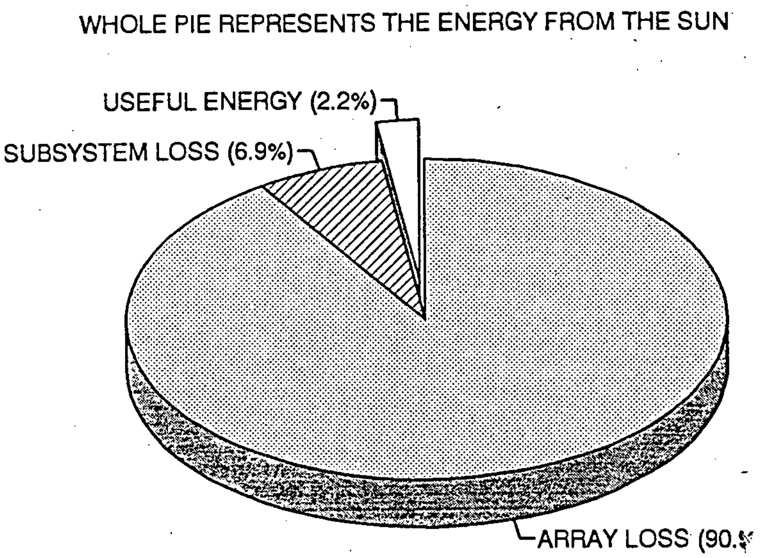


Figure 3.14: Energy Lost at Each Stage of the Whole System: 5 kWh/m2/d Standard Solar Day

The whole pie represents all the energy that falls on the array. Each slice represents the amount of energy lost in that component.

The exploded section shows that only 2.2% of the energy falling on the array is converted in to useful energy (water pumped). (Thus the Daily Energy Efficiency of the system is 2.2%). By far the largest energy loss is in the array (91%). A further 7% is lost in the subsystem.

The efficiency of the array is taken as a given for this project. As so much energy is lost in this section there is obviously scope for much work. But research on this is expensive. This project concentrates mainly on decreasing the losses in the subsystem.

A breakdown of this 7% which is lost in the subsystem is given below.

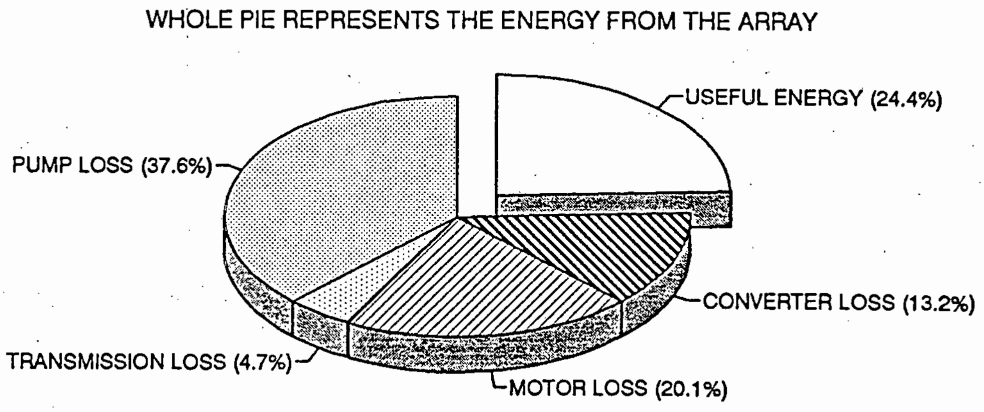


Figure 3.15: Energy Lost in Each Component of the Subsystem

The whole pie represents all the energy coming from the array and each slice the energy lost in that component. Of the energy delivered by the array 24% is converted to useful energy - so the Daily Energy Efficiency of the subsystem is 24%. The energy losses in the subsystem's components are: in the pump 38%, in the motor 20%, the maximizer 13%, and the transmission 5%.

But the figures dealt with above deal only with the efficiency at an insolation of 5 kWh/m²/d. How does the system's efficiency change with changing insolation? This is shown in the figure below.

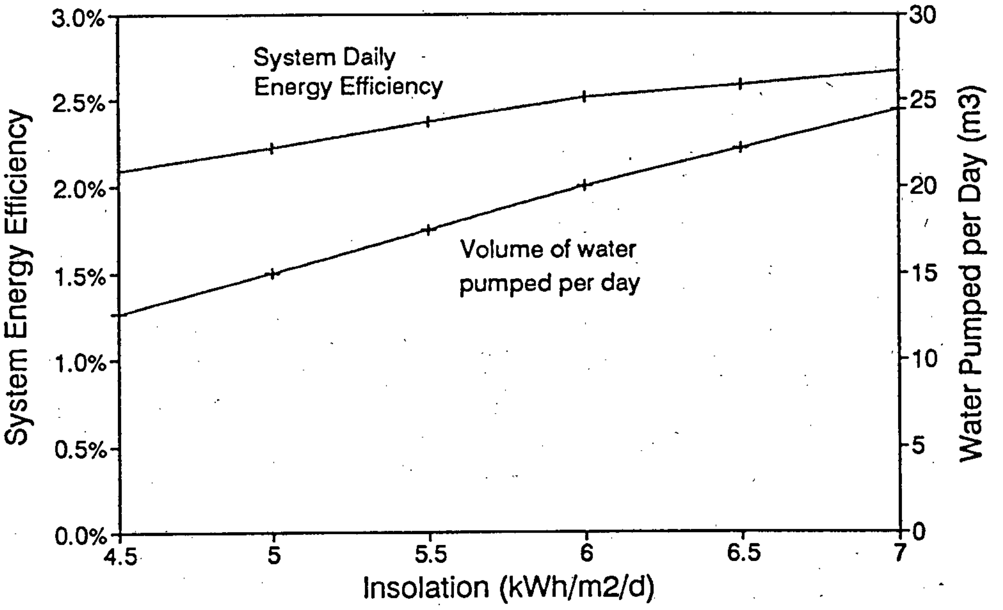


Figure 3.16: System Energy Efficiency and Volume of Water Pumped vs Insolation

The system's efficiency increases from 2.1% to 2.7% with an increase in insolation from 4.5 to 7 kWh/m^2/d. This increase of 1.28 times is due mainly to the increase in array efficiency from 8.8% to 10.1% over the same range. (For a full discussion of the reasons for this increase see Subsection 3.5.2). The efficiency of the power maximizer also increases from 86% to 94%, but that of all other components remains almost constant.

As shown in the graph the volume of water pumped increases from 12.7 to 24.5 m^3/d with an increase in insolation from 4.5 to 7 kWh/m^2/d. This is partly due to the increasing system efficiency and partly due to the increase in energy input to the system. However, the fact that almost double the water is pumped emphasizes the importance of location on the economics of PV pumping: the cost of water pumped in Namibia in summer (7 kWh/m^2/d) would be half that in Durban in winter (4.5 kWh/m^2/d).

c) Comparing the System's Performance to Manufacturers' Specifications and to Systems Studied Elsewhere

The table below gives a comparison between the measured Daily Energy Efficiencies with those measured by Halcrow & Partners (1983).

Table 3.6: Comparing the Sondela System's Efficiency with the Literature

Components	Measured at Sondela	Halcrow Average	Halcrow Best	Sondela / Halc Ave	Sondela / Halc Best
System	2.22%	2.35%	3.28%	0.90	0.65
Subsystem	24.4%	28.7%	38.2%	0.81	0.61

Note: The above are Daily Energy Efficiencies for a 5 kWh/m^2/d day.

The system efficiency for Sondela is low: 2.22% as opposed to 2.35% for Halcrows' average systems (tested in 1982) and 3.28% compared to the best systems they tested. Thus Sondela's system efficiency is 65% that of the best systems they tested (see the rightmost column in the table)

The subsystem efficiency at Sondela is also low: 24.4% as compared with 28.7% for Halcrows' average systems and 38.2% for their best systems.

The reasons for these low efficiencies are examined below by comparing component efficiencies.

Table 3.7: Array and Maximizer Efficiencies: Are they as expected?

Component	Measured Daily Energy Effic.	Measured Best Power Effic.	Values from Literature	Manufacturer's Specifications
Array	9.1%	10.3%	8.4%	12%
Maximizer	86.8%	97.7%	88 to 99%	98%

Note: the Daily Energy Efficiencies above are for a Standard Solar Day of 5 kWh/m^2/d. The array efficiency "from the literature" is from Halcrow (1982). The manufacturer's specifications for the array are for an array temperature of 25 °C.

The Energy Efficiency of the array at Sondela was 9.1%: better than the Energy Efficiency of 8.4% calculated from Halcrows' results for both their good and average systems. So this is not the reason for the low system efficiency at Sondela.

But the array efficiency does not seem to match the manufacturer's claim of an efficiency "as high as 12%". The best Power Efficiency measured was 10.3% at an irradiance of 700 W/m² and an array temperature of 40 °C. This discrepancy is caused by the difference in array temperature - the manufacturers' quotes are for 25 °C. Correlations found from the measurements show that the array at Sondela would, in fact, give an efficiency of 12% at an array temperature of 25 °C and and irradiance of 1000 W/m². So the array does meet the manufacturer's specifications.

The table shows that the efficiency of the maximizer is about that expected. The Power Efficiencies measured for the maximizer after start-up ranged from 84% to 98%. This compares favourably with values given in the literature of 88% to 99%. (These are figures from Pulfrey et al (1987) as Halcrow did not give any test results for maximizer efficiencies). The manufacturers claim an efficiency of 98%. While the maximizer does give an efficiency this high at high irradiances, the average for the day is more likely to be around 87% (the value calculated for a 5 kWh/m²/d day).

The efficiencies of the motor, the transmission and the pump are given below.

Table 3.8: The Efficiencies of the Motor and Pump - Are they as expected?

Component	Measured Daily Energy Effic.	Measured Best Power Effic.	Halcrow Average	Halcrow Best	Manufacturers' Quoted Optimum
Motor	76.8%	77.4%	69%	74%	80%
Transmission	93.2%	93.2%			
Pump	39.3%	42.2%	58%	67%	66%

Note: The Daily Energy Efficiencies above are for a Standard Solar Day of 5 kWh/m²/d. Halcrow's figures for the pumps are Power Efficiencies rather than Daily Energy Efficiencies.

The Daily Energy Efficiency of the motor is 76.8%. This is slightly higher than Halcrows' figures of 69% and 74% for their average and best systems. But it is slightly lower than the 80% optimum efficiency claimed by manufacturers. This, however, is because the motor is not operating at optimum conditions of current and voltage - efficiencies as high as 83% were measured for this motor in the laboratory tests.

There are no figures for transmission efficiency quoted in the literature, but the measured efficiency of 93% is in the range expected.

The Daily Energy Efficiency of the pump is 39.3% and the highest Power Efficiency measured was 42.2%. This is low when compared with the Power Efficiencies of 58% and 67% given by Halcrow for their average and their best pumps.

Halcrow & Partners do not give Daily Energy Efficiencies for their pumps, but these can be calculated from their other figures. If a transmission efficiency of 93% is assumed, energy efficiencies of 41.5% and 59% can be calculated for their average and best systems. Thus the Sondela pump is marginally less efficient than their average pumps and considerably less efficient than their best. So this low pump efficiency is the reason for the low system and subsystem efficiencies at Sondela.

The reason for the low pump efficiency is that the Mono Pump used at Sondela is not designed for these low heads - it gives its best Power Efficiency of 66% at a head of 55 meters, whereas the head at Sondela is 13 meters. For these conditions (low head and low flow rate) few pumps would give efficiencies much better than the Mono Pump - although a correctly sized centrifugal probably would (see Subsection 3.5.5). Daily Energy Efficiencies of 59% for the pump (as measured by Halcrow) would be exceptional for these conditions.

d) Visualizing the Interaction of the Components

It is helpful to visualize the interactions of the components in order to understand the operation of the whole system. While the interactions are complex it is possible to simplify them by considering only the most important parameters. The series of four graphs on page 98 shows the interactions.

Each pair of graphs has a common x-axis (array power for the first and speed for the second pair). The line starting at 600 W/m^2 on the first graph shows how the operating point for each component can be established from the graphs. These graphs can be used to summarize the operation of the system as follows.

The purpose of the array is to convert the sun's power into electrical power. The power out of the array at a particular irradiance depends on the array temperature (as shown) and the array voltage. The effect of array voltage is not shown: the graph assumes that the maximizer is keeping the array at its Peak Power Curve. (This is a reasonable assumption for a system with a good maximizer).

The purpose of the power maximizer (apart from tracking the Peak Power Curve) is to supply the motor with the current it needs to overcome torque and with as high a voltage as possible. This is shown in the second graph.

The third graph shows the operation of the motor. The motor converts the electrical power coming from the maximizer into mechanical power. The two outputs from the maximizer (voltage and current) map directly onto the outputs of the motor (speed and torque). The voltage from the maximizer determines motor speed; the current determines motor torque. Both these relationships are linear and almost independent of each other.

Thus there are two sets of dependencies as follows:

1) Voltage determines motor speed which determines pump speed and thus water flow rate; and
2) Current is determined by the torque the motor must deliver, which is in turn determined by the torque of the pump.

The two sets of y-axes of the graphs indicate these separate dependencies. The operation of the system is followed down the left axes, which represent the more visible outputs from the components: voltage to motor speed to pump speed to water flow rate. These parameters are linearly dependent on one another. The parameters graphed on the right axes are less visible: current to motor torque to pump torque. These relationships are also linear. It would complicate the diagram too much to follow the operation down these axes as well, but the value of each of these parameters can be determined as shown.

So the outputs from the motor are speed and torque. These are then converted to pump speed and torque by the transmission. The effect of the transmission is not shown in a separate graph as it only scales the existing parameters. Instead this effect is shown by the different scales on the x-axes of the bottom pair of graphs (the maximum speed for the motor is 2500 rpm whereas that for the pump is 1300 rpm).

The pump then converts the rotational energy delivered by the transmission to kinetic energy of the water - shown by the water flow rate. As shown the water flow rate is proportional to pump speed at this head. The pump torque is dependent on the total head the pump must deliver. As shown the torque increases marginally with pump speed as the friction component of the total head increases.

More thorough analysis of the operation of each component is given in the following subsections.

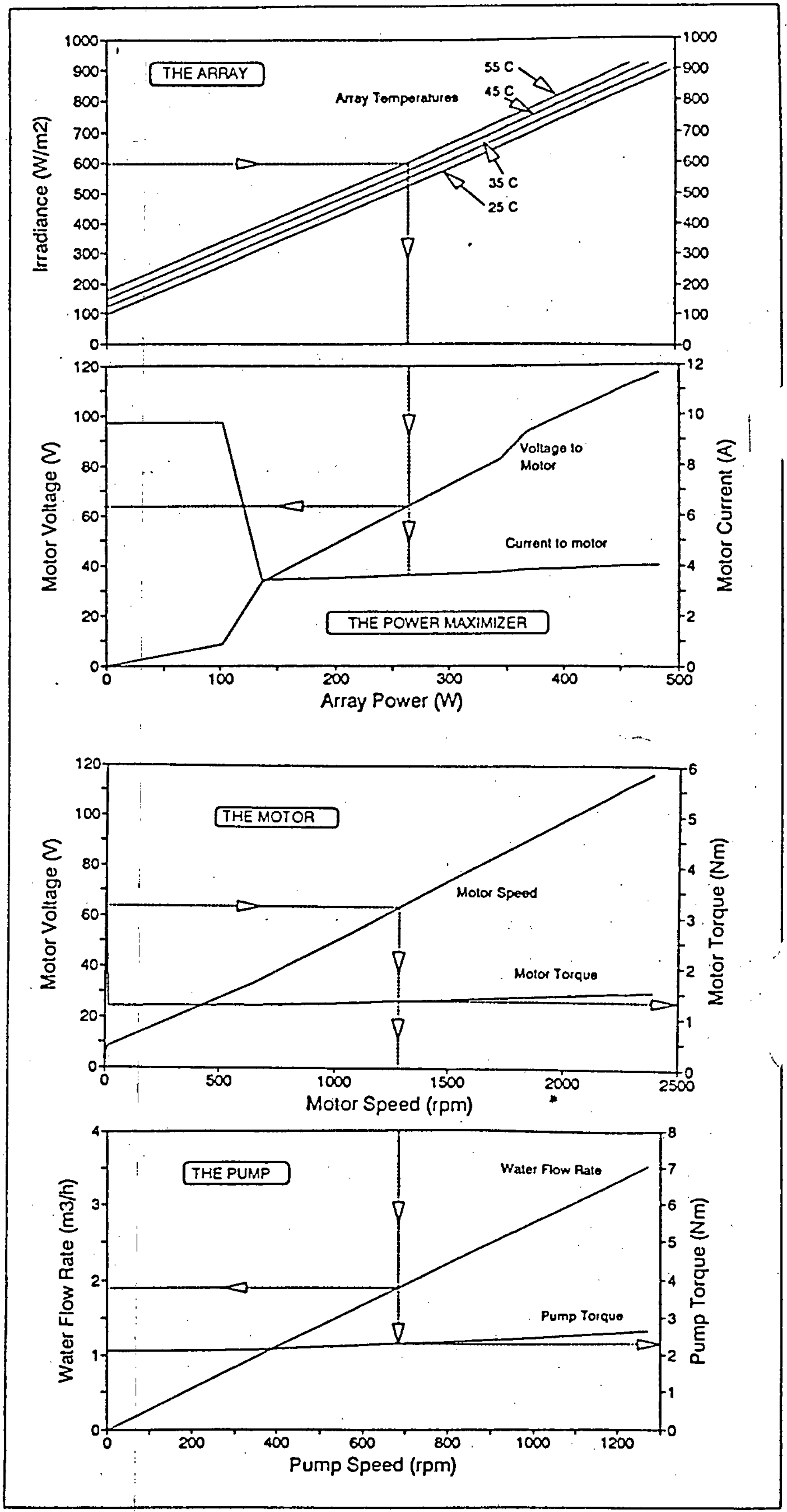


Figure 3.17: The Interaction of the Components of the System

3.5.2 The Array, its Peak Power Curve and the Effect of Bypass Diodes and Shading

This subsection deals with the following questions:

a) Is the array operating as expected and does it meet its specifications?
b) Where is the Peak Power Curve (PPC), and how is it affected by changing irradiance and array temperature? Consequently how effective are various tracking methods used by power maximizers?
c) How is the array output affected by shading and so is a fence over the top of the array to protect it from vandalism financially justified? How important is it that bypass diodes are installed with the array?

Each of these questions will be dealt with in turn below. The method by which these results were obtained is given is Subsection 3.4.1.

<ins>a) Is the operation of the array as expected?</ins>

Tests for the operation of the array were done for four conditions with the fence in and out and with the bypass diodes in and out. The following graphs are all for the condition with no fence over the top of the array and with the diodes installed. The other conditions are discussed in part c) below.

The figure below shows that the shape of the current versus voltage curves are as expected.

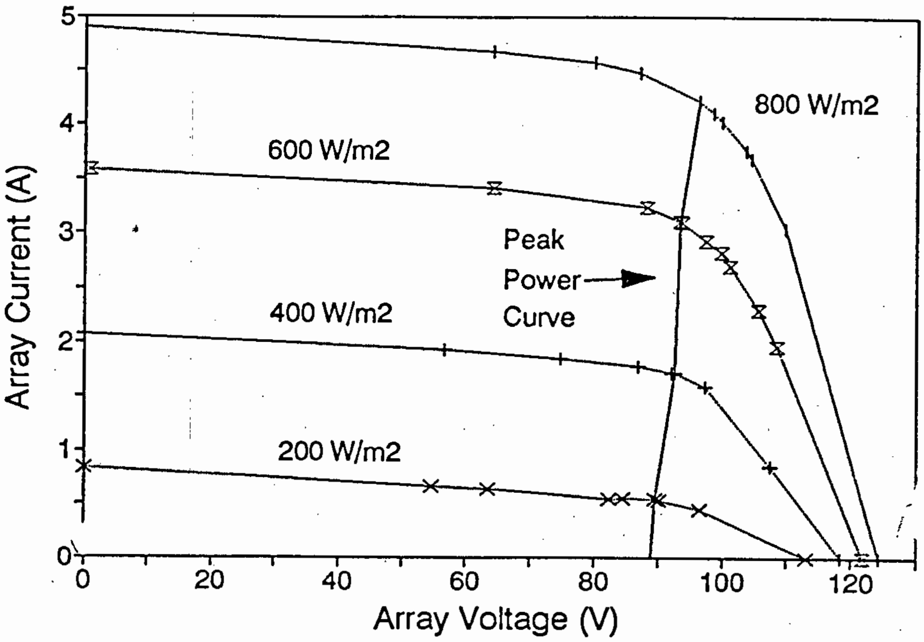


Figure 3.18: The Effect of Irradiance: Array Current vs Array Voltage at 42 C

The readings used for the graph have been standardized to a constant array temperature of 42 °C and constant irradiances from 200 to 800 W/m^2. The Peak Power Curve (PPC) is shown going through the knee of each curve.

As expected the short circuit current is proportional to irradiance. From the short circuit current (0 V) the array current then drops very gradually with increasing voltage until it approaches the PPC after which it drops rapidly to intersect the axis at the open circuit voltage. It can be seen from the spacing of the x-intercepts that the dependence of open circuit voltage on irradiance is logarithmic rather than linear. (As expected).

The effect of array temperature on the current versus voltage curves is shown below:

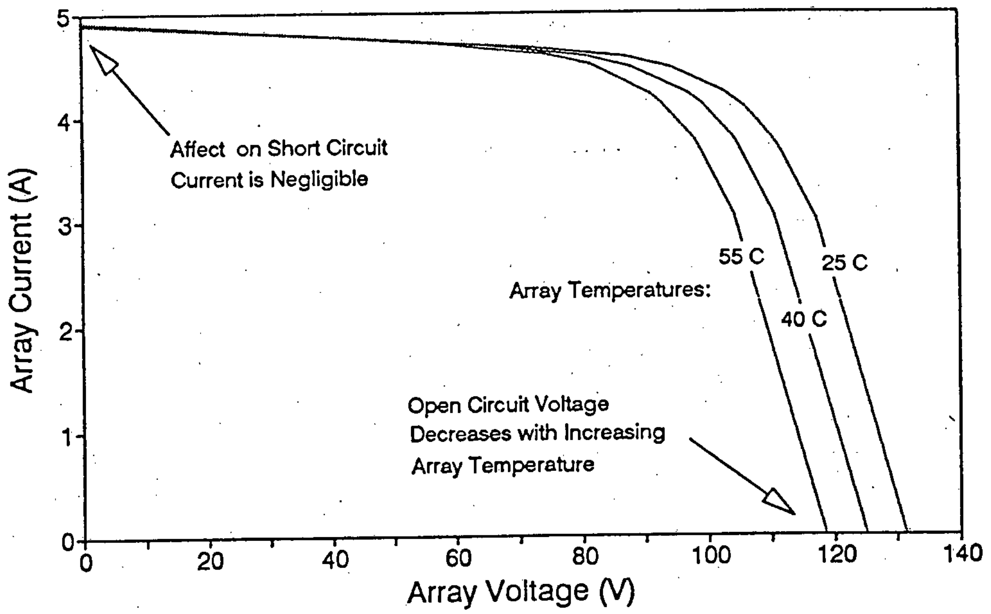


Figure 3.19: The Effect of Array Temperature: Current vs Voltage at 800 W/m2

This is as expected. The three curves are for array temperatures from 25 to 55 °C and a constant irradiance of 800 W/m^2. The effect of array temperature on short circuit current is negligible - an increase in 10 °C increases the short circuit current 0.01 A. The open circuit voltage decreases linearly with increasing array temperature. This effect is important as it changes the position of the PPC. This is discussed more fully in part b) below.

The above graphs were based on actual readings adjusted using correlations to the required conditions. The coefficients for all the correlations discussed in this subsection as well as their correlation coefficients are given in Appendix 3.5.2.

The variation of array power with array voltage is given below. This graph is for a constant array temperature of 42 °C.

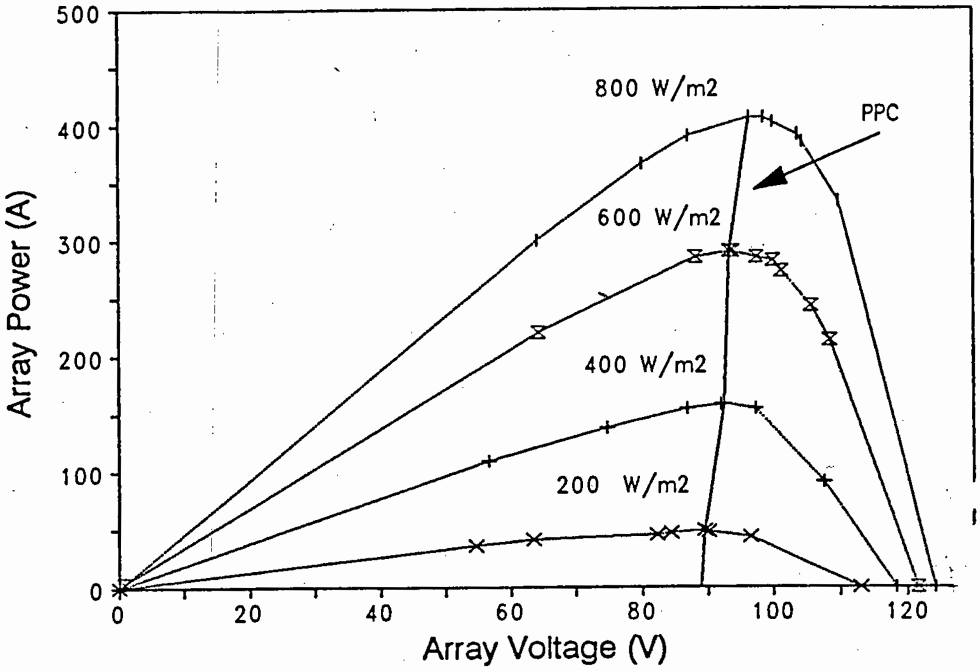


Figure 3.20: Array Power versus Array Voltage at 42 C

The shape of the graph conforms well with theory. Here it can be seen clearly how the position of the PPC is found by finding the maximum power points for each irradiance. Also shown is the sharp drop in array power away from the PPC. The drop is particularly marked at voltages higher than the PPC. Note also that the PPC moves slightly to lower voltages at low irradiance.

Array Efficiency: Comparing to Manufacturer's Specifications

The manufacturers quote a cell efficiency of 16.4% and a module efficiency "as high as 12%". The efficiencies measured were considerably lower as shown in the graph below.

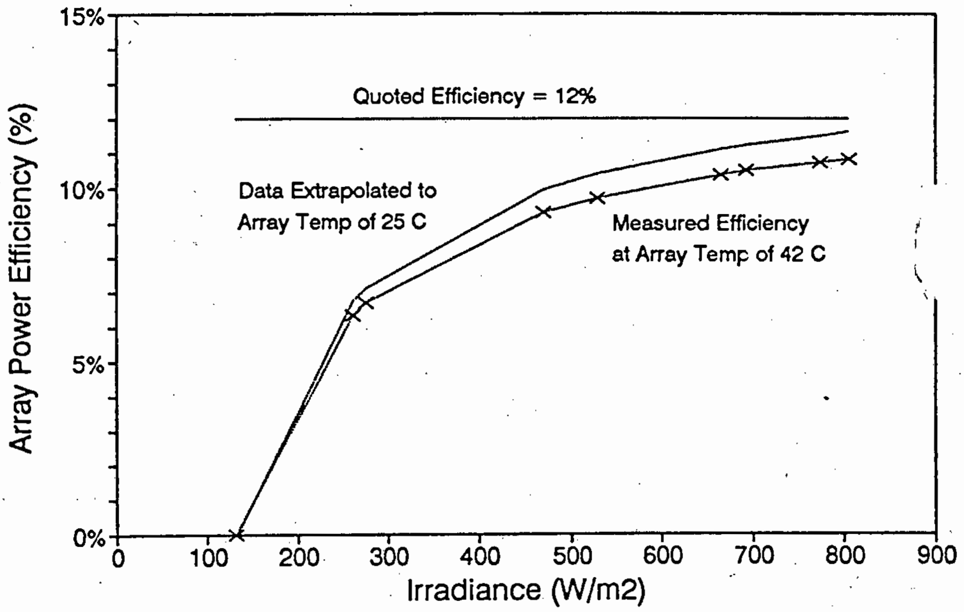


Figure 3.21: Comparing Array Efficiency to Manufacturer's Quotes

The graph gives the quoted efficiency of 12%, and measured efficiencies adjusted to 42 and 25 °C. The manufacturer's figure of "as high as 12%" is probably true because it is for an array temperature of 25 °C. The graphs shows that the array would be expected to give an efficiency of 11.6% at 800 W/m^2 if the array temperature was 25 °C. If this correlation is extrapolated it gives an efficiency of 12% at an irradiance of 1000 W/m^2. These are obviously the conditions the manufacturers quoted at.

However, this figure of 12% is misleading in estimating the actual efficiency of the array. Firstly the efficiency drops with decreasing irradiance reaching 0% at 130 W/m^2. This is because the array is fixed and does not track the path of the sun. When the sun is low its rays impinge on the array at a shallow angle so that much of the irradiance is reflected by the glass. When this angle reaches the critical angle, all the irradiance is reflected.

The Daily Energy Efficiency of the array at an array temperature of 25 °C for a 5 kWh/m^2/d standard solar day was computed to be 9.6%. This is the efficiency one would be likely to get in a real life situation if the array operated at 25 °C. This is 80%

of that quoted by manufacturer (the loss being due to the fact that the array is not tracking the path of the sun and spectral changes when the sun is low in the sky).

The second factor which decreases the efficiency of the array is array temperature - the efficiency drops with increasing temperature. This is shown in the graph by the data which was collected at an average array temperature of 42 °C. The array at 42 °C gives an efficiency which is 94% that it would give at 25 °C. So its daily energy efficiency for a 5 kWh/m²/d is 9% (which is 75% of manufacturer's specifications).

So while the manufacturer's claims are true, the conditions they choose to use are unrealistic for most applications. For a fixed array it would be best to multiply their quoted efficiency by about 0.75 for a quick estimate of likely array efficiency - except for very cold climates.

b) The Effect of Temperature and Irradiance on the PPC

In order to get the optimum performance out of the array it is necessary to draw power from it as close as possible to the Peak Power Curve (PPC). This is done either by using a power matching device or by matching the components carefully. In order to track the PPC it is necessary to know how its position changes with irradiance and with array temperature. This is discussed below.

The voltage at which the array delivers its maximum power (V_{max}) seems to be about 77.5% of the open circuit voltage. (For the four irradiances in Figures 3.18 and onwards the percentage ranged from 76.7% to 78.1%). The following graph illustrates the importance of this for tracking the PPC properly.

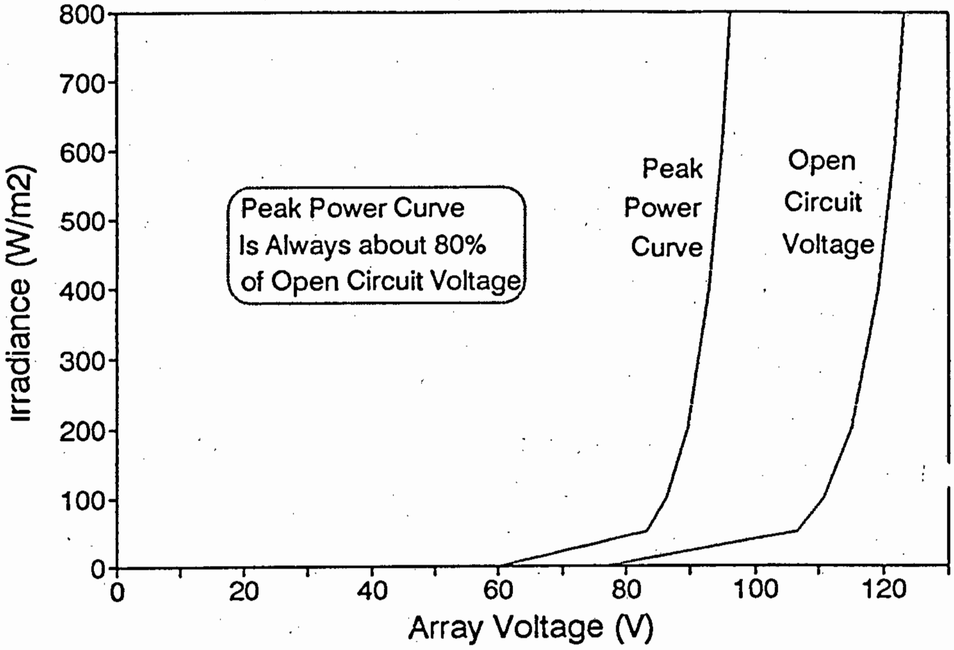


Figure 3.22: The Effect of Irradiance on the PPC

V_{oc} has a logarithmic dependence on irradiance. This is shown by the sharp drop in V_{oc} (and consequently V_{max}) at low irradiances. However, the drop is mainly below 50 W/m² which makes it unimportant: the array only starts producing power at 130 W/m² and the pump is very unlikely to overcome starting torque before 200 W/m². Between 200 W/m² and 800 W/m², V_{max} rises gradually from 89 to 96 V.

The Effectiveness of Three Methods of Tracking the PPC

In the light of this the three main methods of tracking the PPC are examined below. The effectiveness of each method is quantified by calculating its tracking efficiency. This is the power the array actually delivers divided by the power it would deliver at the PPC under those conditions.

The three methods considered are as follows:

a) The most sophisticated of the three methods is "intelligent" searching for the PPC.

b) The next most sophisticated method sets the array power as a fraction of the open circuit voltage (for example $V_a = 0.80\ V_{oc}$).

c) The third method keeps the array voltage constant no matter what the conditions. The required array voltage is set when the pump is installed.

Method 1: "Intelligent" Searching

Maximizers that use this method hunt back and forth to keep the array power at the maximum possible. If the maximizer checks the position of the PPC frequently enough this method can be assumed to give a tracking efficiency of 100%.

Method 2: Array voltage set to a proportion of the Open Circuit Voltage

From my measurements I concluded that the voltage at which the array delivers its Peak Power, V_{max}, is always close to 0.775 times the open circuit voltage, V_{oc}. This holds for all conditions of array temperature and irradiance. From this conclusion it is evident that the second method of tracking would give a 100% tracking efficiency if the ratio used is 0.775. But what if the ratio is not set correctly? The figure below shows the tracking efficiencies for ratios of 0.80 and 0.75.

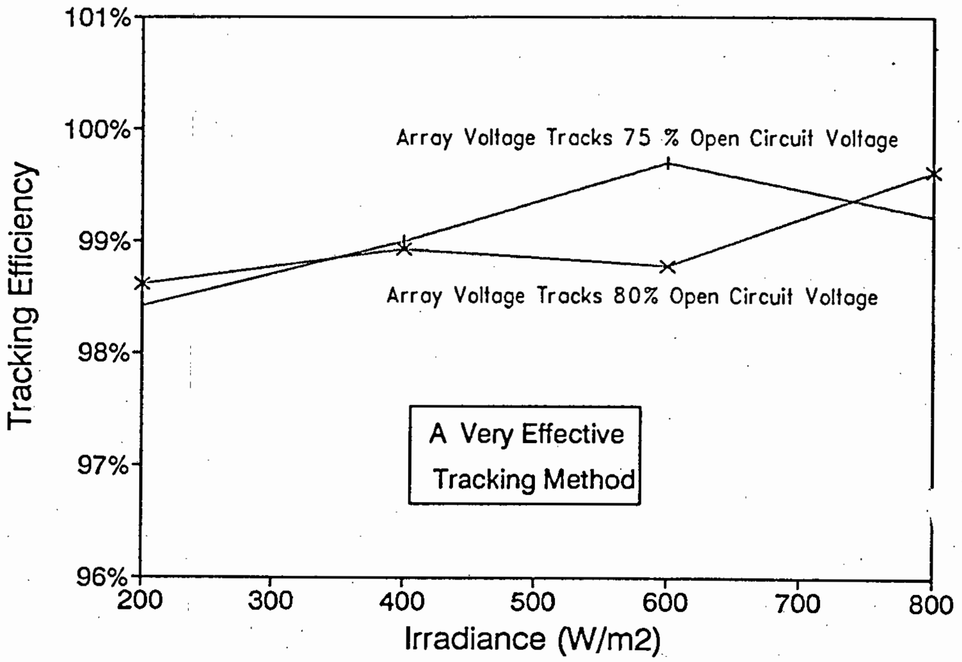


Figure 3.23: The Effect of the Chosen Vmax/Voc ratio

This method of tracking is very effective. Even if the ratio the maximizer uses differs slightly from the ideal one for the array, the tracking efficiency is hardly affected - for both of the ratios (0.80 and 0.75) the average tracking efficiency is 99%.

The reason for this is shown in the figure below.

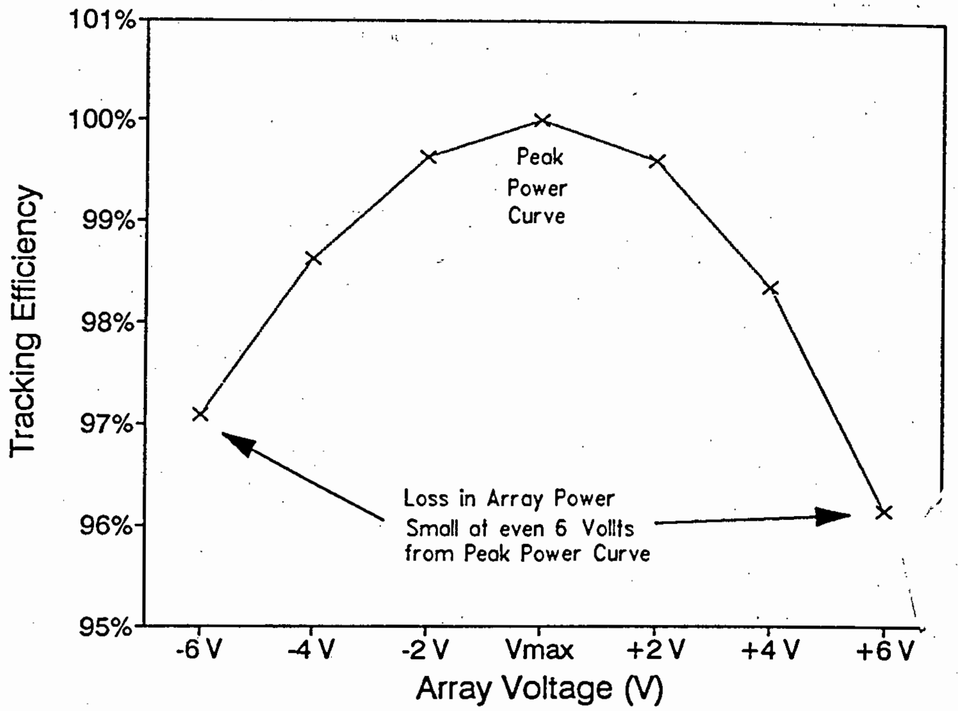


Figure 3.24: The Rate at which Array Power Falls away from its Maximum
Note: V_{max} for this array is about 92 Volts at 42 °C.

The array power does not drop significantly within the first 4 Volts either side of the PPC (the loss of efficiency is less than 1.6% within this range). So this means that very accurate tracking is not essential - the target area is 8 V wide (for an array of seven panels in series where the PPC is at about 92 V). So the ratios 0.75 and 0.80 for V_{max}/V_{oc} cope almost as well as the correct ratio of 0.775.

Method 3: Tracking a Set Array Voltage

The above figure may seem to indicate that the third method of keeping the array voltage constant will give sufficient tracking accuracy. The following figure compares the tracking efficiency at various constant voltages.

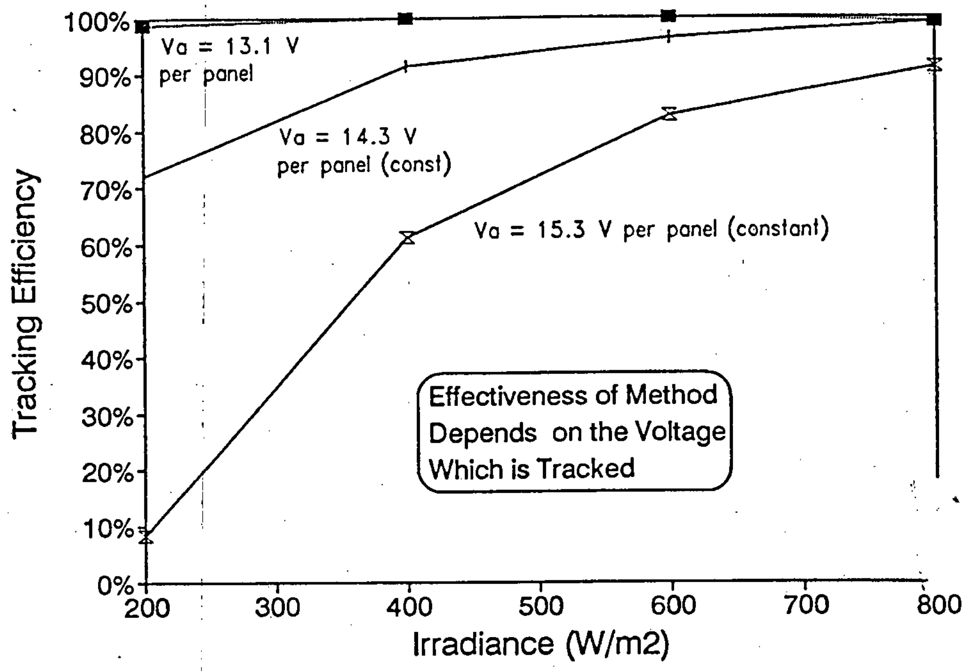


Figure 3.25: The Effectiveness of Using a Constant Voltage to Track the PPC

This figures shows the danger of this method: it works well if the array voltage is correctly chosen but can be inefficient if set incorrectly or if the setting drifts with time.

The specifications for these panels give a rated optimum voltage of 15.3 V. This works out to an array voltage of 107 V for this array. However, the figure shows that if this voltage is used, the tracking efficiency is unacceptably low - less than 10% at 200 W/m^2 (which is crucial because of start-up) and rising to about 90% at 800 W/m^2. The reason that the array operates so badly at its rated "optimum voltage" is that this optimum voltage is based on an array temperature of 25 °C which is unrealistic for most sites in South Africa.

This method can however give good results. If the array voltage is set at 92 V (13.1 V per module) the average tracking efficiency from 200 to 800 W/m^2 is 99.4% which is very good.

The effect of the voltage chosen can be seen more clearly if the Daily Energy Efficiencies for tracking at various voltages are computed. The figure below shows the results.

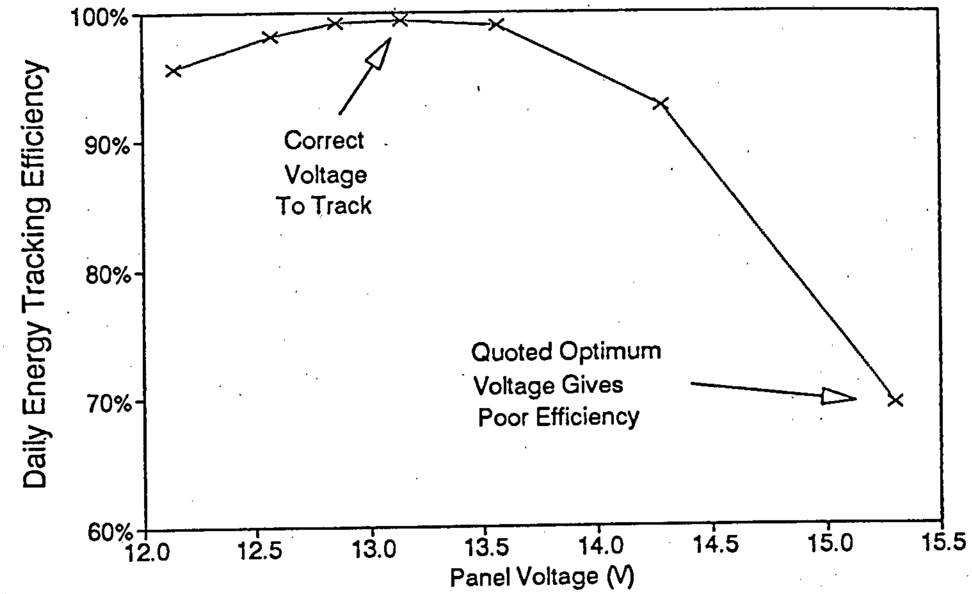


Figure 3.26: The Effect of the Voltage Tracked on Tracking Efficiency

The tracking efficiency for the day is above 98% for panel voltages from 12.6 to 13.6 V (array voltages from 88 to 95 V) but drops to 69% at 15.3 V.

So if the tracked voltage is chosen carefully then this method of tracking is effective. But would the tracking efficiency drop markedly if the PPC changed position due to a changed array temperature? The effect of the array temperature on the PPC is shown below.

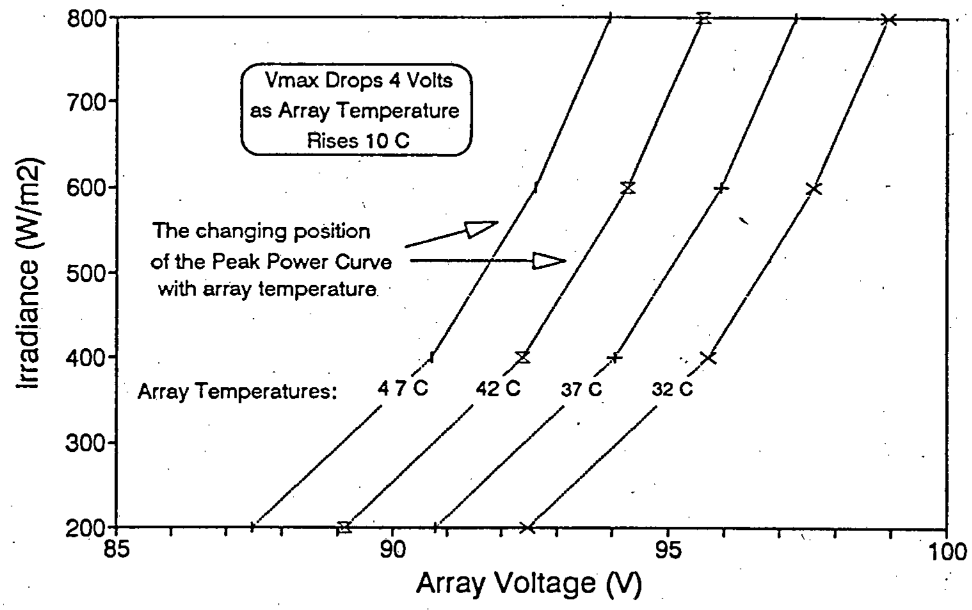


Figure 3.27: The Effect of Array Temperature on the PPC

The graph shows that the PPC moves gradually to lower array voltages as the array temperature increases. The PPC drops about 4 Volts for an increase in array temperature of 10 °C.

The array temperature is affected by both the ambient temperature and the irradiance. The change in array temperature with irradiance is unimportant for the purposes of tracking. This is because as the irradiance increases the array temperature increases, which leads to a drop in V_{max}. This drop in V_{max} counteracts the normal rise in V_{max} with increasing irradiance and so tends to keep the PPC at a more constant voltage than otherwise expected. This makes tracking easier and so this effect is not a problem to be considered.

Of some concern, however, is the effect of ambient temperature on array temperature. It is quite possible for the ambient temperature to move within a range of 30 °C over the whole year (eg 5 °C on some winter's days and 35 °C on some summer's days). The graph below shows the effect of this change on the tracking efficiency.

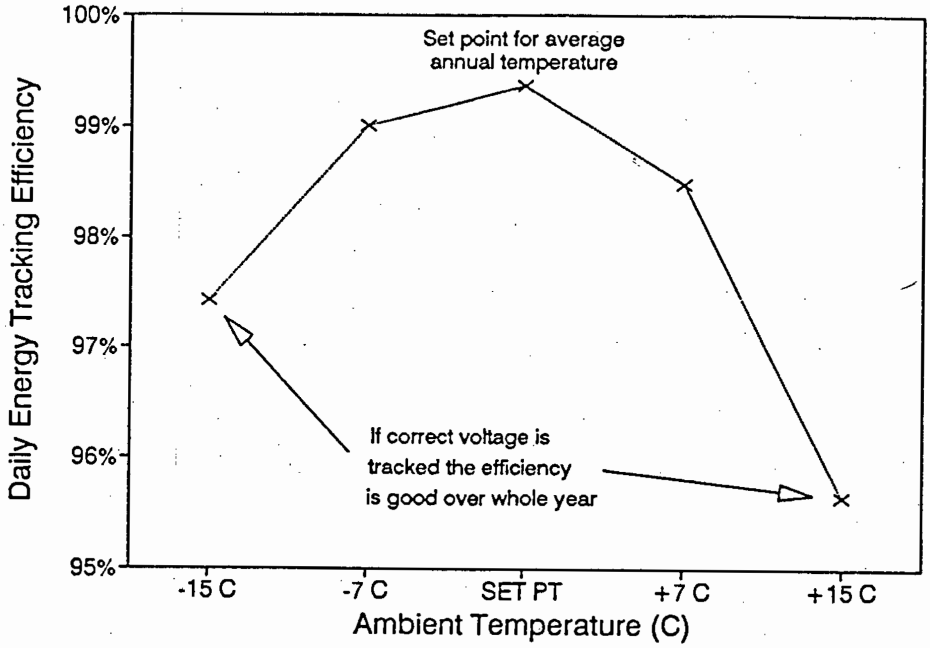


Figure 3.28: The Effect of Ambient Temperature on Tracking Efficiency

If the tracking voltage is set correctly for the mean ambient temperature in the year, the tracking efficiency is almost always above 96%. This is acceptable if not good. However, if the tracked voltage had initially been chosen badly the change in ambient temperature could well exacerbate the situation.

In Conclusion

If the voltage tracked is chosen carefully, tracking a constant voltage is adequate. But choosing the correct voltage is not easy. It would be very logical for somebody installing a pump to set the array voltage to that given in the specifications for the PV modules and get a tracking efficiency as low as 10% at low irradiances. I myself set the array voltage to 13.6 V per panel (rather than the correct 13.1 V per panel because my measurements were based on readings at 800 W/m^2). So if the tracked voltage is set at abnormal conditions it could well be incorrect.

The installer cannot wait for average conditions of irradiance and ambient temperature. So for this method to have a chance of working successfully, the manufacturer should provide a graph of the voltage which should be tracked against various mean annual ambient temperatures. However, this method would still fail if there were a hot spot on one of the panels and the array voltage dropped; or if the setting drifted with time.

For these reasons this method is not recommended. On the other hand the method of setting the array voltage as a fraction of the open circuit voltage is a good method. It accounts for changes in the PPC due to irradiance, array temperature, and unforeseen events like hot spots. If the fraction used can be adjusted to the optimum value for the particular panels used, then the tracking efficiency of this method is likely to be 99% or above for most conditions. (Otherwise a default fraction of between 0.75 and 0.80 of the open circuit voltage should be used). It is not necessary to use more sophisticated methods which search for the PPC.

c) The Effect of Shading on Array Output and the Use of Bypass Diodes

The Reduction in Array Output with the Use of a Fence

The effect of installing a fence over the array in order to protect it against vandalism is shown below.

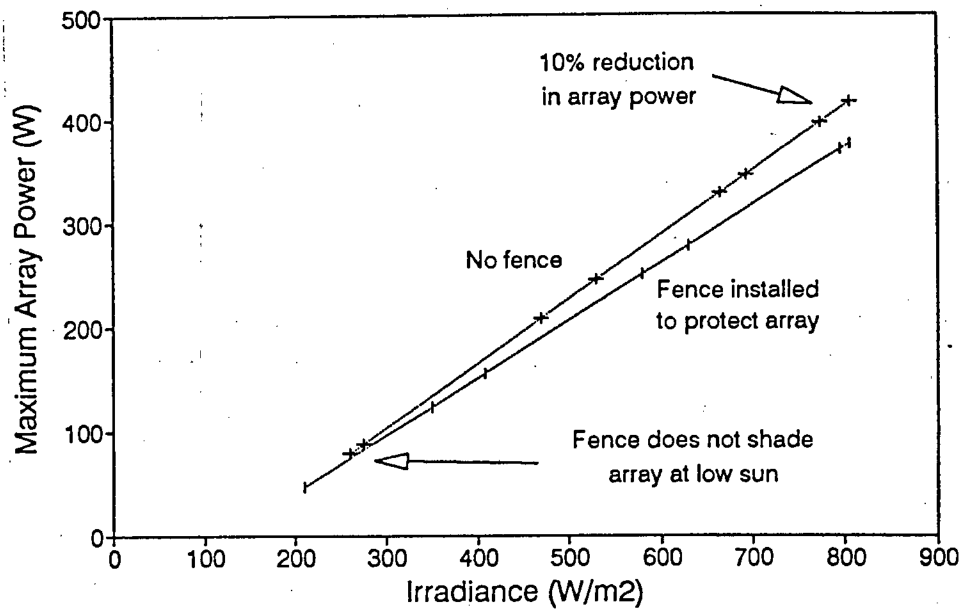


Figure 3.29: The Effect of Installing a Fence over the Array

There is a notable reduction in the power the array delivers when the fence is installed. The difference fades at lower irradiances - because the fence on the top is no longer casting its shadow on the array. At the higher irradiances (800 W/m²) the loss in power due to the fence is 10%.

The fence reduces the daily energy efficiency of the array from 8.76% to 8.01% (for a 4.5 kWh/m²/d Standard Solar Day). This means that if the fence is used the size of the array must be increased by 10%. For an array of 20 modules this would mean an increase in two modules (costing about R 2400). However, if the fence in its lifetime manages to save two modules from vandalism it will have proved a worthwhile investment. The purchaser must weigh up the risks involved for the site considered.

The Effect of Shading the Array

Pieces of cardboard were used to test the effect shading completely small areas of the array. Two sizes were used: 1) small rectangles to show the effect of something like a bird dropping or a similar mark on a panel; and 2) larger squares which blocked out completely one cell to show the effect of a hot spot or some shadow (like that of a fence pole or tree) falling on one cell. Four conditions were tested both with and without diodes.

The graph below shows the effect of the shading. Shortage of space on the graph axes made it necessary to codify the conditions of shading as follows. "BD" stands for the "bird dropping" size shade, whereas "B" stands for the larger full "block", which completely shades a whole cell. (B) stands for "only on the bottom row" whereas (B&A) stands for "below and above". So:

3 BD(B&A):	Three panels on the bottom row and three on the top had one cell each shaded by a small piece of cardboard (bird dropping size - coded BD).
1 B(B):	One panel on the bottom row had one of its cells covered by the larger size of shade (completely shading that one cell).
4 B(B&A):	Four panels on the bottom row and four on the top had one cell each covered by the larger size of shade.

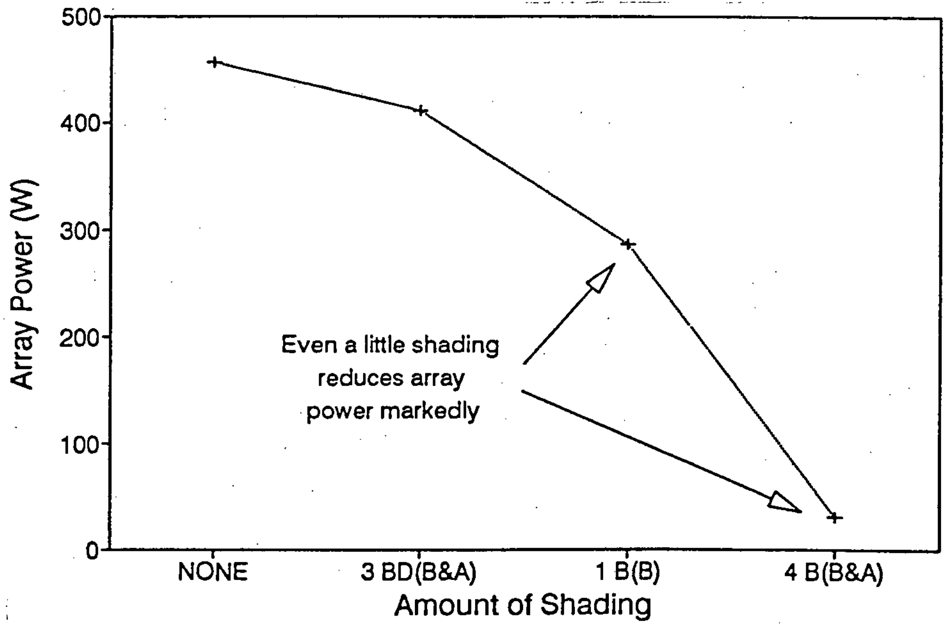


Figure 3.30: The Effect of Shading on Array Power

A small area of shading can bring about a very large reduction in the power delivered by the array. For example, shading completely one cell on one out the 14 modules reduces the array power from 456 W to 287 W (a loss of 37% of the array power). But one cell takes up a tiny fraction of the total area of the array. Further, if four cells on the top row and four on the bottom row are completely shaded the array power falls to 30 W (7% of what it would produce if not shaded).

If the cell is not completely shaded the effect is much less marked. If a total of six cells are shaded with the "bird dropping" shades the array power is reduced to 90% of its original value (shown by condition 3BD (B&A) on the graph).

The array power drops dramatically when a cell is shaded because this cell does not simply stop producing power; rather it turns into a large resistance and dissipates the power produced by all the panels in that string. This is dangerous as the cell then becomes very hot due to the power it is dissipating and one risks a burn out of that cell ruining the panel. This panel then disrupts the functioning of the whole array and may cause further hot spots.

The Use of Bypass Diodes

The use of "bypass" diodes is very important. A panel may dissipate the power of the array if it produces slightly less power than the next because it is badly matched or because it is shaded. When this is the case the excess power that would be forced through it and so cause a hot spot is diverted through the bypass diodes. This has two advantages: firstly the array produces more power, and secondly it is protected from costly damage due to hot spots.

The figure below shows the amount of power lost if bypass diodes are not used.

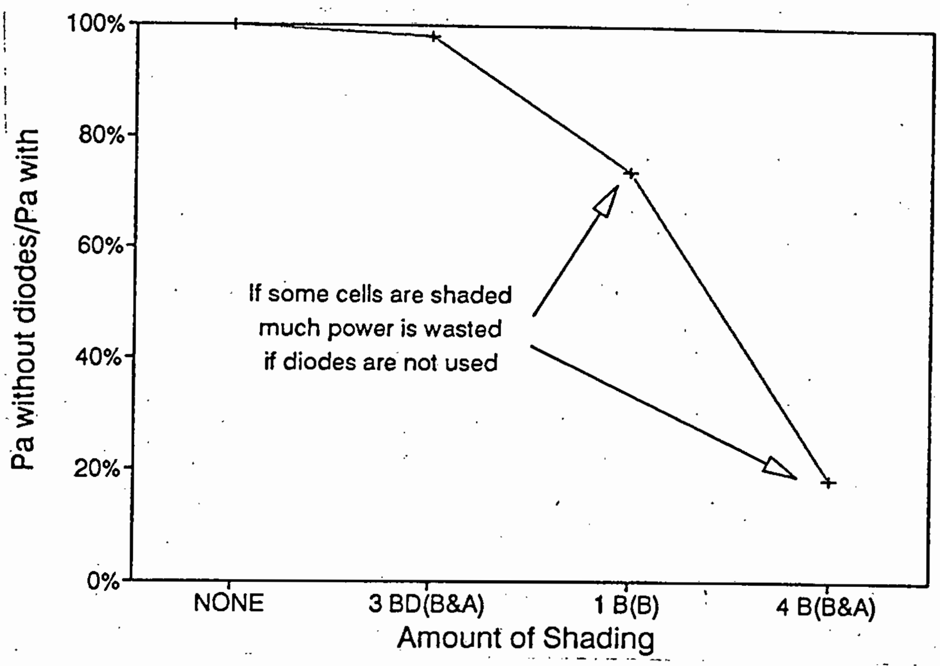


Figure 3.31: The Array Power Lost if Bypass Diodes are not used

For small amounts of shading the loss in power if diodes are not used is negligible as shown by the first condition in the above graph.

However, as the amount of shading increases the difference is marked. If only one cell in the array is completely shaded and diodes are not installed the array produces 74% what it would if diodes were used. If a total of eight cells in the array are completely shaded, the array without diodes will produce only 18% the power it would with diodes.

So bypass diodes should be standard in all applications - they guard against loss of power and damage to the array in unforeseen circumstances. If Schottky diodes are used the voltage loss over the diodes is very small and is easily justified by the increase in array efficiency and the protection the diodes offer.

3.5.3 The Operation of the Power Maximizers

This subsection describes and compares the operation of two power maximizers: the Miltek maximizer which was installed with the system at Sondela, and one produced by the Australian Energy Research Laboratories which was supplied by Mono Pumps for comparision.

This subsection deals with the following questions:

a) What is the difference between the two maximizers? How important are the differences in their design features?
b) Do the maximizers work as expected? How does their operation change with changing irradiance? How well do they each cope with start-up?
c) What efficiency do they each give?
d) What is the effect of changing the torque the motor must deliver by changing the pulley ratio? What is the best trade off between the efficiencies of the array, the maximizer and the motor in choosing the pulley ratio?
e) How is it possible to reduce the system's maintenance costs through good maximizer design?

These are dealt with in turn below. The specifications for the power maximizers tested, the experimental method used and an analysis of the accuracy of the readings is given in Subsection 3.4.3.

<u>a) Description of the two maximizers compared</u>

There are three important considerations in choosing a power maximizer: i) the tracking method it uses, ii) how it handles start-up and iii) how user friendly it is. In terms of these points the differences between the two maximizers tested are as follows:

Tracking method: The Miltek tracks a fixed voltage which is set on installation. As discussed fully in the previous subsection (on the array) this method can give tracking efficiencies of 96% and above for the whole year if the voltage tracked is set correctly. However, setting the voltage correctly is not simple unless the manufacturers give explicit instructions. And this method will not cope well with unforeseen problems like hot spots in the array.

The specifications of the AERL claim that it follows the Peak Power Curve but do not explain the method used. It is probably an intelligent device - which hunts for the PPC. If so it can be assumed that it will give a tracking efficiency of 100% throughout the year. This method will cope well with any problems such as shading of the array and hot spots.

Handling start-up: The Miltek uses no special method of overcoming starting torque. However, it does not start operating until there is enough array power for it to track the voltage it has been set to. So it does have a type of low voltage cut-out which should save the motor from straining for too long before start-up.

The AERL has a useful feature for overcoming the starting torque: it stores the array power and then gives short but sustained high current pulses every 10 to 15 seconds. This is very useful for a cloudy day as it may enable the system to start when another maximizer would not have enough power. Once the pump has started the torque drops considerably and the pump will then be able to operate efficiently. The AERL also has a preset low voltage cut-out. This is to save the motor from straining when there is not enough power to overcome starting torque. It would however be better if this could be set on installation as the starting torque varies from site to site.

User friendliness: there are two functions which are important in making the maximizer user friendly. The one is to protect the system from misuse. The second to help the user identify faults more easily.

The Miltek is a simple design with few frills. Miltek Engineering have designed a more sophisticated model for when the market requires it. This model does however limit the maximum current to the motor to 15 Amps which will prevent a motor burn out. There is no motor voltage limit (to protect the motor from over speeding) because if the components are chosen correctly over speeding would be impossible.

The AERL has both a 28 Amp current limit and a user set motor voltage limit. The 28 Amp current limit is probably set too high for the motor which was used (which had a rated maximum current of 9 Amps). It would be better if the current limit could be set by the user. The maximizer is also protected against damage due to incorrect connections - for example reversing the polarity of the array. This maximizer also uses LED's to indicate whether it is receiving adequate power from the array and whether the motor voltage is being limited or not. This is useful in helping the user identify problems.

b) A Description of the Operation of the Two Maximizers

The Miltek

The two figures below give a very good account of the operation of the Miltek maximizer.

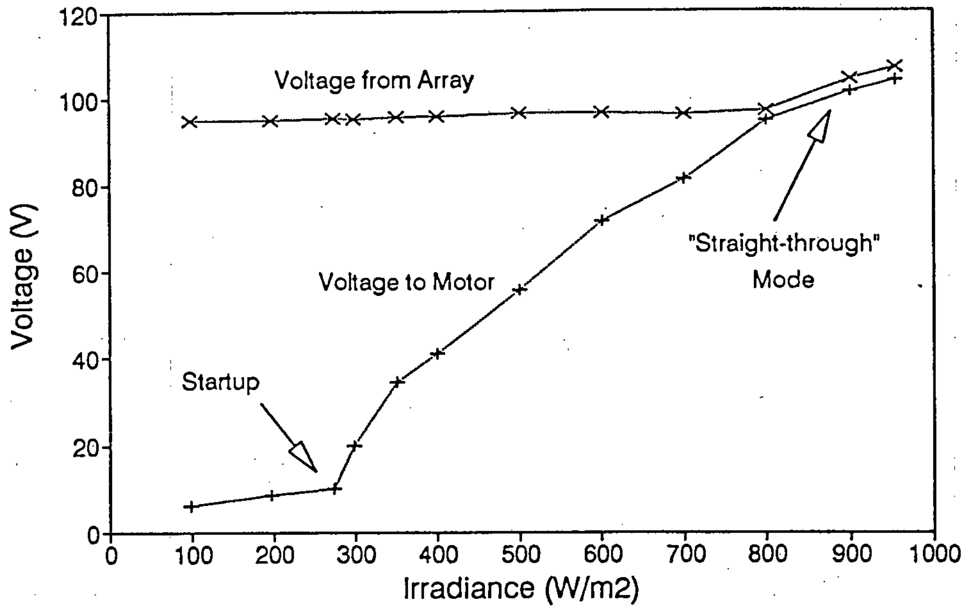


Figure 3.32: Array and Motor Voltage versus Irradiance (Miltek maximizer)

The array voltage had been set to 95 V which is the approximate location of the PPC. The top line in the figure shows how well the maximizer tracks this voltage until about 800 W/m². At this stage the motor voltage reaches 95 V and the maximizer is no longer able to chop down the voltage. The maximizer then stops operating and the voltage in and out of the maximizer become equal ("straight-through" mode).

The motor voltage is initially chopped very low to less than 10 V. At this stage the motor is drawing a high current in order to overcome start-up torque and so all the available output power is used as current. As soon as the starting torque of the pump is overcome (at an irradiance of 270 W/m²), the motor voltage rises steadily as more power becomes available. The speed of the motor increases proportionally with increasing motor voltage.

The variation of the current in and out of the maximizer can be seen in the figure below:

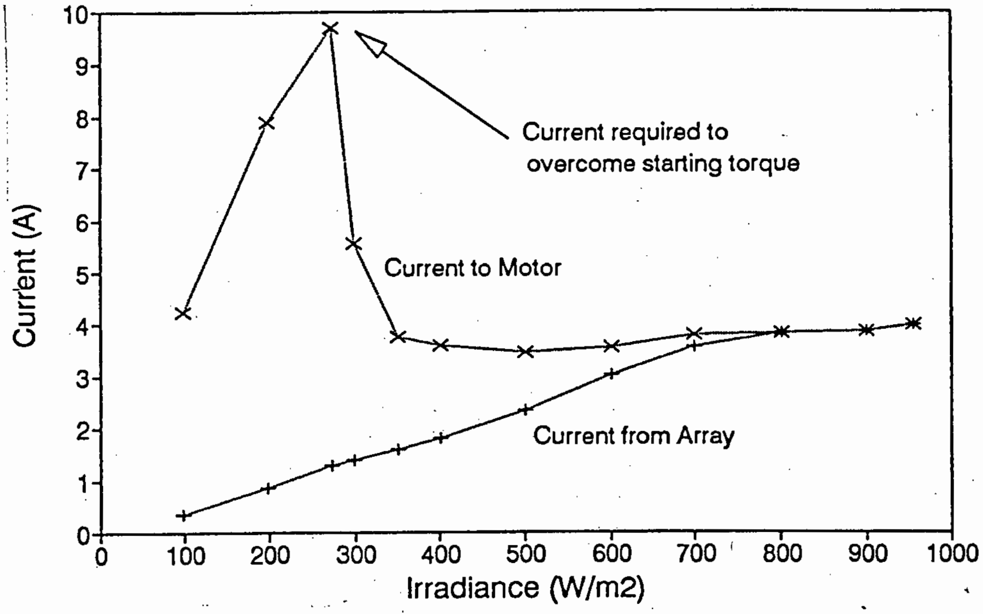


Figure 3.33: Array and Motor Current versus Irradiance (Miltek Maximizer).

The motor current is initially about 4 Amps at 100 W/m^2. As the sun rises to 270 W/m^2 the motor current rises to 9.7 Amps when the motor is able to overcome the starting torque of the pump (4.2 Nm). Once the pump has started the motor current drops sharply to 3.5 A as the torque of the pump drops to its running value (1.3 Nm). It then slowly increases to 4 A as the torque that the motor must provide to overcome the friction head increases to 1.44 Nm. The figure shows that the running torque is 32% (about one third) of the starting torque. This emphasizes the importance of the maximizer coping well with start-up.

The graph shows how the array current initially increases linearly with increasing irradiance. This is because the array voltage is kept constant and so any increase in array power is taken up by the current. When the array current becomes equal to the motor voltage it levels off and any further increase in array power is taken up by the array voltage (which then leaves the PPC).

Comparing the Operation of the AERL Maximizer

The figure below shows the operation of the AERL maximizer for comparison. Only the array voltage and the motor current are shown as these are the parameters which matter.

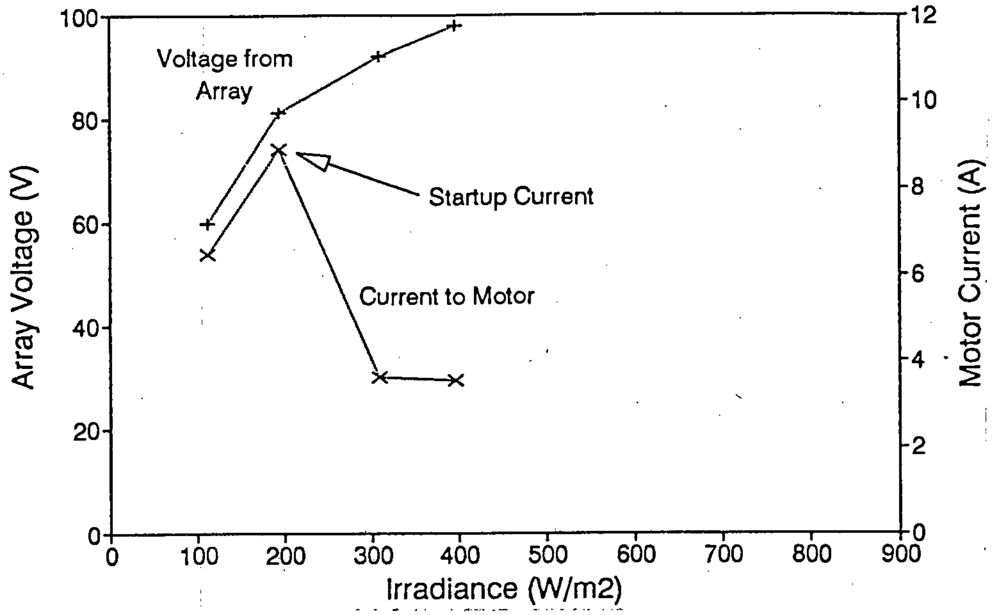


Figure 3.34: Array Voltage and Motor Current versus Irradiance (AERL maximizer with 126 mm pulley)

Unfortunately tests at higher irradiance were unreliable and needed to be discarded - but this graph shows the crucial area. The AERL maximizer does not have a set array voltage but tracks the PPC. So the array voltage is initially lower than when the Miltek is used. It then rises steadily to just over 95 V.

When the AERL maximizer is used the motor current rises to 8.9 A at 190 W/m^2 when the starting torque is overcome. The Miltek maximizer in comparison required 270 W/m^2 to start the pump and drew 9.7 A. This seems to be due to the pulsing method which the AERL maximizer uses: power is stored for 10 to 15 seconds and then a short but sustained high current pulse is given. This enables the AERL to provide enough current to overcome starting torque earlier. The 8.9 A that was recorded is in fact an average for the minute - the pulse may have been much higher. This use of pulsing is an important advantage of the AERL maximizer.

c) Comparing the Efficiencies of the Two Maximizers

The following figure gives a comparison of the efficiency of the maximizers.

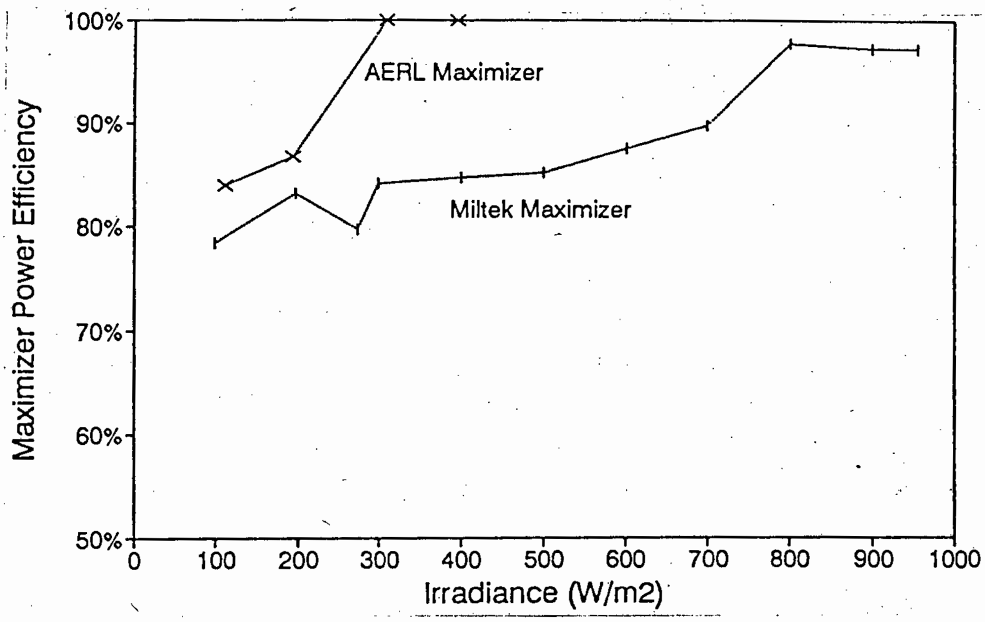


Figure 3.35: The Efficiency of Each Maximizer Against Irradiance

The efficiency of the AERL climbs from 85% at 100 W/m^2 to about 100% efficiency at 270 W/m^2. Although there is no data from here upwards the efficiency is likely to remain near 100% once it has reached there. The efficiency of the Miltek maximizer rises slowly from 80% at 100 W/m^2 to 90% at 700 W/m^2 and then almost 100% from 800 W/m^2 upwards.

Using the AERL maximizer rather than the Miltek would increase the efficiency of the system by 1.08 times on a standard solar day of 4.5 kWh/m^2. This means that one module could be removed from the Sondela array of 14 modules - a saving of about R 900. For the largest array the AERL maximizer can handle (36 modules) it would mean that almost three panels could be removed. The price difference between the two maximizers is R 1,800 (equivalent to two panels), which means that the AERL should be used only for arrays larger than 24 panels. Miltek has produced an updated more sophisticated maximizer and this may be considered as a cheaper alternative to the AERL.

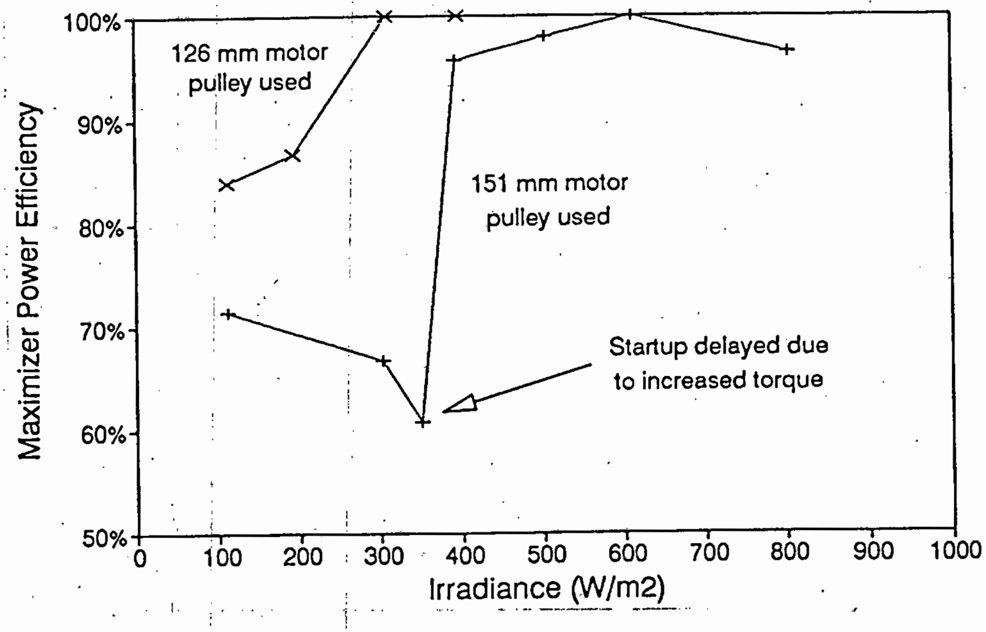


Figure 3.37: The Effect of Pulley Size on AERL Maximizer Efficiency

The change in efficiency is caused by the increased starting torque that the motor must overcome. So if the 151 mm pulley is used the maximizer strains until about 340 W/m² giving an efficiency of 60 to 70%. Only after start-up does it move to near 100%.

These values for efficiency can be averaged over the day to get the Daily Energy Efficiency. This efficiency drops only slightly when the 151 mm pulley is used - from 91% to 89% for a 5 kWh/m²/d day. This is probably the best indication of the effect of the change.

So while using the larger pulley results in a marginally better array efficiency, it reduces the efficiency of the maximizer slightly. What is its effect on the motor?

The Effect on Motor Efficiency

The effect on motor efficiency is the most marked. This is discussed more fully in the next subsection, but in summary: using the 151 mm pulley reduces Daily Energy Efficiency of the motor from 80% to 76% because of delayed start-up; and it further reduces it from 76% to 72% because of less efficient operation after start-up (the current it operates at is less suitable). (All Daily Energy Efficiencies are for a 5 kWh/m²/d).

The Nett Result of the Three Effects

Using the 151 mm pulley rather than the 126 mm pulley has the following effects:

a) It increases the efficiency of the array. But this is only at irradiances above 800 W/m^2 and so this does not affect the computation of the Daily Energy Efficiency.
b) It reduces the Daily Energy Efficiency of the maximizer marginally from 91% to 89%.
c) It reduces the Daily Energy Efficiency of the motor markedly from 80% to 72%.

The nett effect of the three is to reduce the system efficiency to 88% of its original value. Thus if the 151 mm pulley were used, 16 panels rather than 14 panels would be needed for the Sondela system - an increased expenditure of about R 2200.

This emphasizes the importance of what may be considered a minor detail. To consider all the trade-offs for every design would be time consuming. But there should be little error if the following two guidelines are used:

a) The motor voltage should be allowed to go over its rated voltage at very high irradiances (for example a motor rated 90 V could go to 110 V or even 120 V at 950 or 1000 W/m^2). The motor will not be damaged by short spurts at these voltages. (The specifications for the AERL maximizer state that "DC motors can run at at least twice their rated voltage without sustaining damage"). This will mean that the motor voltage and so efficiency is kept as high as possible at low irradiances.

b) The motor running current should not be below 3.5 Amps as motor efficiency falls away rapidly at low currents. (This is for a motor rated at 9 Amps).

e) Designing the Maximizer to Reduce System Maintenance Costs

There are two ways in which the maximizer can be designed to reduce maintenance costs: i) it can cut out when there is not enough power to start the motor and ii) it can use Light Emitting Diodes (LED's) to aid diagnosing problems.

Low voltage cutout

On cloudy days there is often just too little power from the array to overcome starting torque. As the motor is stopped this power is dissipated as heat in the motor windings. At Sondela the motor overcame starting torque when the power to the motor was 110 W: so the motor may spend many cloudy days dissipating around 100 W. A higher head would worsen the situation as the motor would only start with higher powers. This will ruin the insulation around the windings of the motor and reduce motor life.

However, for a particular system the voltage (or power) at which the motor will start can be easily found by observation. It would be easy then to adjust the maximizer to cut out below this voltage and so save the motor. If when the maximizer cut out it used what little array power is available to charge a small battery this power could possibly be used to aid start-up once enough energy has been accumulated.

Diagnosing problems

Photovoltaic pumps require little maintenance - but the maintenance they require is mostly beyond the skills of people in poorer rural communities and requires professionals. And because PV pumps are most economical in remote places the cost of professional service is high - due to the time spent travelling. If a team is called out to find that there is a broken connection, they may well charge R 200 for travel and time. Or if the motor is giving problems they would need to make two trips - one to diagnose the problem and collect the motor, and one to replace it.

These costs substantially reduce the advantage photovoltaic pumps have over diesel pumps because of low maintenance costs. So it is important to reduce these costs if PV pumps are to maintain their advantage.

This can be done if the local agricultural officer could diagnose the component which is not functioning could take the necessary action. If the problem is in the array it would probably be a case of checking for a broken wire or poor connection. If either the power maximizer or the motor is malfunctioning he could get it delivered to the relevant firm for fixing. If the problem is the pump the maintenance team would need to come to site - but a diagnostic trip may be saved and they would come prepared for the problem.

Because the maximizer is in a central position it would be best able to help diagnose the problems. Two (or four) LED's could be used to indicate the following conditions:

a) Whether there is some power being received from the array. Whether this power is sufficient that the motor ought to be running.
b) Whether some power is being supplied to the motor. Whether there is enough power to start the pump.

This, plus a simple instruction sheet should be adequate to enable somebody in the community to identify the component which is malfunctioning and to take the required action.

3.5.4 Comparison of Honeywell and Baldor DC Motors

Two motors were bench tested: the Honeywell 90 V permanent magnet DC motor installed with the system and the Baldor (also 90 V permanent magnet DC). Mono Pumps supplied this motor for comparison as a motor which they had used. The purpose was to model the operation of the motors over the full range of input voltages and currents and to see if there was any significant difference in their operation.

This section deals with the following questions:

a) How does the Honeywell motor operate at constant voltage?
b) How does it operate at constant current?
c) So how is motor efficiency affected by the motor/pump pulley ratio?
d) Is there a significant difference in the efficiency of the two motors?

a) The Operation of the Honeywell at Constant Voltage

The effect of voltage on the efficiency of the motor is shown in the figure below.

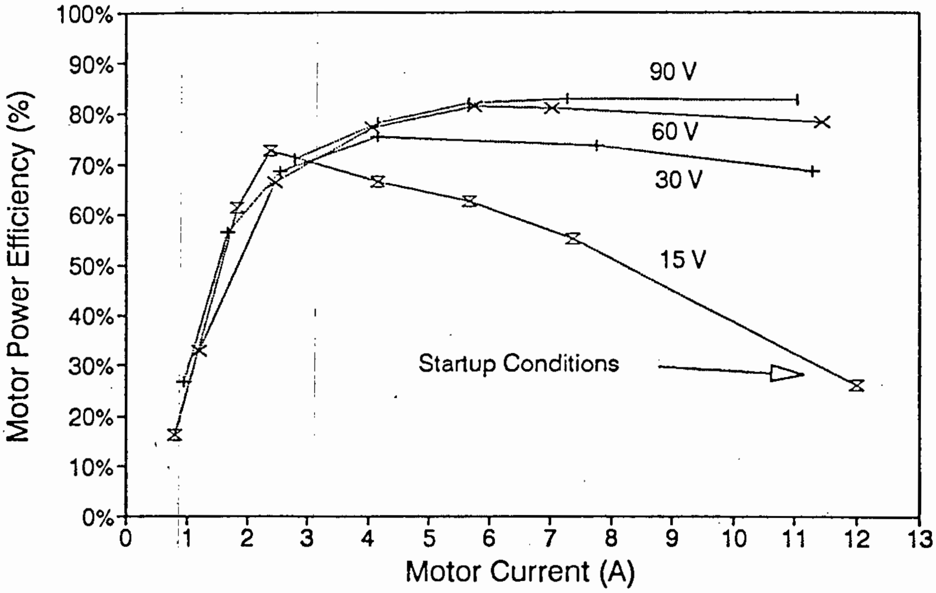


Figure 3.38: Efficiency vs Current at Constant Voltage - Honeywell Motor

At very low voltages such as 15 Volts the efficiency increases rapidly reaching over 70% at about 2 Amps. Then it tails off to below 30% at 12 Amps. This region of low voltage and high current is very important for start up and it will be dealt with more when comparing the Honeywell with the Baldor.

This graph also shows that there is little difference between the efficiency of the motor between 30 and 90 Volts (12% different at most). At these voltages the efficiency of the motor is low at low currents but rises rapidly to about 70% at 3 Amps and 80% at 4 Amps. From here there is little change in the efficiency at higher currents.

b) The Operation of the Honeywell at Constant Current

When used with a Mono pump at an effectively constant total head the motor is required to provide a constant torque and so operates at a more or less constant current. So it is instructive to look at curves for the efficiency at constant current.

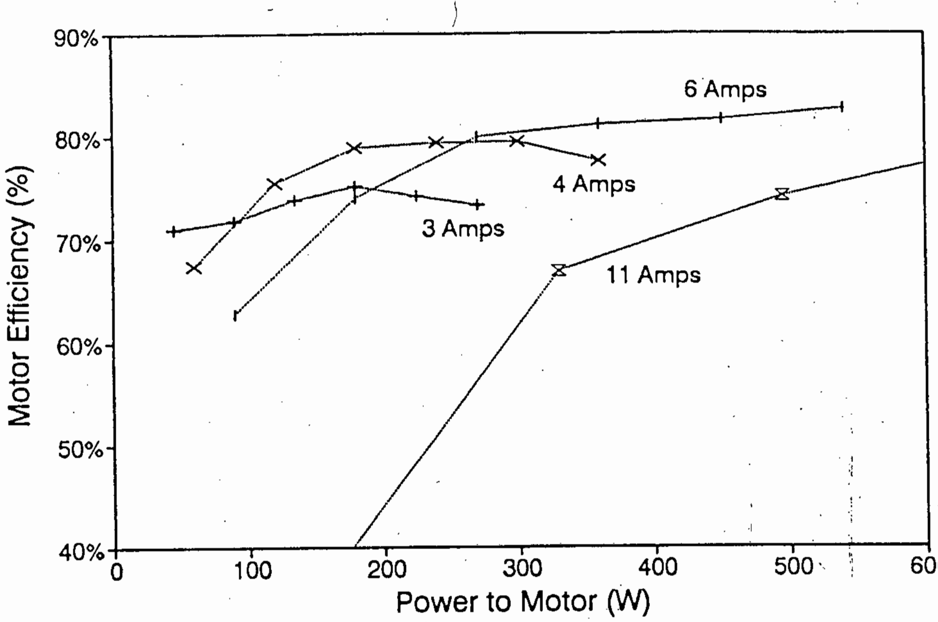


Figure 3.39: Efficiency versus Power at constant current

By changing the motor/pump pulley ratio the almost constant current which the motor draws can be changed. So the above curves give a set of possible operating lines for the motor.

The best motor efficiency is given at 3 Amps for an input power of less than 100 W; but at 4 Amps if the input power is between 100 and 270 W; and at 6 Amps if the input power is higher than 270 W. The motor is inefficient at 11 Amps especially at low power.

So the best operating currents for the motor are between 3.5 and 6 Amps. And the choice between them depends entirely on the range of power the motor will receive: for example if the maximum power the motor will receive is 360 W then the pulley ratio should be chosen to give an operating current of 4 Amps; but if it is 540 W then 6 Amps would be preferable.

c) The Effect of Pulley Ratio on Motor Efficiency

The system was tested with two motor pulleys (151 mm and 126 mm) to test the effect of motor/pump pulley ratio. The operating current for the 126 mm pulley was between 3.5 and 4 Amps while that for the 151 mm was between 4 and 4.8 Amps.

There are two conditions to consider: start-up and normal operation. On start-up the motor must overcome a larger torque and so will operate less efficiently. It was found that start-up was delayed from 190 to 340 W/m^2 when the 126 mm pulley was replaced by the 151 mm pulley (see Figure 3.37, page 124). This delay reduces the Daily Energy Efficiency of the motor from 80% to 76% (for a 5 kWh/m^2/d day).

Normal operation: as noted above the best operating current for the motor depends on the maximum power the motor will receive. For a 5 kWh/m^2/d Standard Solar Day the power input ranges from 0 to 275 W and so the optimum current is 3.5 to 4 Amps - which means that the 126 mm pulley is perfect. Using the 151 mm reduces the Daily Energy Efficiency of the motor further from 76% to 72% because of less efficient operation during the day.

d) Comparing the Honeywell and Baldor motors

In order to choose between the two motors the designer must consider their efficiencies at the two important operating points: at about 4 Amps for when the pump is running, and at about 10 Amps for start-up conditions.

The measurements showed that the difference in efficiency at 4 Amps was minimal. But there was some difference in their efficiency at high currents. The following figure compares their operation at 11 Amps (which is equivalent to a starting torque of 4.7 Nm).

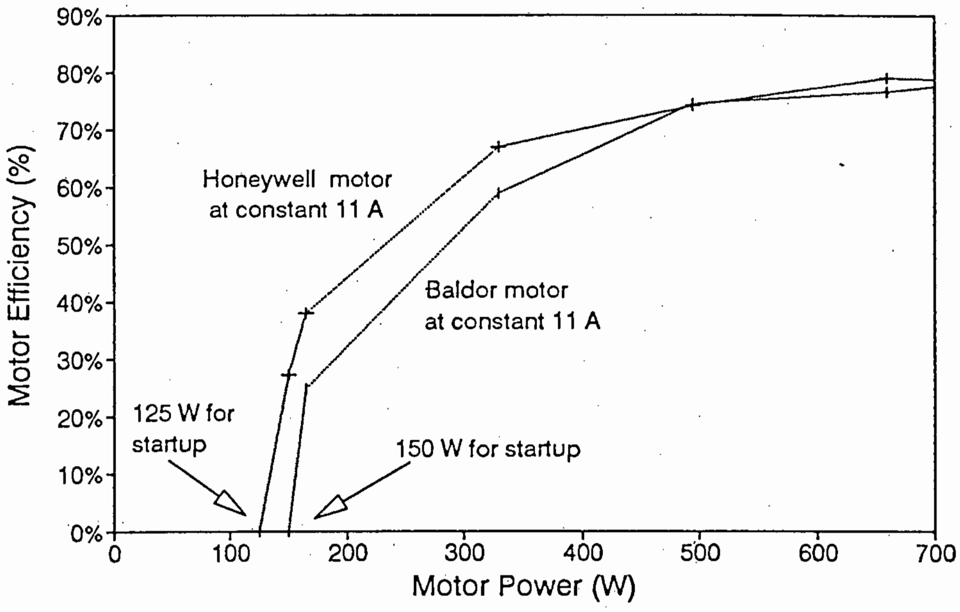


Figure 3.40: Comparing the Honeywell and Baldor Motors: 11 Amps

The figure indicates that at high currents the Honeywell has the edge over the Baldor motor. The x-intercepts show that the Honeywell would require only 125 Watts of input power to overcome the starting torque of 4.7 Nm whereas the Baldor would require 150 Watts. Thus for the Sondela system the Honeywell would start at an irradiance of 270 W/m^2 whereas the Baldor would require 300 W/m^2.

This difference may mean that the Honeywell would be able to get the pump moving on some cloudy days when the Baldor could not. But in the long term this is not an important difference: for a Standard Solar Day of 5 kWh/m^2/d the Honeywell would deliver only 2% more water than the Baldor.

3.5.5 The Operation of the Pump

This subsection deals with the following:

a) A description of the operation of the pump examining each parameter measured in turn and then the pump efficiency.
b) A comparison of the suitability of the Mono Pump at low heads with that of centrifugal pumps.

a) Description of the Operation of the Pump

The effect of irradiance on pump torque and on total head is shown below.

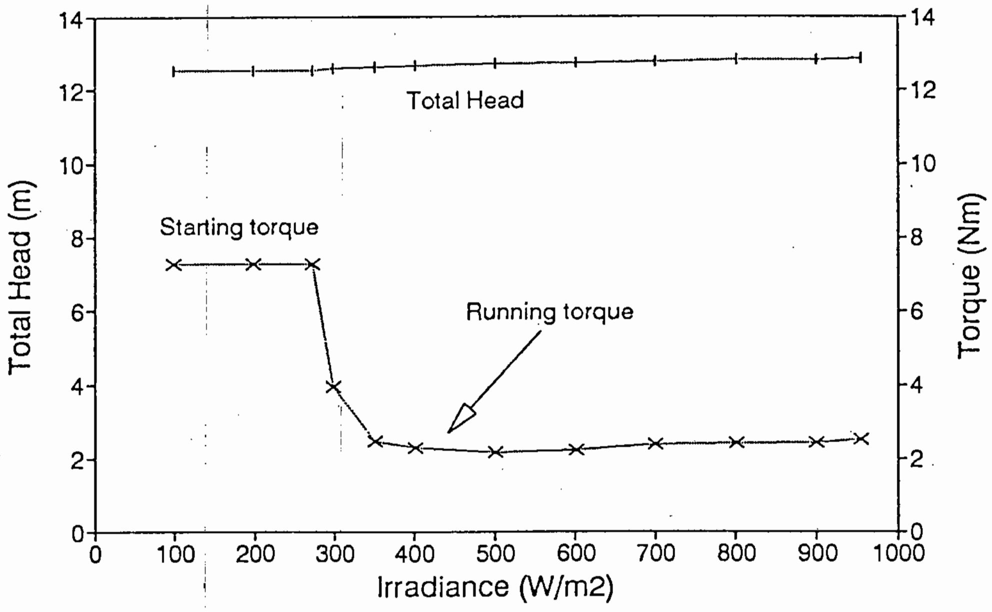


Figure 3.41: Mono SW4L Pump: Head and Pump Torque vs Irradiance

The Head increases slightly from 12.55 at 100 W/m^2 to 12.85 meters at 955 W/m^2 due to increasing friction head. At its highest the friction head is only 0.3 meters. This is due to the large delivery pipe used (65 mm inner diameter).

The torque of the pump is initially high at 7.28 Nm before start-up. On start-up (270 W/m^2) the torque drops rapidly to 2.17 Nm and then rises slowly to 2.52 Nm with increasing friction head. The drop from 7.28 to 2.17 Nm indicates that about 5 Nm of torque is caused by friction on start-up. This is in line with the manufacturers' claim of 4.5 Nm.

The variation of the pump's speed and the water flow rate with irradiance is shown below:

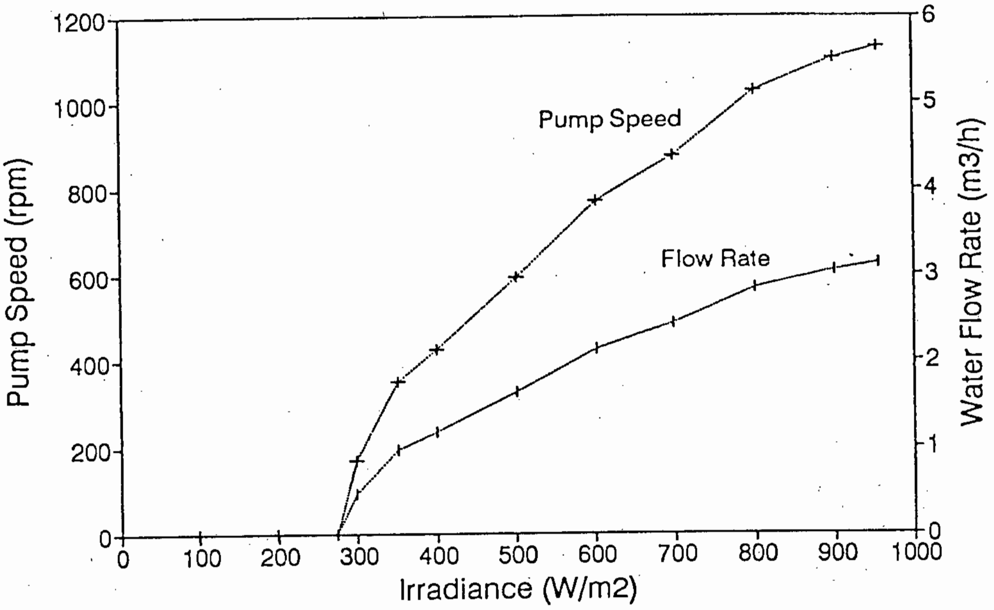


Figure 3.42: Pump Speed and Water Flow Rate versus Irradiance

After start-up the pump speed rises quickly to 428 rpm at 400 W/m^2 as the torque drops to its running value. From there it increases steadily to 1130 rpm at 955 W/m^2.

On start-up the water flow rate rises quickly to 1.18 m^3/h at 400 W/m^2 and then more slowly to to 3.05 m^3/h at 955 W/m^2. The fact that both curves have the same shape indicates that at this head water flow rate is proportional to pump speed.

The effect of all the inputs graphed above on pump efficiency is shown in the following figure.

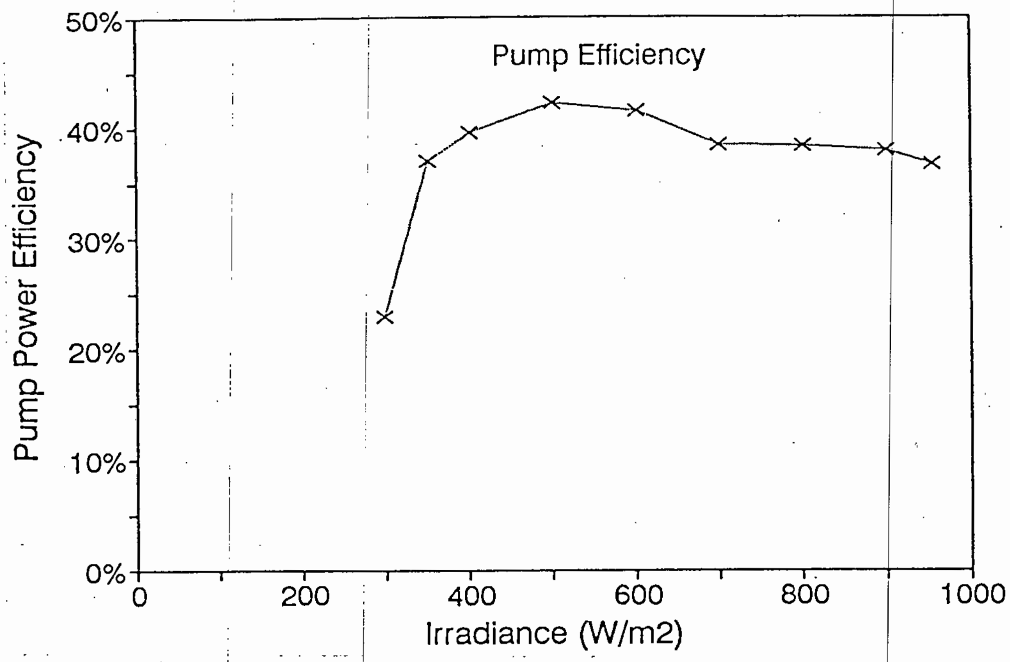


Figure 3.43: Pump Power Efficiency versus Irradiance

Before start-up the efficiency of the pump cannot be calculated as the power input to the pump is zero. Immediately after start-up the pump efficiency is 23% (at 170 rpm). It then shoots up to around 40% and settles there. The graph shows a peak of 42% at 500 W/m^2 and then a gradual decline to 37% at 955 W/m^2. This is not expected (the specifications indicate that the efficiency should remain constant between these speeds).

b) Comparison with centrifugal pumps

The efficiency of the pump shown in the graph above is low in comparison with figures quoted in the literature. Halcrow & Partners (1983) measured Daily Energy Efficiencies of pumps as high as 59% for their best pumps and 41.5% for their average pumps. In comparison the Mono Pump at Sondela gave a Daily Energy Efficiency of 39.3%.

The reason for this is shown in the graph below: the Mono Pump used was not designed to be used at such low heads (13m).

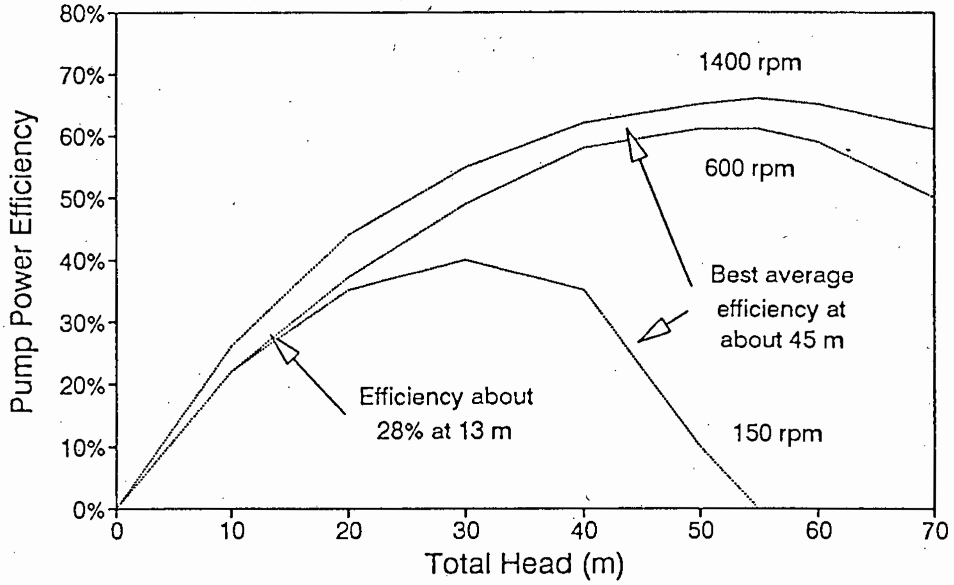


Figure 3.44: Mono SW4L: Power Efficiency versus Total Head

Mono does not have a range of pumps designed for lower heads than the pump which was used - the SW4L. This pump would give its best average efficiency for the whole day at about 45 meters - about 56%. The specifications show a much lower efficiency of about 28% at 13 meters. Although this conflicts with the measured efficiency of 39% the graph nevertheless indicates that this pump is not at its ideal head.

But are there more suited pumps for these conditions? Photovoltaic pumping under these conditions requires a lot from the pump: it must operate efficiently at low heads and over the full range of flow rates; it must have a low starting torque; it must be robust and require little maintenance and be able to handle some impurities in the water; and if possible it must be relatively cheap.

There are two categories of pumps to choose from: positive displacement pumps and centrifugal pumps.

The Mono Pump is a positive displacement type pump. This has the advantage of giving a fairly constant efficiency over the full range of speeds (with the exception of very low speeds). It is also submerged in the water and so does not need to be primed. But positive displacement pumps tend to have low efficiencies at low heads because the energy dissipated by friction is a large proportion of the energy input. In the case of the Mono Pump the length of the rotor and stator can be reduced to decrease this friction; but this also increases leakage and so the best trade-off must be found. Because it is a positive displacement type pump the Mono Pump may not be able to equal the efficiency of centrifugal pumps at low heads.

Centrifugal pumps have the advantage of low friction. Thus at low heads a well-designed centrifugal pump will mostly give a better maximum efficiency than a positive displacement pump. But the efficiency of centrifugal pumps drops sharply at flow rates other than its designed flow rate. This is not important in industry when the desired speed of the pump can be maintained. But it is important for directly-coupled photovoltaic pumps because the flow changes with irradiance. Centrifugal pumps also need to submerged or else to use self-priming.

The graphs below compare the two types of pumps using data from manufacturers' specifications. The first graph compares the maximum efficiency of the Mono Pump with that of two small centrifugal pumps at various heads.

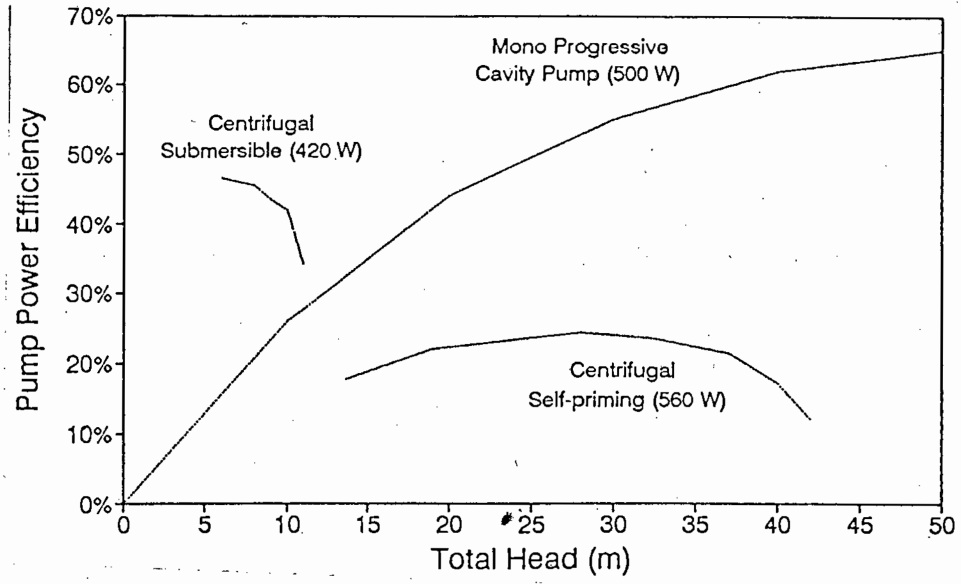


Figure 3.45: Comparing the Efficiency of Three Small Pumps vs Head

The figure shows that self-priming for centrifugal pumps is inefficient. The centrifugal pump which uses self-priming has a very low maximum efficiency of 24.4%. In comparison the maximum efficiency of the submersible centrifugal pump is 46.5%. The loss of efficiency is caused by the venturi which is used in the self-priming pump and which is equivalent to a head of up to 8 meters. So only submersible centrifugal pumps are recommended.

The figure also shows how the efficiency of the Mono Pump drops at low heads. At these heads a submersible centrifugal pump would give better maximum efficiencies than the Mono Pump. But the efficiencies of these small pumps is well below those measured by Halcrow & partners. They measured peak Power Efficiencies as high as 67%. However, few, if any, pumps designed for these low heads and flow rates would give as high efficiencies as that.

The maximum efficiencies shown in the above figure can be misleading for PV applications as it is important that the pumps are efficient over the full range of power supplied to the pump. The figure below compares the curves for a Mono Pump and a centrifugal pump.

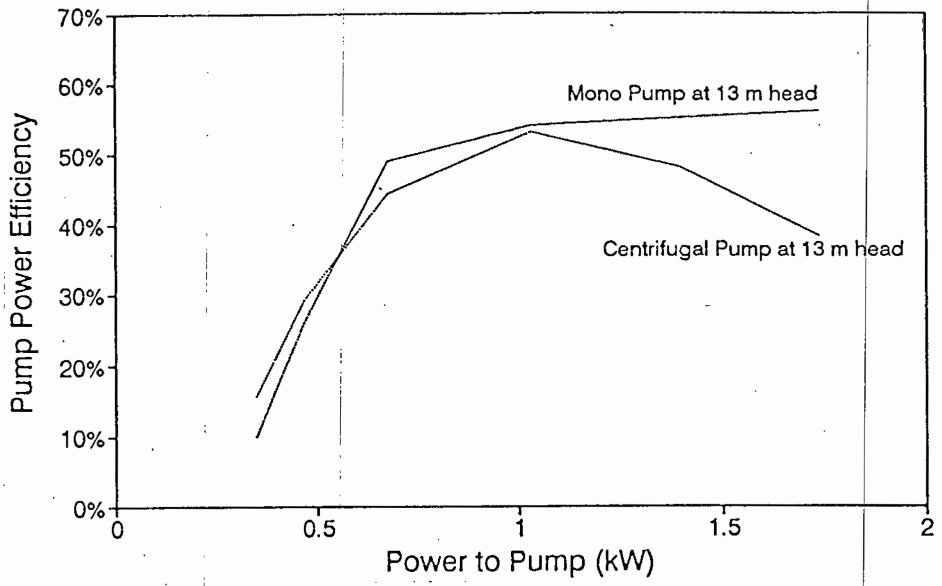


Figure 3.46: Comparing the Mono and Centrifugal Pumps at 13 m Head

These curves were taken from slightly larger pumps than those in the previous figure as there is no detailed information available for the small pumps. As shown the efficiency curve of the centrifugal pump is parabolic, while that of the Mono Pump rises quickly to it maximum and stays there.

The centrifugal pump matches the Mono at low power input, but its efficiency drops at high power output. To match the Mono at higher power inputs a slightly larger centrifugal pump could be chosen. But then it would be inefficient at low power inputs.

If the two pumps above were connected to an optimally sized PV system the Mono Pump would give a Daily Energy Efficiency of 48% whereas the centrifugal pump would give a Daily Energy Efficiency of 40% (for 5 kWh/m^2/d). So while their maximum efficiencies are very similar there is a significant difference in their performances when connected to a PV pump.

The following figure shows the curves for the same two pumps at a higher head of 20 meters.

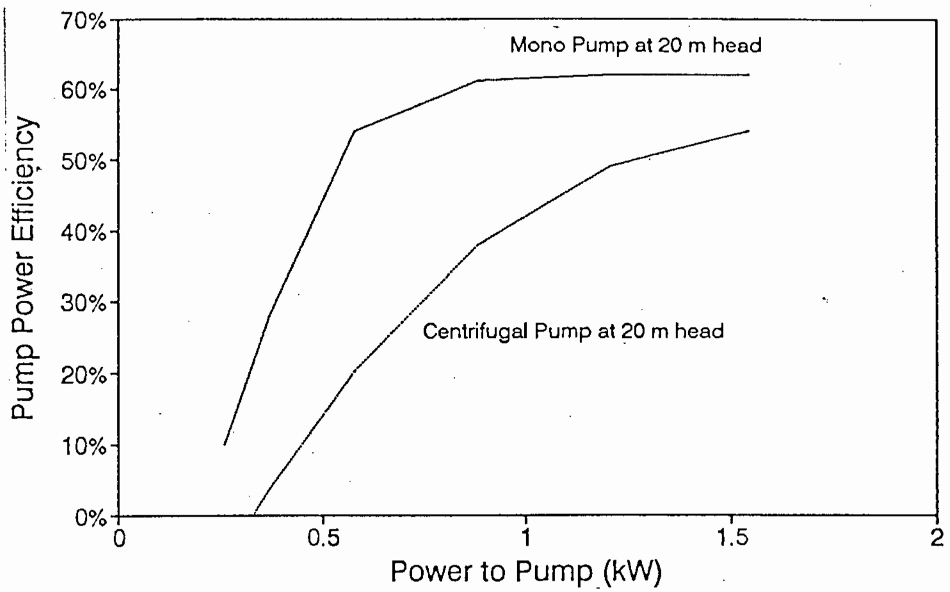


Figure 3.47: Comparing the Mono and a Centrifugal Pump at a 20 m Head

This figure shows that for the same power range but a higher head the efficiency of the Mono Pump is considerably better than that of the centrifugal pump. This is because the efficiency of the centrifugal pump peaks at a higher power. So, as expected, positive displacement pumps are likely to be more efficient for high head and low flow applications.

In conclusion: at low heads (below 10 meters) the centrifugal pump is likely to give the best efficiencies unless Mono Pumps produces a model for heads as low as these. For the middle range (10 to 20 meters) both centrifugal and Mono Pumps should be considered. At higher heads the Mono Pump is most likely to give the best efficiencies.

3.6 Conclusions

There were three focuses to the technical evaluation: a) system and component efficiencies, b) the interaction between the components, and c) the suitability of alternative components. The conclusions below are divided accordingly.

a) System and Component Efficiencies

The best indication of a component's efficiency in a photovoltaic system is its Daily Energy Efficiency (DEE). This is the component's efficiency averaged over a whole day. It is normally computed for a Standard Solar Day for which the irradiance follows a sine curve with time. All the Daily Energy Efficiencies given below are for a 5 kWh/m^2/d Standard Solar Day.

1. System Efficiency: The DEE for the system is 2.22%. This is low - Halcrow & Partners (1983) measured DEE's of 2.35% for their average systems and 3.28% for their best systems. (Halcrow's study was of the 12 best PV pumping systems available in the world in 1982). The system efficiency is low because of the low pump efficiency - see conclusions 6 and 13.

2. Subsystem Efficiecy: The DEE of the subsystem is 24.4% as compared with 28.7% for Halcrow's average subsystems and 38.2% for their best subsystems.

3. Array Efficiency: The array consisted of 14 M.Setek 41 W_p modules. It was configured in two strings of 7 modules. The DEE of the array is 9.13% which compares favourably with the 8.4% calculated from Halcrow's results for all their systems. Correlations show that the array does comply with manufacturer's specifications: at an array temperature of 25 °C and an irradiance of 1000 W/m^2 it would give an efficiency of 12%. However, if the array does not physically track the path of the sun its DEE at 25 °C would be 9.6%. And for a more realistic array temperature of 40 °C the DEE would be 9%. So for most applications it is best to estimate the actual DEE of the array as 75% that given by manufacturers.

The effect of the shading: if a fence is installed over the top of the array to protect it from vandalism the array size needs to increased by 10% due to loss in array efficiency. The effect of solid shading is marked: shading only one cell in the array completely results in a loss of 37% of the array's power.

The use of bypass diodes: Bypass diodes should be standard in all applications as they guard against expensive damage caused by hot-spots. They also increase the array's power markedly if there is some shading.

4. <u>Power Maximizer Efficiency:</u> The power maximizer was designed locally by Miltek Engineering for Mono Pumps. Its DEE was 87%. The range of its Power Efficiency from 84% to 98% compares closely with values of 88% to 99% measured by Pulfrey et al (1987). Its highest efficiency meets manufacturers' specifications of 98% efficiency.

5. <u>Motor Efficiency:</u> A Honeywell DC permanent magnet motor was used. Its DEE was 77% which is higher than the 69% and 74% measured by Halcrow for their average and their best systems. Efficiencies of up to 83% were measured in the laboratory which complies with the manufacturers' claim of an efficiency of 80%.

6. <u>Pump Efficiency:</u> A Mono SW4L progressive cavity pump was used. This is a positive displacement type pump. Its DEE was 39% which is low in comparison to the values of 41.5% and 59% measured by Halcrow for their average and their best systems. See conclusion 13.

7. <u>The Effect of Insolation:</u> The DEE of the system increases from 2.1% to 2.7% as the insolation increases from 4.5 to 7 kWh/m^2/d. The volume of water pumped almost doubles over the same range: from 12.7 to 24.5 m^3/d. So the cost of water pumped by this system in Namibia in summer (at 7 kWh/m^2/d) is half that it would be in Durban in winter (4.5 kWh/m^2/d).

<u>b) Component Interaction</u>

8. <u>The Position of the Peak Power Curve:</u> At any irradiance and array temperature the array voltage at which the array delivers its maximum power is 78% of the Open Circuit Voltage under those conditions. Thus, for the array at Sondela this voltage increased from 89 to 96 V as the irradiance increased from 200 to 800 W/m^2; and it dropped 4 Volts with an increase of 10 °C in array temperature.

9. The Effectiveness of Methods of Tracking the Peak Power Curve: The following three methods are the most commonly used.

   i) Tracking a fixed voltage: This method gives tracking efficiencies from 96% to 100% over the whole year if the correct voltage is tracked. However, choosing the correct voltage is not easy unless explicit instructions are available. This method does not cope well with unforeseen problems like hot spots in the array and shading of the array.

   ii) Using the open circuit voltage: The maximizer can set the array voltage to a constant proportion of the open circuit voltage (eg $V_a = 80\% \; V_{oc}$). If the percentage used was 78% the method would give effectively 100% tracking efficiency (see conclusion 8). The tracking efficiency is above 99% if the array voltage is set to between 75% and 80% of the open circuit voltage. This method copes well with hot spots in the array and with shading.

   iii) "Intelligent" searching: A maximizer using this method constantly hunts for the Peak Power Curve. If implemented properly this method gives a tracking efficiency of effectively 100% under all conditions. Method ii) may however be cheaper and as effective.

10. The Effect of the Motor/Pump Pulley Ratio: Replacing the 126 mm motor pulley with a 151 mm pulley increases the array efficiency slightly due to better tracking, but reduces the efficiency of the maximizer marginally and that of the motor markedly (from 80% to 72%). The system efficiency is reduced to 88% of its original value which means that the array at Sondela would need to be increased from 14 to 16 panels if the 151 mm pulley were used. This would increase the array costs by R 2200.

    The following two guidelines should be used in choosing the motor pulley:

    i) The motor should be allowed to go over its rated voltage at high irradiances in order to keep the motor voltage high at lower irradiances. For example a motor rated 90 Volts could go to 120 Volts at 1000 W/m^2.

    ii) The lowest motor operating current considered should be 3.5 Amps.

c) The Suitability of Alternative Components

11. Power Maximizers: The Australian Energy Research Institute's 1200 P maximizer was compared with the Miltek maximizer used. The DEE of the AERL maximizer was 1.08 times that of the Miltek. Replacing the Miltek with the AERL could thus reduce the required size of a 36 panel array to 33 panels (saving R 3300). The AERL's main advantage is its method of handling start-up: it stores energy for 10 to 15 seconds and then gives a short, sustained current pulse.

    There are two ways the maximizer can help in reducing system maintenance costs. Firstly by having a low voltage cut out which can be set by the user to avoid the motor overheating before start-up. Secondly, by using LED's to help indicate which component is malfunctioning so that users can diagnose problems themselves.

12. Motors: The Baldor motor (also a DC permanent magnet motor) was compared with the Honeywell motor used. The Honeywell handles start-up slightly better than the Baldor but there is no difference in running operation. The DEE of the Honeywell is 1.02 times that of the Baldor.

13. Pumps: Manufacturer's specifications were used to compare the suitability of centrifugal pumps at low heads with the Mono Pump used. The conclusions are:

    i) Submersible centrifugal pumps should be used rather than self-priming centrifugal pumps as self-priming can halve the efficiency at low heads.
    ii) At heads below 10 meters the centrifugal pump is likely to give better efficiencies than the Mono unless Mono Pumps produces a model specifically designed for these heads.
    iii) At heads between 10 and 20 meters both centrifugal and Mono Pumps should be considered.
    iv) At heads above 20 meters the Mono is likely to give the best efficiency - especially at low flow rates.

CHAPTER 4

ECONOMIC EVALUATION

4.1 Introduction

For anybody choosing a pumping technology, economics is one of the most important criteria. This is especially true for disadvantaged communities. However, the economics of a technology do not override all other considerations. For example, three scenarios for the amortized costs of PV pumping versus diesel pumping were presented to some influential members of Sondela garden. All of the members interviewed chose the PV pump above the diesel pump for the "normal" scenario, which predicted that their monthly payments for the PV pump would be twice those for the diesel pump.

These interviews are discussed in depth in Chapter 5. But they do illustrate the importance of accurate calculations to enable prospective clients to compare the costs of different methods of pumping. Once figures are available, the client is able to weigh up the other factors such as reliability in making an informed decision.

In this chapter the costs of photovoltaic water pumping are compared with the costs diesel, petrol, and electric pumps. The following questions are addressed in turn:

a) Which type of pump would be the cheapest for any particular site? In this section (Section 4.2) assumptions for the efficiencies of various systems, the discount rate and fuel price etc are not questioned. Taking the default assumptions for granted, the effect of all the site dependent factors is examined. The site dependent factors are: the average water demand, the peak demand factor, the head, the critical insolation, the number of kilometres to the ESKOM grid and the number of consumers who will connect simultaneously. Break-downs of the costs of each method of pumping are examined in order to determine which assumptions are important for further analysis.

b) If the assumptions used are not correct what effect does this have on the costs? In this section (4.3) the effect of the assumptions identified as important are examined in more detail. These include: the project length, the discount rate, the system efficiencies of the PV and diesel systems, the PV panel price, and the fuel price. If the reader has his/her own beliefs about which assumptions are realistic, this section allows him/her to adjust the conclusions of Section 4.2 accordingly.

c) What method was used to calculate the Life Cycle Costs on which the costs examined above were based? How sophisticated was the computer model and what approximations were made? (See Section 4.4)

d) How accurate are the base case assumptions used here? On what basis were they chosen? What is the opinion of other authors? In this section (4.5) the assumptions relating to each method of pumping are examined in turn. Close examination is critical because the accuracy of the results is entirely dependent on the accuracy of the assumptions.

e) What are the most important conclusions which can be drawn from this analysis? (See Section 4.6)

In order to put the following discussion in context, the method of calculation is discussed briefly and the "base case" assumptions used are tabulated below. This is just for easy reference: their validity will be discussed in detail in Sections 4.4 and 4.5.

Method of Calculation

The standard method of comparing the long term costs of various alternative systems was used - the computation of Life Cycle Costs. This involves discounting all costs to year of purchase of the system in order to get their present value. The present values of all the costs are then summed to give the Life Cycle Costs.

The Life Cycle Costs can then be used to calculate unit costs: such as the cost per cubic metre of water pumped, or the cost per member of a community garden per month.

The costs of the each method of pumping are categorized in order to help analysis. Although each method of pumping requires its own categories, the main categories are as follows:

a) Initial Costs: For the PV pump these are further broken down into i) the costs of the array, ii) the costs of the other major components (the maximizer, motor and pump), and iii) the Balance of System Costs.

b) Running Costs: for the diesel and petrol pumps this is the cost of fuel. For the electric pumps this cost is broken down into the fixed monthly meter charge, and the energy charge for the kilowatt-hours used.

c) Operator's Wages: remuneration for a garden member who starts and stops the pump - only applicable to the diesel and petrol pumps.

d) Maintenance Costs.

e) Replacement Costs.

f) Salvage Value: the resale value at the end of the project.

The "Base-Case" Assumptions

The costs of various methods of pumping vary a lot with the condition that they are used under. Assumptions which are commonly accepted as valid for a "first world" pumping environment where there is a relatively easy access to technical expertise may be totally unrealistic for a "third world" situation. So it is important to focus each study on a particular application.

The focus of this study is a third world, rural situation. The specific model which is used as a reference point is that of the community gardens in the Mpumalanga District of KwaZulu, Natal. Sondela garden, the site of the field-work for this research, is one of these.

For these circumstances the costs of pumping are mostly much higher than those for "first world" farmers due both to the lack of technical expertise available (which results in machines running in poor condition), and to the large distances which must be travelled to service the pumps.

Because there is little measured data for these circumstances, there is a lot of disagreement about which assumptions would be accurate. To account for the range of possibilities two sets of assumptions were used for both the diesel and the PV pumps: a "normal case" which represents what is most likely to occur in these situations, and a "best case" which represents the best likely in these situations.

Two cases were also considered for electric pumps connected to the ESKOM grid: the normal tariff which is applicable to all rural areas in South Africa which are supplied directly by ESKOM ("Tariff D"), and the S1 tariff which is much cheaper for small consumers and may be introduced to these areas if ESKOM finds innovative ways of encouraging electricity consumption and so making it economic. (See Subsection 4.5.3 for a discussion on this).

The following tables for each method of pumping give the assumptions which were chosen for the "base case". The tables deal in turn with PV, diesel, petrol and electric pumps.

Table 4.1: The Assumptions Used for PV Pump Costs

Assumption on:	Normal Case	Best Case
System Efficiency[1]	2.02 to 2.45%	4.67 to 5.10%
Subsystem Efficiency[1]	23.6 to 25.4%	41 to 45%
Array Efficiency[1]	8.84 to 9.66%	11.3%
System Unit Cap. Cost[2]	74 to 32 R/Wp	61 to 28 R/Wp
Array Lifetime	15 years	25 years
Motor Lifetime	15,000 hrs (10 yrs max)	25,000 hrs (14 yrs max)
Pump Lifetime	8,000 hrs (7 yrs max)	15,000 hrs (10 yrs max)
Maintenance Costs	15 c/hour	8 c/hour

1. Efficiency tends to increase with increasing insolation. The range given is for insolation levels ranging from 4.5 to 6 kWh/m^2/d.
2. The unit capital cost decreases with increasing system size. The range given is for system sizes from 160 W_p to 2000 W_p (four to fifty 40 W_p panels).

Table 4.2: The Assumptions Used for Diesel Pump Costs

Assumption On:	"Normal Case"	"Best Case"	Comment
Capital Cost[1]	R 4470 to 10640		For 4 to 8 kW
Engine Efficiency	20%	27%	
Pump Efficiency	40%	50%	
Transmission Eff	93%	93%	
System Efficiency	7.4%	12.6%	
Diesel Price[2]	120 c/l	120 c/l	Price in 1990
Escalation Rate	4.5%	4.5%	From 1990 to 2000
Maintenance Costs	60 c/hr	50 c/hr	
Engine Lifetime (hrs)	10,000	20,000	Max 15 & 20 yrs
Pump Lifetime (hrs)	8,000	15,000	Max 15 & 20 yrs
Operator's Wages	15 to 35 R/month		For 3 to 30 m3/d

1. This is for a Lister Diesel engine and centrifugal pump. The figures above include 13% GST and 10% added for accessories. The range given above is for illustration - linear correlations were used to interpolate or extrapolate.

2. To account for the transport of the fuel to the site (by bus), 10% was added to the fuel price (on top of that shown). The consumption of oil was assumed to be 1% that of diesel (Cedara, 1989).

Table 4.3: The Assumptions Used for Petrol Pumps

Assumption On:	Value	Comment
Capital Cost[1]	R 2070 to R 5080	For 4 to 8 kW
Engine Efficiency	13%	
Pump Efficiency	40%	
Transmission Eff	93%	
System Efficiency	4.8%	
Petrol Price[2]	137 c/l	Price in 1990
Escalation Rate	4.5%	From 1990 to 2000
Maintenance Costs	100 c/hr	
Engine Lifetime (hrs)	6,000	Maximum of 8 yrs
Pump Lifetime (hrs)	8,000	Maximum of 8 yrs
Operator's Wages	15 to 35 R/month	For 3 to 30 m^3/d

1. These figures include 13% GST. The range given is just for illustration - linear correlations were used to interpolate or extrapolate.

2. To account for the transport of the fuel to the site (by bus), 10% was added to the fuel price (on top of that shown). The consumption of oil was assumed to be 1% that of diesel (Cedara, 1989).

Table 4.4: The Assumptions Used on Electric Pumps - ESKOM

Assumption on:	Normal Tariff	S1 Tariff
Connection fee (1-phase)	R 400	R 30
Recoverable deposit	R 750	None
Motor & pump (0.25 kW)[1]	R 2030	R 2030
Motor & pump (0.75 kW)[1]	R 2260	R 2260
Energy Charge		
1st 1000 units	17.77 c/kWh	16 c/kWh
Thereafter	10.28 c/kWh	16 c/kWh
Account Charge	43.17 R/month	None
Line Charges	24 R/100m/month	None
System Efficiency	48%	48%
Motor Lifetime	60,000 hrs	60,000 hrs
Pump Lifetime	8,000 hrs	15,000 hrs
Maintenance Cost	0 c/hour	0 c/hour

1. Motor and pump prices include 13% GST.

The following table lists the base case assumptions for the site of the pump and for assumptions which relate to all pumps such as the project length and discount rate.

Table 4.5: Base Case Assumptions for the Pump Site and for the Project

Assumption on:	Value
Average Daily Water Demand	3 m^3/day/ha
Garden Area	1 hectare
Peak Demand Factor	1.83
Total Head (including friction)	13 metres
Critical Daily Insolation	4.8 kWh/m^2/d
Distance from the ESKOM Grid	1 kilometre
Number of consumers connecting	3
No of consumers sharing an account	1
Project length	20 years
Real Discount Rate (above inflation)	5%

The correctness of each of these assumptions (as well as their effect on the Life Cycle Costs of each method of pumping) will be discussed as each is dealt with in Sections 4.2 and 4.3. The source of each assumption is given in Section 4.5.

4.2 The Base Case: Examining the Effect of Site Dependent Factors

In this section only site dependent factors are examined. The order is as follows:

4.2.1 Average Water Demand and Peak Demand Factor
4.2.2 Total Head
4.2.3 Critical Daily Insolation
4.2.4 Distance to the ESKOM grid
4.2.5 Number of ESKOM consumers connecting simultaneously
4.2.6 Number of consumers sharing one account

Subsection 4.2.1 on the average water demand is by far the most thorough. Quantities which are examined in this subsection are:

a) The cost of pumped water in cents per cubic meter. This is the most fundamental unit cost for water pumping; it is used by Halcrow (1983) and Wiseman (1987). It is easier to conceptualize than the Life Cycle Costs and makes it possible to compare scenarios with different water demands and project lengths on an equal footing. Costs can also be compared to Halcrow's estimate of the highest cost for which irrigation water is still economical.

b) The cost of power in cents per kilowatt hour. Most people have a better intuitive idea of expected values for c/kWh than they do for c/m³, because they can use a reference point of the cost of electricity in cities. This also makes it possible to compare the efficiency of the methods of pumping at varying heads on an equal footing.

c) The cost per member of the garden per month: in the final analysis this is the criterion on which the members of a community garden are going to make the decision. Once this has been calculated the differences between the costs of various methods of pumping can be more easily weighed against other advantages and disadvantages.

d) The Life Cycle Costs. Some people may relate better to figures for the total costs over the whole span of the project.

e) The break-down of Life Cycle Costs into component costs. It is this analysis which is indicates which assumptions affect the costs of each method of pumping most. Through this analysis the assumptions which require closer examination are identified.

This thorough discussion in Subsection 4.2.1 gives an idea of the inter-relationship between these quantities (c/m^3, c/kWh, Life Cycle Costs etc). After that the sensitivity of the other assumptions is examined mainly in terms of "cents per cubic metre pumped water", with the other quantities being used only where particularly relevant.

4.2.1 The Effect of Water Demand and Peak Demand Factor

There are two factors which must be considered when examining the effect of water demand: the average volume of water pumped per day for the whole year, and the variation of water demand throughout the year. This is because PV pumps must be designed to deliver the water demand for the worst month of the year and so will have extra capacity during the rest of the year.

The variation of the water demand during the year is accounted for by the Peak Demand Factor. This is the ratio of the water demand for the "worst" month to the average water demand for the whole year. For example, records for Sondela garden in 1987 show that highest monthly water demand of 5500 litre/hectare/day occurred during September. The average water demand for the whole year was 3000 litres/hectare/day. So the Peak Demand Factor was 1.83 (=5500/3000).

For this situation the PV pump would need to be sized to cope with 5500 litres/hectare per day in September. Whereas the calculations for fuel consumption for the diesel pumps would be based on the average water demand - because if less water is required during the other months, less fuel will be used.

So first the effect of the average water demand on the cost of pumped water is examined; and then that of the Peak Demand Factor (see page 159). Then the effect of average water demand is examined in detail - looking at the cost of power (c/kWh), the monthly cost for each member of the garden, the Life Cycle Costs and their break-downs (page 160 and onwards).

a) The Cost of Pumped Water (c/m3)

The following graph shows the effect of the average daily water demand on PV pumps and diesel pumps.

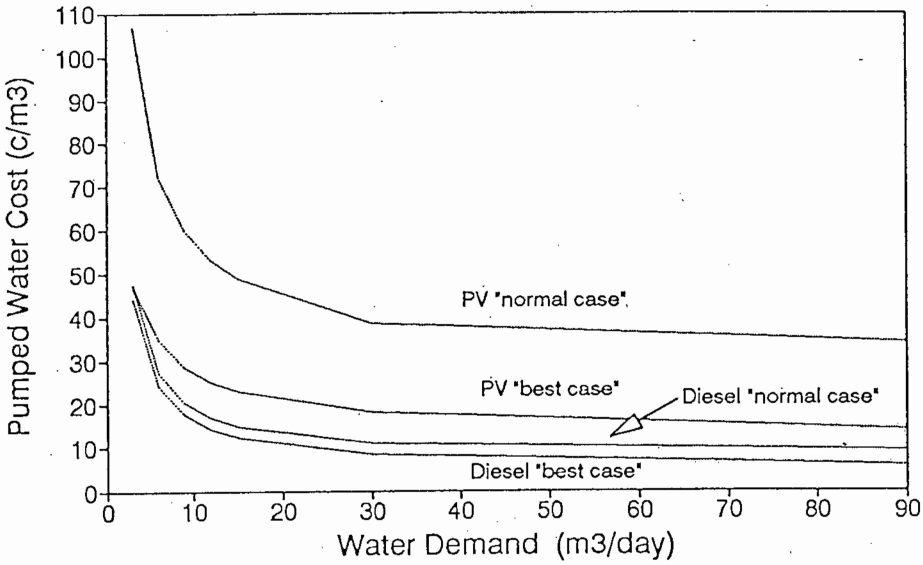


Figure 4.1: PV vs Diesel: The Effect of Water Demand on the Cost of Pumped Water

The Effect of Water Demand on All Pumps

The cost of pumped water for all pumps drops dramatically as the water demand goes up from 3 m^3/day to 30 m^3/day. For example, the cost for the PV "normal case" drops to nearly one third (36%) over this range, while that for the diesel "normal case" drops to less than a quarter. From there the cost of water continues to drop but only gradually.

The reason for this drop is that the fixed costs of the pump become relatively less important as more water is pumped. The decrease is less marked above 30 m^3/day because maintenance, replacement and running costs begin to become important.

This emphasizes the importance of the size of garden - it should, if possible, be large enough to require at least 30 m^3/day. Because the community gardens use water very frugally (3 m^3/ha/day was measured at Sondela), 30 m^3/day may mean a garden of about 10 hectares. This, however, may not be practical in terms of the land available and the number of households in the proximity who would like to be part of a garden - but, nevertheless, the bigger the garden the better within practical limits.

The World Bank estimated that water for irrigation is only economic if it costs less than 33 c/m^3. (This is in 1990 SA cents - equivalent to 10 c/m^3 for 1982 US cents). This figure can only be used as a very rough guide as it was based on international market prices. But, nevertheless, if this was used as a cut-off all the above pumps would be uneconomical at 3 m^3/day, whereas the PV "best case" and both diesel pumps would be economical above 6 m^3/day.

The default assumption used for all the other sensitivity analyses is an average water demand of 3 m^3/day. Although this would normally be considered extremely low, it is the most likely when considering community vegetable gardens. This average water demand was measured for Sondela vegetable garden (which is one hectare in area) over the whole year of 1987. A similar water usage was calculated for nearby Phumalanga garden from records for fuel usage for their diesel pump over the same period.

The average size of the fifty community gardens in this district is about 1 hectare. So for third world agriculture (the focus of this thesis) 3 m^3/day is the most reasonable assumption for the base case. However, for variables which are very energy dependent (such as fuel price and diesel system efficiency) the sensitivity analysis is done for a higher flow rate of 30 m^3/day. Few community gardens require more than this.

PV "normal" versus PV "best"

The graph above also indicates that the cost of pumped water from the PV "best case" is much less than that from the PV "normal case". Water from the "best case" costs about 40% that from the "normal case".

The difference between the PV normal and best cases emphasizes the importance of careful design and production of PV pumps. There are three main reasons why the "best case" is much cheaper than the "normal case":

a) The PV "best case" assumes that the path of the sun is physically tracked. The increased system efficiency results in a reduction of system size of 20% (for a 4.8 kWh/m^2/d day).

b) The PV "best case" assumes an efficiency of the pump itself of 58% instead of the 39% assumed for the "normal case" (at 13 metres head and 4.5 kWh/m^2/d). This efficiency is only achievable if the correct pump is used for the correct application, and the components of the system are well-matched. This improvement in pump efficiency results in a further 30% reduction in system size.

Unfortunately none of the PV pumps readily available in South Africa are designed to give good efficiencies at heads below 20 metres. However, with careful selection of pumps (possibly using a centrifugal pump) it may be possible to get efficiencies this high for the low heads and low flow rates considered in the "base case".

c) The unit capital costs of the "best case" are between 80 and 90% those of the "normal case". This is because the "best case" assumes that the Balance of System (BOS) costs could possibly be halved by modularization and standardization of the system.

So if physical tracking of the sun were used, and if the PV pump used were well-designed for the head, then the "best case" PV pump would be more appropriate. Otherwise, the "normal case" gives a better estimate of the present costs of a PV pump.

PV versus diesel

The above graph also shows that the cost of water from the PV "best case" is equal to that from diesel pumps at 3 m^3/d. It remains low enough as the water demand increases that it may well be chosen rather than a diesel pump even for higher water demands because of its other advantages.

On the other hand the cost of water from the PV "normal case" ranges from twice to four times that from a "normal" diesel pump as the water demand ranges from 3 m^3/day to 90 m^3/day. At low flow the other advantages of the PV "normal" pump may just justify its use - at higher flow this is unlikely.

Diesel "normal" versus "best"

The graph below shows that the difference between the diesel "normal" and "best" cases is not large.

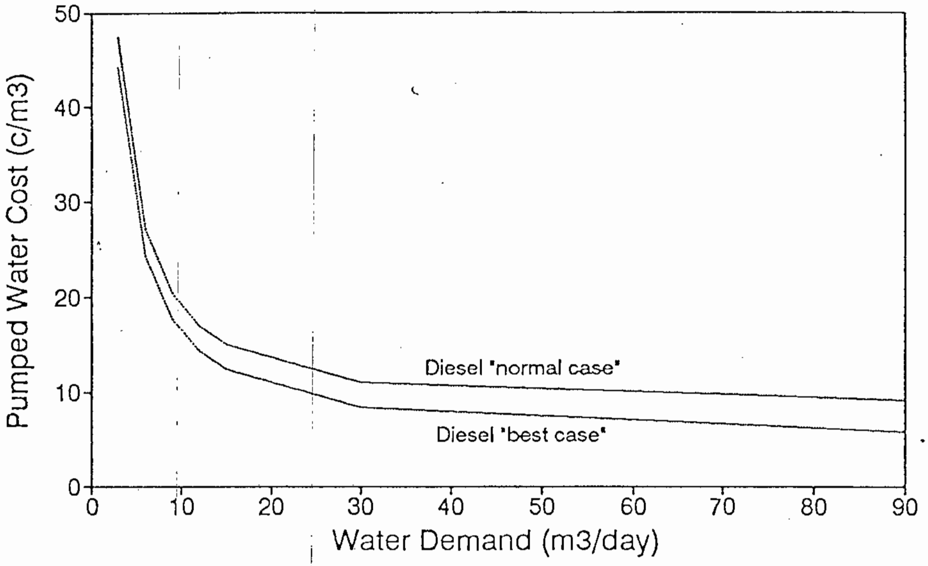


Figure 4.2: Diesel "normal" vs "best": The effect of water demand

The ratio between the "best" and "normal" diesel drops from 0.94 at 3 m³/day to 0.64 at 90 m³/day. So the difference is barely noticeable for small water demands, but fairly important for larger water demands.

The main reason for the difference in costs is the assumption on system efficiency: 12.6% is assumed for the "best case" as opposed to 7.4% for the "normal case". This is why the difference between the two becomes more important at high water demand - only then are the running costs (which are affected by the efficiency) a large proportion of the Life Cycle Costs.

Which set of assumptions is appropriate depends on the way in which the pump is operated. The "normal case" assumption assumes that the engine is run at 15% of its ideal load for 5 hours per session. This is based on records for one year for Phumalanga garden near Sondela. The "best case" is the best that can be obtained for the same amount of water storage available: it assumes that the pump is operated at ideal load until the reservoir is full (for about 45 minutes per session). As the average water demand increases so the pump is more likely to be run at full load, and the "best case" assumptions would become more applicable. (For a full discussion see Subsection 4.5.2.)

Petrol vs Diesel:

The graph below compares the performance of a petrol pump with the diesel "normal case".

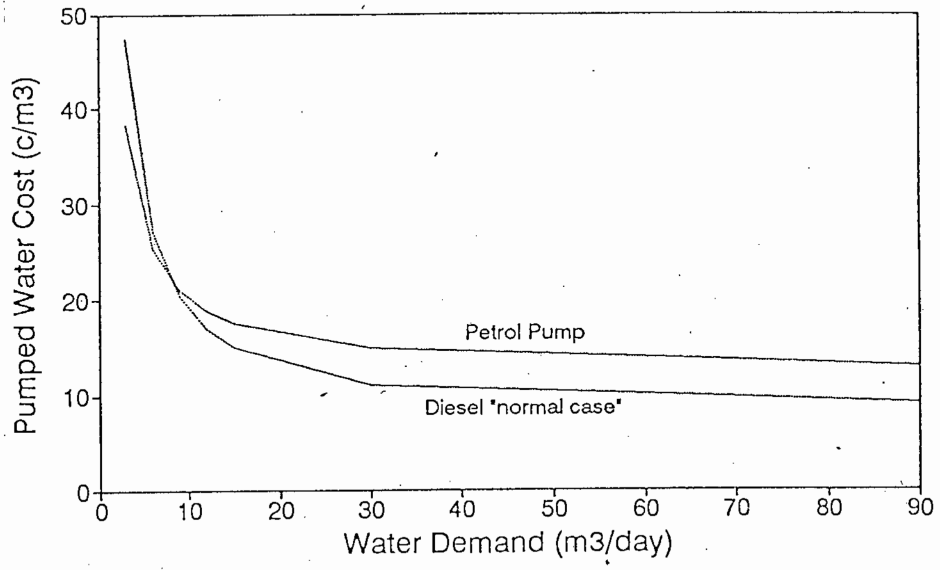


Figure 4.3: Petrol vs Diesel - The Effect of Water Demand on the Cost of Pumped Water

The graph shows that a petrol pump would be cheaper than a diesel pump below 10 m^3/day; but increasingly loses ground at higher flow rates. At 90 m^3/d, the cost of water from the diesel "normal case" is 73% that from the petrol pump (while the diesel "best case" is less than half the petrol).

As will be shown later the petrol pump has lower initial costs than the diesel engine, but higher costs for running, maintenance and replacement. So the petrol pump is cheaper for situations which favour low initial costs - i.e. low head, low flow rate, or a short project life. But the cost difference is not large even for the low flow and low head which is the default - so petrol should only be considered for very small loads or short projects.

PV versus ESKOM:

The following graph compares the cost of pumped water from PV pumps with that from electric pumps connected to the ESKOM grid.

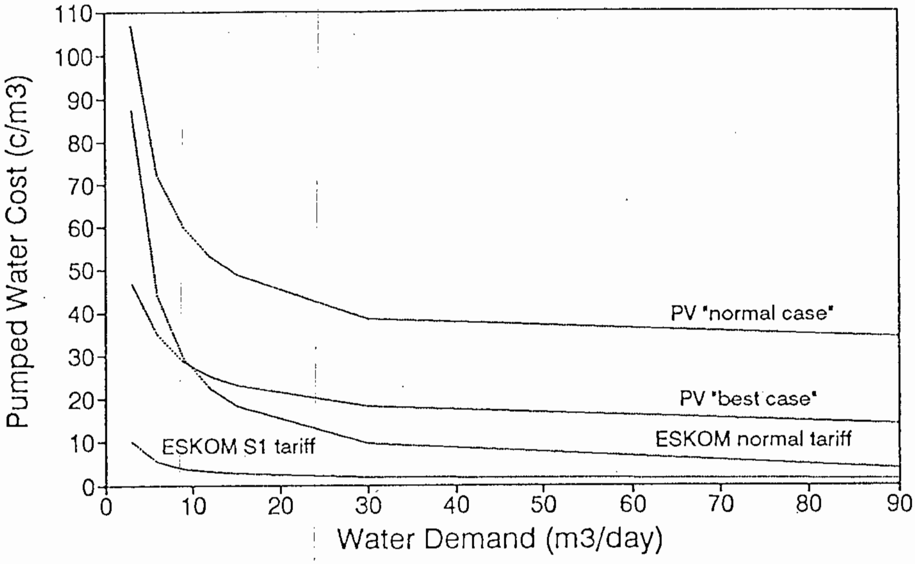


Figure 4.4: PV vs ESKOM: The Effect of Water Demand on the Cost of Pumped Water

The graph shows that where the ESKOM S1 tariff is available it should be the first resort under all circumstances: the cost of pumped water using the S1 tariff ranges from 10 to 1 c/m^3 as the water demand ranges from 3 m^3/day to 90 m^3/day. An electric pump connected to ESKOM is very reliable and requires little maintenance, and so is also preferable to the other alternatives in every other way.

But the S1 tariff is unlikely to be introduced widely in semi-rural areas in the near future. Nevertheless the costs for the S1 tariff are included in many of the graphs below as a reminder to examine whether it may be available at any prospective site before considering other alternatives.

The normal tariff: If the normal ESKOM tariff is used the cost of water varies a lot with the site - the distance from the grid, the number of consumers connecting up simultaneously (and the number of people sharing one account). The effect of these factors will be examined later. The default case (used for the above graph) is for a pump 1 kilometre from the grid, with three consumers wanting to connect up simultaneously (and one consumer per account).

The graph shows that under these conditions the normal tariff would be cheaper than the PV "normal case" at 3 m³/day, but nearly twice the price of the PV "best case". For this water demand a community garden would probably choose the PV pump (assuming there is one that matches the assumptions of the "best case" - in particular one that is efficient at the required head).

But the costs the ESKOM normal tariff drop very quickly and it is cheaper than the PV "best case" from 12 m³/day upwards. It drops to the same price as the diesel "normal case" at 30 m³/day. However, because it is much more convenient and reliable it may well be preferred to a diesel pump from about 15 m³/day upwards.

The reasons for this sharp drop in the costs of the ESKOM normal tariff with increasing flow will be discussed when the break-down of costs is given (see page 174).

b) The Effect of the Peak Demand Factor

The above discussion considers only the effect of the average daily water demand. The following graph shows the effect of the Peak Demand Factor on the cost of pumped water.

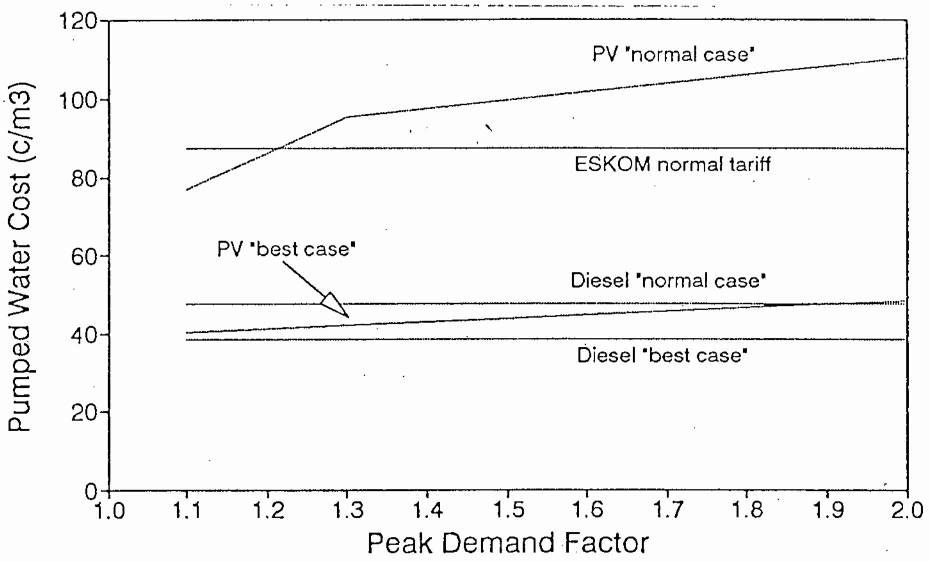


Figure 4.5: The Effect of the Peak Demand Factor on the Cost of Pumped Water

The costs of PV pumping go up almost proportionally with Peak Demand Factor. So, for example, while the PV "normal case" is cheaper than the ESKOM normal tariff at a Peak Demand factor of 1.1, it is more expensive if the Peak Demand Factor is greater than 1.2. (The sudden drop in the costs of the PV "normal case" at Peak Demand Factors below 1.3 is because the energy demand from the pump reduces enough for a smaller and cheaper type of PV pump to be used.)

It is understandable that the effect of the Peak Demand Factor is large - the PV pump is sized for the worst month and so much of its capacity is wasted throughout the rest of the year. Thus PV pumping is best suited to situations where the water demand and the insolation follow very similar patterns. For example, water for domestic use would have a more-or-less even consumption throughout the year, and so a Peak Demand Factor closer to 1 would be applicable. Water for irrigation would be a suitable application if the water demand increased during the summer as the insolation does; but members of gardens such as Sondela have other demands on their time during the summer and the heat discourages intensive gardening.

c) The Effect of Average Daily Water Demand on the Cost of Energy (c/kWh)

So it is not simple to account for the total effect of water demand on the costs as the Peak Demand Factor must also be taken into account. Although this must always be borne in mind, it is simpler to consider only one factor at a time. So the analysis of the effect of average daily water demand is continued below assuming the default Peak Demand Factor of 1.83.

The reason for using this unit of comparison (c/kWh) is that it can be compared to reference points such as the cost of electricity. The kilowatt hours for a particular application were calculated as the amount of energy an electric pump would draw to do the same pumping job. (A system efficiency of 48% was assumed for the electric motor and pump. So for this calculation the kilowatt hours were made equal to the hydraulic energy divided by 0.48.)

The graph below compares the costs of PV pumping with those of diesel pumping.

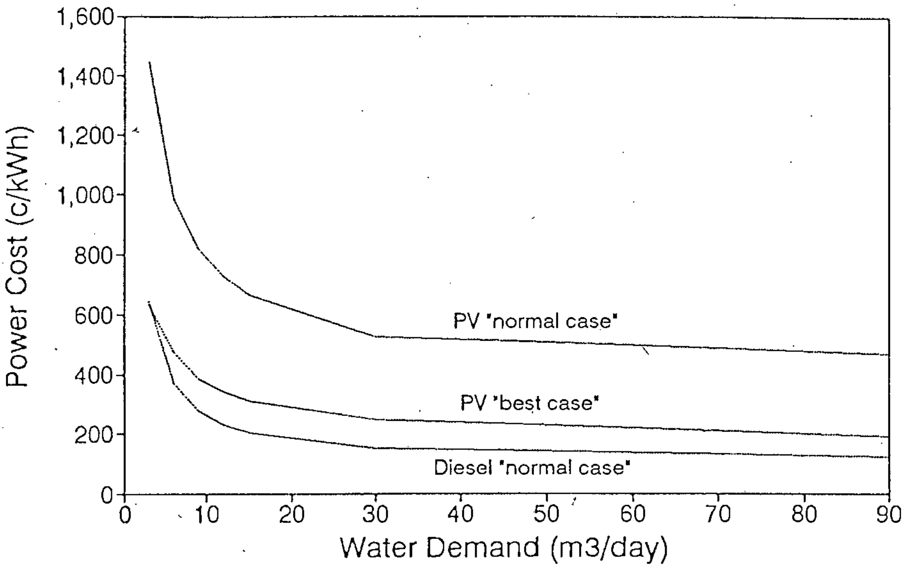


Figure 4.6: PV vs Diesel - The Effect of Water Demand on the Cost of Energy

The costs of energy for water pumping in rural areas is very high. For example as the water demand ranges from 3 to 90 m^3/d, the cost of the PV "normal case" drops from 1400 c/kWh to 570 c/kWh, while that of the diesel "normal case" drops from 630 to 110 c/kWh.

These costs can be compared to cost of ESKOM electricity of 17.8 c/kWh (for the normal tariff for the first 1000 units). However, in this comparison it must be remembered that the ESKOM charge of 17.8 c/kWh is only for energy - whereas the costs of water pumping shown above include the costs of the pumping system, its installation, maintenance and replacement costs, and the wages of the operator for the diesel pump.

This is further emphasized by the following graph which compares electric pumps with PV pumps.

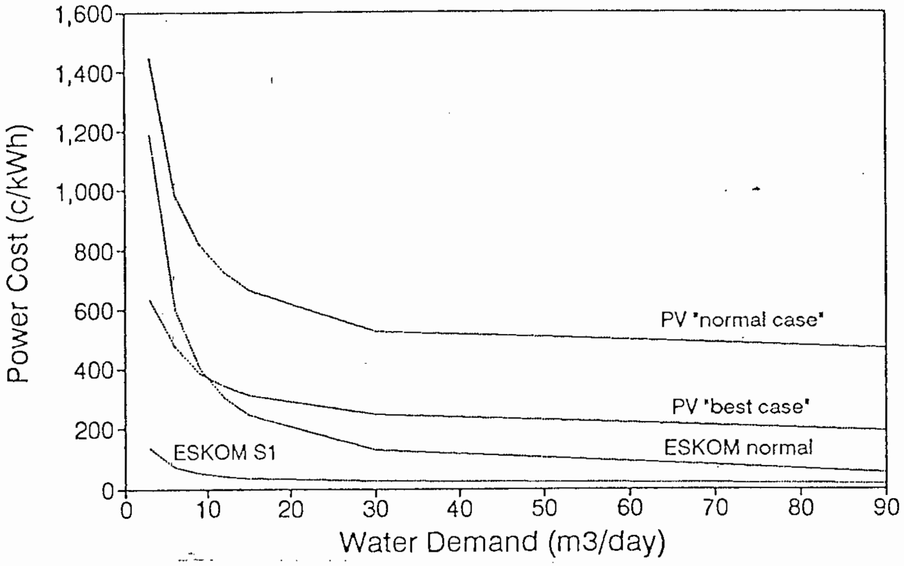


Figure 4.7: PV vs ESKOM - The Effect of Water Demand on the Cost of Energy

As the water demand ranges from 3 to 90 m^3/day, the cost of pumping using the normal tariff drops from 1200 c/kWh to 50 c/kWh, while that using the S1 tariff drops from 140 c/kWh to 17 c/kWh.

So although the energy charge for the ESKOM normal tariff is 17.8 c/kWh, the overall cost of energy for pumping using the ESKOM tariff is between 1200 c/kWh and 50 c/kWh (because it includes the costs of the pump, connection charges, monthly account charges and line charges).

However, when these other charges form only a minor part of the Life Cycle Costs, the overall costs of pumping can approach the energy charges: the costs for the S1 tariff at 90 m^3/day are 17 c/kWh - approaching very closely the S1 tariff energy charge of 16 c/kWh. (However, this is also partly due to the discounting of future expenses: because future energy charges are discounted, when the energy charges are calculated from the Life Cycle Costs they come to 10 c/kWh - instead of 16 c/kWh which is their actual value). In comparison, the costs of pumping using the S1 tariff at 3 m^3/day are much higher (140 c/kWh) because here the costs of the pump form a significant part of the Life Cycle Costs.

So the costs of water pumping will necessarily be more than the cost of energy from ESKOM. But this reference point is the ideal against which other alternatives can be judged.

d) Cost per member per month

In the final analysis the most important criterion is how much each member of a community garden would need to contribute to run a particular pump. It is assumed that all of the pumps are bought using a soft loan - so that the expenses are spread evenly over the length of the project. It is also assumed that there are 50 members per hectare of garden (based on the number of members at Sondela garden).

The graph below shows the costs per member for PV, diesel and electric pumps.

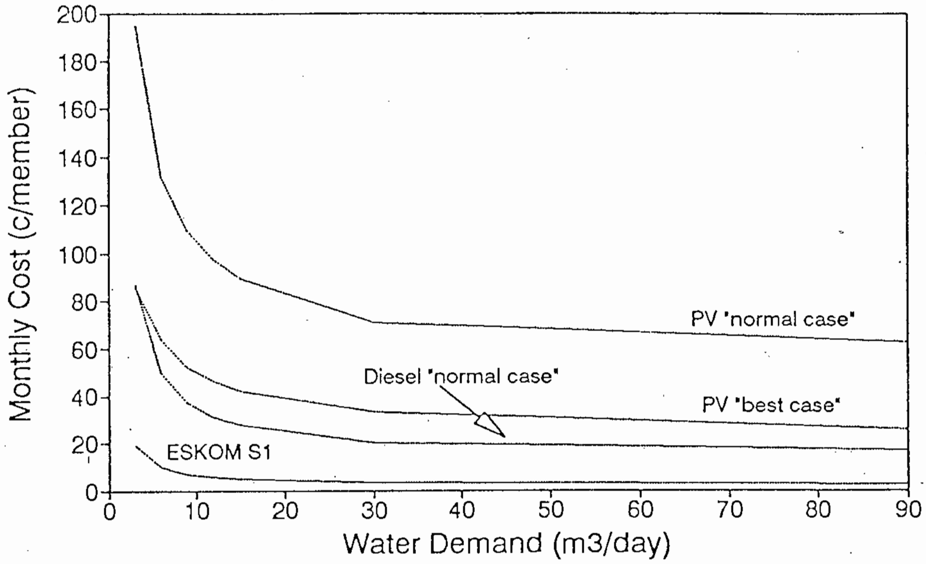


Figure 4.8: The Effect of Water Demand on the Cost per Member per Month

As the water demand increases from 3 to 90 m^3/day, the monthly cost per member drops from 195 to 62 cents for the PV "normal case", and from 85 cents to 25 cents for the PV "best case". Over the same range, the cost of the diesel "normal case" drops from 87 to 17 c/member/month while that of an electric pump using the ESKOM S1 tariff drops from 19 to 2 c/member/month.

This puts into context the importance of the cost difference between pumps. For example, at 30 m^3/day the diesel "normal case" would cost each member 18 cents per member per month, whereas the PV "best case" would cost almost double - 34 cents per member per month. However, the members of a community garden in a remote rural area would most likely choose to spend an extra 16 cents per household per month for the PV pump in order to avoid the chore of collecting diesel from town and of running and maintaining the diesel pump.

This shows that it can be confusing to compare pumps simply on their Life Cycle Costs. For the above case the Life Cycle Costs of the PV pump would be almost double those of the diesel pump. This is such a large increase that the PV pump could well be excluded on these grounds. However, when the costs per household per month are examined it is clear that the increase is not that significant.

But one crucial assumption here is that the costs of the pump can be spread evenly over the lifetime of the project. This requires a loan and therefore a body which is prepared to risk financing the project. This may well be possible through a body such as ESKOM (see Section 5.7).

But if a loan is not possible, the gardens are likely to favour strongly pumps with a low initial costs. Gardens often save for years to get enough to buy a cheap petrol pump or to put down a deposit on a diesel pump.

For example, for the application sited above it was decided that the PV "best case" would most likely be preferable to the diesel "normal case" (on the basis of the cents per member per month). However, the initial cost of the PV "best case" is more than five times that of the diesel pump - R 36,400 as opposed to R 6,800. Without financing (and without the financial understanding to make the calculation done here) the gardeners would almost certainly choose the diesel pump. So one of the most important questions to be addressed by marketers of PV pumps for a "third world" market is financing (see Section 5.7).

e) Life Cycle Costs

All the above unit costs (c/m^3, c/kWh etc) were calculated from the Life Cycle Costs (LCC). Unit costs were used for the comparisons above because they are more tangible quantities. However, it is also instructive to examine graphs for the Life Cycle Costs.

PV versus Diesel

Shown below are the Life Cycle Costs of the PV and diesel pumps.

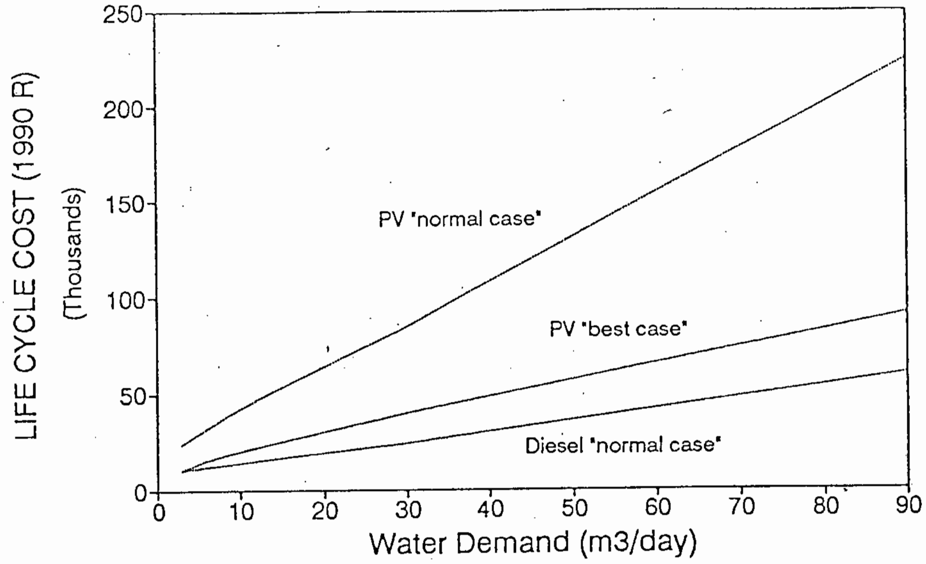


Figure 4.9: PV vs Diesel - The Effect of Water Demand on Life Cycle Costs

The graph shows that PV pumps are affected more by increasing water demand than are diesel pumps. This is because a greater percentage of the LCC of PV pumps is energy dependent. If the water demand doubles the size of the PV pump will double (almost). Larger PV systems have a lower unit capital cost so the LCC of the system will not quite double but it still increases considerably.

In contrast if the water demand for a diesel pump doubles, the initial cost may not increase at all, or may increase only slightly. The initial cost is the largest component of the LCC at low water demands. The running costs and the maintenance costs will, however, double. But these form a small proportion of the LCC - so the gradient in the graph is less steep than for the PV pumps.

The graph also illustrates the effect of efficiency on the gradient of the graph. The PV "normal case" has a much lower efficiency than the PV "best case". Consequently the LCC for the "normal case" rises much more quickly with increasing water demand than that for the "best case".

Conventional Pumps

The graph below, which compares the Life Cycle Costs of all the conventional pumps considered, illustrates the effect of the energy dependence of the pump even more clearly.

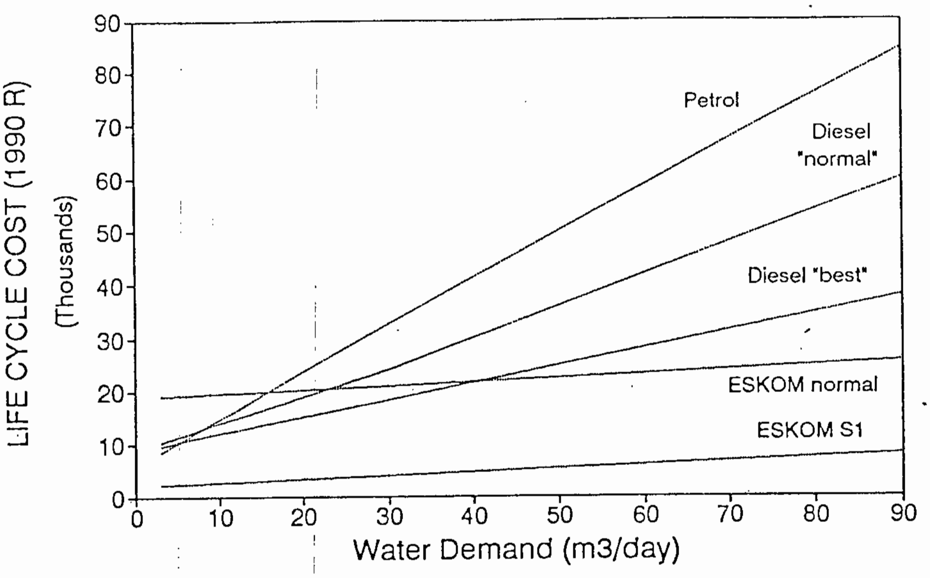


Figure 4.10: Conventional Pumps - The Effect of Water Demand on Life Cycle Costs

The cost of energy for the diesel and petrol pumps is much higher than that for the electric pumps. Energy charges for electricity are very low. Consequently the graphs for the electric pumps are almost flat while those for the diesel and petrol pumps rise more sharply with increasing water demand. The gradient for the petrol pump is steepest because it has the lowest efficiency; it is followed by the diesel "normal case" and then by the diesel "best case".

The graph also indicates that the ESKOM normal tariff is most advantageous when much energy is being used - and so for high water flow, high heads, long project lengths. This is because the energy charges are very small in comparison to the fixed charges which comprise the monthly account charges, and the line charges for extending the grid. It is because of these high fixed charges that the ESKOM normal tariff does not fare well for low water demands, but gets progressively better as the water demand increases.

The graph also illustrates reason for the differences between the diesel normal and best cases: their LCC's are almost equal at 3 m^3/day, but because the "best case" is more efficient its LCC increases more gradually until it is 64% that of the "normal case" at 90 m^3/day.

f) Break-down of the Life Cycle Costs

An analysis of the break-down of the Life Cycle Costs of a pump will indicate which component costs are important, and so how the Life Cycle Costs will be affected by a change in a particular condition or in an assumption. Each pump is analysed in turn below. This analysis gives the basis for understanding the whole of the sensitivity analysis done below on the site dependent parameters and in Section 4.3 on other parameters.

PV "normal case"

The graph below gives the break-down for the PV "normal case" and its variation with water demand.

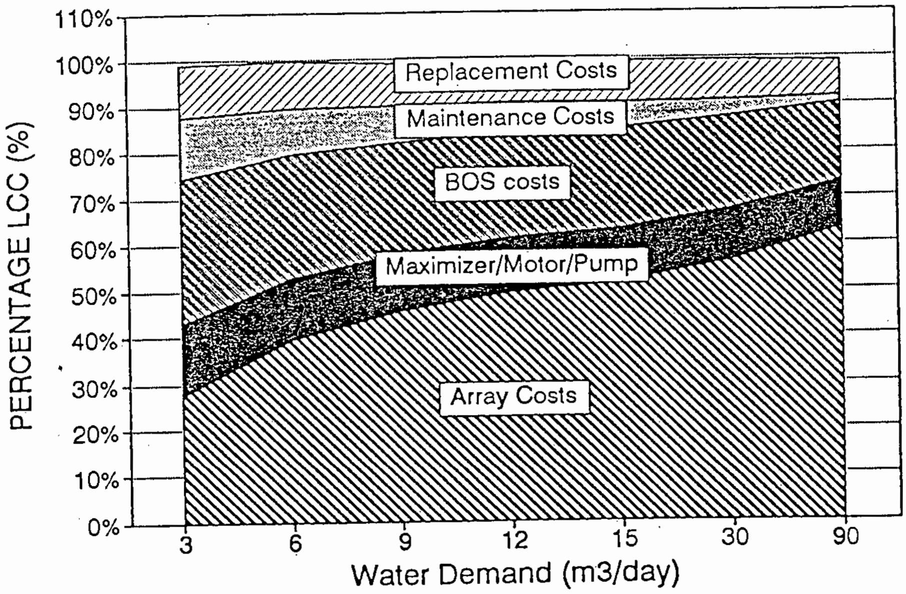


Figure 4.11: PV "normal case" - Break-down of Life Cycle Costs

The initial costs of the PV pump have been further broken down into the costs of the array, the other major components (power maximizer, motor and pump) and the Balance of System Costs (BOS costs) for the sake of interest. (The initial costs for this thesis do not include the costs of the delivery pipe, water storage and the reticulation system).

So the bottom three sections of the graph make up the initial costs. It can be seen that the initial costs form by far the largest proportion of the Life Cycle Costs: ranging from 75% at 3 m^3/day to 91% at 90 m^3/day. An advantage of this is that the Life Cycle Costs of a PV pump can be accurately estimated once the initial cost is known - unlike those of a diesel pump which depend very much on the way the pump is run.

Because the initial costs form such a large percentage of the LCC for PV pumps it is important to examine in more detail the factors which contribute to the initial costs. There are three quantities which determine the initial costs: the system efficiency and the critical daily insolation which together determine the size of the system in terms of the W_p rating of the array; and, thirdly, the unit capital costs which determine the cost of a system once it has been sized (in R/W_p).

The break-down of the initial costs show that the price of PV modules has a large effect on the Life Cycle Costs of the system, particularly for high water demands. The cost of the array forms 28% of the LCC at 3 m^3/day; but 63% of the LCC at 90 m^3/day. The cost of the major components (power maximizer, motor and pump) is relatively small - ranging from 15% to 10%. The BOS costs, however, are quite important: ranging from 32% to 17% of the Life Cycle Costs. This is an area in which PV pump suppliers can try to cut costs by modularization and standardization.

Maintenance costs for a PV pump do not increase much with increasing system size. This is because the maintenance costs are largely for travel and time and so do not depend on the size of the system. For this reason the proportion they form of the LCC decreases from 14% at 3 m^3/day to 1% at 90 m^3/day.

The replacement costs of a PV pump increase with increasing system size - because of the increasing size and thus cost of all of the components. However, they do not increase proportionally with the initial cost because the array is not replaced (as its lifetime is nearly the same as the project's). So the proportion the replacement costs form of the Life Cycle Costs decreases slightly from 11% to 8% as the water demand increases from 3 to 90 m^3/day.

So the following parameters have a large influence on the Life Cycle Costs of a PV pump and will be examined further below and in Section 4.3: critical daily insolation, PV system efficiency, unit capital costs, and PV module price.

PV "best case"

The graph below gives the break-down for the PV "best case".

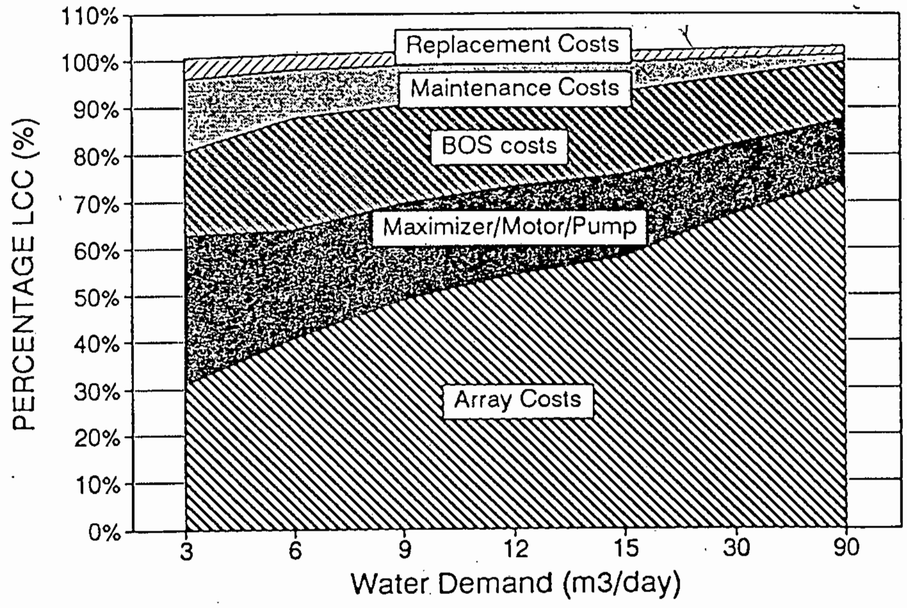


Figure 4.12: PV "best case" - Break-down of the Life Cycle Costs

The PV "best case" shows much of the same pattern as the "normal case". One notable difference is that the salvage value of the system is not negligible: ranging from 1% of the LCC at 3 m^3/day to 3% at 90 m^3/day. This is shown on the graph by the fact that the sum of the other component costs is more than 100%.

The reason for this high salvage value is that the lifetime of the array is assumed to be 25 years - 5 years longer than the project length. For this reason there is some return on the array at the end of the project life. (A double declining balance method was used to calculate salvage value).

The initial costs form a slightly higher percentage of the LCC than for the "normal case": ranging from 74 to 100% (remembering that the sum of all component costs ranges from 101 to 103% because of salvage value). The initial costs form a larger percentage mostly because longer lifetimes have been assumed for the motor and the pump and so the replacement costs are less: ranging from 5% to 2%. The maintenance costs form a larger percentage of the LCC than for the "normal case" simply because the LCC is smaller. Maintenance costs range from 16% to 2%.

The only difference between the assumptions on unit capital costs for the normal and best cases is that the BOS costs for the best case are half the normal case. This is shown in the graph by the proportion the BOS costs form of the initial costs.

Diesel "normal case"

The graph below gives a break-down for the diesel "normal case".

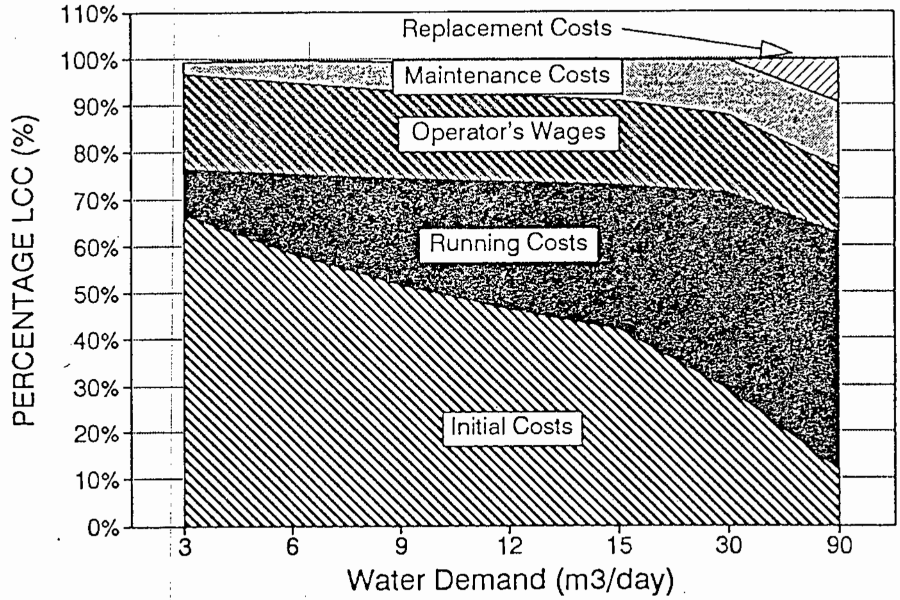


Figure 4.13: Diesel "normal case" - Break-down of the Life Cycle Costs

The break-down for the diesel pump contrasts in the following ways with that of the PV pumps given above.

a) The initial costs form a smaller and declining percentage of the LCC: they drop from 67% at 3 m³/day to 12% at 90 m³/day. (On the other hand those for the PV "normal case" increase from 75% to 91%.)

b) Diesel pumping incurs two extra expenses which the PV pump does not incur. The first is running expenses (the cost of diesel fuel). This is an important component of the costs for high water demands: it increases from 10% of the LCC at 3 m³/day to 51% at 90 m³/day. The second extra cost is for the wages of the pump operator. This ranges from 20% of the LCC at 3 m³/day to 14% at 90 m³/day.

c) The maintenance costs increase with increasing water demand because the pump works longer hours. They rise from 3% at 3 m³/day to 14% at 90 m³/day. (In contrast the maintenance costs of a PV pump do not increase with water demand, and so their percentage of the LCC drops from 14% to 1% over the same range).

d) The replacement costs do not become important until the water demand is over 30 m^3/day. At 90 m^3/day they form 9% of the LCC. This is because the diesel engine is oversized for low flow rates, and consequently works very few hours per week. In contrast the PV pump will work as long as the irradiance is sufficient (averaging 4.8 hours per day for a site with a critical insolation of 4.8 kWh/m^2/d). So replacement costs for a PV pump are important even at low flow (they form about 10% of the LCC at 3 m^3/day).

The parameters which are important for further analysis vary with water demand. At low flow the initial costs form the highest proportion of the LCC. These can be accurately estimated and do not require further analysis. The only other component cost which is important at low flow is that for the operator's wages - it forms 20% of the LCC at 3 m^3/day. However, because the operator's wages depend so much on the specifics of the situation, it is better that adjustments are made with a particular application in mind. The range of possible operator's wages is so large that it is meaningless to analyse further the sensitivity of the LCC to this quantity.

For a high water demand, however, the biggest contribution to the LCC is the running cost (51% at 90 m^3/day). The factors which determine the running costs are: diesel system efficiency, fuel price, and fuel escalation rate. The discount rate is also likely to affect the LCC of diesel engines high water demands considerably as the initial costs contribute only a small percentage to the LCC - so most of the expenses are made later during the lifetime of the project and will benefit from discounting.

So the following factors are important in determining the Life Cycle Costs of diesel pumps at high water demand: diesel system efficiency, fuel price, fuel escalation rate and discount rate. These will be examined in the sensitivity analysis (Section 4.3).

Diesel "best case"

The following graph gives a break-down for the diesel "best case".

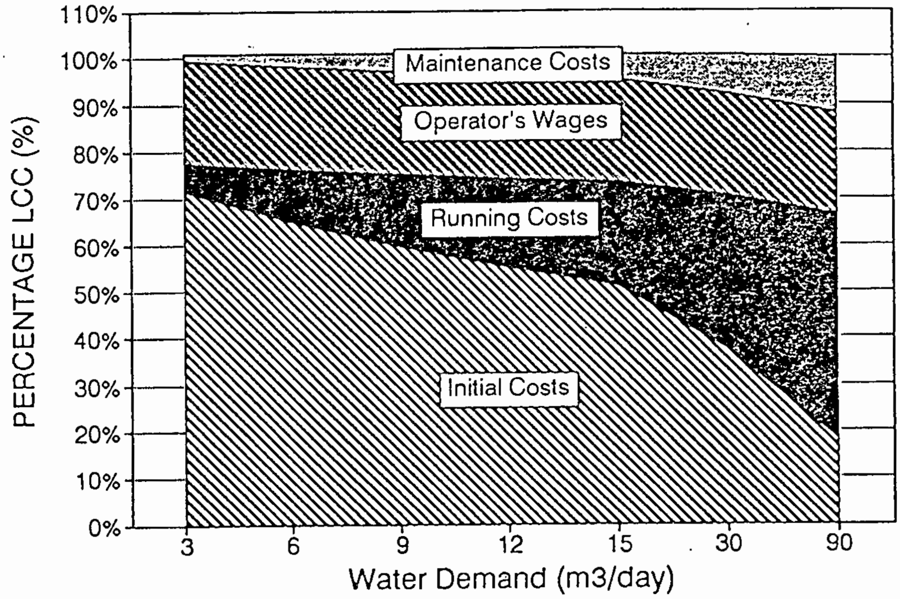


Figure 4.14: Diesel "best case" - Break-down of Life Cycle Costs

The pattern is very similar to the "normal case". The running costs form a lower percentage of the LCC because the system efficiency of the "best case" is assumed to be 12.6% rather than 7.4% for the "normal case". This is the main factor that contributes to the difference between the "best case" and the "normal case": at 90 m^3/day the LCC of the "best case" is 63% that of the normal case.

Maintenance costs are also slightly lower for the diesel best case (50 c/hour rather than the 60 c/hour assumed for the "normal case").

And replacement costs do not become a factor at 90 m^3/hour because the lifetimes assumed for the "best case" engine and pump are almost twice the length of the "normal case" lifetimes. (The lifetimes for the engine and pump are 20,000 hours and 15,000 hours respectively; in comparison with 10,000 hours and 8,000 hours for the "normal case").

Petrol pump:

The following graph gives a break-down for a petrol pump.

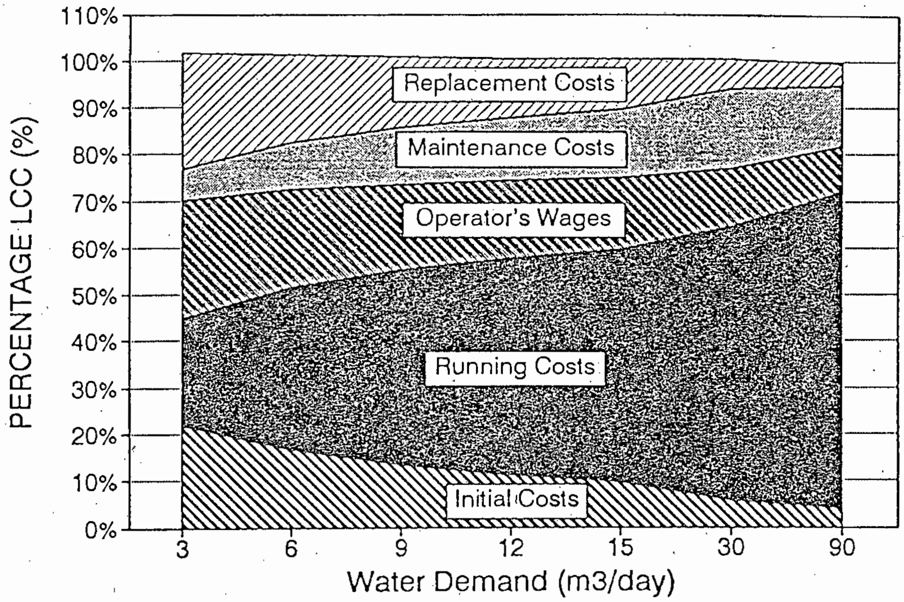


Figure 4.15: Petrol Pump - Break-down of Life Cycle Costs

The pattern is quite different to that for the diesel pump in the following ways:

a) The initial cost is much lower than that for diesel pumps especially for low water demand - it forms 23% of the LCC at 3 m^3/day rather than 68% for the diesel "normal case".

b) The running cost is higher than that for the diesel "normal case". It rises from 23% at 3 m^3/day to 68% at 90 m^3/day (compared with 10% to 51% for the diesel pump). This is because the system efficiency of the petrol pump is lower: 4.8% compared with 7.4% for the diesel "normal case".

c) The operator's wages are the same for both petrol and diesel.

d) The maintenance costs of the petrol pump are higher than for the diesel "normal case" both because the hourly rate is higher (100 c/hour as opposed to 60 c/hour) and because the petrol pump works longer hours for low water demands because it is less powerful. Maintenance costs form between 7% and 13% of the LCC for the petrol pump.

e) The replacement costs of the petrol pump are significant even at low water demands: they range from 25% at 3 m^3/day to 5% at 90 m^3/day. This is both because the petrol pump works longer hours than the diesel and because it has a shorter lifetime (6,000 hours as opposed to the 10,000 hours for the diesel "normal case").

The result of the above is that the LCC of the petrol pump is initially 81% of the LCC for the diesel "normal case" (at 3 m^3/day) but it rises to 141% at 90 m^3/day.

In summary, the petrol pump has a much lower initial cost (particularly at low flow rates) than a diesel pump but considerably higher running and maintenance costs. So the petrol pump should be preferred only in situations which favour low initial costs: short project length, low water demand and head, and high discount rate. These factors are examined further below and in Section 4.3.

ESKOM normal tariff

The following graph gives a break-down for electric pumps connected to the ESKOM grid on the normal tariff. The running costs have been divided into "energy charges" for the number of kilowatt-hours used and "meter charges". The meter charges comprise the account charges (43 R/month) for the administration of the account and the line charges for extending the grid (24 Rand per 100 metres per month).

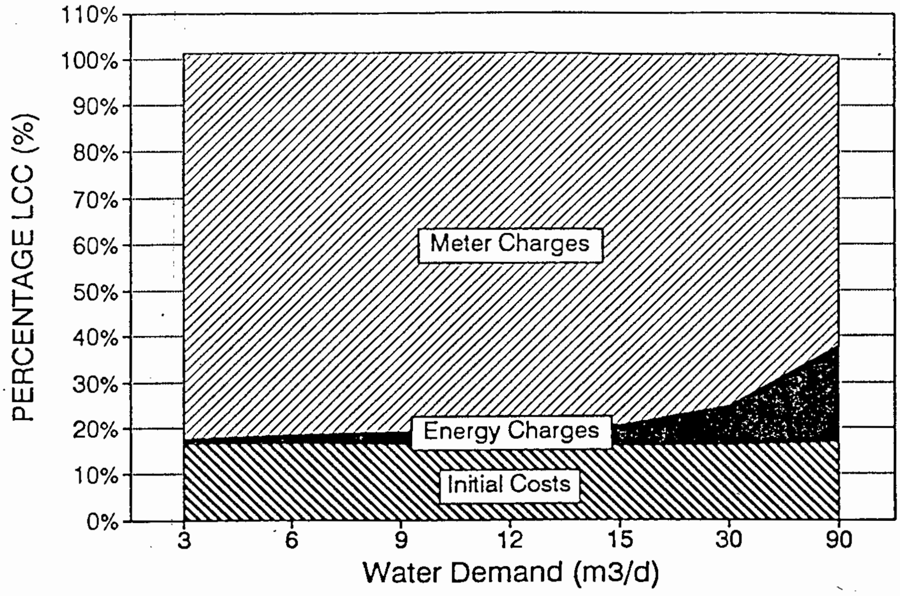


Figure 4.16: ESKOM normal tariff - Break-down of Life Cycle Costs

The most striking feature of the graph is the high proportion that the meter charges form of the Life Cycle Costs: ranging from 84% at 3 m³/day to 63% at 90 m³/day. The monthly account charge of 43 R/month is fixed. But the line charges depend on the distance of the pump from the grid, and on the number of consumers in the area who want to connect simultaneously (as they share the line charges out equally). So these two factors have a considerable effect on the LCC and are examined further below (Subsection 4.2.4 and onwards).

The initial costs form an almost constant 17% of the Life Cycle Costs. Because the initial costs are low the discount rate will have an important effect (as most of the costs are recurring costs). The energy charges are low - initially almost negligible. They rises from 1% at 3 m³/day to 21% at 90 m³/day. And the salvage value is an almost constant at 1%. This is for the recoverable deposit of R 750 paid on connecting to ESKOM.

The maintenance costs were assumed negligible. And replacement costs are zero because it is cheaper to increase the size of the pump than to run it long hours and so need to replace it. So the computer model put a limit on the maximum number of hours per day that the pump is allowed to work in order to avoid replacement costs.

ESKOM S1 tariff

The graph below gives a break-down for electric pumps connected to ESKOM on the S1 tariff.

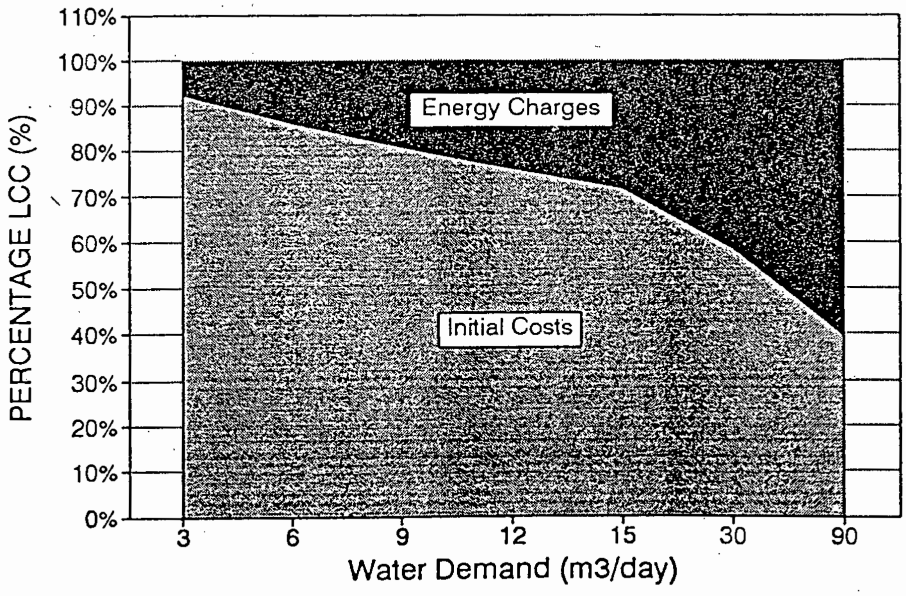


Figure 4.17: ESKOM S1 tariff - Break-down of Life Cycle Costs

The main difference between the ESKOM S1 and normal tariffs is that the S1 tariff does not have the monthly account charges and line charges. For this reason the S1 tariff is very much cheaper. Another change is that the initial charges are less because the charges of connection to ESKOM are R 30 for the S1 tariff as opposed to R 1185 for the normal tariff (which includes the recoverable deposit).

So although the initial charges are less than for the normal tariff, they nevertheless contribute a much higher proportion of the LCC: ranging from 92% to 40% (as opposed to an almost constant 17% for the normal tariff). This is because the LCC for the S1 tariff is so much less than that for the normal tariff.

For the same reason the energy charges, which are similar for both tariffs, form a much larger percentage of the LCC of the pump connected on the S1 tariff: ranging from 7% at 3 m^3/day to 60% at 90 m^3/day.

Both the initial costs and the energy costs for an electric pump on the S1 tariff are so low that there is no point doing a sensitivity analysis on them - the S1 tariff is the best under all circumstances. The only guess-work necessary is in deciding if and when the S1 tariff will be introduced into a particular area. See Subsection 4.5.3 for further discussion.

4.2.2 The Effect of Head

The second site dependent factor which will be examined is the head to which the water is pumped. This is the total head: it includes both static and dynamic heads.

The effect of head is similar to that of the water demand as both of them affect the energy demand on the pump. So the graphs for the effect of head on Life Cycle Costs and their break-downs show very similar patterns to those for the water demand. They are thus not discussed here - the reader can refer to tables in Appendix 4.2.2 or to the graphs in Section 4.2.1. Only unit costs are discussed below.

There is only one difference between the effects of head and water demand on the LCC's: the efficiency of the PV "normal case" at 45 metres and above is 1.5 times its efficiency at 13 metres. This is because the Mono Pump operates more efficiently at higher heads.

a) Cost of Pumped Water (c/m3)

PV versus Diesel:

The following graph shows the effect of head on PV and diesel pumps.

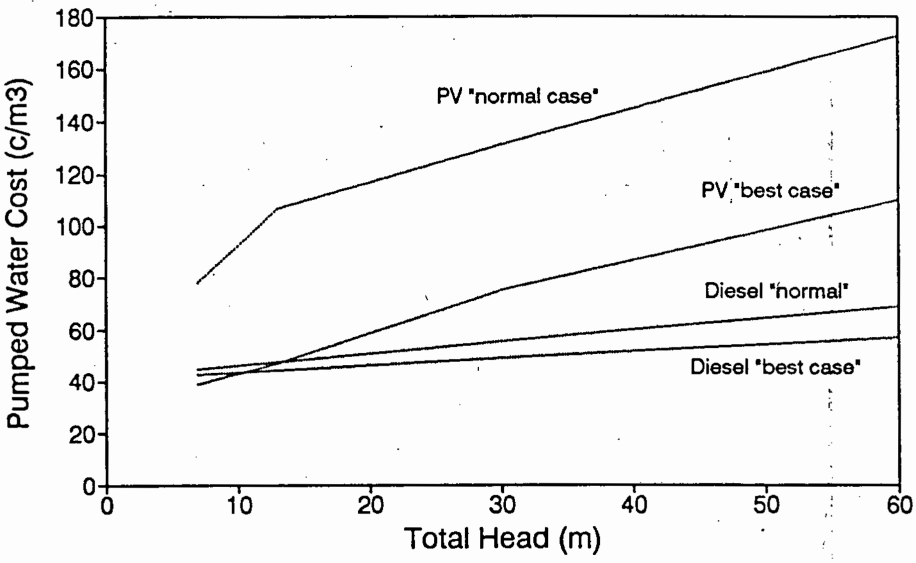


Figure 4.18: PV vs Diesel - The Effect of Total Head on the Cost of Pumped Water

As expected the cost of pumped water from a PV pump rises faster than that from a diesel pump with increasing head. This is because the Life Cycle Costs of the PV pump consist almost entirely of capital and replacement costs all of which are affected directly by the increase in head as a larger system must be used. In comparison only the running costs and maintenance costs of the diesel pump are strongly affected by an increase in head. These form a smaller portion of the Life Cycle Costs of diesel pumps.

The graph shows that at heads below 13 metres the PV "best case" is as cheap as diesel (for the default water demand of 3 m^3/day). Above that the diesel pumps steadily gain ground. However, in order to avoid the problems of fuel collection and maintenance a community garden may well choose the PV "best case" up to about 40 metres (see Subsection 5.6.2).

The World Bank estimate of the cut-off point for economic supply of irrigation water is 33 c/m^3. For the default water demand of 3 m^3/day, none of the pumps are economic. However, for a slightly higher water demand (6 m^3/day) both the PV "best case" and the diesel pumps would be economic - but only at low heads.

This emphasizes the importance of PV designers concentrating on the market for sites with low head and low flow rate. Irrigation (especially for a third world situation) is only economical at low heads. And PV pumps rival diesel pumps only at low flow rates.

At the moment, though, all the PV pumps readily available in South Africa are positive displacement pumps which tend to have low efficiencies at low head. It may be possible to find a centrifugal pump that operates efficiently at both a low head and a low flow rate. The PV "best case" assumes a pump efficiency of 58%, and this case is therefore only valid if a pump is found which is this efficient at low heads and low flow rates.

PV vs ESKOM:

The effect of head on the cost of pumped water from electric pumps is shown below.

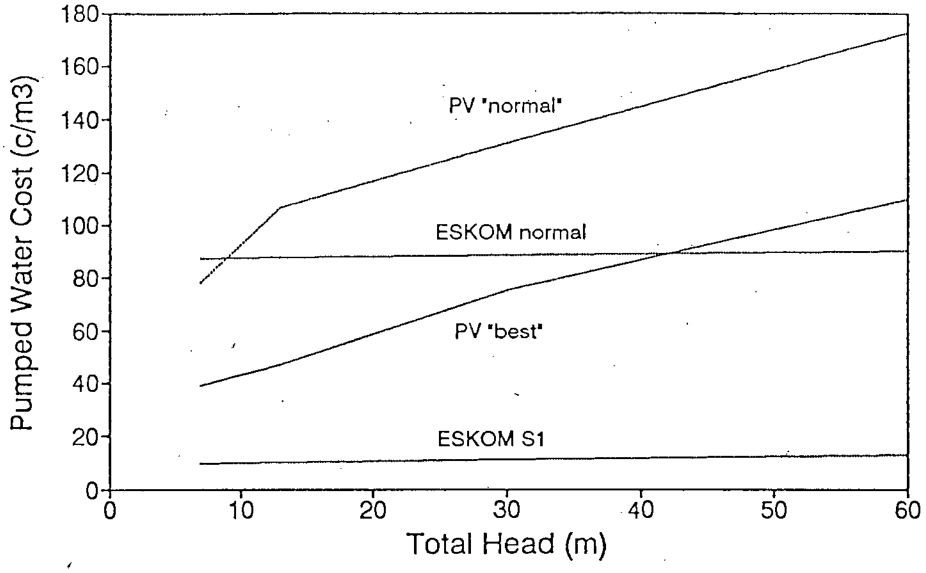


Figure 4.19: PV vs ESKOM - The Effect of Head on the Cost of Pumped Water

As expected the cost of pumped water from an electric pump hardly increases with increasing head - because the energy charges for electricity are so low. Thus at a low head of 7 metres both PV pumps are cheaper than the ESKOM normal tariff (for the default conditions of 1 kilometre to the grid and three consumers connecting up simultaneously, and 3 m^3/day water demand).

However, the difference between the PV "normal case" and the ESKOM normal tariff is so small that ESKOM is likely to be preferred to it because of reliability. Whereas the PV "best case" is considerably cheaper than the ESKOM normal tariff and is likely to be preferred. The PV "best case" remains cheaper than ESKOM normal tariff until the head is about 45 metres.

b) The Cost of Energy (c/kWh)

The cost of energy calculated here is the equivalent for a 48% efficient electric pump. (See the discussion in Subsection 4.2.1 for a full explanation).

The graph below shows the cost of energy for diesel and PV pumps.

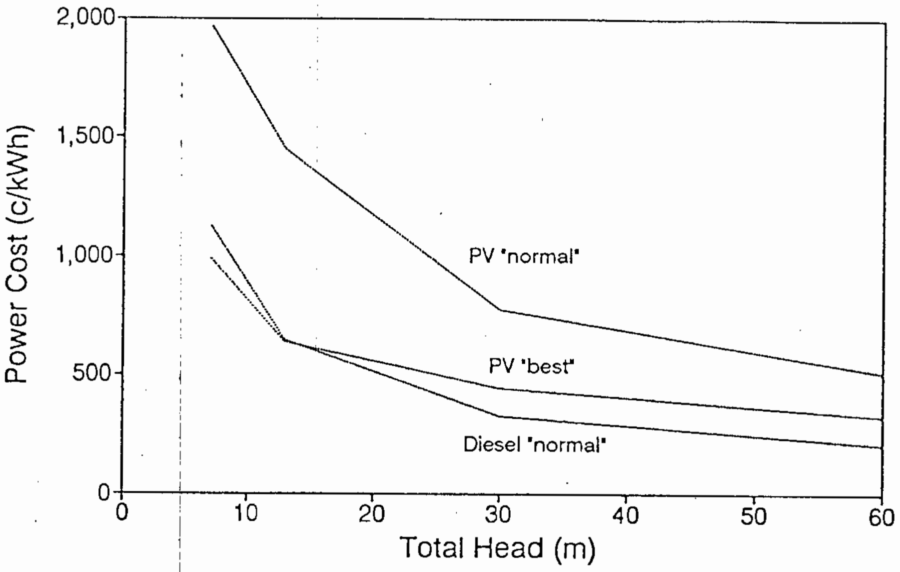


Figure 4.20: PV vs Diesel - The Effect of Head on the Cost of Energy

The cost of energy for all of these pumps drops with increasing head. The cause for costs of the PV "normal case" dropping is the increasing system efficiency and dropping unit capital costs with increasing head. For the PV "best case" it is only the dropping unit capital costs (as the system efficiency is not dependent on the head). The cause of the costs of the diesel pump dropping is the fact that the initial costs (which contribute a large portion to the LCC at low head and flow rate) are not affected by an increase in head (because the pump was initially oversized).

The cost of energy from the PV "normal case" drops from nearly 2000 to 500 c/kWh as the total head increases from 7 to 60 metres. Over the same range the cost of energy from the PV "best case" drops from nearly 1000 to 320 c/kWh; and that of the diesel "normal case" drops from 1100 to 200 c/kWh.

However, it should be noted that while all these pumps are all more efficient at higher heads (that is the cost of energy is lower), the cost of water (in c/m^3) is higher because of the increased head. Therefore sites should be chosen for community gardens with as low a head as possible.

The cost of energy from electric pumps connected to ESKOM is shown below.

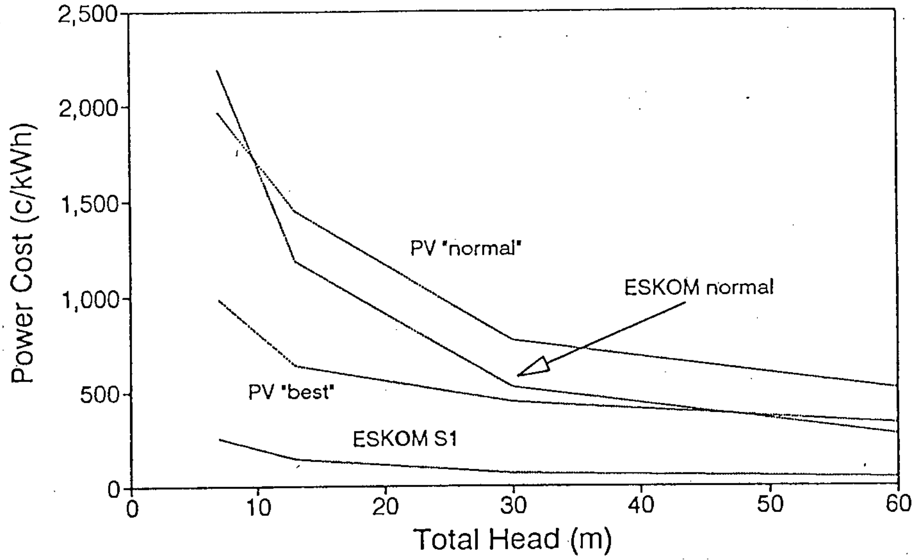


Figure 4.21: ESKOM pumps - The Effect of Head on the Cost of Energy

The cost of energy to a pump connected on the ESKOM normal tariff drops from 2200 c/kWh to 265 c/kWh as the head increases from 7 metres to 60 metres. That for a pump connected on the ESKOM S1 tariff drops from 250 to 40 c/kWh over the same range.

c) Cost per Member per Month

The cost per member per month shows the same pattern as the cost of pumped water discussed above. So only one graph is given below with a cross-section of the pumps under consideration in order to give an idea of the order of magnitude of the costs involved.

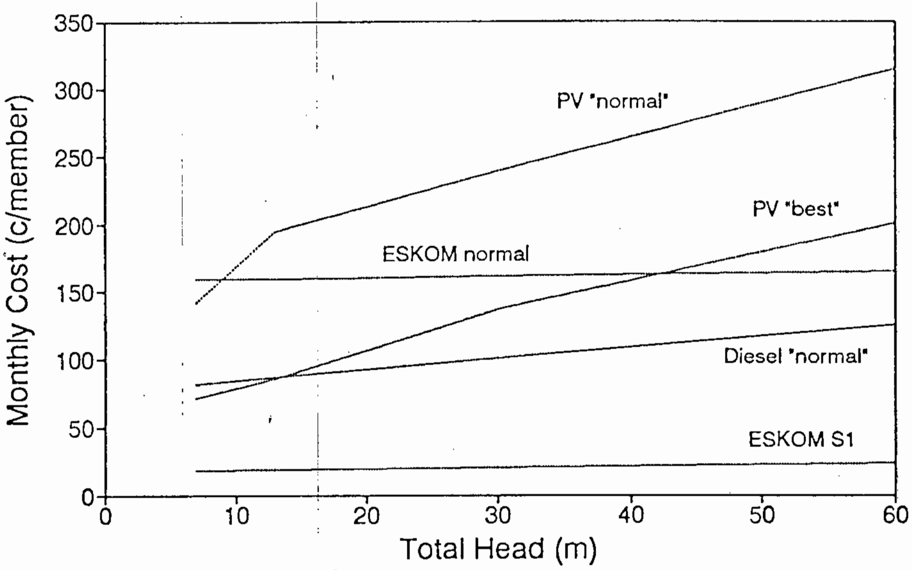


Figure 4.22: All pumps - The Effect of Head on Cents per Member per Month

This calculation is based on the assumption that there are 50 members per hectare (as at Sondela), and that the Life Cycle Costs can be spread evenly over the lifetime of the project.

As the head increases from 7 to 60 metres the cost per member of various pumps increases as follows:

a) PV "normal case": from 142 to 315 c/month
b) PV "best case": from 71 to 201 c/month
c) Diesel "normal case": from 81 to 126 c/month
d) ESKOM normal tariff: from 159 to 165 c/month
e) ESKOM S1 tariff: from 18 to 23 c/month.

4.2.3 The Effect of Insolation

The third site dependent factor considered is the critical daily insolation. This is the average daily insolation for the worst month - the month when the ratio of insolation to water demand is the lowest.

a) Cost of Pumped Water

The effect of critical daily insolation on the cost of pumped water from PV pumps is shown below. The diesel "normal case" and ESKOM normal tariff are used as reference points.

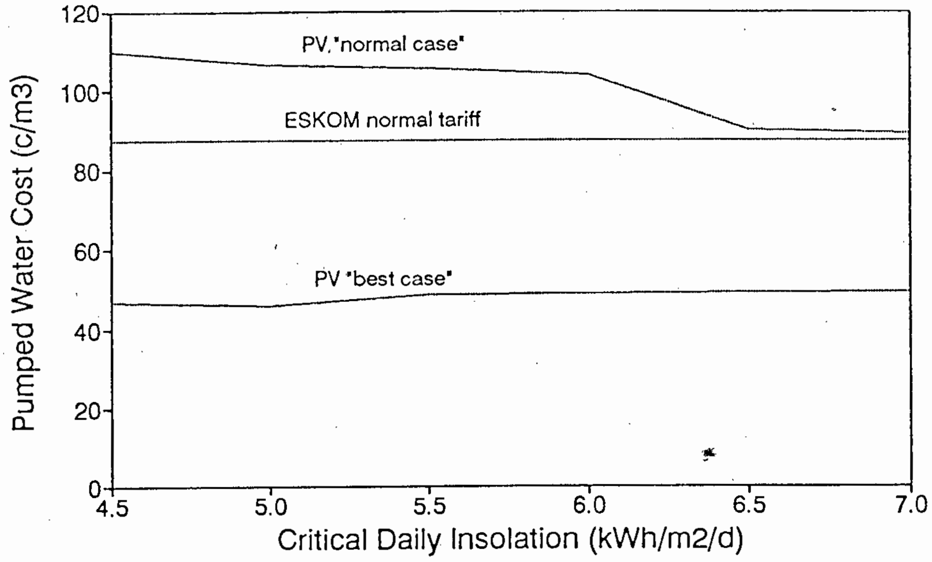


Figure 4.23: PV Pumps - The Effect of Critical Daily Insolation

As shown the critical daily insolation has a fairly strong influence on the cost of pumped water from the PV "normal case": it drops from 110 c/m^3 to 89 c/m^3 as the insolation increases from 4.5 to 7 kWh/m^2/d. (The critical insolation in Durban is 4.8 kWh/m^2/d, while that in Windhoek is about 6 kWh/m^2/d).

There are two reasons for this decrease: i) the system efficiency increases with increasing insolation largely because of an increase in array efficiency; and ii) the required array size decreases with increasing insolation (because more energy is available per unit area of array). For these two reasons the initial costs of the system decrease with increasing insolation: whereas they form 77% of the LCC at 4.5 kWh/m^2/d they form only 54% of the LCC at 7 kWh/m^2/d.

The average number of hours that the system works per day increases proportionally with insolation. So the maintenance costs and replacement costs increase with increasing insolation. If this were not the case the decrease in the cost of pumped water from the PV "normal case" would be more dramatic that shown above.

It is also because of the increase in maintenance and replacement costs that the costs of the PV "best case" do not drop with increasing insolation, but actually increase marginally - the drop in the initial costs is more than offset by an increase in maintenance and replacement costs. The difference between the PV "normal case" and the "best case" is that the efficiency of the "best case" does not improve with increasing insolation as does that of the "normal case". This is because the array for the "best case" physically tracks the path of the sun and so is efficient even at low levels of insolation.

4.2.4 The Effect of Distance from the Grid on the Costs of Electric Pumps

The factors which affect the ESKOM normal tariff are those which affect the monthly meter charges as these account for between 84% and 63% of the Life Cycle Costs. The other costs are almost fixed: the initial cost of the motor and pump, and the energy charges. There are two components to the meter charges:

i) the line charges for the extension of the grid. These depend on both the distance which the grid must be extended to reach the pump, and the number of consumers who connect to ESKOM simultaneously. The effect of distance from the grid is examined below; that of the number of consumers in Subsection 4.2.5.

ii) the monthly account charge which is a fixed rate for all rural customers supplied directly by ESKOM. The account charges can only be reduced if two or more people share one account. This is discussed in Subsection 4.2.6.

The graph below shows the effect of the distance to the grid on the costs of the ESKOM normal tariff.

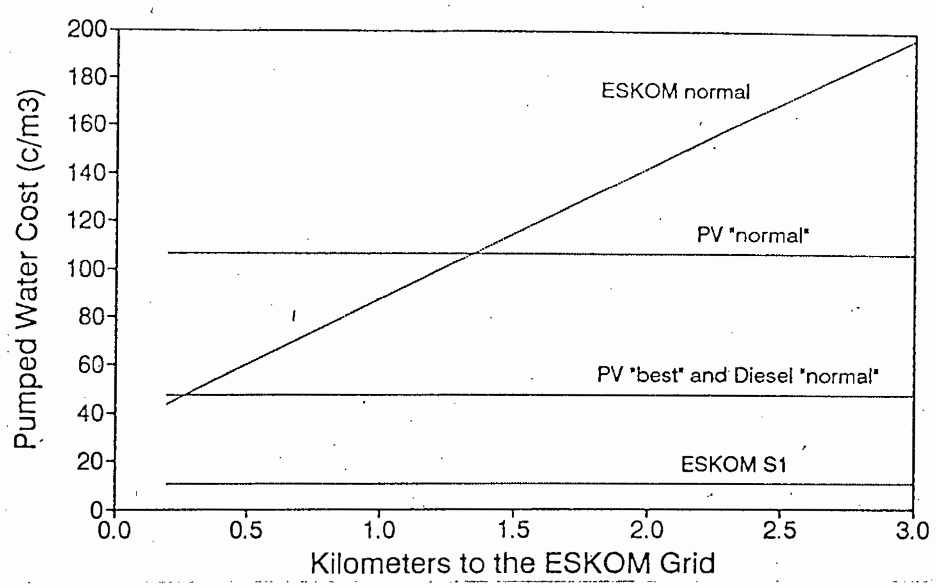


Figure 4.24: The Effect of the Distance to the Grid on the Cost of Pumped Water
For default conditions: 3 consumers connecting simultaneously, one person per account, and a water demand of 3 m³/day.

There are no line charges for extending the grid for the first 200 metres. After that the monthly line charges are calculated as approximately R 24 per 100 metres. These are then divided among the number of consumers connecting simultaneously. The default for the above graph is three consumers. If there were only one consumer the effect would be much more dramatic.

The distance to the existing grid is very important in determining the costs of the ESKOM normal tariff. As the distance goes from 200 metres to 3 kilometres, the costs of the ESKOM normal tariff increase nearly five times (from 44 to 197 c/m³). The graph shows that the ESKOM normal tariff is as cheap as the PV "best case" and the diesel "normal case" up to 200 metres (that is, as long as there are no line charges). It is cheaper than the PV "normal case" up until about 1.3 kilometres.

But this is for the default water demand of 3 m³/day and head of 13 metres. If only the break-even points between the ESKOM normal tariff pump and other pumps are plotted it is possible to condense the information and so examine the effect of head and water demand simultaneously. This is shown in the following graph. On the y-axis is the distance to the grid in kilometres. On the x-axis is the hydraulic head - which has the units m⁴/day and is the product of the water demand (in m³/day) and the total head (in metres).

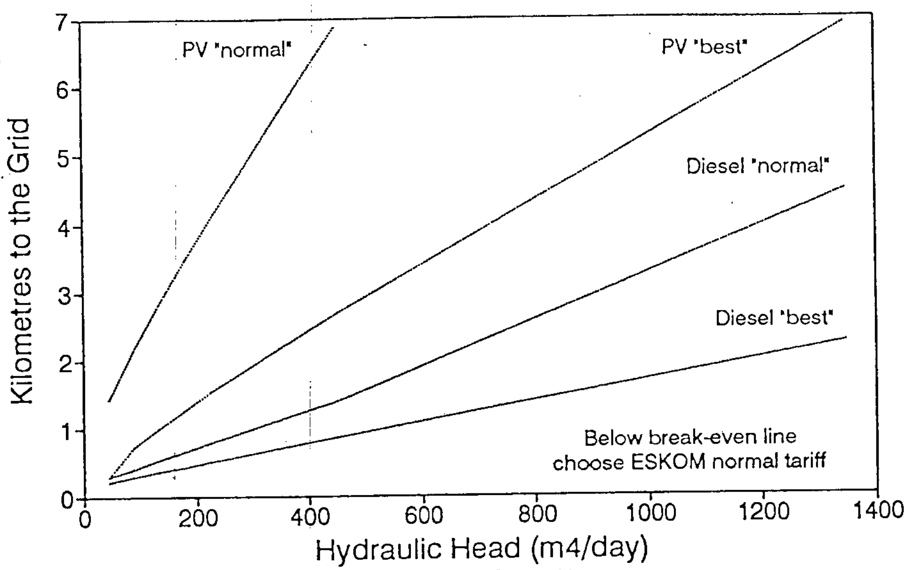


Figure 4.25: Break-even Points with ESKOM normal tariff - Kilometres to the Grid

For a prospective site the hydraulic head can be calculated. For example, if the water demand was 12 m^3/day and the total head 15 metres, then the hydraulic head is 180 m^4/day. Then the break-even distance to the grid can be read off the graph. For example, for a hydraulic head of 180 m^4/day the break-even point for the diesel "normal case" is 0.7 kilometres. Thus for distances less than 0.7 kilometres the ESKOM normal tariff would be cheaper than the diesel "normal case".

Factors other than just the distance to the grid can be taken into account by creating an "ESKOM factor" which takes into account the other site dependent factors which affect the ESKOM normal tariff. Figure 4.28 illustrates this.

4.2.5 The Effect of the Number of ESKOM Consumers Connecting Simultaneously

The effect of the number of ESKOM consumers connecting simultaneously is shown in the graph below.

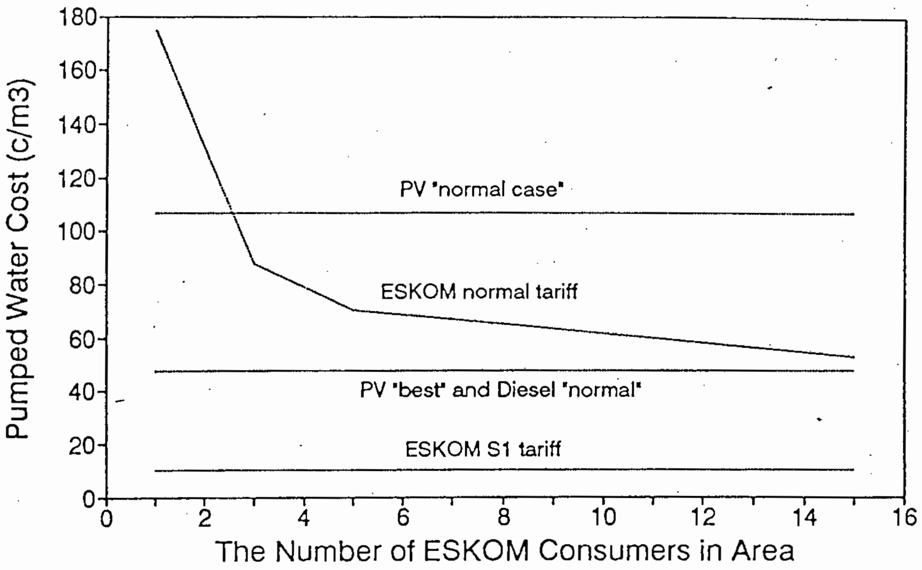


Figure 4.26: The Effect of the Number of ESKOM Consumers on the ESKOM Normal Tariff
For default conditions: 1 kilometre to the grid, one person per account, and a water demand of 3 m^3/day.

The number of consumers connecting simultaneously is a very important factor. The costs of the ESKOM normal tariff halve as the number of consumers increases from one to three. For more than five consumers the effect is less dramatic.

The graph shows that if there was only one consumer in the area, the ESKOM normal tariff is so expensive that it would probably not be considered. But for three consumers, it is already cheaper than the PV "normal case". And from five consumers upwards it is close enough to the diesel "normal case" and the PV "best case" that it may be preferred because of convenience and reliability. (This is for 1 kilometre to the grid, one person per account, and a water demand of 3 m^3/day).

The likely number of consumers in any area varies considerably with the affluence of the area. But shops and schools are likely candidates and five consumers in an area is not unreasonable.

4.2.6 The Effect of Number of Consumers per Account

The only way to reduce the fixed monthly charge is by a number of ESKOM consumers sharing an account. Although this is an unconventional proposal, it is worth considering because it results in a considerable reduction in costs.

The ESKOM office at Cato Ridge said that they would consider connecting two consumers to one account if they were within 300 metres of each other. Although this may cause problems of dividing the account payment fairly, both consumers would be likely to benefit so much that this should not be of concern: the energy charges are very small in comparison to the account charge which would be halved.

The effect of the number of consumers sharing an account is shown below.

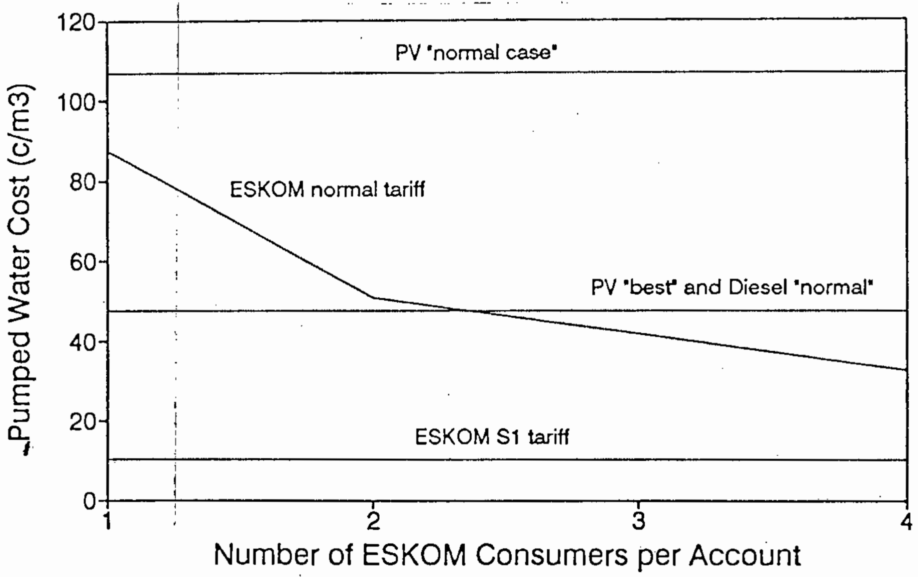


Figure 4.27: The Effect of the Number of Consumers per Account of the ESKOM Normal Tariff

For 1 kilometre to the grid, 3 consumers in the area, and a water demand of 3 m³/day.

The effect of the number of consumers sharing an account is initially considerable. If two share an account the costs of the ESKOM normal tariff drop by 37% (from 87 to 51 c/m³). The effect is less dramatic as the number of people sharing the account increases.

The graph shows that if there is only one consumer per account, the ESKOM normal tariff is nearly double the cost of the diesel "normal case" and the PV "best case", and so would probably not be chosen. However, if just two people can share an account the ESKOM normal tariff is close enough to both the diesel "normal case" and the PV "best case" that it would most likely be the preferred method of pumping.

Thus if just two consumers could share an account the ESKOM normal tariff would be the best method of pumping (aside from the S1 tariff which is always the best if available). This is even for the low head of 13 metres and the very low water demand of 3 m³/day. For higher heads and water demands the ESKOM normal tariff becomes progressively more favourable.

The above is of course for one kilometre to the grid and for three consumers in the area. But it does emphasize the importance of considering sharing an account where the garden is within 300 metres of a potential ESKOM consumer. This is not as unlikely as it may seem - sharing an account may in fact have been practical at Sondela as a nearby shop which belongs to a member of the garden has applied to be electrified.

The ESKOM normal tariff is strongly affected by the three site dependent factors mentioned above. It is possible to create a graph which takes into account all these factors by examining the break-even points between the ESKOM normal tariff and the other pumps. This graph is shown below.

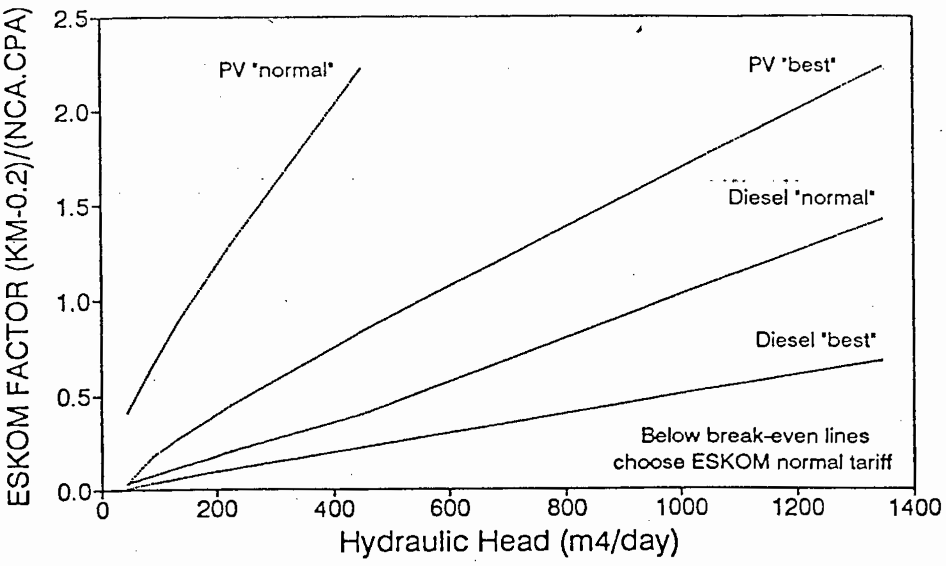


Figure 4.28: Break-even Points with ESKOM normal tariff - All Factors

This graph enables a user to decide on whether the ESKOM normal tariff is competitive for a particular application. First the ESKOM factor for the application must be calculated. This factor takes into account all the site dependent factors which affect the ESKOM costs. It has the following formula:

ESKOM factor = (KM-0.2)/(NCA.CPA)

where: KM is the distance to the grid in kilometres

NCA is the number of consumers in the area connecting simultaneously, and

CPA is the number of consumers sharing an account.

Once this is calculated it is possible to read off the graph the break-even point for the alternative pump which is being considered. For example, if the distance to the grid is 1.2 kilometres, there are 2 consumers connecting simultaneously, and one person per account, then the ESKOM factor is 0.5. From the graph it can be seen that the break-even point for the diesel "normal case" is at a hydraulic head of about 550 m^4/day. So, if the hydraulic head is above 550 m^4/day then the ESKOM normal tariff should be used; otherwise the diesel "normal case" would be cheaper.

4.3 Sensitivity Analysis

This section examines the sensitivity of the cost of pumped water to all the factors which have been identified as important in Section 4.2. It allows the reader to adjust the conclusions arrived at in Section 4.2 to the assumptions which he or she believes are accurate.

The assumptions discussed are categorized according to the type of pump they relate to and discussed in the following subsections:

4.3.1 Assumptions affecting all pumps: the project length and discount rate.
4.3.2 Those affecting only PV pumps: the PV system efficiency, the unit capital costs, and the PV panel price.
4.3.3 Those affecting only diesel and petrol pumps: diesel system efficiency, fuel price and fuel escalation rate.

The factors which most affect the costs of connecting to the grid are all site dependent and were discussed in Section 4.2.

4.3.1 Assumptions Affecting All Pumps

a) Project Length

The following graph shows the effect of project length on the cost of pumped water from a selection of pumps.

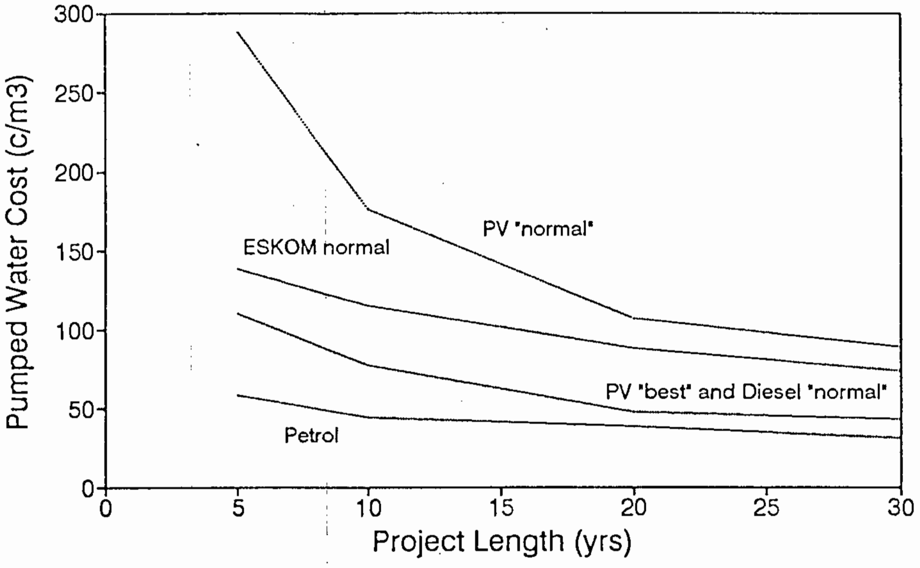


Figure 4.29: The Effect of Project Length on the Cost of Pumped Water
Costs for the PV "best case" and the Diesel "normal case" are so close that they are shown by one line. However, project length affects the PV "best case" slightly more than the diesel pump.

As expected, a short project length favours pumps for which a small proportion of their Life Cycle Costs is the initial costs (and so a high proportion is contributed by recurring costs). So a short project life favours the petrol pump. In contrast the PV "normal case" is favoured by a long project life - preferably 20 years or over. (This is despite the fact that the salvage value of the array would be high for a short project.)

So the likely length of the project is an important parameter to consider when choosing a pump. Banking on a 20 year project length for a pumping system for community gardens is probably optimistic at the moment. This is because of the political turmoil and uncertainty: fighting may force many of the gardeners to abandon the area, a new political dispensation may mean that there is sponsorship for community projects, or rural electrification may be subsidized for political reasons. Also the agricultural officers are regularly moved (after about 5 years). So the garden may dissolve because the agricultural officer is not replaced or because the new agricultural officer is not competent. So, possibly 10 years is more realistic than 20 years for a project life in this context.

b) Real Discount Rate

The following graph shows the effect of discount rate.

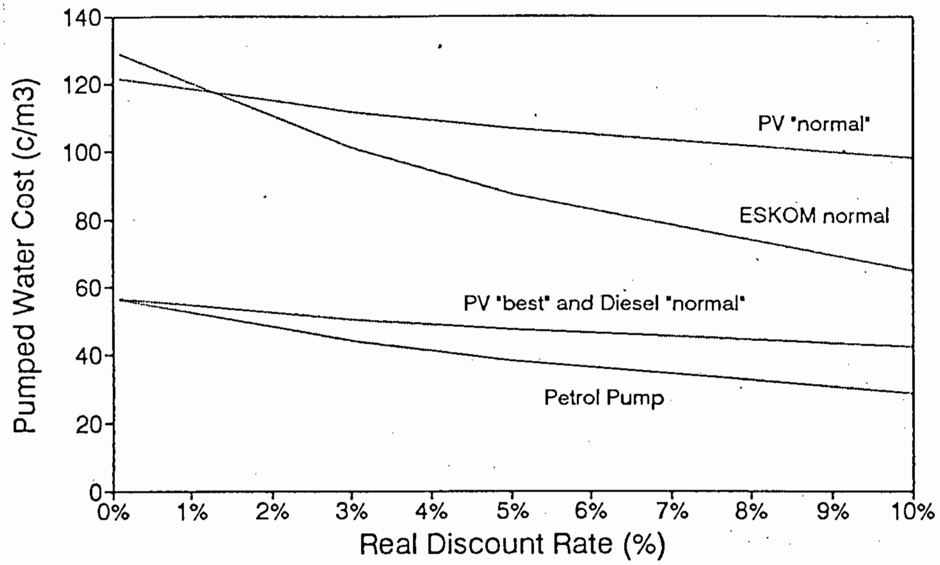


Figure 4.30: The Effect of Discount Rate on the Cost of Pumped Water (3 m3/day water demand)

The PV "best case" and diesel "normal case" are shown as one line for simplicity because their costs are very similar. The PV "best case" is affected less by discount rate than the diesel "normal case".

Again the important factor is the proportion which the initial costs contribute to the pump's Life Cycle Costs. If the initial costs are a large proportion, then the pump's LCC is not affected much by discount rate - for example the gradient of the PV "normal case" is shallow. If, on the other hand, most of the LCC is contributed by recurring costs, then the LCC of the system drops markedly with increasing discount rate. For example about 83% of LCC of the ESKOM normal tariff pump consists of recurring costs, and consequently its costs halve as the discount rate goes from 0 to 10%.

The graph shows that the effect on the petrol and diesel pumps is not as marked. The cost of the diesel pump drops at about the same rate as that of the two PV pumps: so the discount rate hardly affects the decision between these two.

But this is because the above graph is for a low water demand, when the recurring costs do not form a high percentage of the costs of the diesel pump. The following graph shows the effect of discount rate for a high water demand (90 m^3/day).

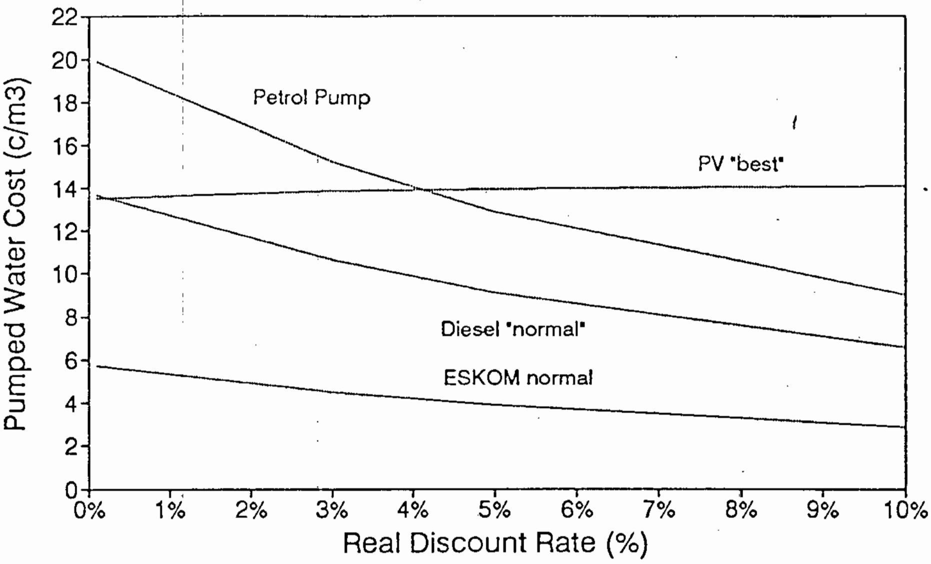


Figure 4.31: The Effect of Discount Rate on the Cost of Pumped Water (90 m3/day water demand)

As can be seen for all the pumps using conventional energy the cost of pumped water approximately halves as the discount rate goes from 0 to 10%. In contrast the cost of the PV "best case" hardly changes because the initial costs are nearly 100% of its Life Cycle Costs (the salvage value of the array approximately cancels out the maintenance and replacement costs.

So the discount rate is an important factor - especially for high water demands. But deciding on the correct value for the discount rate for a community garden is difficult. In industry, the discount rate chosen depends on the risk of the venture: a high real discount rate of about 10% will be used for a high risk venture, whereas a low value of about 3% will be used for low risk ventures. This is because a higher return on the capital is required to justify a high risk. Although buying a pump for a community garden would not normally be regarded as a high risk venture, the success rate for pumping systems in community gardens is low. For this reason a high discount rate may be appropriate in that it favours pumps with low costs early in the project: if the project fails less is lost.

Another way of determining the discount rate is to base it on the lending rate of banks which is normally about 5% above inflation. So this would suggest a real discount rate of 5%. This may well be the most appropriate for community garden as, especially if they choose a PV pump, they may need to loan the capital and so pay this interest (5% above inflation). But the risk of the project failing still needs to be considered, so a higher discount rate may be preferable.

4.3.2 Assumptions Affecting only PV pumps

The three assumptions which affect the cost of a PV pump most are the system efficiency, the unit capital costs, and the price of PV panels. The price of the PV panels affects the system LCC only because of its effect on the unit capital costs; but it is dealt with separately because of its importance.

a) PV System Efficiency

The following graph shows the effect of system efficiency on the PV "normal case". Costs for the diesel pump and PV "best case" (which are almost the same), the ESKOM normal tariff and petrol pumps are given for reference.

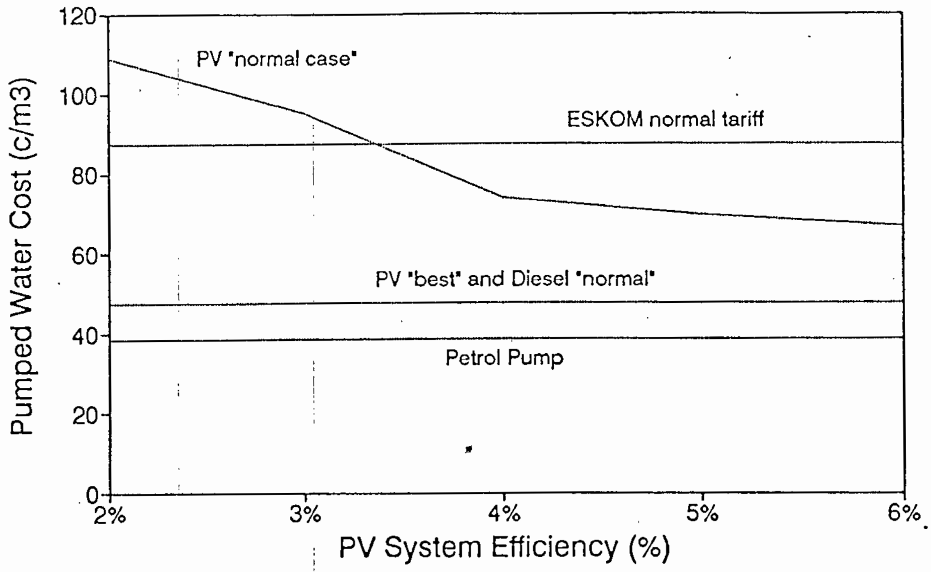


Figure 4.32: The Effect of PV System Efficiency on the Cost of Pumped Water

The PV system efficiency is a very important factor - the costs of the PV "normal case" drop by 40% (from 109 to 67 c/m^3) as the system efficiency goes from 2 to 6%. This is because the system's size is inversely proportional to system efficiency. However, the effect begins to tail off above 4% efficiency because as the system gets smaller so its unit capital costs increase. That is, as the system gets smaller the savings in costs are progressively less. The effect of system efficiency would be even more marked at high flow because the initial costs are 91% of the LCC at 90 m^3/day as opposed to 75% at 3 m^3/day.

The graph also shows that the main difference between the assumptions for the PV normal and best cases is the system efficiency used - the PV normal case uses 2% and the PV best case 4.5% (at 4.5 kWh/m^2/d and 13 metre head). (The other major difference in assumptions is that of unit capital costs).

The system efficiencies chosen for the PV "best case" represent achievable efficiencies for a well-designed system operating under suitable conditions. They are 4.5% to 5.65% for critical insolation levels from 4.5 to 6 kWh/m^2/d. For the derivation of these figures see Subsection 4.5.1.

b) PV Unit Capital Costs

The unit capital costs of a PV system are the total initial system costs divided by the W_p rating of the array. The graph below shows the effect of the unit capital costs on PV system costs, with the costs of other pumps given as reference points.

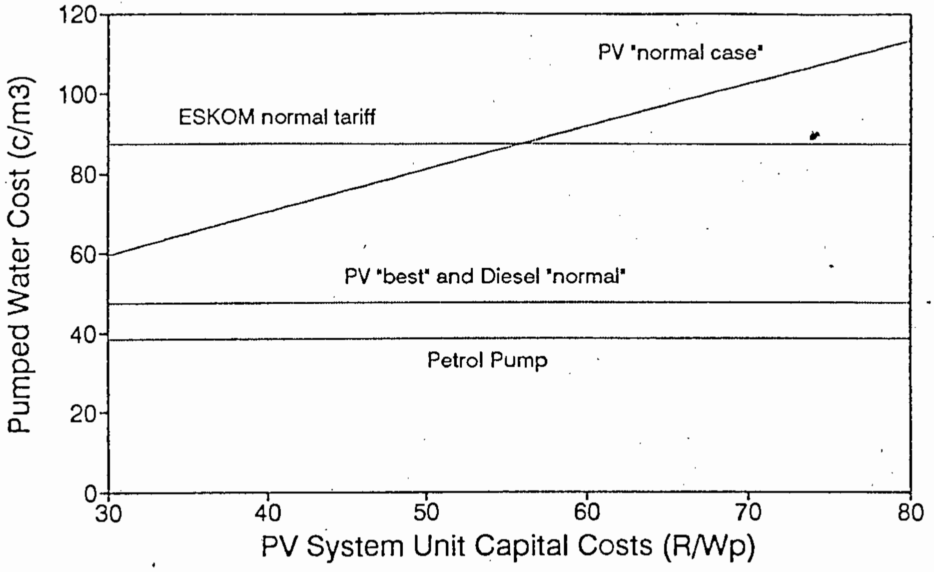


Figure 4.33: The Effect of PV Unit Capital Costs on the Cost of Pumped Water

The initial costs of the PV system are proportional to the unit capital costs. As the initial costs form a high proportion of the LCC of the PV pump (75 to 91%), the unit capital costs obviously have a strong influence on the LCC and so the cost of pumped water: the cost of pumped water nearly doubles as the unit capital costs increase from 30 to 80 R/W_p.

However, there are practical limits to how much the unit capital costs can be brought down without suffering a loss in efficiency. They are inevitably higher for small systems. The following graph shows the values used for the normal and best case assumptions.

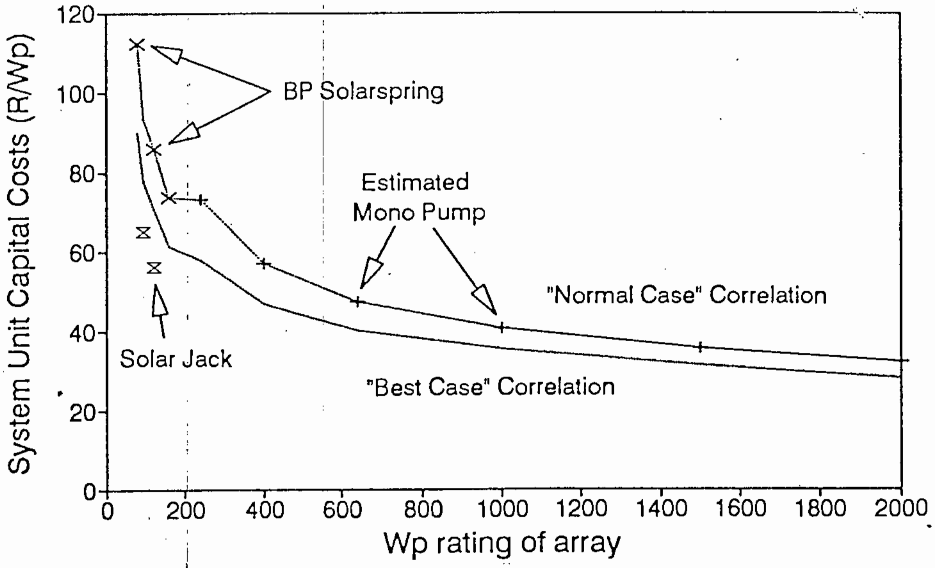


Figure 4.34: Assumptions on Unit Capital Costs: Normal and Best Case

The assumptions for the "normal case" are most likely at the moment in South Africa. The "best case" assumes that the present BOS costs have been halved due to standardization. However, the points for the Solar Jack show that lower unit capital costs are practical. (For further discussion see Subsection 4.5.1).

c) PV panel price

The following graph shows the effect of the price of PV panels on the costs of pumped water from a PV pump.

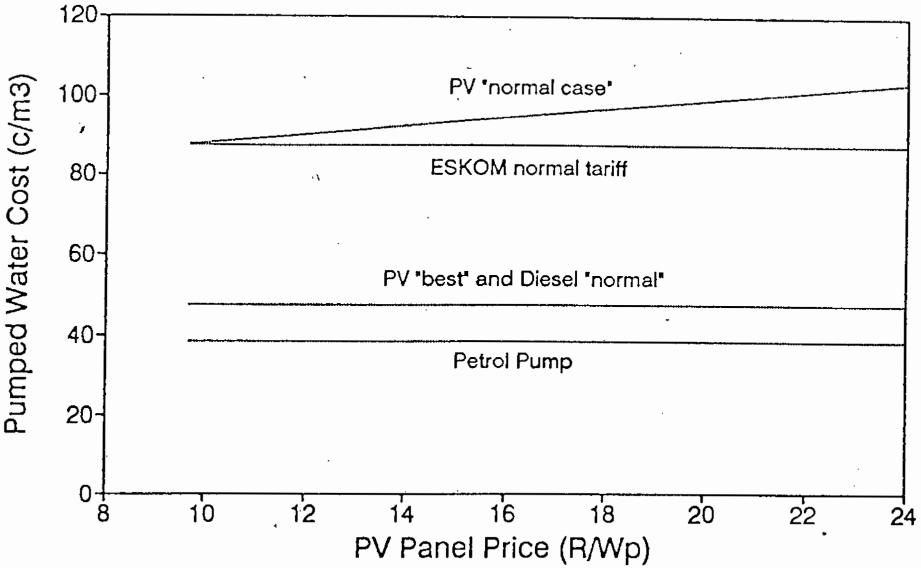


Figure 4.35: The Effect of the PV Panel Price on the Costs of Pumped Water

The effect of the price of PV panels is not as strong as may be expected - if the price of panels halves from 24 to 12 R/W_p, the costs of the PV "normal case" drop by only 13%. This is because for a water demand of only 3 m^3/day the array costs contribute only 28% to the Life Cycle Costs. However, at higher water demands the effect of the PV panel price will be more dramatic: array costs contribute 63% of the Life Cycle Costs of the "normal case" at 90 m^3/day.

Unfortunately, PV pumps are more competitive with other methods at low rather than at high water demands. So the effect of further drops in the PV panel price is not likely to change the competitiveness of PV pumps that much for the applications for which they are most suited - low heads and low water demands.

In order to put the above prices for PV panels into context the table below gives some predictions for future prices of PV panels.

Table 4.6: Predicted and Present PV Panel Prices

Prices of PV panels	Retail Price in mid-1990 1990 US \$/Wp	1990 SA R/Wp[3]
Present Average for Arco panels in SA (for 1 to 3 panels)[1]		28
Present Average for Arco panels in SA (for 20 to 59)		21
Present Average for Arco panels in USA (for 1 to 3)[2]	8.2	24
Present Average for Arco panels in USA (for 12+)	7.5	22
Predicted price for 1990 (Maycock, 1990)	5.00	15
Predicted price for 1995 (Maycock, 1990)	4.00	12
Predicted price for 2000 (Maycock, 1990)	3.33	10
Adjusted prediction (for 12+): 1990	7.5	25
Adjusted prediction (for 12+): 1995	6.0	20
Adjusted prediction (for 12+): 2000	5.0	17

1. Optitron, personal communication, August 1990.
2. Real Goods, 1990.
3. The exchange rate used was 2.57 R/$ - the average for the first quarter of 1990 (IFS, July 1990).

The present US prices are given in order put Maycock's predictions into perspective, and so that adjustments can be made to realistic retail prices in South Africa. While Maycock quotes a price of 5 $\$/W_p$ in 1990, the present retail price (for more than 12 panels) in the US for Arco panels is 7.5 $\$/W_p$. Possibly Maycock's price assumes a larger discount for very large purchases. But the figure of 7.5 $\$/W_p$ is more realistic for the prices that PV pump marketers will be faced with. So the "adjusted predictions" in the table multiply Maycock's predictions by 7.5/5.

Secondly, predictions for prices in South Africa need to account for freighting and for import duties. By comparing present prices in South Africa with those in the US (for 1 to 3 panels) it can be seen that a further 16% must be added (after using the exchange rate and adding GST) to account for these costs.

So realistic predictions for PV panel prices (for more than 12 panels) in South Africa are: 25 R/W_p in 1990, 20 R/W_p in 1995, and 17 R/W_p in 2000. (All prices in 1990 SA Rands). So in the next decade panel prices can be expected to drop by 32%. This will result in a drop in the costs of the PV "normal case" of 9% (for a water demand of 3 m^3/day and a head of 13 metres).

4.3.3 Assumptions Affecting only Diesel/Petrol Pumps

The three most important assumptions which relate specifically to the diesel pump are the diesel system efficiency, the fuel price and the fuel escalation rate. All of these affect only the running costs and so are only important for large flows. This is because the running costs form only 10% of the LCC for the diesel "normal case" at 3 m^3/day, but they form 51% of the LCC at 90 m^3/day. For this reason all the graphs in this subsection are based on a higher water demand (30 m^3/day) than considered before. Because community vegetable gardens are unlikely to be larger than 5 hectares, this water demand represents the likely upper limit for a water demand for a community vegetable garden (considering a normal water demand of 3 m^3/ha/day).

a) Diesel System efficiency

The effect of the system efficiency on the costs of the diesel "normal case" is shown below.

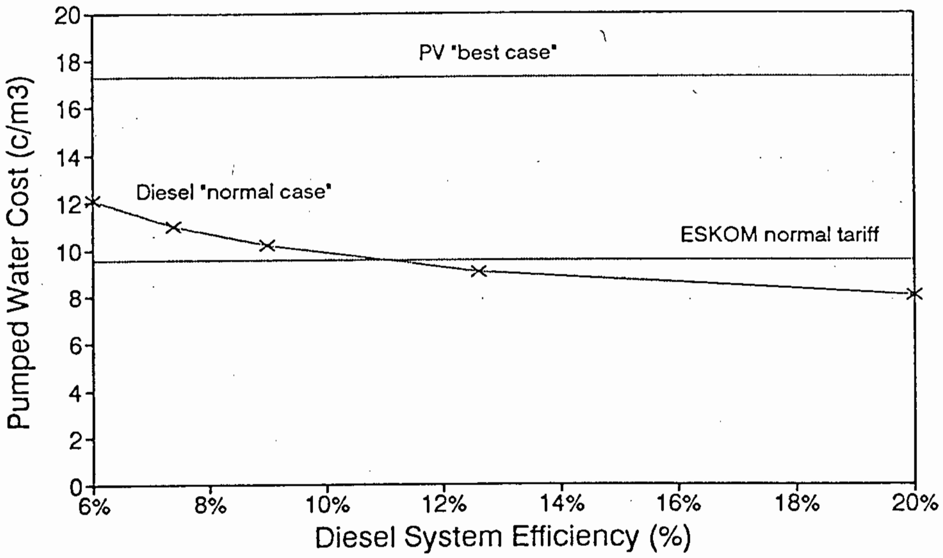


Figure 4.36: The Effect of Diesel System Efficiency on the Cost of Pumped Water (for 30 m3/day)

The effect of the system efficiency is not as marked as might have been expected: as the diesel "normal case" system efficiency more than doubles (increasing from 6% to 12.6%), the cost of pumped water drops by one quarter (from 12.1 c/m^3 to 9.1 c/m^3).

This is because the running costs of the diesel "normal case" (which are inversely proportional to system efficiency) contribute only 42% of its Life Cycle Costs for a water demand of 30 m^3/day.

At the lower water demands, the effect of the system efficiency is less important. But even for this water demand (the upper limit for community vegetable gardens), the system efficiency is unlikely to affect the choice of pump: whether the efficiency is 6% or 20%, the costs for the ESKOM normal tariff are so close that it would most likely be preferred because of reliability and convenience.

The points shown on the graph represent the assumptions of different authors: 6% and 9% are Halcrow's normal and best cases (1982), 7.4% and 12.6% are the assumptions for the normal and best cases in this thesis and 20% is Wiseman's assumption (1987). Values between 6 and 15% are reasonable - 20% is unrealistically high as it would require a engine efficiency of 33%, a pump efficiency of 60% and a transmission efficiency of 100%.

b) Fuel Price

The Chem Systems (1990) prediction of oil prices were used for this sensitivity analysis. The prediction gives three scenarios each of which have a real price in 1990 and an escalation rate from 1990 to 2000. From the year 2000 the prediction assumes that the real price is constant. The pump price for diesel at the coast in South Africa was worked out from these. The following table gives the results:

Table 4.7: Predictions of South African Coastal Pump Price of Diesel

Prediction for:	Pump Price (1990 R) 1990	2000	2010	Escalation Rate[1] (1990 to 2000)
Diesel - High	1.20	1.79	1.79	4.5%
Diesel - Central	0.95	1.39	1.39	4.4%
Diesel - Low	0.71	1.00	1.00	4.1%
98 Octane - High	1.37	1.96	1.96	4.5%
98 Octane - Central	1.12	1.56	1.56	4.4%
98 Octane - Low	0.87	1.16	1.16	4.1%

1. The escalation is only for 1990 to 2000 - from then on the price remains constant in real terms. (The escalation rate is an increase in real value - not simply monetary value).

So first the effect of changing the price assumed for 1990 is examined with the three values for the high, central and low scenarios being used. In addition, a price even higher than the high scenario is used - 1.45 R/litre for the diesel pump price at the coast which is based on an oil price of 26 $/bbl - the price predicted until the end of 1991 after the Iraqi invasion of Kuwait (Business Day, 21/9/90). Then the effect of changing the fuel escalation rate is examined - using values from 0 to 8%.

The graph below shows the effect of a change in the 1990 diesel price. (The price of petrol for the petrol engine in the graph below is found by multiplying the diesel price by the ratio 1.37/1.20).

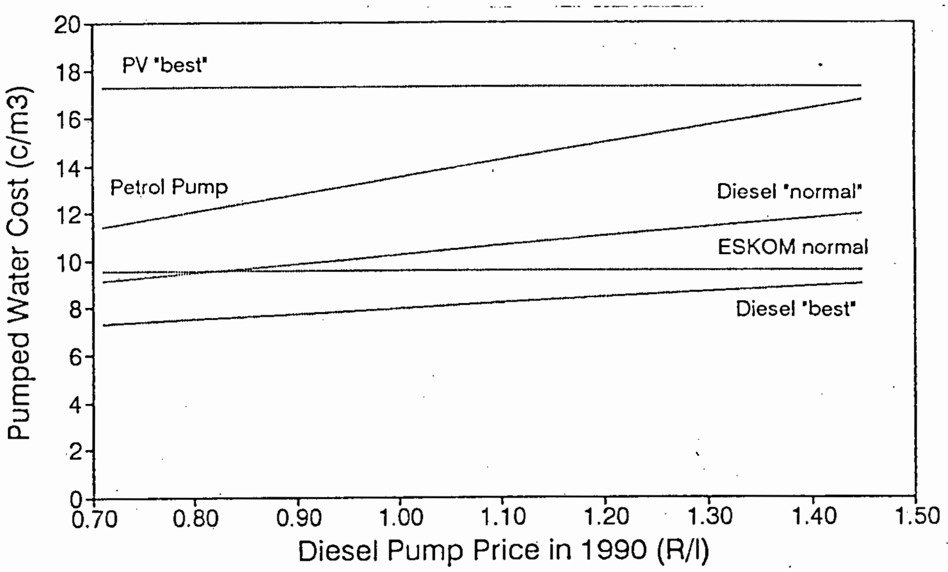


Figure 4.37: The Effect of Diesel Price on the Cost of Pumped Water (30 m3/day Water Demand)

It can be seen how the engine efficiency affects the sensitivity of the costs to fuel price: the effect on the petrol engine (which has a system efficiency of 4.8%) is much more marked than the effect on the diesel "best case" (which has a system efficiency of 12.6%).

Although the effect of fuel price is considerable, it is not dramatic: if the price doubles (from 71 to 145 c/litre), the costs of the diesel "normal case" rise by 31% from 9.1 to 11.9 c/m³. As in the case of the diesel system efficiency, the fuel price is unlikely to affect the choice between the diesel pump and an electric pump.

c) Fuel Escalation Rate

The effect of the fuel escalation rate (the increase in the real fuel price above inflation) on the costs of the diesel and petrol pumps is shown below.

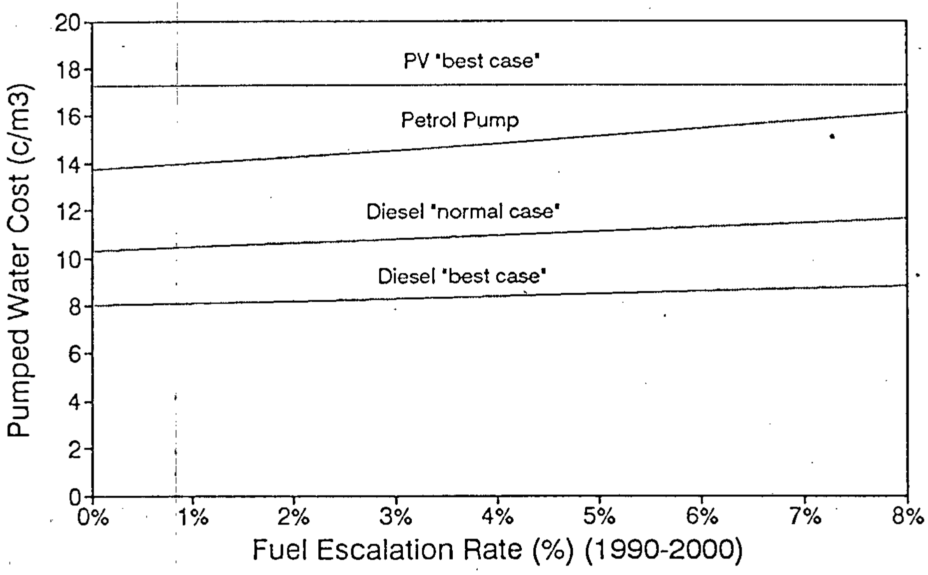


Figure 4.38: The Effect of the Fuel Escalation Rate on the Cost of Pumped Water (30 m3/day water demand)

The effect of fuel escalation rate is surprisingly small: if the escalation rate of fuel is 8% the fuel price in 20 years time would be nearly five times what it would be if the escalation rate were 0%. This would be expected to have a dramatic effect on the LCC of diesel and petrol pumps. However, as the escalation rate increases from 0% to 8% the cost of pumped water from the diesel "normal case" rises by only 13%, while that for the "best case" rise by just 10%. The reason for this is that the future expenses are discounted at 5% per year and so affect the Life Cycle Costs much less than expenses early in the life of the project. So the variation between escalation rates from the low to the high scenario in the Chem Systems prediction (4.1% to 4.5%) is negligible.

4.4 The Method of Calculation (Life Cycle Costs)

The purpose of economic models is to reduce all the costs over the whole lifetime of proposed solution to a problem to a single number (for example cents/m^3 pumped water). It is then a simple matter to compare the economic performance of all the alternative solutions and to see how their performance changes with changing conditions.

The method used is based on the calculation of the Life Cycle Costs. This method is used by most authors - with variations only in the degree of sophistication. The Life Cycle Cost of a system is the sum of the present values of all the costs over the whole lifetime of the project.

The various costs are categorized as follows:

a) Initial Costs: these are the initial expenses and include the cost of the power source, the pump, and the installation (including transport and labour). Excluded are the costs of the delivery pipe, water storage and reticulation system.

b) Running Costs: expenditure on fuel for the diesel and petrol pumps. The meter and energy charges for electric pumps.

c) Maintenance Costs: this includes all maintenance aside from the cost of the replacement of major components.

d) Replacement Costs: the costs of replacing major components if their lifetimes are shorter than the length of the project.

e) Operator's Wages: this would normally fall under running costs. But most authors do not account for it, so it is accounted for separately here so that it can be more easily included or excluded depending on the circumstances at a proposed site.

f) Salvage value: this is the resale value of the system at the end of the project life. It is in fact a source of income and not a cost. However, it is accounted for in the computer model by considering it to be a negative cost. The Double

Declining Balance method was used to calculate the depreciation of each component of the pumping system. This method accounts for the sharp drop in resale value in the first few years of project life (67% of the value of a component is written off in the first half of its life).

The salvage value of all components is taken to be zero at the end of their lifetimes. So salvage value is only calculated for a component which has not yet come to the end of its lifetime when the project ends.

Discount Rate: The more accurate the economic model is the better the decision can be between various alternatives. To be an accurate representation of the effective cost to the user the model must weight the importance of future expenses relative to present expenses. This is done using the discount rate.

The discount rate accounts for the potential growth or decline in the <u>real</u> value of money if it is invested. If, for example, R 1000 could be profitably invested and grow <u>in real terms</u> to R 1100 in one year, then it could be said that R 1000 now is effectively the same value as R 1100 in a year's time. Thus the discount rate would be 10%. All future expenses would then be discounted at 10% per year to get their "present values" - their effective value at the start of the project. Only after discounting are all expenses on an equal footing and they can be summed to give the Life Cycle Costs.

Inflation rate: Apart from the possible increase or decrease in the real value of invested money over time, there is also an increase purely due to inflation. This, however, is an unnecessary complication and is only of concern when there are different rates of inflation for various components of the system. The computer model used only real prices and so did not need to account for inflation. Where a price is expected to increase or decrease over time <u>in real terms</u> this is taken into account by an escalation rate. (The "escalation rate" could also account for a decline in real prices, in which case it would be negative).

The price of most components is considered to be constant in real terms for the life of the project. The escalation rate is considered only for petrol and diesel prices.

Unit Costs: These are calculated from the Life Cycle Costs. For example, the "cents per cubic metre pumped water" is equal to the Life Cycle Costs divided by the volume of water pumped over the whole length of the project.

Interest charges on loans: because of the uncertainty of the method of financing available for various pumps, interest charges on loans were not considered. Unfortunately, these could affect the answers of the model considerably and they should be taken into account by a more sophisticated model. This model is thus only accurate if a soft loan is available for each pump - a loan for which the interest charges are equivalent to inflation. Otherwise, figures should be adapted according to the type of financing available.

4.5 The Validity of the Assumptions Used

Most authors use the method of Life Cycle Costs outlined in Section 4.4 with various levels of sophistication. The method itself is sound and simple enough that there can be little error. Despite this, the conclusions that the authors come to vary dramatically. This is because the assumptions used vary widely: the output of the model can only be as accurate as the assumptions used as input. And so it is crucial that the assumptions used are examined carefully.

There is such a large variation in the assumptions used for two reasons. Firstly the costs of various methods of pumping vary widely depending on the situation of the pump. Factors which have a large influence on costs are: the technical expertise of the owners, the remoteness of the site, weather and water conditions and fuel prices. Secondly, there is a dearth of reliable information on the costs of various methods of pumping under various conditions.

Because the cost of pumping varies greatly with the application, it is necessary for each study to tailor the assumptions used to a particular situation. As noted in Section 4.1, this thesis focuses on disadvantaged communities in remote rural areas - with particular reference to community gardens in these areas. For these circumstances the costs of pumping are mostly much higher than for "first world" farmers due to the lack of technical expertise (which results in machines running in poor condition), and to the large distances which must be travelled to service the pumps.

To account for the wide variation in assumptions used by various authors, two sets of assumptions were used for both the diesel and the photovoltaic pumps (as noted previously): a "normal case" which represents what is most likely to occur in these situations, and a "best case" which represents the best likely in these situations.

Two cases were also considered for electric pumps connected to the ESKOM grid: the normal tariff which is the standard at the moment, and the S1 tariff which is much cheaper for small consumers and may be introduced to these areas if ESKOM finds innovative ways of encouraging electricity consumption and so making it economic. (See Subsection 4.5.3 for a discussion on this).

This section is broken into subsections dealing with the assumptions relating to each type of pump: PV pumps, then diesel/petrol pumps, and finally electric pumps. At the beginning of each subsection there is a table summarizing the assumptions for that type of pump. (These are the same tables as given in Section 4.1 - they are repeated for easy reference).

4.5.1 Assumptions on Photovoltaic Pumps

The most important assumption to consider for a photovoltaic pump is its capital cost as this comprises most of its Life Cycle Costs. Capital costs (including initial and replacement costs) for between 86% and 99% of the Life Cycle Costs of the PV "normal case" (see Subsection 4.2.1). Other important assumptions are those about component lifetimes (which affect the replacement costs), and those about maintenance costs. There are no running costs as no fuel is required. And the pump is self-starting so there is no need for operator's wages.

Two cases were considered:

a) the "normal case" is based on the measured efficiency of the Mono Pump at Sondela. The efficiency of this system is not ideal because the pump is not designed for the low head at Sondela.

b) the "best case" is the best that is reasonable at the moment in South Africa. It assumes that the correct pump is chosen for the application, that the community can themselves install the prepackaged pumps, that the array physically tracks the path of the sun, and that the power maximizer has diagnostic functions to reduce maintenance costs.

The table below gives a summary of the assumptions used.

Table 4.8: The Assumptions Used for PV Pump Costs

Assumption on:	Normal Case	Best Case
System Efficiency[1]	2.02 to 2.45%	4.67 to 5.10%
Subsystem Efficiency[1]	23.6 to 25.4%	41 to 45%
Array Efficiency[1]	8.84 to 9.66%	11.3%
System Unit Cap. Cost[2]	74 to 32 R/Wp	61 to 28 R/Wp
Array Lifetime	15 years	25 years
Motor Lifetime	15,000 hrs (10 yrs max)	25,000 hrs (14 yrs max)
Pump Lifetime	8,000 hrs (7 yrs max)	15,000 hrs (10 yrs max)
Maintenance Costs	15 c/hour	8 c/hour

1. Efficiency tends to increase with increasing insolation. The range given is for insolation levels ranging from 4.5 to 6 $kWh/m^2/d$.
2. The unit capital cost decreases with increasing system size. The range given is for system sizes from 160 W_p to 2000 W_p (four to fifty 40 W_p panels).

The basis for the assumptions are discussed below under the cost which they affect: initial cost, replacement costs or maintenance costs.

a) Initial Cost

There are two stages in calculating the initial cost of a PV pump:

i) the system's size in terms of the W_p rating of the array is found from the system efficiency; and

ii) the costs of the components are calculated from correlations in terms of the W_p rating of the array and then summed to give the total installed cost. These two stages are discussed in turn below.

System Efficiency

Normal Case: The component efficiencies of the Mono Pump at Sondela which were measured during the technical evaluation were used for the "normal case" (see Subsection 3.5.1). A correlation was used to account for the fact that the measured system efficiency increased linearly with insolation level.

The design of a PV pump is normally based on the critical insolation - the insolation for the month in which the insolation level to load ratio is at its lowest. For South African conditions a useful range of critical insolation levels is from 4.5 to 6 kWh/m²/d (corresponding approximately to the critical insolations in Durban and Windhoek). Over this range the system efficiency of the "normal case" varies from 2.02% to 2.45%.

Best Case: The "best case" was based on measured efficiencies but all the efficiencies were adapted to ideal conditions. The most important changes were made to the efficiency of the array and to that of the pump itself. It was assumed for the best case that the array would physically track the path of the sun; and that the pump efficiency would be based on the Mono Pump at its ideal head (45 metres). The effect on these assumptions are shown below.

Table 4.9: Best Case Assumptions for Array and Pump Efficiencies

Component	4.5 kWh/m²/d		6 kWh/m²/d	
	"Normal"	"Best"	"Normal"	"Best"
Array	8.8%	11.3%	9.7%	11.3%
Pump	39%	58%	40%	62%

Note: the array efficiency used is for single crystal panels - based on measurements for M.Setek panels. See Subsection 3.5.2.

The validity of the "best case" assumptions: In Section 3.5.2, it was found that the array would have given its quoted efficiency of 12% if it tracked the path of the sun and if it operated at 25 °C. It is practical for the array to track the path of the sun (passive devices are marketed commercially in South Africa). However, an array temperature of 25 °C is unreasonable for most sites in South Africa and a more reasonable temperature of 42 °C (that measured at Sondela) was assumed. The efficiency of the array at 42 °C is 94% its efficiency at 25 °C. The array would thus give an efficiency of 11.3% at 42 °C if it tracked the path of the sun.

(The above assumes that single crystal PV panels are used. If other types of panels were used the efficiency may well be lower - but the panel price would also be lower so the overall effect on the system price would be similar).

The SW4L Mono Pump gives its best Daily Energy Efficiency at a 45 meter head. It maximum power efficiency at this head is 62%: so it was assumed that it would give a Daily Energy Efficiency of 58% at 4.5 kWh/m²/d and of 62% at 6 kWh/m²/d. Halcrow measured Daily Energy Efficiencies of 59% for his best pumps (in 1982) so 58% to 62% is not an unreasonable assumption for the "best case".

Minor changes were made to the measured efficiencies of the other components - as shown in the table below.

Table 4.10: Best Case Efficiencies for Other Components

Component	4.5 kWh/m^2/d "Normal"	4.5 kWh/m^2/d "Best"	6 kWh/m^2/d "Normal"	6 kWh/m^2/d "Best"
Power Maximizer	86%	94%	91%	96%
Motor	76%	80%	76%	80%
Transmission	93%	95%	93%	95%

The AERL power maximizer gave a Daily Energy Efficiency of 94% at 4.5 kWh/m²/d mainly because it handled start-up better than the Miltek. So the range of 94 to 96% efficiency for the power maximizer is not unreasonable for the "best case".

The highest Power Efficiency measured for the motor (during the laboratory test) was 83% - so it is assumed that if the current that the motor draws is set carefully, a Daily Energy Efficiency of 80% is not unreasonable.

The efficiency of the transmission was increased slightly from 93 to 95%. Direct coupling is more expensive than the V-belt but may give even higher transmission efficiencies.

The resulting system and subsystem efficiencies are given below.

Table 4.11: Best Case Subsystem and System Efficiencies

Component	4.5 kWh/m^2/d "Normal"	4.5 kWh/m^2/d "Best"	6 kWh/m^2/d "Normal"	6 kWh/m^2/d "Best"
Subsystem	23.6%	41%	25.4%	45%
System	2.01%	4.67%	2.45%	5.10%

The subsystem efficiency of the "best case" is 41% at 4.5 kWh/m²/d and 45% at 6 kWh/m²/d. This is a reasonable assumption: the subsystem efficiency of the "Solarspring" pump designed by BP Ltd was estimated from their specifications to be about 44% for this range of insolation levels.

This results in a system efficiency of the "best case" ranging from 4.67% at 4.5 kWh/m²/d to 5.10% at 6 kWh/m²/d (as the array efficiency is 11.3%).

Component Cost Correlations

A precise and instructive quantity to represent the overall initial cost of a system is the unit capital costs. This is the total system cost divided by the W_p rating of the array. If this quantity is used it is relatively easy to compare the costs of systems of different sizes.

Correlations for each component were used to calculate the installed cost of the system from the W_p rating of the array. The results of this method are shown in the following graph in terms of the unit capital costs of the installed system. The graph also shows the unit capital costs of the three most established solar pumps in South Africa.

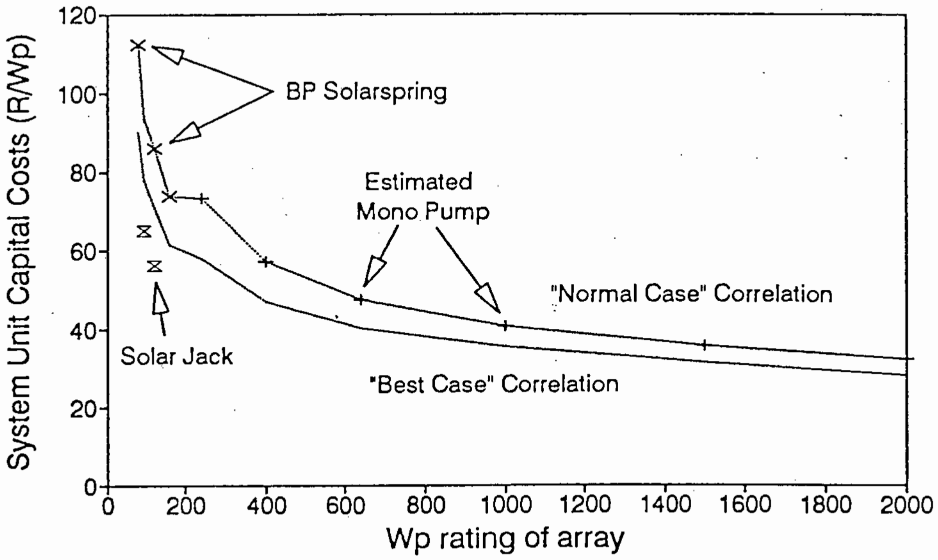


Figure 4.39: Correlations Used for PV Capital Costs

Two sets of correlations are used for the "normal case": below 160 W_p the correlation is based on prices for the BP Solarspring; above it is based on the Mono Solar Pump. Prices for the Solarspring were obtained from BP in April 1990. Installation costs were not included as it is claimed that the client can install the system himself; and because no installation costs were included in the assumptions for diesel engines.

The estimates of the costs of the Mono Pump were based on component prices. Prices for a full range of components were obtained from Mono Pumps in April 1990. Correlations were used to interpolate so that all sizes of pump could be considered. Only two of the costs contributing to the total system costs required more careful consideration: the price of the PV panels and the Balance of System (BOS) costs.

Most marketers of PV panels give a discount for large quantities. So the price of panels was made to decrease linearly from 28 R/W_p for one panel to 20 R/W_p for 40 panels. If more than 40 panels are required the price of panels remains at 20 R/W_p which is the bottom limit. These prices include 13% GST and are based on prices for Arco panels from Optitron in April 1990. The higher price 28 R/W_p is for single panels, whereas the lower price of 20 R/W_p is for bulk buying (20 to 59 panels).

(It may be argued that the pump marketer buys panels in bulk in any case and so it is not valid to use different prices for systems which use many panels. However, it is likely that the marketer will give a preferential price to a client who requires a large system. The profit that the marketer takes is accounted for by the BOS costs).

The Balance of System Costs (BOS costs) comprise all system costs except those of the major components. They include installation costs, labour and transport, and protection (a fence and an alarm), and the profit margin of the pump marketer.

A correlation for BOS costs in terms of system W_p rating was found by examining a break-down of the BOS costs to determine what proportion of the costs is dependent on size and what proportion is independent of size. It was decided that 30% of the BOS costs were size depedent (see Appendix 4.5.1 for details). This has been confirmed as a reasonable assumption by Mono Pumps Ltd, and it predicts well quoted costs of larger systems.

"Best Case": The only difference in the assumptions used for the "best case" is that the BOS costs are assumed to be half those of the "normal case". The costs of the system can mostly not be reduced by reducing the costs of the actual components as there would most likely be a drop in quality and so efficiency. So costs can only be cut by reducing the BOS costs. This could possibly be done by standardization and modularization.

Assuming that the BOS costs could be halved was arbitrary. But the result is that the ratio of the unit capital costs for "best case" to that for the "normal case" is between 0.80 and 0.88. And it seems reasonable that the present costs may be reduced to about 85% of their present value by good design.

The unit capital costs of the Solar Jack also confirm that the reduction in capital costs is possible. However, the Solar Jack has a slightly lower efficiency than that assumed for the "best case": so although the graph shows that its unit capital costs is less than the "best case" correlation, when its efficiency is taken into account the "best case" correlation predicts its behaviour accurately.

b) Replacement Costs: Component Lifetimes

The replacement costs are calculated from component lifetimes. The following table shows a comparison between the assumptions on component lifetimes used in this thesis and those used by other authors.

Table 4.12: Component Lifetimes for the PV Pump

Model	COMPONENT LIFETIMES		
	Array	Motor	Pump
"Normal Case"	15 yrs	15,000 hrs (10 yrs max)	8,000 hrs (7 yrs max)
"Best Case"	25 yrs	25,000 hrs (14 yrs max)	15,000 hrs (10 yrs max)
Halcrow	15 yrs	20,000 hrs (10 yrs max)	20,000 hrs (10 yrs max)
Wiseman	20 yrs	20 yrs	20 yrs

The array: photovoltaic panels have not been commercially used for long enough for there to be a body of knowledge on their lifetimes. However, the M.Setek panels used at Sondela are guaranteed to produce in excess of 90% of their original power for 20 years.

However, the lifetime of the array is not simply affected by its ability to withstand the elements: other factors such as theft and vandalism need to be taken into account. The level of risk can be estimated only for a particular situation. But in the light of this it is probably reasonable to assume an array lifetime of 15 years for the "normal case" and 25 years for the "best case". These estimates agree quite well with Halcrow's assumption of 15 years and Wiseman's of 20 years.

The motor: the lifetime of a motor used with a PV pump will be shorter than one using ESKOM power. This is because it is continually stopping and starting. Mono Pumps estimated a lifetime of 10 years for a motor connected to a PV pump. This works out to 17,000 hours at an average of 4.8 hours of pumping per day. (The formula for the hours pumped per day is given in Appendix 4.5.1.) So the lifetime of the motor is assumed to be 15,000 hours for the "normal case" and 25,000 hours for the "best case".

This estimate agrees well with Halcrow's assumption of 20,000 hours. Wiseman used only a lifetime for the whole system and did not differentiate between the components. So his estimates are not useful for motor and pump lifetimes.

The pump: The lifetime of a pump depends a lot on the quality of water. Mono Pumps estimated a pump lifetime of 8,500 hours after considering the condition of the water at Sondela. So a pump lifetime of 8,000 hours is assumed for the "normal case" and 15,000 for the "best case" (assuming better quality water). This is low in comparison with Halcrow's assumption of 20,000 hours - but he assumes a high quality of water.

c) Maintenance Costs

The table below shows the assumptions made for the "normal" and "best" cases and compares them to figures used by Halcrow and Wiseman.

Table 4.13: Assumptions on PV Pump Maintenance Costs

Model or Author	c/hour	Rand/yr	Comment
"Normal Case"	15	260	Based on quotes by Mono Pumps
"Best Case"	8	130	
Halcrow	4	180	(1990 R) = 3.64 * (1982 $)
Wiseman		270	1% of Initial Cost per year

The best standard of comparison is the annual maintenance costs as the hourly maintenance costs are affected by the assumption on the average number of hours pumped per day. The annual maintenance cost was assumed to be R 260 for the "normal case" and R 130 for the "best case". This is in the same ball-park as the assumptions of R 180 used by Halcrow and R 270 used by Wiseman.

The assumptions used in this thesis were based on estimates made by Mono Pumps Ltd - the firm which will maintain the pump at Sondela. The table below gives a break-down of the maintenance costs.

Table 4.14: Maintenance Costs for the PV pump

Maintenance For:	"Normal"	"Best"	How often?
Replacing the pump	315	315	Every 5 years
Motor repairs	380	200	Every 3 years
Other minor repairs	135	0	Every 2 years

Replacing the pump: after 5 years the rotor and stator of the pump wear down to the point where the pump must be replaced. The cost of the replacement pump is covered separately under "Replacement Costs". The R 315 in the table above accounts for travel and time (6 hours) to change the pump.

Motor repairs: every 3 years the motor needs a complete service. This includes changing the brushes, removing carbon deposits, and skimming the commutator at a total costs of R 200. The "best case" assumes that the fault is diagnosed by the community (with the help of a user-friendly power maximizer) and so there are no travel charges. The cost for the "normal case" is R 380 as it includes two trips to site (to collect and replace the motor).

Other minor repairs: every 2 years there may be a need for some other minor maintenance. The charge of R 135 is for travel and two hours of time. It is assumed in the "best case" that the community is able to diagnose and fix all minor problems (with the help of the power maximizer - see Subsection 3.5.3).

4.5.2 Assumptions for Diesel and Petrol Pumps

Which assumptions are most crucial for diesel pumping depends on the energy demand. For low energy applications the initial costs form the major portion of the Life Cycle Costs of the diesel "normal case" (67% for 3 m³/day and a 13 metre head). The operator's wages are the next most important (about 20% of the LCC).

However, for high energy applications the running costs become the most important. (They form about 51% of the LCC at 90 m³/day and a 13 metre head). So, for high energy, the important assumptions are those that affect running costs: system efficiency, fuel price and fuel escalation rate. At 90 m³/day all other components of the LCC are relatively minor (forming from 9 to 14% of the LCC each).

The table below gives a summary of the assumptions used for the "base case".

Table 4.15: The Assumptions Used for Diesel Pump Costs

Assumption On:	"Normal Case"	"Best Case"	Comment
Capital Cost[1]	R 4470 to 10640		For 4 to 8 kW
Engine Efficiency	20%	27%	
Pump Efficiency	40%	50%	
Transmission Eff	93%	93%	
System Efficiency	7.4%	12.6%	
Diesel Price[2]	120 c/l	120 c/l	Price in 1990
Escalation Rate	4.5%	4.5%	From 1990 to 2000
Maintenance Costs	60 c/hr	50 c/hr	
Engine Lifetime (hrs)	10,000	20,000	Max 15 & 20 yrs
Pump Lifetime (hrs)	8,000	15,000	Max 15 & 20 yrs
Operator's Wages	15 to 35 R/month		For 3 to 30 m3/d

1. This is for a Lister Diesel engine and centrifugal pump. The figures above include 13% GST and 10% added for accessories. The range given above is for illustration - linear correlations were used to interpolate or extrapolate.

2. To account for the transport of the fuel to the site (by bus), 10% was added to the fuel price (on top of that shown). The consumption of oil was assumed to be 1% that of diesel (Cedara, 1989).

The following table summarizes the assumptions for petrol pumps.

Table 4.16: The Assumptions Used for Petrol Pumps

Assumption On:	Value	Comment
Capital Cost[1]	R 2070 to R 5080	For 4 to 8 kW
Engine Efficiency	13%	
Pump Efficiency	40%	
Transmission Eff	93%	
System Efficiency	4.8%	
Petrol Price[2]	137 c/l	Price in 1990
Escalation Rate	4.5%	From 1990 to 2000
Maintenance Costs	100 c/hr	
Engine Lifetime (hrs)	6,000	Maximum of 8 yrs
Pump Lifetime (hrs)	8,000	Maximum of 8 yrs
Operator's Wages	15 to 35 R/month	For 3 to 30 m^3/d

1. These figures include 13% GST. The range given is just for illustration - linear correlations were used to interpolate or extrapolate.

2. To account for the transport of the fuel to the site (by bus), 10% was added to the fuel price (on top of that shown). The consumption of oil was assumed to be 1% that of diesel (Cedara, 1989).

a) Capital Cost

The capital cost was calculated from quotes from firms in Pietermaritzburg and Durban in April 1990 for the smallest petrol and diesel pumps. As the volume of water pumped per day increases so it may be more economical to use a bigger engine and pump. To adjust for this a straight line calibration was found for the price of each engine and pump against its kW rating. The table below gives the data used for capital costs.

Table 4.17: The Information Used for Capital Costs

Make	kW rating	Price (ex. GST)
Lister Diesel LT1C	5.6	R 3568
Lister Diesel LV1	6.4	R 4534
Lister Diesel TS1A	7.3	R 5690
Centrifugal Pump VEG32	3.2	R 1698
Centrifugal Pump VEG40	4.0	R 1899
Centrifugal Pump VEG50	5.0	R 2099
Centrifugal Pump VEG65	6.5	R 2378
Honda Petrol G140 & Hymec Pump	3.7	R 1637
Honda Petrol G300 & Hymec Pump	5.3	R 2700
Honda Petrol G240 & Hymec Pump	5.3	R 3099

Note: the Lister engines were coupled with the appropriate VEG centrifugal pumps (depending on power rating).

The above prices for the diesel pumps account for only the major components (engine and pump). To account for accesories such as the coupling frame, strainer, foot valve and gate valve, 10% was added to the total cost of the major components (Mathew, 1990: pers. comm.).

Derating the diesel engine for altitude also affects the capital cost of the system. At higher altitude the engine produces less than its rated power and so a larger engine may be necessary. For example an engine will give 73% of its rated power at an altitude of 2000 meters. The amount of derating varies linearly with altitude and these figures were used to find a straight line correlation. (The engine also needs to be derated for increasing ambient temperature, but as this is a minor effect it is ignored).

b) Running Costs

The running costs are affected by the engine efficiency, transmission efficiency, pump efficiency and the fuel price. These will each be dealt with in turn.

Because the system efficiency includes both the engine and pump efficiencies, it is helpful to tabulate them both in one place. It is the assumption on system efficiency which is important in the final analysis.

Table 4.18: Diesel Pump Efficiency - from the Literature

Source:	Efficiency of: System[2]	Engine	Pump
Diesel "Normal"	7.5%	20%	40%
Diesel "Best"	12.7%	27%	50%
Halcrow normal (1983)	6%	10%	60%
Halcrow best (1983)	9%	15%	60%
Wiseman (1987)	20%	(33%)[1]	(60%)[1]
Berry (1990)		22%	

1. Wiseman assumed only a system efficiency - this break down between engine and pump efficiencies is what he most likely would have used (had he given a break down).

2. A transmission efficiency of 93% is assumed - the same as measured at Sondela. So the system efficiency is the product of engine, transmission and pump efficiencies.

The source of the assumptions on engine efficiency, pump efficiency and fuel price are discussed in turn below.

Engine Efficiency

Diesel engines: The efficiency of a diesel engine is affected by the following three factors:

a) the length of time it is run per session;
b) the load it is under (or capacity factor); and
c) the speed it runs at.

These factors are particularly important when considering the efficiencies of engines used by community gardens as the gardeners normally only pump small amounts of water. Because they mostly do not use sprinklers the amount of water pumped will be determined by the storage capacity at the garden. So even if they used the smallest diesel pump available they would only be able to pump for between 20 minutes and 1 hour at full load. Thus they either pump at full load for a short time (which is inefficient because much energy goes into warming the engine) or at a low load for a longer period (which is also inefficient because of the low load).

For this reason a model was designed to account for these three factors, as follows:

The effect of time per session: this was calculated from theory considering the energy required to raise the engine to its operating temperature of 130 °C. (For details see the Appendix 4.5.2).

The effect of capacity factor and engine speed: The capacity factor is the fraction the actual load is of the full load. If the engine is at half load the capacity factor is 50%. For a given system the capacity factor will vary with the engine speed so these two factors are dealt with together. Data from field trials (Kenna, 1987) were used to find a correlation for this effect.

The graph below shows the final model which accounts for all the three factors mentioned above: the effect of time operating per session, and the combined effect of capacity factor and engine speed.

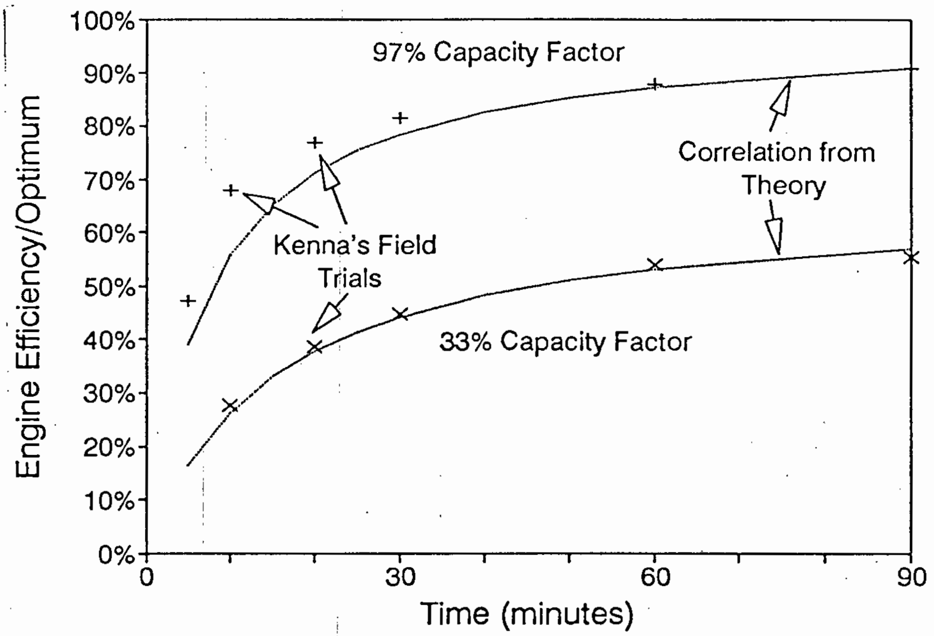


Figure 4.40: The Model Used for Engine Efficiency - Compared to Kenna's (1987) Field Trials

The y-axis in the graph represents the engine's cumulative efficiency since start-up (rather than its instantaneous efficiency) divided by the optimum efficiency. The optimum efficiency is the efficiency the engine would give at the ideal load and speed and after it has already warmed up. This can be found from manufacturers' specifications. It is 32% for the SR1 - the smallest Lister engine available near Durban.

The figure shows that the effect of the time that the engine runs per session is marked. The cumulative efficiency of the engine rises sharply initially reaching about half its optimum after 10 minutes, and then 80% of its optimum after 30 minutes. It then rises more slowly to reach 92% of its optimum after 90 minutes.

The effect of the capacity factor is also considerable: if the capacity factor is 33% the efficiency of the engine reaches about 50% of its optimum after 90 minutes - whereas at almost full load the efficiency is 90% of its optimum after the same time.

Also shown on the graph are efficiencies measured by Kenna in the field (relative to the optimum efficiency of 34% for the larger ST1 engine he monitored). The graph shows how well the correlations established here model the real behaviour of the engine. The efficiency of the engine he monitored rises more sharply initially because it has a higher power/mass ratio.

There is another factor which affects the efficiency of the engine: its size. Engine efficiency increases with engine size. This, however, was ignored as for community gardens normally the smallest engine available is required.

Another factor which some people believe affects efficiency is the derating of the engine for altitude. This, however, affects only the size of the engine required, not its efficiency.

Default conditions: The above model accounts for the effect of all the major factors on engine efficiency. But what are reasonable assumptions for small community gardens? Records for the diesel pump used at nearby Phumalanga community garden were used as a guide. The size of Phumalanga garden is the same as Sondela (1 hectare).

Records collected for one year show that the pump was mostly pumped for 5 hours per session at 15% capacity factor. For these operating the model above predicts a cumulative efficiency of 20% (or 61% of the optimum). The engine would have given a better efficiency if it was run at full load, but the efficiency would still be low because the engine would have filled the reservoirs in 45 minutes (and thus the time pumped per session would be short). If this had been done the engine efficiency would have been 27%.

So the default conditions are chosen as follows:

a) "Normal Case": 19.5% engine efficiency which corresponds to the way the engine at Phumalanga garden was run (5 hours per session at 15% capacity factor); and
b) "Best Case": 27.3% engine efficiency. This efficiency would be achieved if the engine was run at full load. This efficiency could be achieved fairly easily with adequate instruction on correct operation of the engine.

Comparing the assumptions used by others: the most reliable data available in the literature is that of Kenna (1987). The graph above shows how well the correlations used agree with this data.

Halcrow & Partners (1983) consider two engine efficiencies: 15% for their "best" case (the best which could be expected for an engine in a developing country) and 10% for their "normal" case (what is considered normal for a developing country). The reasons they give for these low estimates are that diesel engines rarely run at their optimum speed in practice and that they are often "out of tune". However, once a diesel engine has been factory set there is nothing that can go "out of tune" (Mathew, 1990 - pers. comm.).

Wiseman (1987) uses a combined engine and pump efficiency of 20% which is based on manufacturers' data. If the efficiency of the pump is assumed to be 60% then the engine efficiency must be 33%. As he used manufacturers' specifications this is an optimum efficiency - in other words he does not account for the fact in many third world settings it is impractical to run the engine at full load for a long time per session.

Berry (1990), for the Department of Agricultural Development, assumes an efficiency of 22% for a 4 kW diesel engine. This is based on practical knowledge but is for farmers who pump larger volumes of water and have a higher level of technical expertise than members of the community gardens. So it agrees fairly well with the assumptions used in this thesis of 19.5% for the "normal case" and 27.3% for the "best".

So the figures for efficiency used in this thesis agree well with data from Kenna and the Department of Agriculture. However, they are lower than those chosen by Wiseman and higher than Halcrow's.

Petrol engines: the efficiency of a petrol engine is lower than that of diesel engines. As with diesel engines it depends on the capacity factor and the speed at which it is run. But its dependency on the time it is run per session is negligible because of the smaller mass of the engine. Unlike diesel engines its efficiency does depend on its state of tune.

The Department of Agriculture estimates the efficiency of a 4 kW petrol engine to be 22%. However, this is under full load, at the optimum speed and in a good state of tune. If this is scaled down for capacity factor and speed as done above for the diesel engine more likely efficiencies for the field can be found. The efficiencies chosen for default conditions are 13% for "normal" and 19% for the best case.

Pump Efficiency

The assumptions on pump efficiency were based on manufacturers' data on the VEG 32C centrifugal pump. This is a small pump which is the best available for low heads and the most likely to be coupled with the diesel engine. The figure below shows how dependent the efficiency of a centrifugal pump is on the shaft power it receives (and so on flow rate and speed).

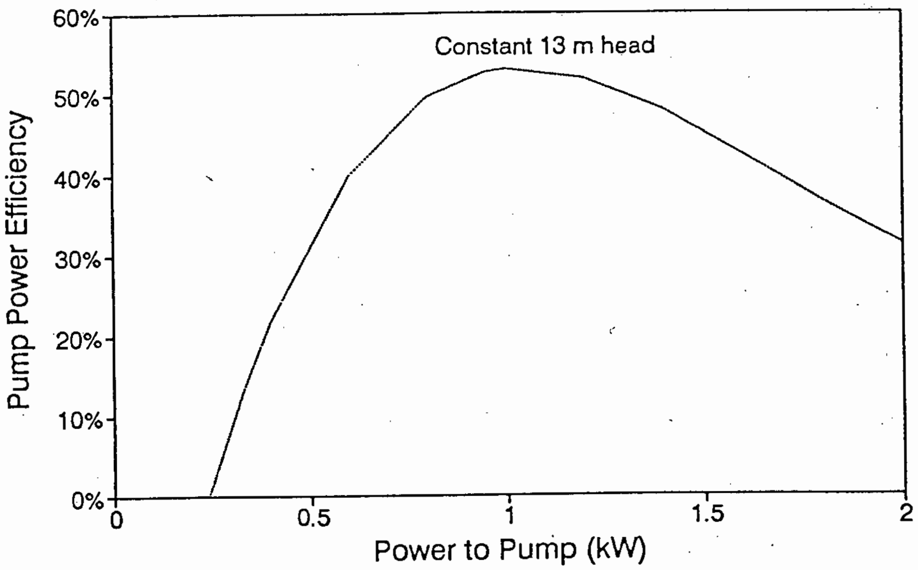


Figure 4.41: Centrifugal Pump Efficiency versus Power

This graph is for a constant head of 13 meters (as at Sondela). The optimum efficiency of the pump is 53% at 1 kW input shaft power. But its efficiency drops away sharply if it is not run at this optimum power: if the input power drops to 60%

of its optimum the efficiency of the pump drops from 53% to 40%. The pump efficiency also drops, but less sharply, above its designed power input.

Default conditions: The pump will seldom be run at its optimum efficiency for a few reasons: i) it needs to be matched to the engine and considerations of the power output of the engine and the pulley sizes available will affect the design; and ii) the users will often not run the pump at its designed flow rate (see information on Phumalanga garden above).

Because of the small amounts of water pumped many community gardens may run their systems slowly - so a pump efficiency of 40% is chosen for the "normal case". The best reasonable efficiency for a well-run system is 50%.

The assumptions used by others: Halcrow & Partners assume a pump efficiency of 60% for both their best and normal cases. This is based on a pump with an optimum efficiency of 67%. Their figures are higher than those used above because they are working with higher flow rates and so larger pumps working closer to their optimum.

As noted above Wiseman gives only a combined engine and pump efficiency (of 20%). As it is unreasonable to assume an engine efficiency above 33% this indicates he assumes a pump efficiency of 60% or higher.

Fuel Price

In the context of small community gardens the fuel price is far less important than is mostly assumed. This is because the water demand is so low that the running costs are only a small part of the Life Cycle Costs. Even at 30 m^3/day (which is about the normal upper limit for community gardens) the difference is not that marked. For example, if the high scenario in the graph below were to come true the cost of water from a diesel pump would be only about 25% higher than if the "low scenario" were true.

The assumptions on the fuel price were based on the Chem Systems forecast in June 1990. Their three scenarios for the crude oil price in Middle East (fob) are shown in the figure below. The currency used is 1990 US $.

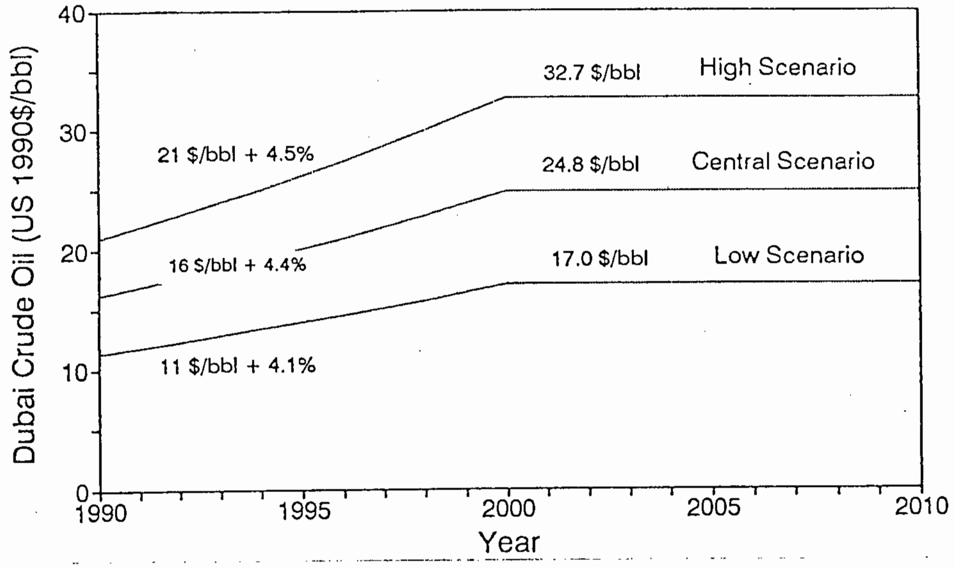


Figure 4.42: Forecast of Crude Oil Price (Middle East, fob)
Source: Chem Systems (1990)

Since the above prices were forecast, Iraq has invaded Kuwait and oil prices have rocketed. The effect of this on the oil price needs to be taken into account. However, it would be unrealistic to use current prices as these are very high immediately after the crisis. The International Monetary Fund predicts that the average oil price will be $ 26 per barrel in 1990 dropping back to $ 21 per barrel towards the end of 1991 (Business Day 21/9/90). Because the forecasts in this thesis deal with Life Cycle Costs over the next 20 years, it is more realistic to use this figure of $ 21 per barrel rather that the current $ 26 per barrel as a starting point. This takes into account the long term effect of the invasion of Kuwait without overestimating its effect by using current prices. This starting price is equivalent to the high scenario of Chem Systems - so this high scenario is used as the base case assumption for this thesis ($ 21 per barrel in 1990 and a 4.5% escalation rate until the year 2000).

For all the community gardens near Sondela the diesel was transported to the gardens by bus. The bus fare was approximately 10% of the cost of the diesel bought. So transport was accounted for in the computer model by adding 10% to the fuel price.

From these predictions for crude oil prices the pump prices at the coast in South Africa were calculated. The In Bond Landed Cost (IBLC) was calculated using correlations based on the historical relationship between the two costs (Stelna, 1990: pers. comm.). The pump price was calculated from the IBLC price using the exchange rate for the first quarter of 1990, and figures for the percentage cuts that go to taxes, to retail, and to the wholesale margin (SASOL, 1989). Details are given in the appendices.

This resulted in the following table showing predicted diesel and 98 Octane petrol prices at the coast.

Table 4.19: Predicted Coastal Pump Prices for Diesel and Petrol.

Prediction for:	Pump Price (1990 R) 1990	 2000	 2010	Escalation Rate[1] (1990 to 2000)
Diesel - High	1.20	1.79	1.79	4.5%
Diesel - Central	0.95	1.39	1.39	4.4%
Diesel - Low	0.71	1.00	1.00	4.1%
98 Octane - High	1.37	1.96	1.96	4.5%
98 Octane - Central	1.12	1.56	1.56	4.4%
98 Octane - Low	0.87	1.16	1.16	4.1%

1. The escalation is only for 1990 to 2000 - from then on the price remains constant in real terms. (The escalation rate is an increase in real value - not simply monetary value).

A few years ago these forecasts would have seemed very optimistic. The graph compares the central scenarios of four forecasts. The two forecasts at the bottom are the most recent (1989 and 1990). The highest forecast is from the earliest publication (CERG, 1983).

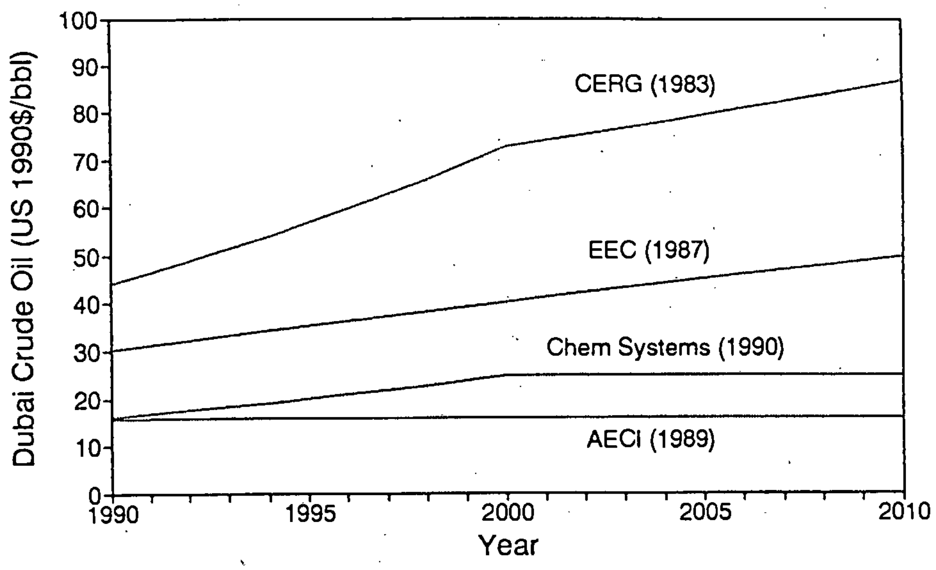


Figure 4.43: Four forecasts of Dubai Crude Oil Price
Sources: Eden (1983) for Cambridge Energy Research Group (CERG)
Guilmot (1987) for Commission of European Communities (CEC)
Stelna (1989) for African Explosives & Chemical Industries (AECI)
Chem Systems (1990)

The graph emphasizes the uncertainty involved in predicting the crude oil price - as well as the importance of accurate predictions. For example, the CERG predicts a price of 87 $/bbl in 2010; whereas AECI predicts 16 $/bbl. Which one turns out to be correct will affect the cost of diesel pumping dramatically.

The reasons for the recent decline in the predictions of crude oil prices are outlined by Stelna (1989):

a) In the late 1970's and early 1980's it was widely believed that non-communist oil supplies would not be able to grow past the mid-1980's. However, oil reserves have not only kept pace with oil production but have in fact outstripped it. For example, in 1979 the expected lifetime of the oil reserves was 26 years; ten years later in 1989 it had increased to 41 years.

b) Contrary to prior belief the oil production of the developing non-OPEC countries has increased until it recently matched their oil consumption. Consequently the dependence on OPEC has decreased rather than increased over the past decade. However, in the long term OPEC will still dominate the market.

c) Improvements in exploration and recovery of oil may still improve the situation for non-OPEC countries. For example, new techniques allow as much as 70% of the oil to be recovered, in comparison to the 30% which is possible with primary methods.

d) The increase in demand for oil has not grown nearly as fast as predicted - the oil consumption at the end of the 1980's was only slightly higher than at the beginning. The growing concern for the environment may mean that the growth in the use of oil will be further curbed.

c) Maintenance Costs

Estimates of the cost of maintaining a diesel pump vary widely as shown in the table below:

Table 4.20: Estimates of the Cost of Maintaining a Diesel Pump

Source	Maintenance Cost (R/hr)	(R/yr)	Comment
"Normal Case"	0.60		
"Best Case"	0.50		
Scaffold and Plant Hire	0.03	40	Hires out diesel/petrol pumps
Cedara Faculty (1989)	0.23	414	45 kW engine
Morris (1988)	0.70		5.6 kW Genset - less travel costs
Berry (1990)	0.99	2000	Department of Agriculture
Halcrow "normal"	1.46	1460	Converted from 1982 US$
Halcrow "best"	0.73	730	Converted from 1982 US$
Wiseman (1987)	1.68	215	5% Capital Cost per year
Maintenance Contractor	11.00	12000	Maintains KwaZulu Govt Pumps

Note: all figures are converted to 1990 SA R (where necessary).

The estimates of maintenance costs vary from 3 c/hour to R 11 per hour, but are mostly below R 2 per hour. All the estimates above are for a small diesel engine (3 to 4 kW) except that of 23 c/hour by Cedara Agricultural Faculty for a 45 kW engine.

The irony is that the two extreme estimates of 3 c/hour and R 11 per hour are made by the two people who have the most practical experience on the subject. The low estimate is by Ryan Reddy of Scaffold and Plant Hire in Pietermaritzburg. He has a fleet of diesel and petrol generators and pumps which he hires out. For this reason he needs to keep accurate track of the costs of running and maintaining the engines and also has much experience because of the number of machines involved. His engines work an average of 5 hours a day for 5 days a week. He claims that Lister engines require very little maintenance and that R 40 per year is adequate (which works out to 3 cents per hour).

The high estimate of R 11 per hour is by John Burton of Engines and Electric in Durban. He is contracted to maintain all the pumps established by the KwaZulu Department of Works in a particular area. His estimate is based on one service per month with the following break-down for each service:

1)	Travel:	R 260	(260 km * R 1 per km)
2)	Time:	R 720	(2 people * 12 hrs * R 60 /hour)
3)	Components:	R 150	

The discrepancy between these two estimates emphasizes the importance of the method of maintenance: the second estimate is very high because it includes costs of travelling and generous charges for professional time. Ryan Reddy does all the maintenance on his own property and so costs are lower.

A community garden would not be able to afford hiring a contractor to do the maintenance on site. So they would ask the agricultural officer to take the diesel engine and pump in for maintenance. The agents for Lister diesel charge R 250 for a regular service. If the engine was serviced every 400 hours this would give a cost of 60 cents per hour. So the base case assumptions used are 60 cents per hour for the "normal case" and 50 cents per hour for the "best case".

This is line with Morris's calculation of 70 c/hour. His estimate is based on records for 20 months for a diesel generator in the Kruger National Park. The travel costs (which formed 10.5% of the total) have been subtracted.

Petrol pumps: The maintenance costs for petrol engines are higher than for diesel engines - so a figure of 100 cents per hour was assumed for petrol pumps. The only other estimate available is 40 c/hour by Sinclair (1989). But this is based only on manufacturer's information and so may be low - particularly as it is lower than that calculated from records for diesel engines by Morris.

d) Replacement Costs: Component Lifetimes

Engine Lifetime

The following table gives various estimates of the life of a diesel engine.

Table 4.21: Estimates of the Lifetime of a Diesel Engine

Source	Lifetime (hours)	Comment
"Normal Case"	10000	Maximum of 15 years
"Best Case"	20000	Maximum of 20 years
Halcrow "normal"	3700	Maximum of 7.5 years
Halcrow "best"	5000	Maximum of 10 years
Berry (1990)	8000	Department of Agriculture
Wiseman	10000	
Williams (1989)	15000	
Scaffold & Plant Hire	20000	15 years at 1300 hr/yr
Cedara Faculty (1989)	22000	12 years at 1800 hrs/yr (45 kW)

Again the estimates vary widely from 3,700 hours estimated by Halcrow for their "normal" case to around 20,000 hours estimated by both Scaffold & Plant Hire and the Cedara Agricultural faculty. Williams (1989) in a survey of generators in South Africa reported than many diesel engines were still working well after 20,000 working hours. He accepted 15,000 hours as his default.

Because his survey included only "first world" farmers, his estimate is probably optimistic for community gardens. So a lifetime of 10000 hours is assumed for the "normal case" for this thesis. In order to account for the possibility of a long lifetime, 20000 hours is assumed for the "best case".

Petrol pumps: the lifetime of a petrol pump is much less than that for a diesel machine. So a lifetime of 6000 hours was assumed (with a maximum life of 8 years).

Pump Lifetime

The following table compares the assumptions used in this thesis with estimates made by others.

Table 4.22: Estimates of the Lifetime of a Pump

Source	Pump Lifetime	
"Normal Case"	8,000	(15 years max)
"Best Case"	15,000	(20 years max)
Mono Pumps Ltd	8,500	
Halcrow	40,000	(7.5 years max)
Wiseman	10,000	

The lifetime of a pump depends a lot on the quality of water. Although a strainer is used at Sondela the water still carries some grit - this is inevitable if river water is pumped. Mono Pumps estimates a lifetime for their pump of 5 years under these conditions. At 4.7 hours pumping per day this gives a lifetime of 8,500 hours. Most pumps would give similar lifetimes under these conditions.

So a pump lifetime of 8,000 hours is assumed for the "normal case" and 15,000 for the "best case" (assuming better water). This is low in comparison with Halcrow's assumption - but they assume more ideal conditions.

e) Operator's Wages:

Neither Halcrow nor Wiseman accounted for wages for the pump operator. But in all the community gardens around Sondela which had diesel or petrol pumps the pump operator was given a small amount of money by the other gardeners. So this was included in the model used here. Phumalanga garden was used as a basis. Here the pump operator was given R 20 per month for a one hectare garden.

As the computer model deals with various flow rates it is necessary to scale these wages according to the size of the garden. It is not much more trouble running a diesel engine for 5 hours a day than it is for 1 hour as the engine can run unattended. But the wages do need to increase because of added responsibility and added problems with maintenance. So the following table was used as a basis - from it a correlation was found for the operator's wages in terms of water flow rate.

Table 4.23: The Operator's Wages as a Function of Flow Rate

Water Pumped (m^3/day)	Operator's Wages (R/month)
3	15
30	35
150	100

The operator at Phumalanga worked only 10 months of the year as no water was pumped during two of the summer months - so this scale was adjusted accordingly.

4.5.3 Assumptions on Electric Pump Using ESKOM

The highest part of the Life Cycle Costs for an electric pump are the ESKOM charges. These are easily determinable for a given situation. The capital cost of the pump is also easily found. And the maintenance and replacement costs are almost insignificant. So all the major costs of an electric pump are easily determined and thus the Life Cycle Costs of an electric pump can be calculated accurately. There is not the same degree of guess-work involved as when considering a diesel or PV pump.

However, there is some guess-work involved: two tariff structures were considered - the normal tariff for rural areas around Cato Ridge, and the "S1 tariff". While the normal tariff is expensive for users who require only small amounts of electricity, the S1 tariff is very cheap and would transform the cost of energy in rural areas. The guess-work involved concerns when (or if) the S1 tariff will be introduced into a particular area.

This question is dealt with first; and then the validity of the assumptions is discussed.

Will the S1 Tariff be introduced widely?

Description: The S1 tariff is able to be much cheaper because of the use of prepayment meters and cheaper methods of reticulation. Users pay for units of electricity at a central point. The number of units they have paid for is then recorded on a magnetic card and transferred to their prepayment meter by this card. The use of these cards has three important advantages:

a) there is no need to read each individual meter which is expensive especially in rural areas;
b) the user pays in advance and so cannot build up a large debt which he is then unable or unwilling to pay; and
c) more people can afford the charges and so costs of extending the power lines and of the transformers can be shared by more people.

The S1 tariff will only be introduced to areas where the electricity consumption is likely to be high enough to make it economic. ESKOM would consider electrifying an area using the S1 tariff if there are more than 7 customers per kilometre and if the average household consumption is 350 kWh/month (Addis, ESKOM: pers. comm.).

In many areas the average consumption would not be that high: the average at a pilot study at Empangeni was found to be 220 kWh/customer/month. So ESKOM is considering ways of encouraging the use of electricity by soft loans for electrical equipment such as stoves.

It seems that in many semi-rural areas (such as that surrounding Sondela garden) it would be quite easy to find 7 customers per kilometre who would want to connect up if the S1 tariff were available. But the average consumption would probably not be as high as 350 kWh, unless ESKOM succeeded in encouraging increases consumption. Even if a rural area does qualify the townships would probably be given priority as they would be more economically viable.

So semi-rural areas are not likely to get the S1 tariff in the immediate future. But it is worth bearing in mind because it may be appropriate in some situations where there are a number of schools and shops in the vicinity; and because an area could be prioritized if somebody motivated strongly for it.

The Assumptions

The following table summarizes the "base case" assumptions used for electric pumps.

Table 4.24: The Assumptions Used on Electric Pumps - ESKOM

Assumption on:	Normal Tariff	S1 Tariff
Connection fee (1-phase)	R 400	R 30
Recoverable deposit	R 750	None
Motor & pump (0.25 kW)[1]	R 2030	R 2030
Motor & pump (0.75 kW)[1]	R 2260	R 2260
Energy Charge		
1st 1000 units	17.77 c/kWh	16 c/kWh
Thereafter	10.28 c/kWh	16 c/kWh
Account Charge	43.17 R/month	None
Line Charges	24 R/100m/month	None
System Efficiency	48%	48%
Motor Lifetime	60,000 hrs	60,000 hrs
Pump Lifetime	8,000 hrs	15,000 hrs
Maintenance Cost	0 c/hour	0 c/hour

1. Motor and pump prices include 13% GST.

a) Capital Costs

The capital costs for each tariff and those of the motor and pump are given in the table below:

Table 4.25: Capital Charges for Electric Pumps

Charged for	Normal Tariff	S1 Tariff
Connection fee (1-phase)	R 400	R 30
Recoverable deposit	R 750	None
Motor & pump (0.25 kW)	R 2030 (incl GST)	
Motor & pump (0.75 kW)	R 2260 (incl GST)	

These figures emphasize the advantages of the S1 Tariff: the total initial outlay is only R 30 for the S1 Tariff in comparison to R 1150 for the normal tariff. (The fact that the deposit for the normal tariff is recoverable is accounted for in the model by making it part of the salvage value of the system.)

The prices for the motor and pump were got from MacBeans in Pietermaritzburg. Very low power motors can be used as the pump can be operated continuously if necessary. However, the cost of the motor and pump increases only 10% for a three-fold increase in power (from 0.25 kW to 0.75 kW), so it is probably better to choose a slightly larger motor/pump and run it for less time.

b) Running Costs

The running costs are shown in the table below:

Table 4.26: The Running Costs of an Electric Pump

Charge for	Normal Tariff	S1 Tariff
Energy Charge		
1st 1000 units	17.77 c/kWh	16 c/kWh
Thereafter	10.28 c/kWh	16 c/kWh
Account Charge	43.17 R/month	None
Line Charges	24.00 R/100m/month	None
Pump Efficiency	60%	60%
Motor Efficiency	80%	80%
System Efficiency	48%	48%

Note: the first 200 meters are free from line charges. Tariff charges are for April 1990.

The account charge is for reading the meter every month and for administration. It is a flat rate and does not depend on the amount of electricity used.

The line charges are for the extension of the power lines. The first 200 meters is free - thereafter there is a monthly flat rate of about R 24 per 100 metres extended. If there are a number of consumers wanting to be connected then the extension charges are divided among them. This may reduce the monthly charges considerably.

The S1 tariff will dramatically reduce running costs especially for small users who are at a distance from the grid (if it is introduced to these areas). This is because the user pays only for energy which, for domestic loads, is a fraction of the monthly account charge and possible line charges.

The efficiency of the motor is taken to be 80% while that of the pump is taken to be 60%. This gives a combined efficiency of 48%. Because the motor is connected to a constant voltage it runs at a constant speed. For this reason it is possible to ensure that the pump runs at its ideal speed. So a pump efficiency of 60% is, in fact, a conservative estimate.

c) Replacement Costs - Component Lifetimes

Motor lifetime: the motors are designed for continuous operation at low loads. For this reason a lifetime of 60,000 hours is commonly accepted (Eloff, 1990: Pers. Comm.).

Pump lifetime: as for the diesel and PV pumps the lifetime of the pump is set to 8,000 hours for the "normal case" and 15,000 hours for the "best case" (because of the condition of the river water).

d) Maintenance Costs

The maintenance costs for a small electric pump are very low - almost negligible. The motor/pump unit is small and can easily be taken in for repair which obviates the need for expensive on-site maintenance.

A computer model developed by Cedara Agricultural Faculty estimates the maintenance costs for a 45 kW electric motor and pump to be 1 cent per hour. So the maintenance costs for a 0.5 kW unit could be safely ignored.

4.6 Conclusions

All costs given below are in 1990 SA Rands. All figures are given for the default assumptions and conditions tabulated in Section 4.1.

a) General Conclusions

1. Choosing between PV, diesel and electric pumps is complex because of the many site conditions and assumptions which may vary. For example, the sensitivity of 15 site conditions and assumptions was examined in this thesis - but each analysis had to assume that all the other assumptions were at default conditions. This limits the usefulness of this analysis. Ideally, the spreadsheet used to generate these results should be produced as an executable program so that any set of conditions and assumptions can be easily considered.

2. Before choosing a pump, the siting and size of the garden should be carefully considered. The cost of pumped water for all pumps drops dramatically as the water demand increases from 3 m^3/day to 30 m^3/day. For example, the cost for the PV "normal case" drops by 64% over this range, while that for the diesel "normal case" drops by 75%. As the water demand increases further (above 30 m^3/day) the cost of water continues to drop but only gradually. Because the costs of PV pumps drop less rapidly with increasing water demand than do those of diesel and electric pumps, PV pumps are more competitive at low water demands.

   The head should be kept as low as possible. The cost of pumped water rises steadily with head: it increases by 70% for the PV "normal case" as the head rises from 7 to 30 metres; and by 22% for the diesel "normal case" over the same range. Because the costs of PV pumps increase more rapidly with increasing head than do those of diesel and electric pumps, PV pumps are more competitive at low heads.

   When sizing the pump it should be remembered that third world farmers use water very frugally: an average water demand of 3 m^3/ha/day for the whole year was measured at Sondela. The Peak Demand Factor was 1.83.

b) Connecting to the ESKOM grid should be considered first

3. Connection to ESKOM on the S1 tariff is by far the cheapest and most desirable option, and its possibility should be investigated before other pumps are costed. The cost of pumped water from an electric pump connected on the S1 tariff drops from 10 to 1 c/m^3 as the hydraulic head increases from 40 to 1200 m^4/day. In comparison, the cost of water from other pumps over the same range is: 107 to 34 c/m^3 for the PV "normal case", 47 to 9 c/m^3 for the diesel "normal case", and 87 to 4 c/m^3 for the ESKOM normal tariff.

   ESKOM would consider electrifying an area using the S1 tariff if there are more than 7 customers per kilometre and if the average household consumption is 350 kWh/month (Addis, ESKOM: pers. comm.). While in most areas there would be more than 7 customers per kilometre, the household consumption is unlikely to be as high as 350 kWh/month in rural areas. So the likelihood of ESKOM introducing the S1 tariff into rural areas depends on their success in encouraging higher electricity consumption by the use of soft loans for equipment such as stoves and geysers.

4. Because of the reliability and low risk involved, connecting to the ESKOM grid under the normal tariff should be considered next. The economics of the ESKOM normal tariff depend very much on site dependent factors - the number of kilometres to the grid and the number of ESKOM consumers that connect to the grid simultaneously.

   An unconventional strategy for reducing the costs of the ESKOM normal tariff is sharing an account. ESKOM will consider connecting two consumers to one account if they are within 300 metres of one another. If two consumers share an account the costs of the ESKOM normal tariff drop by 42% (at default conditions).

The following graph can be used to determine when the ESKOM normal tariff is cheaper than alternative pumps.

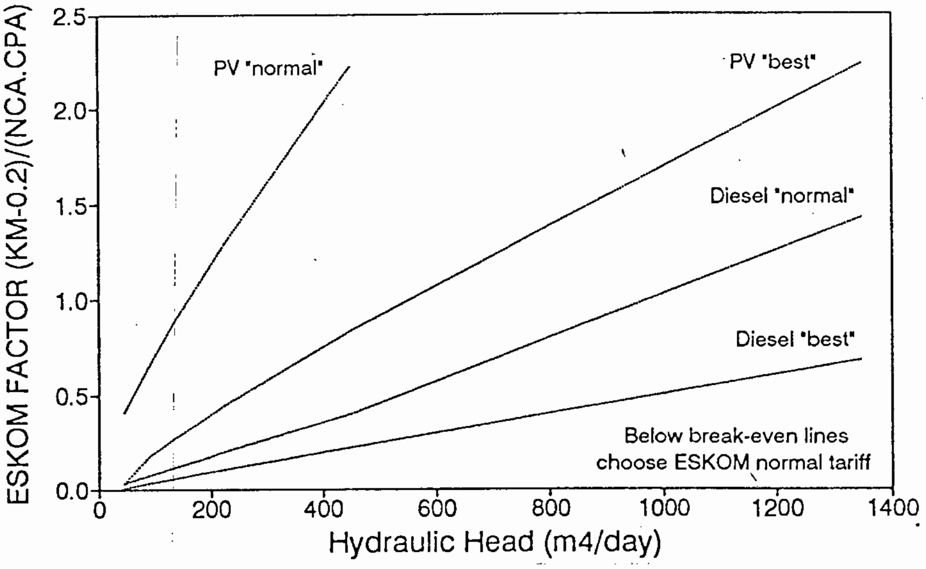


Figure 4.44: Break-even Points with ESKOM normal tariff - All Factors

First the "ESKOM factor" for the particular site must be calculated. This factor takes into account all the site dependent factors which affect the ESKOM costs. It has the following formula:

ESKOM factor = (KM - 0.2)/(NCA.CPA)

where: KM is the distance to the grid in kilometres,
NCA is the number of consumers in the area connecting simultaneously, and
CPA is the number of consumers sharing an account.

Once this is calculated it is possible to read off the graph the break-even point for the alternative pump which is being considered. For example, if the distance to the grid is 1.2 kilometres, there are 2 consumers connecting simultaneously, and one person per account, then the ESKOM factor is 0.5. From the graph it can be seen that the break-even point for the diesel "normal case" is at a hydraulic head of about 550 m^4/day. So, if the hydraulic head is above 550 m^4/day then the ESKOM normal tariff should be used; otherwise the diesel "normal case" would be cheaper.

b) The PV Pump: "normal" versus "best" case

5. The design of the PV pump affects its Life Cycle Costs dramatically: the costs of the PV "best case" are about 40% those of the PV "normal case" under most conditions. The "best case" is based on the following three adaptations from the "normal case":

   i) The path of the sun is physically tracked,
   ii) The efficiency of the pump itself is between 58% and 62%, and
   iii) The Balance of System costs of the "normal case" have been halved by modularization and standardization of the system.

6. The assumptions which affect the costs of the PV pump most are: PV system efficiency, unit capital costs, and Peak Demand Factor. The critical daily insolation does not have as large an effect as expected because the maintenance and replacement costs increase with increasing insolation. The effect of dropping PV panel prices is not as marked as may be expected: PV panel prices are likely to drop by about 30% in the next ten years resulting in a drop in the costs of PV pumps of about 10% (at default conditions).

c) Diesel and Petrol Pumps

7. The ratio of the diesel "best case" to the diesel "normal case" drops from 0.94 at 40 m^4/day to 0.64 at 1200 m^4/day. So the difference is barely noticeable for low hydraulic heads, but fairly important for higher hydraulic heads. The main difference in the assumptions used is in system efficiency: 12.6% for the "best case" and 7.4% for the "normal case".

8. Petrol pumps are favoured by low water demand, low head, short project length and high discount rate. For the default conditions, the petrol pump is slightly cheaper than the diesel "normal case" for hydraulic heads less than 130 m^4/day, but becomes progressively more expensive until it is 1.4 times the price of the diesel "normal case" at an hydraulic head of 1200 m^4/day.

9. The factors which affect the costs of the diesel pump most at high hydraulic heads are: system efficiency, fuel price and fuel escalation rate. Most community gardens have low hydraulic heads (40 to 400 m^4/day), and so these factors are not as important as expected. The factor which affects diesel pump costs most at low hydraulic heads is the operator's wages.

d) Choosing between PV and diesel pumps

10. The cost of pumped water from the PV "best case" is the same as that from the diesel "normal case" at an hydraulic head of 40 m^4/day. As the hydraulic head increases the PV "best case" becomes progressively less competitive until at 1200 m^4/day its cost is 1.4 times that of the diesel "normal case". However, because of the other advantages of PV pumps people in remote rural areas may choose them above diesel pumps if their long term costs are up to two times those of the diesel pumps (see Section 5.6). So the PV "best case" may be preferred to the diesel "normal case" over the whole range of hydraulic heads considered.

11. The cost of pumped water from the PV "normal case", however, ranges from two to four times that from the diesel "normal case" as the hydraulic head increases from 40 to 1200 m^4/day. So the PV "normal case" may only be preferred to the diesel "normal case" at very low hydraulic heads.

CHAPTER 5

SOCIAL EVALUATION

5.1 Introduction

No matter how efficient or cheap a device is, if it is not suitable to the social needs of a community it will not sell. So the social evaluation is of paramount importance - it is the social factors which determine the relative importance of the various technical and economic factors.

The purpose of the social evaluation was to determine how suitable photovoltaic water pumping is to developing areas by examining the situation of the Sondela garden in detail. The gardeners were asked which pump they would have chosen given the comparative costs computed in the economic evaluation - and given their experience of the PV pump. They were given information from other gardens which had experience of diesel pumps to put the decision in a realistic context.

The structure of the chapter is as follows:

a) Section 5.2 describes the method used in the three sets of interviews. These interviews were conducted over a period of 5 years, from before the introduction of the pump until 4 years after introduction.

b) Section 5.3: the suitability of the pump can only be evaluated if there is thorough knowledge of its context. This section describes the community into which the pump was introduced - covering such things as the economic activity and employment levels in the area, the history of the pump's introduction, the economic and educational status of the gardeners, and the productivity of the garden.

c) Section 5.4 describes the effect of the introduction of the pump on the operation of the garden - including the amount of time saved, the uses that this time was put to, and the effect of the pump on the value of the gardeners' time.

d) Section 5.5: the purpose of studying a pump installed in the field was to discover practical problems which PV pumping has outside the laboratory. This section discusses the problems encountered (floods, theft, and vandalism), as well as precautions taken and possible precautions considered.

e) Section 5.6: the suitability of PV pumping is compared with that of diesel pumping using information on the advantages and disadvantages of diesel pumps gained from interviews, and costs computed in the economic evaluation.

f) Section 5.7: the problem of the high initial cost and risk of PV pumping, which is the main barrier to its dissemination, is discussed and a possible solution advocated.

g) Section 5.8: the conclusions from this chapter are summarized.

5.2 Method of Research

The effect of the pump on Sondela garden has been well-studied. The information used in this section is drawn from interviews conducted over a period of 5 years: from before the pump was introduced to 4 years after the installation of the pump. The following interviews were conducted:

a) In September 1985: a baseline study of the community before the introduction of the pump (Atmore, 1986).

b) In September 1986 and April 1987: two sets of interviews gauging the effect of the introduction of the pump (Udit, 1987a and 1987b).

c) In April 1990: in-depth interviews to compare the suitability of PV pumping with other methods of pumping. These interviews were done as part of this report and summaries of the responses are included in Appendix 5.2.

In addition to the knowledge gained from interviews, some of the information in this chapter was gained over the 21 months in total that I spent at site.

The method used for each set of interviews is discussed briefly below.

a) Before the Pump's Installation (September 1985)

The first survey was done by Atmore before the pump was installed. The interview dealt with the following: the history of the garden, perceptions of the garden, the organization of the garden, perceptions of the PV pump and expectations, and background data such as household income and size. It was administered in Zulu by field workers to a random sample of 16 of the 46 plot holders. Each interview took 1 to 2 hours.

b) Documenting the Effect of the Pump

Two subsequent interviews were done by Udit (1987a and 1987b). The first set of interviews was done in September 1986 directly after the installation of the pump. It concentrated on the garden's operation before the pump was installed and complemented the data collected by Atmore. It added information on the time spent collecting water in the garden, the most arduous tasks in the garden, the garden's productivity and the perceived need for marketing. The second set of interviews was done after the pump had been in operation for eight months. It aimed to gauge the effect of the pump on the gardeners' activity and perceptions, and covered the same topics as the first set.

These interviews were also administered in Zulu by field workers. All 46 plot holders were interviewed.

c) In-depth interviews (April 1990)

The last set of interviews was done in April 1990 after the pump had been working for a total of 24 months (before and after the floods). The pump and garden had encountered many problems: the pump had been washed away in the floods, two panels had been stoned, and seven had been stolen. Various methods had been used to protect the new pump.

The purpose of this interview was to gauge the gardeners' opinions about how suitable the pump was to their needs, how effective the methods of protection had been, what methods of protection they would recommend, and, given the advantages and disadvantages of PV and diesel pumps and their comparative costs, which pump would they recommend.

Because these questions are complicated it was decided that in-depth interviews would be the most effective. Most of the gardeners do not have enough interest in the garden to wade through estimates of costs and to weight them against the advantages and disadvantages of each type of pump. If these decisions had to be made the opinions of most of the gardeners would be informed by the most influential members. For this reason it was more important to consult the opinion makers in the garden. Furthermore, statistical data was already available from Udit's surveys of the garden before and after the pump's installation.

Interview Method

A structured interview was administered individually to all the respondents. I personally administered the interview in Zulu, so that I could probe their answers where necessary. I was confident that I would understand all the nuances of their answers having spent a total of 21 months in the area (14 of them staying with a Zulu family). Because of the time that I had spent in the area, much of it working on site at the pump, I had no doubt that the respondents would feel relaxed with me and would be honest.

Special effort was taken to guard against two common pitfalls in interviews: i) the respondent tries to give the answer she thinks the interviewer is looking for; and ii) she adapts her answer to what she considers her best advantage because she feels that her answer may affect her predicament. To ensure truthful information it was stressed firstly that I was not advocating any method of pumping and would not be offended by any criticisms of the PV pump; that, in fact, I would like to know all possible problems. And secondly it was stressed that the pump and all accessories were theirs - they would not be asked to pay for anything depending on their responses to the questions.

With their permission the interviews were tape recorded, so that their time was not wasted while their responses were written down. This encouraged them to answer in full and not to hold back something to avoid lengthening the interview. To encourage them to give their full attention and consideration to the questions, they were each given a small gift to compensate for the time the interviews took. (The interviews ranged from 2 to 4 hours.)

The intention was to interview a cross-section of six of the gardeners. However, after the first three interviews it became obvious that little would be gained by interviewing more gardeners: there was little fundamental disagreement, and the quality of the answers was decreasing. It was obvious that the three already interviewed, because of their close involvement with the affairs of the garden, would be most likely to influence the decisions of the garden and in a sense spoke for the garden.

Profile of the respondents

Mrs Mdluli has been the chairperson almost since the beginning of the garden. Initially she was vice-chairperson when there was a man who was nominally chairperson - but she was still the main mover. She has proved herself to be a very good leader - always considering decisions carefully, encouraging everybody to give their ideas, and has given much time to being a go-between between the various agencies dealing with the garden and the gardeners. Her answers always seemed well-considered and balanced. She is 49, married, and there are 12 people in her household. She does not know how much her husband earns, but he gives her R 120 a month for groceries.

Mrs Nene has been the treasurer of the garden for one year, and has been with the garden since its inception. Because she has been on the committee for only a year she is not that closely in touch with the affairs of the garden - although she is treasurer she was unable to give an idea of how the R 2 monthly contribution of each gardener is spent. She is married, 37 years old, and has 8 people in her household. She does not know how much her husband earns, but he gives her R 140 a month for groceries. None of her children are working at the moment.

Mrs Mkhize is not on the committee at the moment, but was secretary in 1987, and treasurer from 1988 to 1989. She is knowledgeable because of her involvement in the affairs of the garden and is an outspoken member in meetings. However, she tends to treat most things with humour, and some of her responses seemed a little glib - she did not seem to take seriously potential problems. She is married, 64 years old, and there are 12 people in her household. Her children are married and stay at home but do not tell her how much they earn. Her husband gives her money for groceries. Mrs Mkhize's household seems to be one of the more wealthy because all her children are earning - she is the only one in the garden with a hose pipe and she employs a man to help with the gardening.

Supplementary Interviews

In order to complement the interviews of the women at Sondela, who had experience only of the PV pump, the following people were also interviewed:

a) The chairperson of a garden which had used a diesel pump.
b) The agricultural officer of a neighbouring ward where there were three petrol pumps.
c) Mr Mdlolo, the agricultural officer for Sondela garden.

Information from these supplementary interviews is discussed in Section 5.6.

5.3 Social Profile of the Area and the Garden

The suitability of a method of pumping can only be evaluated if its context is known. This section attempts to describe this context dealing in turn with the following:

a) The area surrounding Sondela garden (Mpumalanga district) - including its location, population density, agricultural potential and agricultural activity, and other economic activity.

b) Sondela garden itself - including its history, suitability for irrigation, fertility, water usage, and productivity.

c) The gardeners - including household income, levels of employment, other work engaged in, and educational levels.

5.3.1 Profile of Mpumalanga District

a) Location

The PV pump which was used as a case study was installed in Sondela Community Vegetable Garden near Durban in Natal. The following two maps show the location of Sondela Garden. The first is a large scale map showing the location of the area of interest within South Africa:

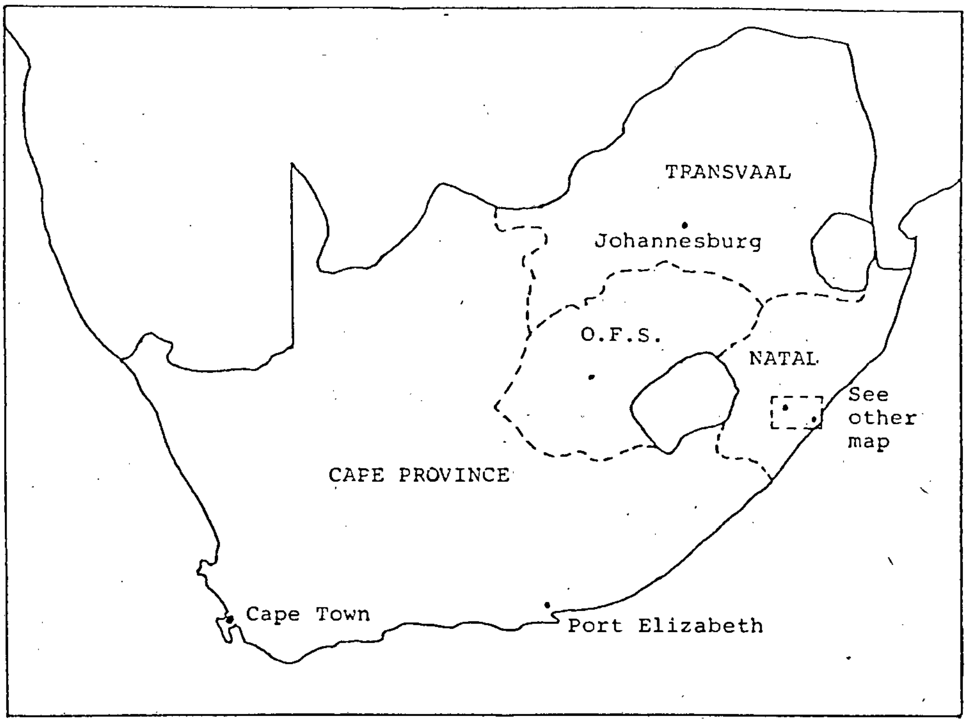


Figure 5.1: The Location of the Site of Study within South Africa

The area of interest is shown by the block marked "See other map". This area is blown up for more detail in the following figure.

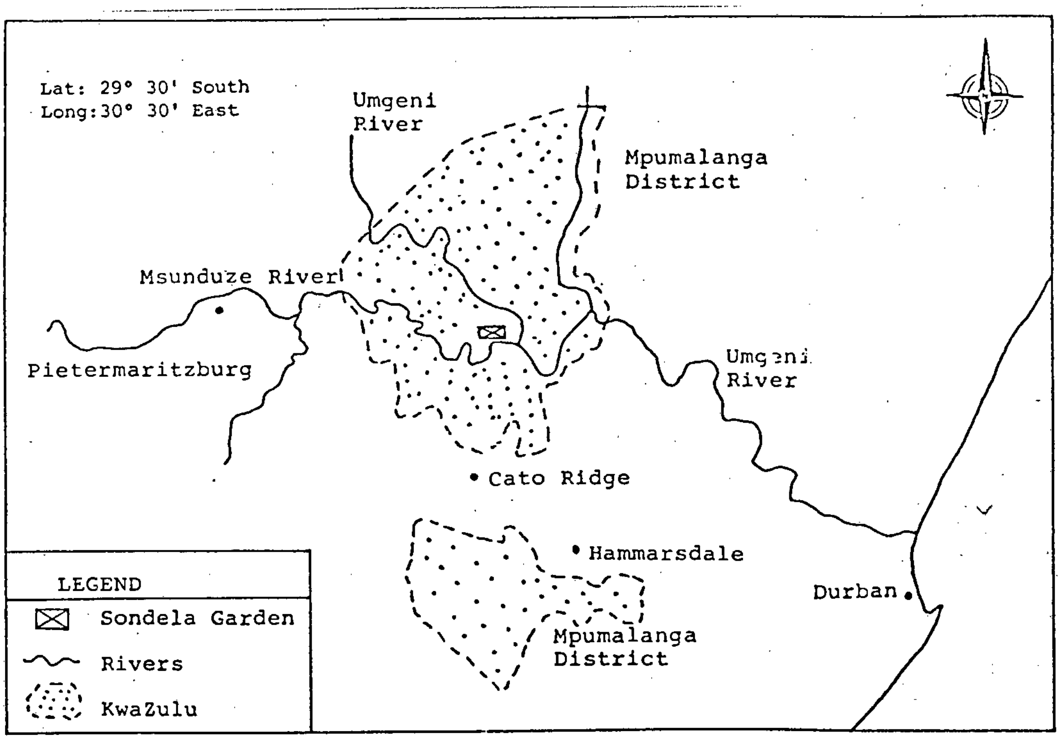


Figure 5.2: The Location of Sondela Garden within Mpumalanga District

The position of Sondela Garden (near the confluence of the Msunduze and Umgeni Rivers) is shown on the map (see the legend). The garden is in the Mpumalanga Magisterial District of Kwazulu. It is about 45 kilometres from both Pietermaritzburg and Durban. Other towns which are near by are Cato Ridge and Hammarsdale.

The Mpumalanga District is divided into six wards. Each ward is under the authority of a traditional chief, who runs the ward with the help of his "indunas" and the tribal council. Sondela is in Nyavu ward under Chief Mdluli.

The garden is on a good sand road about 3 kilometres from the main tarred road from Cato Ridge to Nagle Dam. There are bus and taxi services which run through the ward to Pietermaritzburg, Cato Ridge, Hammarsdale and Durban.

b) Population Density

The population of the area was less than 100 people per square kilometre in 1978 (Thorrington-Smith). According to the 1985 census, the total population of Mpumalanga district is 190,000 with most people (130,000) residing in the rural areas of the district (GIS, 1990). The area is semi-rural - less sparsely settled than a township, but without enough land for people to survive on only agriculture. Most households have enough land to grow a few crops.

c) Agricultural Potential

The area is low-lying - between 305 and 610 metres above sea-level, with the slope of the land generally less than 1:6. The veld type is Valley Bushveld (Thorrington-Smith, 1978).

The average annual rainfall measured by the agricultural officer in Nyavu ward over the last four years is 640 millimetres per year. The ward is in a rain shadow - the average for the same period at the Regional Agricultural Offices just 8 kilometres away was 890 millimetres.

The following bar chart shows the variation of rain during the year.

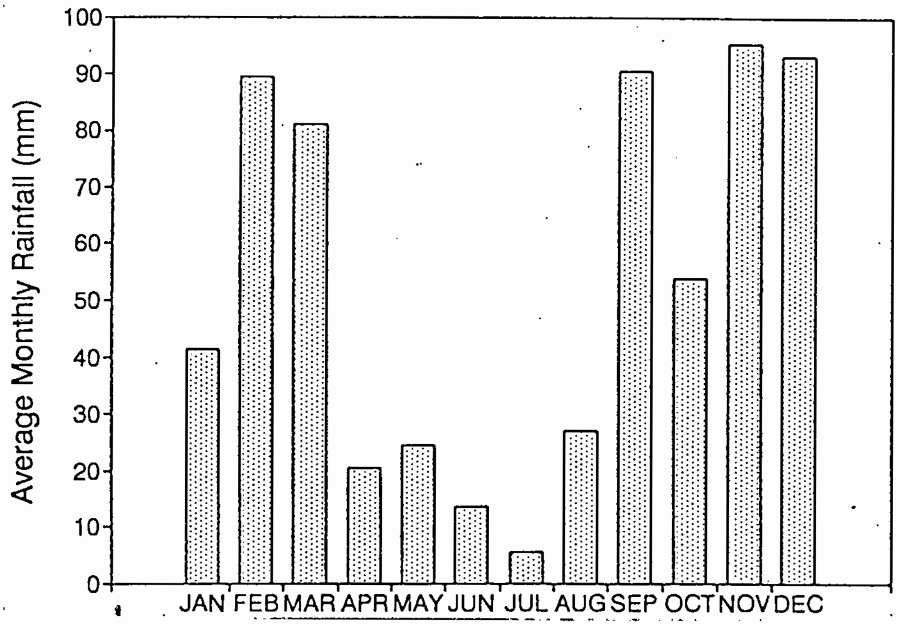


Figure 5.3: Monthly Rainfall Figures for Nyavu Ward (average 1986 to 1989)

The monthly rainfall varies from a high of 95 millimetres in November to a low of 6 millimetres in July. The average for the five low rainfall months (during winter) is about one quarter of that during the rest of the year (18 millimetres in comparison with 78 millimetres). This variation in rainfall in conjunction with the fact that main gardening season is winter means that the variation in irrigation requirements from summer to winter is large. This is disadvantageous to PV pumping.

d) Agricultural Activity

The main form of agricultural activity in the ward is the community garden system. Cattle and goats are also reared by the more wealthy members of the community. These graze freely throughout the ward on communal land, making it necessary to fence cultivated land. Some of the more wealthy households also cultivate dry land maize, beans, or pumpkins; but no irrigation was observed on private land.

In each of the six wards in Mpumalanga District there is an agricultural officer, who may have one or two assistants. They provide most of the technical advice in the ward: advice to the gardens on fencing, irrigation, pesticides, crops and seeds; advice on establishing sources of clean potable water by protecting springs and establishing boreholes; as well as advising on appropriate sites for new houses or schools.

The agricultural officers are employees of the Kwazulu government. They receive four years training at Owen Sithole Technical College. The district offices for Mpumalanga provide back-up in the form of continued training, help in buying seeds and fertilizers, and access to equipment such as tractors.

The agricultural officers are usually moved on to another ward after about 5 years. This ensures that no ward will be saddled for too long with an incompetent agricultural officer. However, it is a factor when considering a PV pump - one cannot be sure that good technical assistance is going to be available for the following twenty years. A ward may spend some time without an agricultural officer during a change over; and the motivation of the agricultural officers varies.

The following information on the whole district is based on a report which was compiled after the September 1987 floods (Gosnell, 1987). Although the figures pertain to the situation in 1987, there have been no major changes.

There are 53 community gardens in the whole district with an average area of 1.1 hectares. The size of gardens ranges from 0.3 hectares to 9.5 hectares. However the 9.5 hectare garden is an exception - it was established when an expensive diesel pump was donated to Ximba ward by the government to try to persuade the people to submit to the introduction of betterment planning. Only 2 of the 53 gardens in the district are larger than 3 hectares.

In the whole district there are a total of 1500 households which have plots in community gardens. The average number of households per hectare of garden is 25. Most plot holders in the community gardens are women. They are often helped to cultivate the plot by other family members. The value of all the vegetables grown on the 60 hectares of community gardens in the district is estimated as R 2.3 million (see Subsection 5.3.2).

On average one in seven gardens is irrigated. The members of the other gardens carry water on their heads from nearby rivers or springs. In 1987 there were a total of 7 pumps in the ward (for 53 gardens): 2 petrol pumps, 4 diesel pumps and the photovoltaic pump at Sondela. Most of the gardens are situated on the banks of the rivers to reduce the amount of walking to irrigate the plots. So the heads involved are low: between 5 and 25 metres. For this reason most of the gardens are vulnerable to damage by floods. There is little ground water in the area, so most proposed irrigation schemes use surface water (streams and rivers).

The gardens are all placed near to water sources, and so the deep trench method advocated by Valley Trust is not used. The gardeners seem to prefer to carry more water than to go to the considerable effort of deep trenching their whole plot. Methods of water conservation, such as mulching, are used to limited extent.

The mix of personal responsibility and group sharing in the community garden seems to work well. The group takes responsibility for negotiating a suitable site, fencing the garden, buying seeds and fertilizers in bulk, and buying an irrigation system if desired. The group also shares the advice of the agricultural officer: they all plant the same crops at the same time, use the amount of fertilizer and type of pesticides recommended by him, and rotate their crops together so that the soil is not depleted. So by sharing the members can all benefit from the advantages of bulk buying, government transport for the buying of seeds and fertilizers and the advice of the agricultural officer.

But each member is responsible for planting, watering and weeding her own plot. Thus each member benefits directly from the work she puts into the plot and is not affected by lack of effort of other members.

e) Levels of Economic Activity and Employment in Nyavu Ward

Apart from the agricultural activity there is little economic activity in the ward: one bus company (owning about 10 buses), about five mini-bus taxis, six shops, and four schools. The income of the ward is derived mainly from wages in the surrounding metropolitan areas.

There are no health facilities in Nyavu ward. The nearest clinic is in the neighbouring Ximba ward. The ESKOM grid is at the moment being extended into the area to electrify three sites near Sondela garden - a school, the chief's house, and a shop.

According to the 1985 census, 23% of rural population of Mpumalanga district which is of employable age (15 to 64 years) is economically active. Most of the economically active population (80%) work in urban occupations (GIS, 1990).

The levels of education for rural people in the district are low: 35% of the population which is over 20 years have passed Standard 4; and only 4% have passed Standard 9. (GIS, 1990)

5.3.2 Sondela Garden

a) History

The Sondela community garden is one of 11 community gardens in Nyavu ward. It was initiated in 1982 when a group of women approached Mr Mdlolo, the agricultural officer, requesting that he help establish a community garden. With the help of a member of the Tribal Council, the use of some land on the banks of the Msunduze river was negotiated. Much of the land was church property; some of it was the traditional property of individual households. This land was donated to the group because it was for a community garden.

All the interested women in the area then came together and the garden was established with 46 members. A standard constitution was supplied by the agricultural officer. This provides for a committee comprising a chairperson, a treasurer, a secretary and two non-portfolio members. The committee is elected annually. The gardeners meet weekly to conduct the business of the garden. They have a group bank account which is organized by the treasurer. Each member contributes R 2 per month to the costs of seeds and fertilizers (1990).

In 1984, two years after the garden had been established, the gardeners approached the agricultural officer about buying a pump. A diesel pump was recommended and the gardeners began to save towards this. However, they struggled to put aside enough money. In March 1986, R 1000 had been collected but the gardeners had lost interest (Atmore, 1986). It was as this stage that Mr Gandar of the Institute of Natural Resources contacted the Regional Agricultural Offices proposing the establishment of a PV pump for research. Because Sondela garden had been saving for a pump for two years, and because it is a well-run garden, this site was proposed.

Mr Gandar introduced the concept of PV pumping to the gardeners using a demonstration model. It was agreed that pump would not be paid for by the garden as it was an untested method and they could not be expected to take the risk. The pump (costing R 22,800) was donated to the garden by the Development Bank of Southern Africa. The gardeners paid for the cement needed to build the reservoir and for the components of the reticulation system (totalling R 1300). They also provided labour for the digging of trenches in which the reticulation piping was laid and for the building of the reservoir.

The pump was guaranteed for its first year of operation while teething problems were sorted out. After that the responsibility for maintaining the pump was given to Sondela garden.

b) Agricultural Method

The following table gives the details of the garden, its members, and the irrigation water used.

Table 5.1: Details of the Garden and its Members

Quantity	Value
Number of members	46
Area of garden	1 hectare
Number of plots[1]	50
Size of plots	180 m^2
Cultivated area	0.9 hectares
Head to reservoir	12.5 meters
Water usage (winter)	4,600 l/day
Annual rainfall	640 mm/year
Costs of seeds and fertilizer	R 24 per member per year
Value of produce	R 754 per member per year

1. Spare plots are used to nurture seedlings. In the past some members also had more than one plot, and the agricultural officer had a plot.

Sondela garden is run on the basis of low input subsistence agriculture. The minimum of water, fertilizer, and pesticides is used. What is considered the cheapest and most effective method is used: there is no insistence on the use of only organic agricultural methods. Most of the produce of the garden is for domestic consumption; a little is sold and some given away to friends and relations.

The Soil Fertility and Suitability for Irrigation

The soil type and structure in Sondela garden was examined by Mr Auerbach, an agriculturist from the Institute of Natural Resources. His full report is included in the Appendix 5.3.2. He concluded that the soil is ideal for irrigation - it is well-drained and has an effective rooting depth of 1 metre. However, because the soil is well-drained it is vulnerable to leaching. The following table shows the level of nutrients in three samples taken from the garden.

Table 5.2: Soil Fertility in Sondela Garden

Sample Description	P	K	Ca	Mg	Na	Zn	Acid Sat.	KCl Ph
Pit A (above garden)	8	85	2089	469	0	1.0	1%	5.7
Sample B (in garden)	12	109	792	221	0	2.4	4%	4.9
Pit C (below garden)	9	78	1117	303	0	3.6	1%	5.4

Note: All units are in mg/kg

The lower Calcium and pH (and consequently higher acid saturation) in the cultivated section indicate a probable decrease in organic matter due to cultivation. Mr Auerbach recommended the use of kraal manure and mulching as well as a standard type fertilization programme to rectify this.

According to the chairperson of the garden, Mrs Mdluli, kraal manure is readily available to all members of the garden if they contact those who own stock. She commented that many gardeners do not use it simply because of laziness. Mulching is used but not extensively. And some of the organic waste from the garden is composted or burnt to return the nutrients to the soil.

Measured Water Usage in the Garden

In order to measure the exact amount of water used by the gardeners a Kent water flow meter was installed in the pipe leading from the water reservoir to the garden. This meter was read weekly from March to September 1987 (at which stage the experiment was interrupted by floods). The table below shows the amount of water used, as well as the rainfall in the ward (as recorded by the agricultural officer).

Table 5.3: Measured Water Usage and Rainfall at Sondela Garden

MONTH	IRRIGATION l/day	IRRIGATION mm/week	RAINFALL mm/week	TOTAL mm/week
MAR	1533	1.2	28.0	29
APR	2099	1.6	8.2	10
MAY	5626	4.4	0.0	4
JUN	3881	3.0	2.3	5
JUL	5664	4.4	2.3	7
AUG	4965	3.9	17.3	21
SEP	5543	4.3	77.2	81

Note: The calculation of mm/week for irrigation is based on a cultivated garden area of 0.9 hectares (50 plots of 180 m^2). The column "Total" gives the sum of the irrigation and rainfall - i.e the total application of water.

The amount of water used is much less than would normally be recommended for vegetable farming. The average for the winter months (April to September) is 4600 litres per day. The normal recommendation for commercial vegetable farming is 1 inch per hectare per week, which would work out to 29,400 litres per day for Sondela Garden. So the measured water usage is one sixth of that which would normally be considered optimum.

In order to determine accurately the optimum amount of irrigation for the garden, an agriculturist from the Institute of Natural Resources, Mr Auerbach, was asked to examine the garden. His report (included in Appendix 5.3.2) recommended 30,300 litres per day for the garden (almost exactly 1 inch per hectare per week). This recommendation was based on a study of the soil type using two 1.5 metre deep pits, a measurement of the infiltration rate, calculations for evapotranspiration, and the water usage of the actual crops which were being grown that year.

So a very accurate estimate of the actual irrigation requirement for that year for Sondela garden is 30,300 litres per day. However, despite the fact that only 4,600 litres per day was being used, Mr Auerbach commented that the vegetables were growing very well and there was no sign of wilting. He concluded that despite the apparent discrepancy it seemed that the vegetables were in fact getting an adequate amount of water. The only explanation is that the gardeners were applying the water very efficiently: they watered the roots of each plant so that no water was wasted.

These results are very important for the planning of irrigation schemes in community vegetable gardens. If measured water usage at Sondela is used as a guide to design, a PV pump would need to be designed to deliver 6,300 l/ha/day. (This is based on the maximum amount of water used - of 5,700 l/day in July for 0.9 hectares of irrigated garden). On the other hand if the standard recommendation of 1 inch/ha/week is used the pump would be designed to provide 33,300 l/ha/day. The cost of the pump would consequently be almost five times higher.

Also, PV pumps are more competitive for lower energy applications. So, if the design is based on 6,300 l/ha/day PV pumping is more likely to be favoured.

The crops produced and profitability

Each plot of 180 m² is divided into six equal sections (of 30 m² each). Each of these sections is used for at least one crop per year: sometimes a section will be used twice if a second crop is grown on it in the summer. Crops which are commonly grown are: cabbages, tomatoes, beetroot, spinach, carrots, potatoes, onions, butternut, beans, aubergines, peas, and cauliflower. Chillies and green peppers are grown in between the plots to help control erosion.

The main growing season is the winter. In the winter the women spend about 2.5 times as much time per week working in the garden than they do in the summer (calculated from data in Udit, 1987a). There are a number of reasons for this: the heat in the summer makes work less pleasant; pests are more common during the summer; and the women have other tasks such as cultivating dry-land maize at their homesteads, and cutting grass for mats.

Winter crops are planted from February onwards and are harvested throughout the winter. Summer crops, mainly butternut and sweet potato, are planted in spring and are harvested from January to March.

In order to estimate the profitability of the garden, the agricultural officer, Mr Mdlolo, was asked to provide detailed information on the likely productivity of each plot and an estimate of local prices of food. For an average year it was assumed that six crops were grown over the winter months, and that butternut was grown in the summer. The estimates of the profitability of these crops are summarized in the table below (full details are given in Appendix 5.3.2).

Table 5.4: Estimate of the Productivity of Sondela Garden

Crop	Units produced	R/unit	Kilograms	R/kg	R/section
Cabbage	72 heads	1.25			90
Spinach	45 bunches	0.50			23
Carrots	60 bunches	2.50			150
Tomatoes	72 plants		84	3.00	252
Onions	150 tubers		25	2.50	63
Potatoes	462 tubers		46	3.00	139
Butternut	30 butternuts		30	1.29	39
Total annual profit per garden member (180 m^2 plot)					754

Note: the prices of the first three crops are given in R/unit - for example Rands per head of cabbage or per bunch of carrots. The other crops are priced per kilogram and so the mass of the product is estimated.
Source: Mr Mdlolo, agricultural officer for Nyavu ward.

So the estimated value of the produce from each plot is R 754 a year. The annual expenses on seeds and fertilizers are R 24 per plot holder, giving an annual profit of R 730 (or R 61 per month). Thus, the profit per hectare of garden is R 37,700; and that for the whole Mpumalanga District is R 2.3 million.

5.3.3 The Gardeners

The data below is drawn from two sets of interviews: the first by Atmore in September 1985 before the introduction of the pump; the second by Udit in September 1986 directly after the introduction of the pump. Atmore interviewed a random sample of 16 of the 46 members of the garden; Udit interviewed all 46 members. For this reason, percentages are used, so that the data from the two sets of interviews can be compared.

a) Household Income

The following table shows the distribution of income per household as reported by the respondents.

Table 5.5: The Distribution of Household Incomes - Sondela Garden

Income bracket (R/hsehold/mo)	No of families in bracket Atmore[1]	 Udit[2]
< 50	6%	7%
51 - 75	25%	33%
76 - 120	25%	18%
121 - 185	38%	11%
>186	6%	7%
Don't know		24%

1. Interview of 16 households in September 1985 - Atmore (1986)
2. Interview of 46 households in September 1986 - Udit (1987)

The results from the two interviews are similar. Udit reported an average household income for all the plot holders of R 124 per month. This is equivalent to R 200 in 1990 (assuming wages keep pace with the Consumer Price Index).

However, the 1990 interviews indicated that most women are not told how much other members of their families are earning. So the above figures may not be very accurate.

Household incomes must be taken in context of the size of the households. The distribution of the household sizes is shown in the table below.

Table 5.6: The Sizes of Households - Sondela Garden

People per household	No of households Atmore[1]
< 5	25%
5	25%
6	6%
7	19%
8	6%
9	6%
10	0%
> 10	13%

[1] Interview of 16 households in September 1985 - Atmore (1986).

The average household size is 6.3 members (calculated from the table). This means that the income available for use on each member of the household is R 32 (in 1990). This is very low, and for this reason the community gardens are a crucial survival strategy for their members.

This is confirmed by the 1990 interviews: all the respondents said that they would not be able to get by without the garden - before the garden was established they only managed to scrape by and did not have enough nutritious food to eat. A large proportion of their weekly food comes from the garden.

The garden also seems to supply enough for the needs of the plot holders: all but two of the 46 plot-holders reported that they reaped enough for all their household consumption. Of those 41 had enough to sell some of their crops, and 3 did not sell but gave small amounts to relatives and friends. Two of the plot-holders did not reap enough to support even their households because they were in poor health and unable to give their plots adequate attention (Udit, 1987a).

The following table gives the sources of income reported by the respondents.

Table 5.7: The Sources of Household Incomes - Sondela Garden

Source of Income	No of households Atmore[1]	Udit[2]
Wages only	50%	55%
Pension only	6%	18%
Pension and wages	44%	27%

1. Interview of 16 households in September 1985 - Atmore (1986)
2. Interview of 46 households in September 1986 - Udit (1987)

The two sources agree that about 50% of the households rely only on wages. Between 6% and 18% of the households rely on only pensions.

b) Levels of Employment

Determining the level of employment is difficult because the two sets of interviews used different bases for measurement: Atmore reported the percentage of the members of the household employed; whereas Udit reported the number of members of each household employed. It is impossible to compare these results without access to the original interviews, so each report is dealt with separately. The following table gives Atmore's figures.

Table 5.8: Employment Levels for Sondela Households (Atmore)

%age of members of household employed	No of households in bracket
25%	13%
33%	6%
50%	13%
66%	19%
100%	50%

Note: Interview of 16 households in September 1985 - Atmore (1986)

Atmore reported a high rate of employment: half the households claimed 100% employment, while a total of 82% of the households had more than half their members employed. From the table an overall rate of employment of 74% for all the families can be calculated.

However, the parameters used to define "unemployed" here are important. Anyone who was looking for work, and not attending school was regarded as unemployed. Women employed in household work were regarded as employed. However, these parameters may not correctly determine the level of employment because any woman who is not formally employed would be required to do housework, and would thus probably be reported as "employed" whether or not she would prefer to be formally employed.

Udit asked for only the <u>number</u> of employed members in each household. The table below gives her figures.

Table 5.9: Employment Levels for Sondela Households (Udit)

No of People in Household Employed	No of households in bracket
None	26%
One member	58%
Two members	4%
Three members	7%
Four members	4%

Note: Interview of 46 households in September 1986 - Udit (1987a)

Udit did not clarify the parameters she used, but it is clear from her discussion that she was considering only formal employment - work in their homes did not qualify as "employed". It is probably for this reason that she identified 26% of the households (12 households) as having no-one employed; whereas Atmore reported that all households had some members employed (because household work was included).

According to the 1985 census 37% of the rural population of Mpumalanga are of employable age - between 20 and 65 years old (GIS, 1990). From this it can be calculated from Udit's figures that 42% of the members of Sondela households are in formal employment (based on an average of 6.3 members per household). In conjunction with Atmore's figures, this would indicate the following employment profile for the gardeners' households: 42% in formal employment, 32% employed in household work, and 26% unemployed. (This is a high rate of formal employment when compared to the figure of 23% given for the rural areas of Mpumalanga by the 1985 census).

However, the people in the area perceive lack of employment as a big problem. In the in-depth interviews in April 1990, Mrs Mdluli (the chairperson of the garden) indicated that possibly 25% of men who wanted work and 50% of women who wanted work could not find it. She noted that none of her four daughters who were of employable age, had work, even though two of them had matric certificates. All the women interviewed listed lack of employment and the current UDF/Inkatha conflict as the two biggest problems faced by the people in the area. The fighting had caused many people in the area to lose jobs because members of the opposing political group had tried to monopolize employment at particular places of work.

c) Other tasks which plot holders engage in

The other tasks which members of the garden are engaged in are shown in the following table.

Table 5.10: Other Tasks Sondela Members are Engaged in

Type of Work	Percentage of women engaged in it
Household work	91%
Wood collection	82%
Water collection	71%
Church attendance	42%
Tending children	20%
Cattle herding	9%

Source: Udit (1987a) - interview of 46 households in September 1986. Atmore used different categories and so her figures are not comparable.

Apart from work in the garden, most of the plot holders also do household work, and collect wood and water for domestic consumption. The plot holders who do not do these are probably too old - the younger women in the household are required to do them. Some plot holders also attend church, tend to children and herd cattle.

d) Educational Level

The following table gives a break-down of the education levels of the plot holders.

Table 5.11: Education Levels of Garden Members

Education Level	Percentage of garden members
No schooling	50%
Standard 3	26%
Stds 4 to 6	13%
Higher than Std 6	11%

Source: Udit (1987a)

The levels of education among the garden members are low. Half the gardeners never attended school. Of those who did, only 11% (5 gardeners) went further than primary school. It is likely that these are the younger members of the garden. These levels of education seem to be about the same as those for the whole rural population of Mpumalanga (see 5.3.1 part e).

5.4 The Effect of the Pump on the Garden

This section examines the effect of the introduction of the pump on the operation of the garden. The following questions are focused on:

a) What benefits of the pump were perceived by the members of the garden? (Subsection 5.4.1)

b) How much time does the pump save the women? (Subsection 5.4.2)

c) What effect does this have on the value of the women's time? Is a pump financially justifiable? (Subsection 5.4.3)

d) How did the women use saved time - and what would be the most financially rewarding use for their saved time? If the women used saved time in the garden would they be able to sell their produce? Could they farm their existing plots more intensively? (Subsection 5.4.4)

5.4.1 Perceived Benefits of the Pump

In April 1987, after the pump had been in operation for a total of eight months, the women's perceptions of the pump were gauged by questionnaire. The table shows which benefits were perceived by the most women.

Table 5.12: Perceived Benefits of the Pump after Six Months Operation

Perceived Benefit of Pump	Percent Positive Response
Pump saves time	91%
It eases the workload	72%
There is now sufficient water	18%
The production has increased	3%

Source: Interview of all 46 plot holders in April 1987 (Udit, 1987b)

Almost all the women (91%) indicated that the pump had saved them time, and 72% reported a reduction in work load. Relatively few (18%) indicated that they now had sufficient water whereas they had not had before; and only 3% indicated that they felt that productivity had increased due to the pump.

In interpreting these results it should be noted that the pump had been out of operation twice during the eight month period before the interview. In the first incident, in February, the cable from the array to the pump was torn from the array during a flash flood, and the pump was out of operation for three weeks. In the second incident, just before the interview, the pump was out of operation for a week due to repair work to the flow meter used for monitoring the pump.

It is interesting to note that a few women did not report a reduction in time spent on the garden or work load. There could be two reasons for this: i) many of the women spend little time in the garden during the summer because of other tasks at their homesteads and so they had possibly not yet felt the real benefit of the pump; and ii) the older or less healthy members may have worked as hard in the garden, but been more effective due to the pump - this group may represent the 18% who indicated that now they could apply sufficient water to the garden.

Another indication of the perceived benefits of the pump is the change in how arduous the plot holders regarded various tasks. Before the pump's introduction water collection from the river was ranked as the most time consuming job by most of the women; followed by tilling and then weeding. After the pump had been working for six months, tilling ranked first, followed by weeding and then by the distribution of water from the taps. Because work in the garden had become less arduous three women who had intended to resign did not (Udit, 1987a & b).

In the in-depth interviews in 1990, all three respondents interviewed indicated that it was very important that there was a pump in the garden. Mrs Mkhize indicated that before she had come to the garden at 4 am in the morning to begin to carry water while it was still cool. Now she could come at any time of day and there would be water. The chairperson, Mrs Mdluli, estimated that maybe one quarter of the gardeners would not stay in the garden if there was no pump.

Both Mrs Mdluli and Mrs Mkhize felt that they grew more vegetables directly because of the pump; Mrs Nene felt there had been no difference - only that she had worked less for what she had got.

5.4.2 The Amount of Time "Saved"

The amount of time saved per person by the pump can be calculated from measurements taken by Udit (1987a) before the pump was introduced. She measured the time taken to collect water from the river by four different women. She found that on average, it took 40 minutes to collect 100 litres of water. So on average each woman could save 40 minutes each day (as their average water usage for the winter months came to 100 litres per plot). Thus the pump saves each woman an average of 5 hours per week.

Mrs Mdluli indicated that before the pump's introduction she had had to spend twice the amount of time in the garden that she spent afterwards. This indicates that the women on average spent 10 hours per week in the garden before the introduction of the pump. These figures can be used to calculate the effect of the pump on the value of the women's time. However, the above estimates are based on the winter months (100 litres per plot per day). Because the women spend about half the time in summer that they do in winter, it can be calculated that the time that they spent in the garden per year was probably 400 hours before the pumps introduction and 200 hours afterwards.

5.4.3 The Effect of the Pump on the Value of the Gardeners' Time

The following table summarizes the effect of the pump on the productivity of the gardeners' work.

Table 5.13: The Effect of the Pump on the Value of Time

Quantity	Value per plot (180 m^2)		Refer to:
	With no pump	With a pump	
Value of produce	754 R/yr	754 R/yr	Subsection 5.3.2.
Expenses:			
Seeds & fertilizer	24 R/yr	24 R/yr	Subsection 5.3.2
Pump (PV "normal")		20 R/yr	Chapter 4
Profit	730 R/yr	710 R/yr	
Time spent in garden	400 hr/yr	200 hr/yr	Subsection 5.4.3
Value of time	1.80 R/hr	3.55 R/hr	

The figures above are those for each plot holder. The table shows that the cost of the pump is small in comparison to the value of the produce, and so the "profit" each member makes from the garden drops only slightly if a pump is introduced (from 730 R/year to 710 R/year). This is on the conservative assumption that the pump does not increase the productivity of the garden, but only helps to save time. The saving in time is large - the pump halves the time the gardeners spend in the garden. In conjunction with the only slight drop in profit, this means that their time is far more productive: they make 3.55 R/hr if there is a pump and 1.80 R/hr if not.

5.4.4 Uses and Potential Uses of Saved Time

So a pump would seem to be financially justifiable because of the increase in productivity of their time. But, in an economy where cash is very short, the gardeners may still not be able to afford the pump - unless the time "saved" can be used for income producing work. This subsection examines the use the gardeners in fact did put their time to; and the profitability of other possible uses.

Ways time "saved" was spent

After the pump had been in operation for eight months, Udit asked the plot holders what they did with the time saved. She found that 64% of the gardeners spent their saved time on household work and tending to children, 43% to cleaning the gardens and fields around their homes, and only 9% (3 women) spent this time on income producing work such as the making of mats, and crocheting. One of the women had earned R 20 from selling the mats she made.

So most of the women did not use the time "saved" in ways that would offset the costs of the pump - although one woman showed that this was definitely possible. This raises the question as to what would be the most productive use for their saved time.

Formal Employment:

Although many of the women would not be able to take up formal employment because of household commitments the wages from it are used as a reference point. Most of the gardeners would only be able to get unskilled work. The standard wage for piece work in the area is R 6 per day. The cost of transport to the closest work centres is at least R 2 return. So the women would have nett earnings of about R 4 for approximately 10 hours of work - including travelling time. This works out to 40 cents per hour.

Craft Work

Mrs Mdluli could not give a precise figure for how much profit one could make per hour doing craft work but she felt that it was more than the 40 cents per hour she would be likely to earn for piece work. But she said that there was quite a bit of hidden work involved in craft work such as buying the material and trying to sell the end product. On the other hand, she said that when she works in the garden she sells to passers-by while she works and she knows that she will have no problem selling produce.

Garden work

This is the third most obvious alternative: they could use their "saved" time by cultivating a larger plot in the community vegetable garden. There is, in fact, land available across the road and the idea of using the overflow water from the present reservoir has been mooted. However, Mr Mdlolo has just been transferred and they are waiting for another agricultural officer to be allocated to Nyavu ward to help them to organize the acquisition of the land and the reticulation system.

It seems that this would be by far the most profitable use they could put their time to. If a gardener worked enough land so that she spent 10 hours in the garden each day instead of taking up formal employment, she should be able to earn R 36 per day; in comparison with nett earnings of R 4 from piece work. Garden work is also flexible and does not interfere with household work.

However, earning income from the garden may be limited if there is not a large enough market. Both Mrs Mdluli and Mrs Mkhize, who were keen to acquire extra plots, felt that there were many people in the area who would buy their produce and that they would have no trouble in selling. Most of the plot holders already sell some of their produce: the average was estimated from interviews as R 14 per year per plot holder (equivalent to R 23 in 1990) (Udit, 1987a). While this is not a lot, it is more than the cost of the "normal case" PV pump - R 20 per plot holder per year. If the pump enabled the gardeners to produce just a little extra and sell this, then the cost of the pump would not be a barrier.

However, Udit found that half of the gardeners regarded marketing their produce a problem (1987b). They noted that the local people do not buy daily and so some of their crops tended to rot in the ground. They felt that a more active form of marketing was necessary: suggestions were to transport their produce to a market outside the area (40%), building a farm stall at Sondela (33%), and selling the produce to local shop owners (4%) (Udit, 1987a).

Although these suggestions were made in 1987, nothing has yet happened. However, the intervening period has been one of uncertainty: after the 1987 floods, the pump was only recommissioned in June 1989; and since then some of the panels were stolen and the area has been destabilized with UDF/Inkatha fighting. If there is enough stability, and if enough excess produce is grown, perhaps the gardeners will still establish a marketing method. It does seem that a formal mechanism for selling produce would encourage all the plot holders to sell all their excess, and no wastage will occur with crops rotting.

It is also possible that the women could increase their productivity because of the pump without increasing the size of their plot - simply by farming more intensively. Mr Mdlolo based his estimates of the productivity of each plot on a spacing between each row of vegetables of 1 metre - as is the practise. However, according to Mr Auerbach, an agriculturist from the Institute of Natural Resources, 0.5 metre spacing is adequate for vegetables. If they reduced the spacing they could double the output and thus the profit from their existing plots. The time "saved" by the pump could be used for more intensive cultivation.

Secondly, they could farm more intensively by cultivating more crops during the summer. The reasons given for not working much in the garden in summer are:

a) The women have other work around the house, and the summer heat makes work in the garden unpleasant. But, the pump reduces both the time required for work in the garden, and the arduousness of the work. All the respondents in the 1990 interviews said that the most important benefit of the pump was saved effort - not saved time. And the fact that there is a high unemployment rate indicates that there are enough household members who could help. So it seems that time is actually available; and that if they did not need to carry water in the summer heat, many of the gardeners would work more during the summer.

b) Secondly, disease is more common in the summer. But, with the use of the correct pesticides this problem could be overcome.

The women have not yet taken up this idea - possibly because the pump has not been working for long enough under stable social conditions for them to begin to exploit its potential. (It has only been there for two summers: the first directly after its introduction when they still were unsure of it; and the second at the end of 1989 during which time the garden almost collapsed because many members had fled the fighting in the area). However, the potential is there. And if the pump stimulated a better method for marketing their produce, the motivation for increased productivity would also be there.

Conclusion

So, a pump increases the productivity of the gardeners' time considerably. And extra work in the garden is the most productive use they could put their time to. It seems that the market for their produce is there. But which method of pumping is the most appropriate for their situation - should they choose a PV or a diesel pump? Section 5.5 examines the problems encountered with PV pumping; and then Section 5.6 examines the opinions of the gardeners as to which pump they would choose given their various costs, advantages and disadvantages.

5.5 Problems Encountered with PV pumping

The Sondela project has been useful in spotlighting many of the potential social problems which PV pumps are vulnerable to. The following problems have been encountered since the pump was first installed in July 1986:

a) In September 1987 the pump was washed away when the Umsunduze river burst its banks in the Natal floods.
b) In January 1989, just after the system had been reinstalled in a safer position, two of the panels on the array were stoned.
c) About three weeks after this incident, towards the end of January, seven of the fourteen PV panels which made up the array were stolen. This represented a loss of R 6,300. Later in June 1989, before the system had been properly protected against theft, another panel was stolen.

All of these problems are inherent to PV water pumping applications because the array, which is very expensive, is necessarily sited in the open (and thus exposed to the elements and to vandalism) and often sited away from the owner's house (thus vulnerable to theft). The array represents the running costs of the PV pump - it is equivalent to the expenditure on fuel for the diesel pump. But for the PV pump all the "fuel" is bought at the beginning of the project, and cannot be locked inside away from danger. So other methods of protection must be considered.

Each of the problems listed above as well as the precautions taken and other precautions considered will be discussed in turn below.

5.5.1 Flooding

The PV pump was originally sited with the array on the bank of the river and the pump and motor grouted to a cement causeway which spanned the river. The bottom of the array was 4 to 5 metres above the water level; while the motor and head of the pump were 2.5 metres above water level. The element of the Mono pump needs to be submerged in water, and it was for this reason that the motor/pump installation was installed over the river, and not on the bank. Mono Pumps had consulted some local people about the highest level the water would be likely to rise to, and they considered the installation very safe.

There were three minor flash floods in early 1987, and each time the water rose above the top of the motor and pump. However, no damage was done. It was obvious that the pump was not ideally placed and after consultation with gardeners, it was decided that the pump should be moved onto the bank of the river. A channel was to be dug into the river bank so that the pump element could be submerged in water.

Final plans for moving the pump were being made when the floods of September 1987 washed the pump away. The fact that the proposed new site for the pump was also washed away emphasized the need for conservative planning when considering a long term installation such as a PV pump. The floods were, however, exceptional: the water in the Umsunduze rose well above the 100-year flood mark.

Fortunately the installation was covered by UCT insurance as it was still being researched. Two methods of reinstalling the pump more safely were considered. The first, the method eventually used, was to grout the pump to a small cliff face on the river near the one corner of the garden. Because the cliff drops directly into the river, the pump element could still be submerged in the river. The pump head and motor would be about 6 metres above the surface of the water; the array could be installed at the top of the cliff about 11 metres above the surface of the water.

The second method considered was digging a 50 metre channel into the river bank. A large pipe, 30 to 50 centimetres in diameter, would transport the water to a sump at the end of the channel. The pump would be installed with the pump element submerged in water in the sump. The array could be installed further up the bank to be safer.

5.5.2 Vandalism

In determining possible methods of guarding against vandalism it was necessary to determine who had most likely stoned the two panels and why. The respondents in the 1990 interview felt that it was most likely adults "who enjoy causing trouble". Mrs Mdluli felt that it could have been the same people who came back three weeks later to steal seven of the panels. However, they did not feel that these people were determined to destroy the project.

This is important: if there are people who intent on destroying the pump because of jealousy or vengeance, then it is almost impossible to protect the pump. Methods which could be used would be expensive (for example, armour-plate glass). But if the motivation for vandalism is less extreme then putting a small gauge chicken wire fence over the top of the panels may be adequate. This, however, reduces the efficiency of the array by 10%. This should be taken into account when costing this method of protection; but a 10% increase in the cost of the array is probably warranted considering the amount of damage that can be done by stoning.

5.5.3 Theft

Few precautions against theft were originally taken: the gardeners assured us that there was little danger because the project had the blessing of the community. Also the technology was new at that stage, so it seemed that few people would know how to use the PV panels. However, the fact that two of the PV panels recovered by the police after the theft were installed on roofs charging batteries, indicates that this is no longer so. PV panels are becoming much desired objects as the knowledge of the method of their use and of their value spreads. Because most townships and rural areas are not yet electrified there is a large market for the resale of stolen panels.

For all these reasons sound methods of protection are recommended for all PV pump installations - especially those which are owned communally. The array at Sondela was surrounded by a fence with a locked gate - but this is no deterrent to a potential thief.

The following are some of the possible methods of guarding against theft:

a) Using an alarm that will sound a siren if a panel is removed from the array (and possibly if the panel is vibrated).
b) Locking the panels into the frame.
c) Installing an electric fence around the array.

After careful consideration a combination of options a) and b) was used. The advantages and disadvantages of each are discussed below.

a) Using an alarm

An alarm is only effective if the pump site is near enough to the houses of people who will respond. The homes of a number of members of Sondela garden are close enough that they would be awakened by the alarm. They agreed to take on the responsibility of responding if the alarm sounded.

Magnetic switches were used to trigger the alarm. These switches were installed between each of the 7 pairs of panels in such a way that if one was moved the alarm would be triggered. The alarm also sounds if the wire connecting the magnetic switches is cut. The alarm system and siren were powered by a battery. All the key components were installed inside a metal cupboard so that the functioning of the alarm could not be tampered with. The wires carrying the electricity from the panels to charge the battery were disguised so that if somebody tried to cut the power wires they would set off the alarm.

Vibration switches were considered as a complementary method of triggering the alarm: they would sound the alarm as soon as the panels were tampered with, or if they were stoned. However, these were considered too temperamental for a rural installation. They are also affected by temperature and the temperature of the back of the array varies widely during the day.

The cost of the installation is shown in the following table:

Table 5.14: The Costs of the Alarm System Installed

Item	Cost (1990 R)[1]
12 V car battery	70
7 magnetic switches	100
Control box	60
Tamper-proof box	90
Siren	50
Power Supply IC (eg MAXIM MAX743)	30
Total	400

1. Including 13% GST

The battery for the alarm at Sondela was charged by an extra panel using a battery regulator. However, this is expensive. The costing above is based on the use of a Power Supply integrated circuit chip to use power from the existing array to charge the battery safely.

The cost of the alarm system is R 400 for a PV pump with 14 panels (1.3% of the price of the pump itself). It is one of the most effective ways of protecting the panels and should be used in most circumstances - especially for large arrays. It has one weak point, however: alarms are known to be temperamental and it may give false alarms and be switched off; or it may just stop working after some years. The proposed alarm system has been kept as simple and robust as possible to reduce the likelihood of failure: no vibration switches or infra-red rays are used. But it is still necessary that other methods are used in conjunction with this method.

b) Locking the panels into the frame

If the array frame is designed correctly this method could be one of the most effective and cheapest means of protection. It must be possible for somebody to maintain the panels and so to be able to remove them. For this reason more permanent methods such as welding the panels in should be avoided. It is also not enough to simply attach the panels securely to the frame of the array - the panel frame itself is made of weak aluminium alloy and can be easily broken. Rather, a second iron frame that locks over the edge of the front of the panels preventing them being removed should be made. This frame could be locked in place by a thick padlock, so that only authorised people would be able to remove the panels.

c) Electric fence

The electric fence could work off a 12 V battery which is charged as described above for the alarm. The electric fence system could consist of a Gallagher energizer and seven strands of electrified wire on the inside of the existing fence around the array. Because the whole system is on the inside of the existing fence there is little chance that children or animals would be inadvertently shocked. In order to make it more difficult to jump over the fence and climb out again between the strands of wire, the electrified wire could be offset by about 20 centimetres from the existing fence.

The cost of the system is as follows:

Table 5.15: The Costs of an Electric Fence to Protect Against Theft

Item	Cost (1990 R)[1]
Gallagher E12 Energizer	470
Fencing and offsets	180
12 V car battery	70
Control key and box	60
Power Supply IC (eg MAXIM MAX743)	30
TOTAL:	810

1. Including 13% GST.

This system is twice as expensive as the alarm system; but less effective. An electric fence can be neutralized fairly easily. Firstly the electrified wire is always insulated from its supports. These insulators are attached to the supports either by nails into wood or by wire (as in the offsets). A person can work safely with the insulated side of the system and could just cut the offsets with wire cutters or pull the nails out. The electrified wire would drop to the ground where it would short out the whole system.

The second method (probably the easiest) is to short it out: if a piece of wire is held touching the ground above the wire from the energizer and dropped onto that wire, the whole system will be shorted out and made ineffective.

The third method is rather unsophisticated, but is simple enough for most people to work out: five to seven blankets could be used to insulate the intruder from the shock.

The advantage in electric fences is that they have an aura of danger about them and will prevent less educated intruders. But my experience staying on a farm which had electric fences in the same area as Sondela taught me that a number of the local people know how to short out electric fences.

An alarm system, on the other hand, is much more sophisticated and it would take someone with good technical knowledge to be able to neutralize the system. For this reason, only two methods of protection were used at Sondela: the alarm, and brackets of angle iron which locked the panels in place.

d) The Choice of the Gardeners

The attitudes of all the respondents in the 1990 in-depth interview were gauged as to the effectiveness of each of these methods; and as to which methods they would choose given the costs. When presented with each method in turn, they all said that the cost of each one individually was worth it. The costs used in the interview were: R 410 for the alarm system (R 9 per member); R 280 for the adaptations to the frame in order to lock the panels in (R 6 per member); and a previous estimate of R 510 for the electric fence (R 11 per person). Once they knew all the individual costs they were asked to choose a method or combinations of methods which they felt gave sufficient protection and was cost effective. They all chose to combine two methods: the adaptations to the frame to lock the panels in, and the alarm at a total cost of R 690 (R 15 per member).

5.5.4 All risks

While the pump was being researched it was covered by UCT insurance. When this insurance lapsed the gardeners had to consider whether it would be worth their while insuring the pump; or whether less conventional methods such as a type of "self-insurance" or asking an "isangoma" (traditional healer) to do a ceremony of protection on the pump would be adequate. Their opinions on these three options were explored in the 1990 interviews.

a) Conventional Insurance:

Insurance would be expensive because the system cannot be locked in a building, and is vulnerable to floods, lightning and vandalism. It would probably be practical only if a development agency tacked the pump onto the end of a large existing insurance policy and the women paid premiums to the agency; premiums for the pump only would be exorbitant. An annual premium was worked out at 5% of the total value of the system. This was based on figures supplied by UCT insurance. Thus the annual premium for the original Sondela pump is R 1,100 (R 2 per member per month).

Mrs Mdluli and Mrs Nene said that it would be too much for the members to pay an extra R 2 per month for insurance. Mrs Mkhize, who seemed to have fewer scruples with money than most of the gardeners, felt that it was worth it. However, she was possibly not taking into account that this would be added onto their present contribution R 2 to seeds and fertilizer, as well as the cost of the pump (about R 1-70 per member per month). This would mean a total monthly contribution of R 5-70, which few gardeners could afford.

b) Self-insurance:

The second option discussed was a type of self-insurance. If they put about 40 cents per member per month in the bank, they would build up some reserve to cope with disasters. This would have the advantage that if nothing happened they could use the money to buy another pump when this one reaches the end of its life. Also in the event of a disaster they would not have to wait for the insurance claim to be processed. However, if there was a major disaster soon, they would have too little money saved to cushion the blow.

All the respondents felt that this method is preferable to conventional insurance.

c) "Doctoring" the pump:

The third option considered was to ask a traditional healer to perform a ceremony of protection on the pump. This idea was prompted by a report in The Star of a PV pump in Lesotho which had been repeatedly vandalised. After it was "doctored... with a mixture of bark and beads" for protection, it had experienced no problems .

All the respondents reacted to this suggestion with some mirth. They did not know how to contact somebody who knew how to do such a ceremony, and did not have much faith in the effectiveness of the method. They felt that this would only act as a deterrent if its effectiveness was demonstrated - if someone touched the pump and was affected as predicted.

5.5.5 The Gardeners' Attitudes to Future Problems

The respondents in the 1990 interviews were asked what are the major problems of the garden. All of them replied that there were now no problems, and Mrs Nene added that possibly lack of health prevented some members working well. Possible problems were suggested in order to double check their response.

They confirmed that the following presented no problem: getting water in the garden as the pump had been working well and the reticulation system was no longer giving any problems; and the ability of the garden to make decisions and organize their affairs.

The following were considered minor problems: the rising costs of seeds and fertilizers; the fact that not all seeds took root; and the current lack of access to advice. While their access to advice and knowledge had been good when Mr Mdlolo had been there, he had been transferred and they had not yet got a replacement.

When asked whether they felt apprehensive about future problems with the pump Mrs Mdluli and Mrs Nene said they felt some apprehension because I was leaving. I told them that I would leave a comprehensive paper on who to contact in the event of any troubles. The paper also contained estimates of future expenses that the pump would incur and some suggestions on how to save for these.

In many such situations the gardeners would be provided with little information on what to do in the event of a break-down and of how to budget for future expenses. For this reason alone, a pump may be out of working order for a long time, may have a short lifetime because some precautions are not taken, or may stop working because of lack of funds to replace a particular part. While it is possible to inform the community of these things, most PV pump marketers do not have the time (or language skills) to do this effectively for rural communities.

Concluding Remarks

PV pumping is inherently vulnerable to floods, vandalism and theft. However, it is possible to take precautions against these without increasing the total cost of the pump by more than 10% in most situations. However, a greater danger is that the community may not be given enough information on what to do in the event of a break-down, and on probable future expenses and ways of budgeting for them. It is these problems which are more likely to cause the project to fail - rather than the more tangible dangers such as theft. A method of financing the PV pump is discussed in Section 5.7 which could overcome these problems.

5.6 Comparing the Suitability of PV and Diesel Pumps

The comparative suitability of PV and diesel pumps was investigated in two stages:

a) People who had been closely involved in the running of diesel and petrol pumps in similar situations to Sondela garden were interviewed to get an accurate idea of the practical implications of running a diesel pump in these areas. This is dealt with in Subsection 5.6.1.

b) Information gained from these interviews was used to brief the interviewees from Sondela garden for the in-depth interviews as to the realistic implications of each method of pumping for their situation. They were then asked which pump they would choose given three different scenarios of comparative costs. (Subsection 5.6.2.)

5.6.1 The Experience of Gardens with Diesel and Petrol Pumps

Two interviews were done in order to gauge the suitability of diesel and petrol pumps:

a) The first was with Miss Xulu, the chairperson of Phumalanga garden where a diesel pump had been installed. The garden is very similar to Sondela in size and situation.
b) The second was with Mr Nkosi, the agricultural officer of Table Mountain ward where a number of petrol pumps were used.

The information from the interviews is summarized below:

a) The diesel pump at Phumalanga garden

General Impressions

The diesel pump at Phumalanga worked without any problems. It was installed in 1984 and worked without maintenance until the September 1987 floods. Because the pump was still new some of the potential problems of maintenance had not yet surfaced. But apart from this, the garden had the advantage of a well-motivated agricultural officer, and the leadership of Miss Xulu who is interested and knowledgeable. (She is also one of Mr Mdlolo's assistant agricultural officers).

Finances

The pump was bought in 1984 for R 2,022 (equivalent to R 4,500 in 1990). They managed to raise a loan from KFIC: the garden paid a down payment of R 1,000 and paid the balance over the next 7 months. The money was collected quickly and without problems.

Each member gave a contribution of 50 c/month towards the running of the machine (1987). This covered the costs of diesel and oil, and the wages of the operator (R 14 per month). There was no problem in collecting this money.

No money was saved towards the maintenance costs of the pump. If a repair of say R 500 became necessary, Miss Xulu felt that, although some of the women would complain, the money would be collected.

Miss Xulu listed the benefits of the pump in the following order of importance:

a) Saved effort: many of the plot holders are old and cannot carry water. If there was no pump, the garden would either fold or there would be only a few members.
b) Saved time.
c) Increased productivity: this increase in productivity was worth more than the 50 c/month contributed by each member for the pump's expenses.

However, in 1987 Phumalanga was the only garden with a pump of the nine gardens in Nyavu ward (apart from Sondela which had the PV pump donated).

When asked why so few gardens have got pumps if it pays itself back financially, she answered that many community gardens were not prepared to listen to persuasion. There may be some feelings that they are not visited often enough by the agricultural officer and so when the subject is brought up they crush it from spite.

Maintenance

There had been no need for maintenance in three years before the flood. However, as there are no local skills for maintenance, they would need to transport the engine to town in the event of a problem.

Ease of Operation

It was easy to get a volunteer to operate the pump. The volunteer had no problems learning to start the engine, and she always remembered to put in oil and water.

There were complaints that she did not pump often enough. The gardeners were talking about hiring a man from outside the garden to operate the pump when the floods arrived. But this would have cost them more. A possible solution would have been to raise her pay, but the members may have complained.

Reasonable wages for an operator for a garden of 1 hectare for 1990 are 20 R/month.

Safety

Diesel pumps are threatened only by floods. Because the efficiency of centrifugal pumps decreases with increasing head, the pump is normally placed less than five metres above the surface of the river. Because the pump is too heavy to move easily, it could be washed away in severe floods. (Petrol engines on the other hand are more portable and can be removed more easily).

The danger of theft is minimal for diesel engines because of their size; in comparison petrol engines are more vulnerable.

Comparison with other types of pumps

Diesel vs petrol: Miss Xulu said she would recommend a diesel pump. Petrol pumps are portable and need to be transported to and from the site every time they are used. They also have higher maintenance costs.

Diesel vs hand pumps: She questioned how long it would take to fill a reservoir using hand pumps and doubted whether the women would take turns regularly to pump. She said they are old and would find many excuses. It is easier to share the financial expenses of a diesel pump fairly than the effort of hand pumping.

b) Petrol pumps - Table Mountain ward

Only petrol pumps are used in Table Mountain ward. There are now pumps in three of the thirteen gardens in the ward. There had been four, but one was recently sold by the garage they took it to for repairs to defray costs. Mr Nkosi, the agricultural officer, does not remember this pump ever working since he came to the area in 1985.

One of the remaining pumps has not been in use since its reservoir was washed away in the 1987 floods. And the other two pumps are new. They were bought with loans from KFIC. The cost of the pump was spread over 11 months at R 160 per month. Despite the fact that the payments are small, the gardeners are beginning to miss payments - partly because the organization of the garden has collapsed due to the recent Inkatha/UDF conflict.

Mr Nkosi has found the plot holders to be reluctant in paying for the running and maintenance costs of the pump. If there is a big meeting at the garden about finances they will pay, but soon start defaulting again.

He feels that the gardeners may well prefer hand pumps. They have children who may do the pumping for them.

5.6.2 The Preferences of Sondela Gardeners: PV versus Diesel

The respondents opinions about the comparative advantages of PV and diesel pumps were gauged in the in-depth interviews in 1990. Firstly their opinion was asked before any information about costs and likely problems was given. Then the advantages and disadvantages of each pump were discussed and how important they felt each of these is was established. Then likely amortized costs of each pump were given and they were asked which they would choose considering the advantages and disadvantages discussed.

a) First opinion: Would they choose a PV pump or diesel pump or another type?

Mrs Mdluli said she would choose a PV pump because the PV pump does not involve any work - there is no need to put diesel in it or to service it. The other two said that they did not know other types of pumps, but would choose the PV pump because they know that it works well and gives no problems.

b) Comparative Advantages and Disadvantages

Start-up: It was explained that whereas the PV pump starts automatically, a diesel pump would need to be filled with diesel and oil, started once a week, run for four hours and then switched off.

None of them felt this presented major problems. They felt that it would not be difficult to find a member of the garden willing to learn to start the pump, and all of them said they would be prepared to take on the job. There was disagreement about payment: Mrs Mkhize felt the person should be paid about R 30 per month, while the others felt payment was not necessary.

Purchase of fuel: It was explained that while a PV pump does not need fuel, a diesel pump would use about 25 litres of diesel a month.

All of them felt that collection of the diesel fuel could present major problems unless the agricultural officer agreed to collect it using the government vehicle. He may not do this because the kilometres he can travel using the government vehicle are restricted. If they had to collect the diesel on foot it would mean a 4 kilometre walk to the bus stop, a bus trip to the garage (costing R 3 return) and another 4 kilometres carrying the 25 litres.

Mrs Mkhize felt that this would most likely cause arguments as to whose turn it was to collect the fuel, and the few more dedicated members would end up doing all the work - as has been the case with buying seeds and fertilizer. Mrs Mdluli commented that they would not be able to pass through the neighbouring ward because it is currently UDF controlled (whereas Nyavu is Inkatha controlled). So they would have to go to Pietermaritzburg which would be more expensive. Mr Mdlolo commented that carrying fuel on public vehicles is dangerous at the moment because one political group may use it to attack the opposing side.

Collection of financial contributions to diesel pump: it was explained that the gardeners would need to make regular contributions for the costs of diesel, and to contribute to the maintenance costs when necessary. If it was preferred these costs could be spread evenly over the life of the pump.

Mrs Mdluli and Mrs Nene felt that they couldn't be sure that all the members would contribute the money every month. Mrs Mkhize felt that this would not cause problems: if they want water they will have to pay up.

Collection of financial contributions to PV pump: It was explained that if they bought a PV pump they would be required to pay a monthly contribution to repay all expenses for 20 years (assuming a loan was available and the costs were amortized). This contribution would be agreed upon beforehand, and would be in the region of R 1-70 per member per month. If the garden defaulted on their payments the agency which gave the loan would be entitled to reclaim some of the PV panels to cover the remaining debt.

Mrs Mdluli and Mrs Nene felt that if the amount was agreed to beforehand there should be no problems - but Mrs Mdluli commented that R 1-70 is quite a lot and some members would be strained to contribute that amount. Mrs Mkhize felt there would be no problem - they would pay because they did not want to lose some of the panels.

Methods of Coercion: All of the respondents felt that adequate methods exist to deal with those who do not pay their contribution to the pump. Defaulters would either be asked to leave the garden, or the other gardeners would prevent them from using the water. All the respondents felt that there were enough people who would be keen to join the garden to take the place of members expelled. It seldom happens that members do not give their contributions towards seeds and fertilizer - but if it does, they are simply not given their share of the supply.

Maintenance of the diesel pump: One major service a year should be budgeted for. They all agreed that it would be necessary that the diesel pump be transported to town for this maintenance as no-one locally has even the most basic maintenance skills.

On the other hand, it was explained, the solar pump would need to be maintained once every two or three years. The assistant agricultural officer might be able identify the problem and take the component in for servicing. If there were major problems Mono Pumps would have to be called out from Durban. In order to ensure trouble free operation it would also be necessary for someone to check once a month that the filter on the water inlet pipe did not silt up.

Given this information all of the respondents felt that the PV pump would be less trouble to maintain. They all felt this to be an important advantage.

c) The comparative costs of the two pumps

The above advantages and disadvantages were recapped. Then each respondent was asked which pump she would choose given three different scenarios - a "normal" scenario, one which favoured PV pumps and one which favoured diesel. It was assumed that all the costs of the pump could be amortized over the life of the project and that they needed to pay only monthly installments.

The following table summarizes their responses.

Table 5.16: PV versus Diesel - Interview Responses

Scenario	Contribution per member (c/month) PV pump	 Diesel pump	Responses
Normal	170	85	All chose PV
Favouring PV	90	110	All chose PV
Favouring Diesel	270	65	Undecided

All figures were based on the economic model used in Chapter 4, with the assumptions that were being used at the time of the interview. The values of the assumptions used for the different scenarios are given in the following table.

Table 5.17: Assumptions used for each scenario

Assumption	Normal	Favouring PV	Favouring Diesel
Project length	20 yrs	30 yrs	10 yrs
Discount rate	5%	1%	10%
Peak Demand Factor	1.83	1.3	1.83
Insolation (kWh/m^2/d)	4.5	5.5	4.5
Diesel price	90 c/l	118 c/l	89 c/l
Fuel escalation	4%	4.5%	1%

The assumptions which affect the amortized costs most are: the project length, the discount rate, the Peak Demand Factor and the insolation.

Normal Scenario: The PV pump costs are twice those of the diesel pump (170 c/month against 85 c/month per member). Mrs Mdluli, after much thought, decided that she would choose the PV pump. Mrs Nene also said that it was a difficult choice, but that she would choose the PV pump because of the trouble involved in collecting diesel. Mrs Mkhize chose the PV pump with no hesitation because she felt that it is a better quality product.

Favouring PV: For this scenario the costs of the "best case" PV pump were used. The costs of the PV pump were slightly less than those for diesel: 90 c/month against 1-10 c/month. All the respondents chose the PV pump without hesitation.

Favouring Diesel: In the third scenario the cost of the PV pump is 4 times that of the "diesel" pump: R 2-70 c/month against 65 c/month. (The costs of a petrol pump were in fact used for the "diesel" as this was the cheapest conventional pump for this short project length, and other factors such as fuel collection and maintenance were considered comparable). Mrs Mdluli felt that the gardeners could hardly afford R 2-70 per month for water, but she was reluctant to give up the advantages of the PV pump. In the end she was unable to come to a decision. Mrs Nene also could not come to a decision - she felt that the high cost of the PV pump would divide the gardeners with the more wealthy wanting the PV pump. Mrs Mkhize chose the PV pump on the grounds that if you buy quality your purchase lasts; whereas if you choose the cheapest available you inevitably get problems.

All of the respondents regarded the cost of the pump as a very important criterion in their decision.

The above comparison is only valid if the life cycle costs of the PV pump can be spread evenly over the life of the project. This question is considered in Section 5.7.

5.7 The Problem of Capital and the Risk of PV Pumping

PV pumping has many important advantages over diesel pumps for remote area applications. Because of these advantages the gardeners at Sondela would prefer the PV pump to the diesel pump even if its amortized life cycle costs were up to twice that of the diesel pump's (R 1-70 per plot holder per month against 85 c per plot holder per month for the diesel).

However, if the gardeners were unable to get a loan they would inevitably choose the diesel pump simply because its initial cost is much less: R 7,000 against the R 17,500 for the PV pump. The gardeners may even choose a cheaper but less reliable diesel pump, or a petrol pump.

This pinpoints the most important barrier to the marketing of PV pumps - their high initial cost. This fact has the following consequences:

a) Because of shortage of capital, community gardens would tend to choose the pumping method with the lowest initial costs and may ignore factors such as reliability, maintenance requirements and running costs. There is not enough knowledge in most of the communities to compare the advantages, disadvantages and long term costs of various methods of pumping.

b) Budgeting fairly for a PV pump would be far too complex for a community garden. (Only 11% of Sondela garden members have more than a primary school education. The membership of a community garden is continually changing as some members leave and others join. To budget fairly it would be necessary for the expenses over the whole life of the pump to be spread evenly between all the members - and not only the current members. For example, if a member left 3 years after the introduction of the pump, it would be necessary for somebody taking her place to buy out her share of the pump. This budgeting would be complex because the life of the pump is not accurately known, and the recurring costs cannot be accurately predicted. Budgeting would be made much more difficult if the number of members in the garden varied. The fact that a prospective member had to buy into the garden may discourage others joining the garden.

c) Thirdly, because of their high initial costs PV pumps are a high risk option - expensive equipment is placed necessarily in the open with little natural protection. Community gardens could not risk the loss of a pump through some natural disaster or through theft - and of then being required to pay off a loan for 20 years without benefiting from the pump.

For all these reasons PV pumps should not be recommended for community gardens unless a better method of financing them is found. ESKOM has recently produced a draft document that outlines possibly the most workable solution available (Barnard, 1990). It proposes that ESKOM supply alternative energy systems (such as photovoltaics) to customers for which this option would be cheaper than extending the grid. ESKOM would pay for the initial costs of the system and would recover this cost from the customer over a set period of time.

While the system remained its property, ESKOM would maintain it. If the ownership was transferred to the customer, ESKOM would offer an optional maintenance contract. The customer would get a rebate from ESKOM if he called them out fewer times than budgeted for in the maintenance contract. This would encourage the customer to look after the installation. There would be a small connection fee equal to 3 months payments and no deposit. Three options would be offered by ESKOM:

1. For systems which cost more than R 5,000 ESKOM would recover the capital costs over 10 years. The customer would, however, continue to pay these charges for as long as he required electricity. The payments would increase at 6% per year. The maintenance contract would be compulsory for as long as the customer requires electricity.

2. For systems which cost less than R 5,000 the capital costs would be recovered over 5 years, increasing at 10% per year. During these 5 years there is a compulsory maintenance contract. After 5 years the ownership of the system is transferred to the customer, who may choose to continue with the maintenance contract.

3. The customer may choose to pay all or a portion of the capital costs of the system to ESKOM at the beginning. The outstanding capital costs are paid off over an agreed number of years. Ownership is transferred once the system is paid for in full - at this stage the maintenance contract becomes optional.

This policy would have a number of significant advantages to the customer.

a) Because the initial costs are low (equal to three months' payments), he would not have to negotiate a loan.

b) The customer need take no risk. If he uses option 1 outlined above, ESKOM guarantees to provide power for any number of years at rates agreed to beforehand. The customer incurs no financial loss if the system is destroyed by a natural disaster. On the other hand, he may choose option 3 outlined above and pay off the pump at an agreed rate. After that he takes ownership and with it the risk of loss; but he no longer needs to pay tariffs.

c) Maintenance is likely to be more regular and cheaper than that provided by PV suppliers. This is because ESKOM has many more branches throughout the country and in more remote places than any PV supplier - and so the time taken and distances travelled to maintain the system are less.

d) The customer is more likely to get the best option available. ESKOM has the option of extending the grid and of installing any of the PV pumps available on the market. It is in ESKOM's interest to choose the most cost effective solution and to pass some of the savings on to the customer. Further, the quality of PV systems is also likely to improve as ESKOM sets standards which it finds are necessary for satisfactory operation.

   Before this scheme was introduced the customer had to choose between a number of different options advocated by different groups without having access to the experience or knowledge to decide which would be the cheapest. He could have been persuaded to install a poor quality or inappropriate PV system by a zealous sales person; or, on the other hand, he could have decided to connect to the grid even though it was more expensive in the long run because its initial costs are lower, or because he was unaware that photovoltaics existed.

e) Flexibility: If the grid is extended to the area while ESKOM remains the owner of the system, the customer could easily connect up to the grid and enjoy the greater flexibility this allows. (ESKOM could remove the PV panels and install them elsewhere for another customer.) However, if the customer had bought the system himself, he would have been saddled with a less flexible source of power for many years to come.

This scheme also has a number of advantages for PV marketers. They are likely to sell more pumps because the major barriers of high initial costs and high risk are overcome. Also much of their marketing is done for them - somebody who approached ESKOM requesting that the grid be extended would quickly be persuaded of the advantages of a PV system if the monthly payments were less. The customer may have had no prior knowledge of photovoltaics.

The scheme also has a number of advantages for ESKOM. It would be able to supply affordable electricity to customers who before were too remote, and so it would increase its revenue base. It would also gain loyal customers in areas which will eventually be electrified and so encourage them to begin to buy electrical appliances. Thus, when the grid is eventually extended, it will be more economic because of higher electricity consumption.

So this scheme offers many advantages to all concerned. The PV industry would benefit a lot if it made every effort to exploit the possibilities of this system as much as possible and to help to refine its operation.

5.8 Conclusions

The following are the most important conclusions of this chapter. All costs, prices and profits given below are in 1990 Rands. Where necessary they were converted from their original year by using the Consumer Price Index (see Appendix 4.5.2).

1. The gardeners at Sondela would choose a PV pump in preference to a diesel pump if its amortized costs were up to twice those of the diesel pump (170 c/plot holder/month for PV against 85 c/plot holder/month for the diesel pump). (See Section 5.6)

2. The main barriers to the marketing of PV pumps are their high initial costs and the risks involved. A new scheme offered by ESKOM will overcome these problems. ESKOM will put up the capital, guarantee the supply of electricity and provide the maintenance for a PV system. It will then recover the costs of the system by monthly tariffs. Through this scheme the customer is likely to be provided with the most cost effective solution without having to have any capital, and without having to take the risk of loss of expensive equipment. (See Section 5.7)

3. PV pumping is inherently vulnerable to floods, vandalism and theft. However, it is possible to take precautions against these without increasing the total cost of the pump by more than 10% in most situations. However, a greater danger is that the community may not be given enough information on what to do in the event of a break-down, and on probable future expenses and ways of budgeting for them. It is these problems which are more likely to cause the project to fail - rather than the more tangible dangers such as theft. (See Section 5.5)

4. Work in the garden is far more financially rewarding for the plot holders than both formal employment and most types of craft work - especially if there is a pump. So the best way that the women could use saved time is in garden work. There are three ways in which they could increase the output from the garden and use their saved time: a) they could double the output from their existing plots by reducing the distance between rows of vegetables from 1 to 0.5 metres; b) they could cultivate more crops during the summer because the

pump reduces the arduousness of the work - but they would have to use the necessary pesticides; and c) they could extend the area of the garden by using adjacent land. They plan to extend the garden but are waiting for the new agricultural officer to arrive. (See Subsection 5.4.4)

5. The pump increases the productivity of the gardeners' time from 1.80 R/hour to 3.55 R/hour, largely because it halves the amount of time they need to spend in the garden. The cost of the PV "normal case" pump of R 20 per plot holder per year could be easily offset if the pump increased the productivity in the garden even slightly. (See Subsection 5.4.3)

6. The value of the produce from Sondela garden was estimated as R 754 per plot holder per year. This is equivalent to R 37,700 per hectare per year which means that the value of the produce for all 60 hectares of community gardens in Mpumalanga district is R 2.3 million. (See Subsection 5.3.2)

7. The garden supplied more than enough for the domestic consumption of almost all the plot holders. Most plot holders were able to sell a little produce bringing in on average about R 23 per plot holder per year in cash. (See Subsection 5.4.4)

8. The average household income of the plot holders is R 200 per month. This is equivalent to R 32 per month per member of each household. For this reason the community gardens are crucial to the households' economy. (See Subsection 5.3.3)

9. The gardeners at Sondela used the equivalent of 5100 l/ha/day during the winter months after the pump was introduced. An accurate estimate of the optimum irrigation required was 33,700 l/ha/day (about 1 inch/ha/week), which is over 6 times that used. However, the vegetables were growing well, and there was no sign of wilting. It can only be concluded that the women applied the water very efficiently and so required less water. If the PV pump had been sized for worst month then 6,300 l/ha/day would have been adequate. These figures should be noted when sizing irrigation systems for developing areas. (See Subsection 5.3.2)

CHAPTER 6

BIBLIOGRAPHY

ADDIS, P (1990). ESKOM, Durban. Personal Communication in September.

APPELBAUM, J & BANY, J (1979). "Performance Analysis of D.C.-Motor-Photovoltaic Converter System - Part I", Solar Energy, Vol 22, pp 439-445.

APPELBAUM, J (1981). "Performance Analysis of D.C.-Motor-Photovoltaic Converter System - Part II", Solar Energy, Vol 27, No 5, pp 421-431.

ARVIZU, D E (1987). Crystalline Cell Research Status and Direction. Proceedings of the 3rd International Science and Engineering Conference, Tokyo, Japan, (3-6 Nov).

ATMORE, N (1986). It's a Woman's Life: A Study of the Sondela Women's Community Garden in Nyavu Ward Kwazulu, with Specific Reference to the Introduction of a Photovoltaic Water Pump into the Garden. Unpublished B.A. (Hons) Dissertation, Dept of Sociology, University of Cape Town.

BANKS, D (1991). Wits Rural Facility, Klaserie. Personal Communication in January.

BARNARD, H B (1990). Distribution and Marketing Group Pricing Structures for Alternative Energy Systems in ESKOM. (Rev 1: September 1990). Unpublished draft document of Pricing Policy Department, ESKOM.

BEALE, W T (1979). A free cylinder Stirling engine solar powered water pump. Proceedings of the International Solar Energy Society International Congress. Georgia: Atlanta.

BERRY, C G (1990). Guide to Machinery Costs. Bulletin 408 of the Department of Agricultural Development, Directorate of Agricultural Economics, Pretoria.

BRAUNSTEIN, A & KORNFELD, A (1981). "Analysis of Solar Powered Electric Water Pumps", Solar Energy, Vol 27, No 3, pp 235-240.

BURESCH, M (1983). Photovoltaic Energy Systems: Design and Installation. New York: McGraw-Hill.

BURTON, J (1990). Engines and Electric, Durban. Personal communication in April.

CEDARA AGRICULTURAL FACULTY (1989). Computer Program Compiled by S Beghin, R Gordijn, R Mottram.

CHEM SYSTEMS INTERNATIONAL LTD (1990). Petroleum and Petrochemical Economics in Europe. Executive report Number 2. London.

COULSON, J M & RICHARDSON, J F (1977). Chemical Engineering. Vol 1, 3rd Edition. Oxford: Pergamon Press.

COULSON, K L (1975). Solar and Terrestrial Radiation, Methods and Measurements. New York: Academic Press.

COWAN, W D (1989). Photovoltaics for Educational Television in Rural Schools. Unpublished M Phil (Eng) Dissertation, Energy Research Institute, University of Cape Town.

DINGLEY, C E (1990). Electricity for all in South Africa: the need and the means. Report of the Department of Electrical and Electronic Engineering, University of Cape Town.

EBERHARD, A A (1986). The Potential for Renewable Energy Technologies in South Africa. Conference Paper No 45, Renewable Energy Potential in Southern Africa Conference, Energy Research Institute, University of Cape Town, (8-10 Sept).

EDEN, R & OTHERS (1983). World Energy Outlook to 2020. Published by the Energy Research Group, University of Cambridge, Cambridge, England.

ESKENAZI, D; KERNER, D & SLOMINSKY, L (1986). Evaluation of International Photovoltaic Projects, Vol 2. Technical Report No SAND85-7018/2. New Mexico: Sandia National Laboratories.

ERi Energy Research Institute (1987). ERi Perspective - Energy Statistics. University of Cape Town.

ERi Energy Research Institute (1988). Selected Energy Statistics - South Africa, No 6. University of Cape Town.

GIRARDIER, J P & VERGNET, M. "The solar pump and integrated rural development", Appropriate Technology: Problems and Promises, Ed. Nicholas Jequier.

GIS Geographical Information Service. Computerized information service of the Institute of Natural Resources, University of Natal, Pietermaritzburg.

GOSNELL, R J (1987). An Initial Evaluation of the Costs of Reconstructing Community Gardens in Mpumalanga District after the September 1987 Floods. Institute of Natural Resources, University of Natal, Pietermaritzburg.

GUILMOT J & OTHERS (1987). Energy 2000: A reference projection and alternative outlooks for the European Community and the world to the year 2000. Cambridge: Cambridge University Press.

HALCROW, Sir W (1983). Small-scale Solar-powered Pumping Systems: The Technology, its Economics and Advancement. UNDP Project GLO/80/003 executed by World Bank. London, Swindon and Reading: Intermediate Technology Power Ltd.

HALCROW, Sir W (1984). Handbook on Solar Water Pumping. UNDP Project GLO/80/003 executed by World Bank. Reading and Swindon: Intermediate Technology Power Ltd.

HAMAKAWA, Y (1986). "The Birth of Clean Energy Technology - Solar Photovoltaics", Business Japan, June, pp 28-32. Cited in Sinclair (1988).

HAMAKAWA, Y (1987). "Photovoltaic Power", Scientific American, August, pp 77-82. Cited in Sinclair (1988).

HOFFMAN, K (1985). "The Commercialization of Photovoltaics in the Third World: Unfulfilled Expectations and Limited Markets", Development and Change, Vol 16, pp 5-37. Cited in Sinclair (1988).

HSIAO, Y R & BLEVINS, A B (1984). "Direct Coupling of Photovoltaic Power Source to Water Pumping System", Solar Energy, Vol 32, No 4, pp 489-498.

HUBBERT, M K (1971). "The Energy Resources of the Earth", Scientific American, September, pp 61-70.

IEA International Energy Agency (1988). Energy Prices and Taxes, Second Quarter 1988. Paris: Organisation for Economic Co-operation and Development.

IFS International Financial Statistics, (1990). Vol XLIII, No 7, July.

ISEIR International Solar Energy Intelligence Report (1986). Vol 12, No 5, pp 42-44.

ISEIR International Solar Energy Intelligence Report (1987). Vol 13, No 6, pp 120-122.

KENNA, J (1987). Cost and performance data on diesel engine generators and pumps. IT Power Ltd contractor report, SAND87-7109, Sandia National Laboratories.

KISS, Z J (1982). "Economics of Thin-Film Photovoltaics", Sunworld, Vol 6, No 3, pp 63-66.

LASNIER, F; GAN ANG, T & SABAI LWIN, K (1988). Solar Photovoltaic Handbook. Bangkok: Asian Institute of Technology.

LOVEJOY, D (1985). "Technical Note on Comparative Costs of Solar, Wind and Diesel Pumping at Village Sites in Nigeria and Somalia", Natural Resources Forum, Vol 9, No 1, pp 77-80.

MARTZ, J E & ROBERTS, A F (1985). Operational Performance of the Photovoltaic-powered Grain Mill and Water Pump at Tangaye, Burkina Faso (Formerly Upper Volta). NASA Technical Memorandum 86970.

MASENG, L & JACOBS, G (1984). Test of Mogonye Photovoltaic Pumping System. Report of Botswana Technology Centre, Gaborone.

MATHEW, J (1990). South African Transport Services, Pretoria. Personal communication in April.

MATLIN, R W (1979). Design Optimization and Performance Characteristics of a Photovoltaic Micro-Irrigation System For Use in Developing Countries. MIT Lincoln Laboratory Report No COO/4094-33.

MAYCOCK, P D (1990). International photovoltaic markets, developments and trends. Paper no. 1, Seminar Proceedings of "The Sun at Work", SESSA congress. 27-29 June.

MCNELIS, B (1987). "Solar Water Pumping - the Current Status", Appropriate Technology, Vol 14, No 1, pp 5-7.

MORRIS, G J (1988). Performance Evaluation of Photovoltaic and Diesel Electricity Generation Applications in the Kruger National Park. Engineering MSc Dissertation, University of Cape Town.

NBRI, National Building Research Institute (1978). Availability of Solar Radiation in South Africa. NBRI Information Sheet X/BOU 2-40, Council for Scientific and Industrial Research, Pretoria.

OBLOCH, H (19-). A New Inverter for Photovoltaic Pumps. AEG unpublished paper A47E52, West Germany.

OLIVIER, N (1990). National Energy Council, Pretoria. Personal communication.

PAYNE, S A E (1986). The Design and Production of Solar Powered Positive Displacement Pumping Systems. Unnumbered Conference Paper, Renewable Energy Potential in Southern Africa Conference, Energy Research Institute, University of Cape Town, (8-10 Sept).

POTGIETER, A W (1988). Die Struktuur en Analiese van Hernuurbare Energiestelsels in die Bree Tipologie. MSc Dissertation, University of Pretoria.

PULFREY, D L; WARD, P R B & DUNFORD, W G (1987). "A Photovoltaic-powered System for Medium-head Pumping", Solar Energy, Vol 38, No 4, pp 255-265.

REAL GOODS (1990). Alternative Energy Sourcebook. Ukiah: Real Goods Trading Company.

REDDY, R (1990). Scaffold and Plant Hire, Pietermaritzburg. Personal Communication in April.

ROGER, J A (1979). "Theory of the Direct Coupling Between D.C. Motors and Photovoltaic Solar Arrays", Solar Energy, Vol 23, pp 193-198.

ROGER, J A (1982). "Water and Photovoltaics in Developing Countries", Solar Cells, Vol 6, pp 295-308.

SASOL (1989). Annual Report, p 42.

SCHAEFFER, J F (1985). Results of a Survey of 111 Photovoltaic Water Pumping Systems in New Mexico. New Mexico Energy Research and Development Institute report No 2-72-4232, Santa Fe, New Mexico.

SERI Solar Energy Research Institute, (1984a). Basic Voltaic Principles and Methods. SERI Publication. New York: Van Nostrand Reinhold Co. Cited in Sinclair (1988).

SERI Solar Energy Research Institute, (1984b). SERI Photovoltaic Advanced Research & Development, An Overview. Cited in Sinclair (1988).

SERI Solar Energy Research Institute, (1985). Photovoltaics: Technical Information Guide. Technical Information Branch of SERI. Cited in Sinclair (1988).

SERI Solar Energy Research Institute, (1986). Annual Progress Report: Photovoltaics. Cited in Sinclair (1988).

SINCLAIR, D J & EBERHARD, A A (1988). Photovoltaic Market Research Project: International Developments in Photovoltaic Technology and Economics. Report No CON 38/2 of the Energy Research Institute, University of Cape Town.

SINCLAIR D J (1989). A Review of International and Local Developments in Photovoltaic Technology and Economics for Developing Areas. Unpublished MSc (Eng) Dissertation, Energy Research Institute, University of Cape Town.

SMITH, D V (1985). Technology and Employment Programme. Photovoltaics : Socio-economic Impact and Policy Implications. Working Paper of the World Employment Programme Research, International Labour Office, Geneva.

STELNA, Y (1989). Preliminary Report: Oil Price Study. Unpublished report, AECI (African Explosives and Chemical Industries), Johannesburg.

THORRINGTON-SMITH, ROSENBERG & McCRYSTAL (1978). Towards a Plan for Kwazulu: A Preliminary Development Plan. Volumes I and II. Published by Kwazulu Government. Cited by Atmore (1986).

UDIT, P (1987a). A socio-economic study of the Sondela community garden in Nyavu, Kwazulu. Unpublished progress report of the Institute of Natural Resources, University of Pietermaritzburg.

UDIT, P (1987b). A socio-economic impact assessment of Sondela community garden in Nyavu Ward, Kwazulu. August 1987. Unpublished progress report of the Institute of Natural Resources, University of Pietermaritzburg.

WADDINGTON, D & HERLEVICH, A (1982). Evaluation of Pumps and Motors for Photovoltaic Water Pumping Systems. Solar Energy Research Institute report SERI/TR-214-1423, Colorado.

WANG, Y J (1987). The Sizing of Stand-alone Photovoltaic Systems. MSc (Engineering) thesis, Asian Institute of Technology, Bangkok, Thailand.

WILLIAMS, A T (1986). Diesel Power - The Cost to Beat in Remote Areas. Conference Paper No 40, Renewable Energy Potential in Southern Africa Conference, Energy Research Institute, University of Cape Town, (8-10 Sept).

WILLIAMS, A T (1989). Off-grid Small Power Supply Potions for Rural Areas. Energy Research Institute Report No. GEN 130, University of Cape Town.

WISEMAN, K & EBERHARD, A A (1987). Technical, Economic and Social Analysis of Alternative Water Pumping Technologies for Underdeveloped Rural Areas. Energy Research Institute Report No. GEN 121, University of Cape Town.

ZWEIBEL, K (1986). "Photovoltaic Cells", C&EN, Vol 64, No 27, pp 34-48. Cited in Sinclair (1988).

THE APPENDICES

Note the information in the Appendices maps directly onto that in the main body the report - for example, Appendix 3.2 has information relating to Section 3.2 in the main body. Where there is no backup information for a particular chapter or section in the main body there will be no corresponding Appendix. So, for example, there is no Appendix 3.1, as Section 3.1 in the main body is an introduction for which there is no back up information

APPENDIX 1: INTRODUCTION

See the main body. There is no Appendix 1 as there is no back-up information for the Introduction.

APPENDIX 2: LITERATURE REVIEW

See the main body. There is no Appendix 2 as there is no back-up information for the Literature Review.

APPENDIX 3: TECHNICAL EVALUATION

Appendix 3.1: Introduction

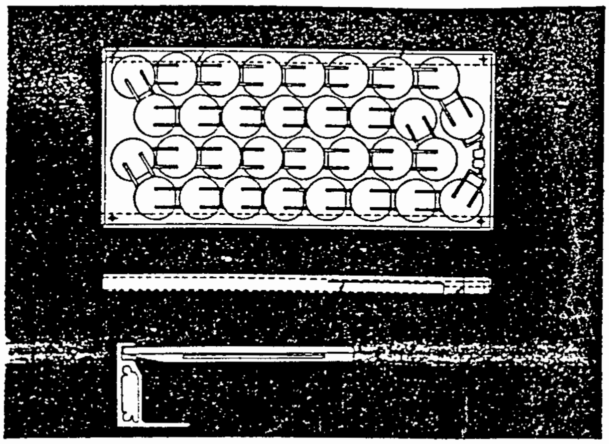
There is no back-up information for Section 3.1 in the main body.

Appendix 3.2: Specifications for the Components of the PV Pump Tested - at Sondela

This section contains the manufacturers' specifications for the M Setek PV modules, the Honeywell DC permanent magnet motor, and the Mono SW4L pump. No product information is available for the Miltek power maximizer.

HIGH-QUALITY, HIGH-PERFORMANCE SOLAR CELL MODULE

Highly pure silicon crystals of MSP-103 are product of the most stabilized CZ method, offering unrivaled quality and performance.



Extraordinary Durability under the Severest Outdoor Conditions

MSP-103 package made from tempered white glass, resin, and special films is a highly reputed achievement of out packaging technology with longtime history. This unique packaging method guarantees superb durability under all imaginable stringentest conditions.

High Electric Conversion Efficiency

A special anti-reflection film covering the solar cell front surface and Back Surface Field structure, plus the high purity silicon. All these contribute to attaining the 16.4% or more cell conversion efficiency and module efficiency as high as 12.0%

Lightweight

of lightweight aluminum and resin drastically reduced the weight of module.
This means simplified and easy transport and installation.

Fig. 1 MSP-103
Current, Power vs. Voltage Characteristics

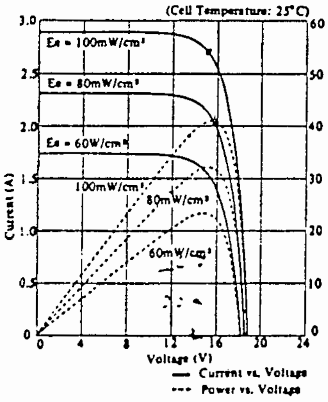


Fig. 2 MSP-103
Open Circuit Voltage, Short Circuit Current vs. Irradiance

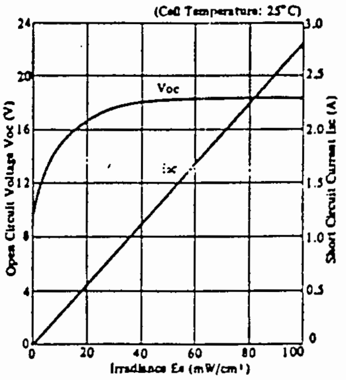
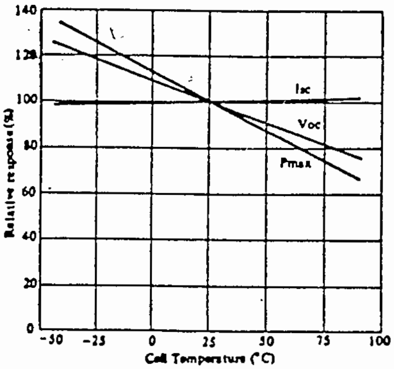


Fig. 3
Temperature Characteristics



Specifications

Element size	100mm dia silicon cell
No. of element	32
Voltage	DC 12V systems
Power output	41W
Dimensions	873(W) x 390(H) x 35(D) mm
Weight	4.7kg

Absolute maximum ratings

Ratings	Symbol	Value	Units
Operating temperature	Topr	−40 ~ +90	°C
Storage temperature	Tstg	−40 ~ +90	°C

Electro-optical characteristics

(Cell temperature : 25°C)

Characteristics	Symbol	Type	Units	Conditions
Open-circuit voltage	Voc	19.0	V	Ea = 100mW/cm²
Optimum operating voltage	Vop	15.3	V	
Short-circuit current	Isc	2.89	A	
Optimum operating current	Iop	2.68	A	
Maximum power output	Pmax	41	W	
Conversion efficiency	[illegible]	16.4	%	

*Ea : Irradiance from the sun at sea level

M. SETEK CO., LTD.
HEAD OFFICE/DAIWA BLDG. 6-16, Yanaka 3-chome, Taito-ku,
Tokyo 110, JAPAN
phone 824-1241 TOKYO
TELEX. 2657679 MSETEK J

HONEYWELL

Performance Data SCR Controlled Permanent Magnet DC Motors

90-VOLT MOTORS – Continuous Duty

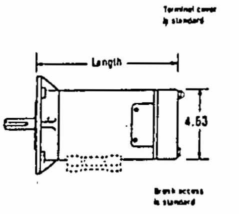
RPM	CATALOG LISTING	RATINGS HP	RATINGS CURRENT AMPS	RATINGS TORQUE LB-IN	RATINGS DEMAG. CURRENT	REFERENCE INFORMATION NO LOAD SPEED RPM	REFERENCE INFORMATION STALL TORQUE LB-IN	PARAMETERS K_E V/KRPM	PARAMETERS R_A OHMS	PARAMETERS J LB-IN²	PARAMETERS L mH	LENGTH INCHES	WEIGHT LBS.	ENCL.
1200	SR3624-8362-7-56C	1/8	1.4	6.7	37	1355	94	66	5.2	4.3	20.7	9.13	19	TENV
	SR3632-363-7-56C	1/4	2.4	13.5	38	1300	160	69	2.7	5.5	12.3	10.13	22	TENV
	SR3640-8364-7-56C	1/3	3.1	18.0	67	1420	182	62	2.5	6.6	9.5	11.13	26	TENV
	SR3640-8365-7-56C	1/2	4.6	27.0	48	1300	187	69	2.1	6.6	9.5	11.13	26	TENV
	SRF3748-4500-7-56C	3/4	7.5	39.5	55	1340	330	68	1.1	11.4	9.6	12.75	28	TEFC
	SRF3756-4502-7-56C	1.0	10.0	52.5	68	1410	400	64	1.0	12.4	7.1	13.75	30	TEFC
1800	SR3616-8290-7-56HC	1/8	1.5	4.5	36	1900	67	46	4.7	3.2	19.4	8.13	16	TENV
	SR3624-8291-7-56HC	1/4	2.5	9.0	34	1920	118	44	2.4	4.2	10.1	9.13	19	TENV
	SR3632-8292-7-56HC	1/3	3.2	12.0	70	1880	170	48	1.7	5.3	7.2	10.13	22	TENV
	SR3640-8293-7-56HC	1/2	4.7	18.0	95	1880	292 298	48	1.0	6.6	4.7	11.13	26	TENV
	SRF3736-4243-7-56HC	3/4	7.5	27.0	80	1900	310 337	45	0.8	8.8	6.0	11.25	25	TEFC
	SRF3744-4266-7-56HC	1.0	9.3	35.0*	75	1910	410 364	48	0.6	10.6	5.1	12.25	27	TEFC
2400	SR3616-8179-7-56C	1/8	1.7	3.3	46	2570	104	35	2.5	3.2	11.1	8.13	16	TENV
	SR3624-8129-7-56C	1/4	3.0	6.6	72	2570	163	35	1.6	4.2	6.3	9.13	19	TENV
	SR3632-8130-7-56C	1/3	3.3	8.8	95	2650	190	34	1.0	5.3	4.0	10.13	22	TENV
	SR3632-2890-7-56C	1/2	5.0	12.6	74	2570	270	35	0.7	5.3	3.4	10.13	22	TENV
	SRF3740-4504-7-56C	3/4	7.3	20.0	84	2460	300	37	0.5	9.3	3.6	11.25	26	TEFC
	SRF3748-4506-7-56C	1.0	9.6	27.0	98	2520	450	36	0.4	10.7	2.8	12.25	27	TEFC

*All 90 volt fractional horsepower motors are available in 180 volt ratings.

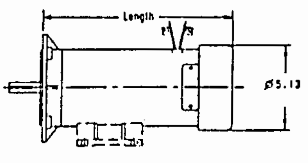
180-VOLT MOTORS – Continuous Duty

RPM	CATALOG LISTING	RATINGS HP	RATINGS CURRENT AMPS	RATINGS TORQUE LB-IN	RATINGS DEMAG. CURRENT	REFERENCE INFORMATION NO LOAD SPEED RPM	REFERENCE INFORMATION STALL TORQUE LB-IN	PARAMETERS K_E V/KRPM	PARAMETERS R_A OHMS	PARAMETERS J LB-IN²	PARAMETERS L mH	LENGTH INCHES	WEIGHT LBS.	ENCL.
1200	SRF3748-4501-7-56C	3/4	3.8	39.5	28	1340	330	135	4.4	11.6	46.1	12.75	28	TEFC
	SRF3756-4503-7-56C	1.0	5.0	52.5	34	1410	400	129	4.0	12.4	34.1	13.75	30	TEFC
	SR5348-3913-45C	1.5	8.0	78.0	52	1350	500	130	1.6	23.0	49.0	16.75	61	TEFC
	SRF5572-3927-82C	2.0	11.0	105.0	66	1400	948	135	1.3	39.3	39.0	19.75	80	TEFC
1800	SR3640-1034-7-56HC	1/2	2.5	18.0	48	1900	292	96	4.51	6.3	21.6	11.13	26	TENV
	SRF3736-4272-7-56HC	3/4	3.8	27.0	40	1900	310	91	3.3	8.8	28.8	11.25	25	TEFC
	SRF3744-4273-7-56HC	1.0	4.6	35.0	36	1910	410	95	2.5	10.6	24.5	12.25	27	TEFC
	SR5348-3920-45BC	1.5	7.0	54.0	60	2000	508	90	1.3	23.0	26.0	16.75	62	TEFC
	SRF5556-3928-82BC	2.0	9.5	72.0	85	1950	624	89	1.1	29.8	23.0	18.00	68	TEFC
	SRF5572-3929-82BC	3.0	14.0	108.0	115	2000	1040	90	0.7	39.3	18.0	19.75	79	TEFC
	SRF3740-4505-7-56C	3/4	3.8	20.0	42	2460	300	74	2.0	9.3	17.3	11.25	26	TEFC
	SRF3748-4507-7-56C	1.0	4.8	27.0	48	2520	450	73	1.5	10.7	13.5	12.25	27	TEFC
	SR5332-3923-45C	1.5	7.0	37.8	70	2650	353	68	1.6	18.8	22.0	14.75	41	TEFC
	SR5340-3924-45C	2.0	9.8	50.4	83	2700	509	67	0.9	22.4	17.0	15.75	49	TEFC

Screen indicates stock motors. Note: stock motors are supplied with brush access.

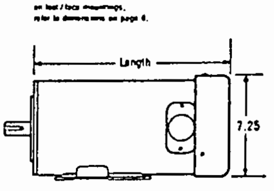


SR 36 Frame

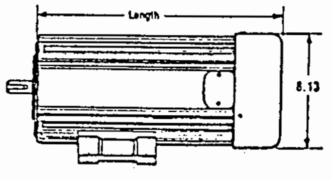


98 115

SRF 37 Frame



SR 55 Frame

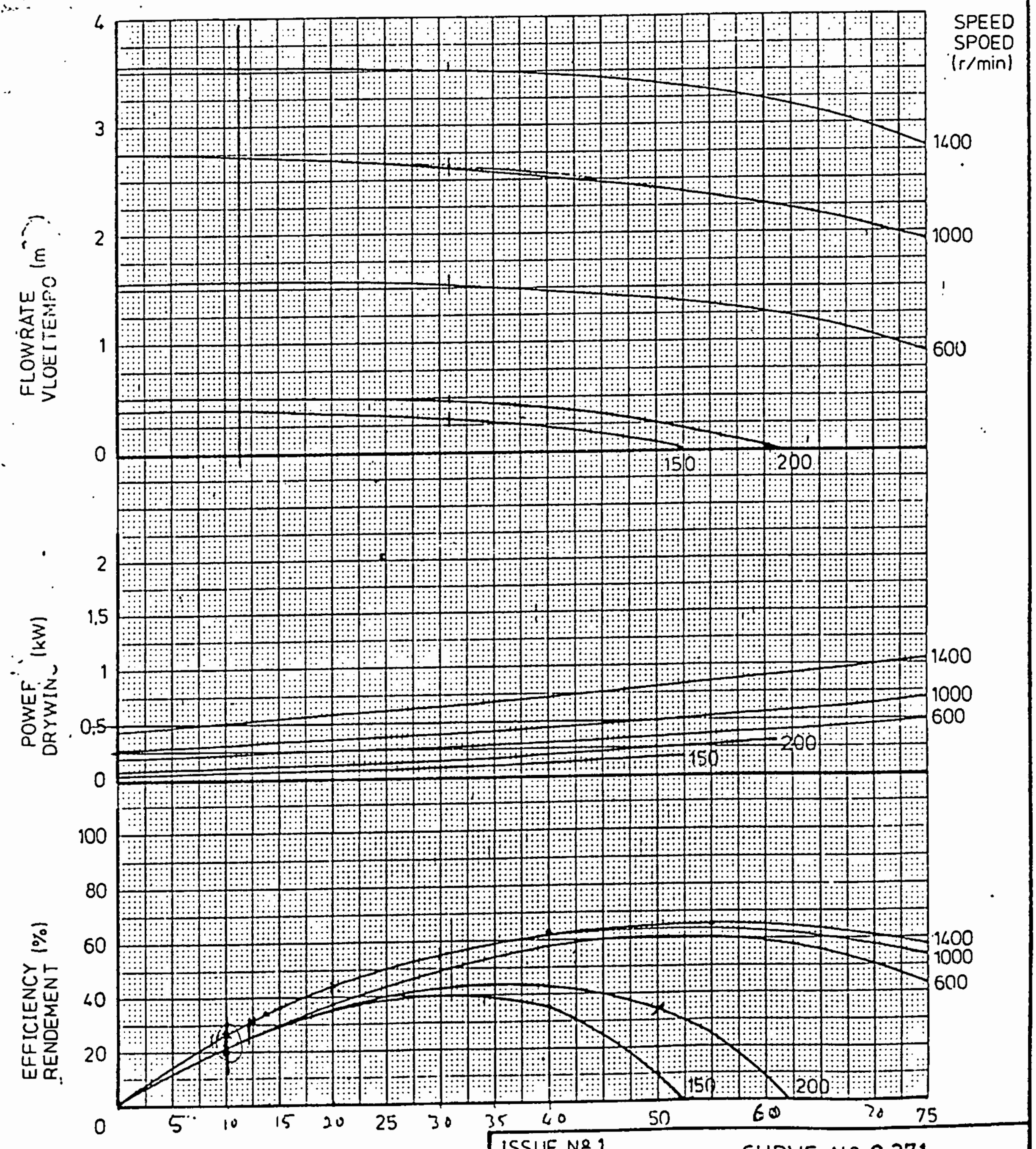


SRF 55 Frame

MONO PUMPS

SOLAR SONKRAG	TYPICAL, AVERAGE PERFORMANCE TIPIESE GEMIDDELDE POMPPRESTASIE	PUMP SIZE POMP GROOTTE	S4L

MAX HEAD 75 m — MAKS HOOGTE
MAX SPEED 1500 r/min — MAKS SPOED
40 mm COLUMN 13 mm SHAFT UP TO 75 m — 40 mm PYPE 13 mm STANGE TOT OP 75 m
mm COLUMN mm SHAFT UP TO m — mm PYPE mm STANGE TOT OP m
MONOSTROOM DISCHARGE HEAD UP TO 75 m — MONOSTROOM ONTSLAGKOP TOT OP 75 m
DISCHARGE HEAD UP TO m — ONTSLAGKOP TOT OP m
MINIMUM STARTING TORQUE 4,5 ~~7~~ N.m — MINIMUM DRAAIMOMENT



ISSUE Nº 1
DATE 01-09-88

CURVE Nº C 271

Appendix 3.3: Instrument and Data Logger Specifications

This section contains the specifications for the LM35D temperature sensors, the Pepperl & Fuchs NJ5 proximity sensor for speed measurement, the Weber Flow Captor 4113.30 flow meter, and the Kent PSM 5 flow meter used to measure the garden's usage water. No product information is available on the Kipp & Zonen thermopile solarimeter. All other measurements were done using electronic circuits made by the Energy Research Institute.

Also in this section are the specifications the MC Systems MCS 120-02 Version 2.371 Data Logger.

The Formula Used to Calculate Friction Head

The method used was taken from Coulson & Richardson (1977) pages 42 and onwards.

The Blasius correlation for smooth pipes Reynolds numbers between 2,500 and 100,000 was chosen (see equation 3.8). The flow rates corresponding to this range Reynolds numbers are 0.6 m^3/h to 23 m^3/h for the 65 mm delivery pipe at Sondela. So this correlation covers the correct range (the highest flow rate expected at Sondela is 4 m^3/h). The Blasius correlation gives:

F = $0.396\ Re^{-0.25}$; where F is the Friction Factor and Re the Reynolds number

The Reynolds number is given by the following formula:

Re = (u.d.rho)/v where
u = water velocity [m/s]
d = pipe inner diameter [m]
rho = water density [1000 kg/m^3] and
v = water viscosity [10^{-3} $N.s/m^2$]

The velocity in the above formula is found in terms volumetric flow rate, Q, as follows:

$$u = \frac{Q\ [m^3/h]}{(3600\ s/h * PI/4 * d^2)}$$

$$= Q\ [m^3/h]\ /\ (2827.35\ d^2)$$

This formula can be substituted in that for the Reynolds number to get:

$$Re = \frac{Q * d * 1000\ kg/m^2}{2827.35\ d^2 * 10^{-3}\ N.s/m^2}$$

$$= 353.688 * Q\ [m^3/h]\ /\ d\ [m]$$

This formula can then be substituted into the Blasius formula to give:

$$F = 0.0396 * Re^{-0.25}$$
$$= 0.0396 * (353.688 * Q/d)^{-0.25}$$
$$= 9.13146 * 10^{-3}\ (Q/d)^{-0.25}$$

It can be proved from theory that for a incompressible fluid the friction head is given by the following formula (see C & R equation 3.17):

H_d = 8 F (l/d) $(u^2/2g)$ where
H_d is the friction head [m]
l is the pipe length [m]
g is gravitational acceleration [9.8 m/s^2]

Substituting the formulae found above for the friction factor, F, and water velocity, u:

$$H_d = 8 * 9.13146 * 10^{-3}\ (Q/d)^{-0.25} * (l/d) * (Q/2827.35\ d^2)^2/(2 * 9.8)$$
$$= 4.659 * 10^{-10}\ Q^{1.75}\ d^{-4.75}\ l$$ where

Q is volumetric flow rate [m^3/h]
d is pipe inner diameter [m]
l is pipe length [m]

This is the correlation which was used. Friction due to elbows was accounted for by adding 35 pipe diameters to the value used for length for each elbow.

National Semiconductor

PRELIMINARY

LM35/LM35A, LM35C/LM35CA, LM35D
Precision Centigrade Temperature Sensors

General Description

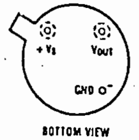
The LM35 series are precision integrated-circuit temperature sensors, whose output voltage is linearly proportional to the Celsius (Centigrade) temperature. The LM35 thus has an advantage over linear temperature sensors calibrated in ° Kelvin, as the user is not required to subtract a large constant voltage from its output to obtain convenient Centigrade scaling. The LM35 does not require any external calibration or trimming to provide typical accuracies of ±¼°C at room temperature and ±¾°C over a full −55 to +150°C temperature range. Low cost is assured by trimming and calibration at the wafer level. The LM35's low output impedance, linear output, and precise inherent calibration make interfacing to readout or control circuitry especially easy. It can be used with single power supplies, or with plus and minus supplies. As it draws only 60 µA from its supply, it has very low self-heating, less than 0.1°C in still air. The LM35 is rated to operate over a −55° to +150°C temperature range, while the LM35C is rated for a −40° to +110°C range (−10° with improved accuracy). The LM35 series is available packaged in hermetic TO-46 transistor packages, while the LM35C is also available in the plastic TO-92 transistor package.

Features

- Calibrated directly in ° Celsius (Centigrade)
- Linear + 10.0 mV/°C scale factor
- 0.5°C accuracy guaranteeable (at +25°C)
- Rated for full −55° to +150°C range
- Suitable for remote applications
- Low cost due to wafer-level trimming
- Operates from 4 to 30 volts
- Less than 60 µA current drain
- Low self-heating, 0.08°C in still air
- Nonlinearity only ±¼°C typical
- Low impedance output, 0.1 Ω for 1 mA load

Connection Diagrams

TO-46
Metal Can Package*



TL/H/5516-1

*Case is connected to negative pin

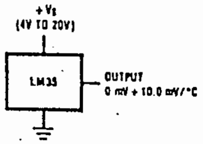
Order Number LM35H, LM35AH, LM35CH, LM35CAH or LM35DH
See NS Package H03H

TO-92
Plastic Package

TL/H/5516-2

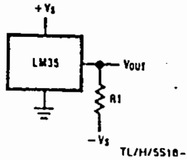
Order Number LM35CZ, or LM35DZ
See NS Package Z03A

Typical Applications



TL/H/5516-3

FIGURE 1. Basic Centigrade Temperature Sensor (+2°C to + 150°C)



Choose R1 = −VS/50 µA

V_{OUT} = +1,500 mV at +150°C
= +250 mV at +25°C
= −550 mV at −55°C

TL/H/5516-4

FIGURE 2. Full-Range Centigrade Temperature Sensor

Absolute Maximum Ratings

Supply Voltage	+35V to −0.2V
Output Voltage	+6V to −1.0V
Output Current	10 mA
Storage Temp., TO-46 Package,	−60°C to +180°C
TO-92 Package,	−60°C to +150°C
Lead Temp. (Soldering, 10 seconds):	
TO-46 Package,	300°C
TO-92 Package,	260°C

Specified Operating Temperature Range: T_{MIN} to T_{MAX} (Note 2)

LM35, LM35A	−55°C to +150°C
LM35C, LM35CA	−40°C to +110°C
LM35D	0°C to +100°C

Electrical Characteristics (Note 1) (Note 6)

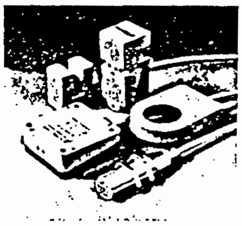
Parameter	Conditions	LM35A			LM35CA (Note 10)			Units (Max.)
		Typical	Tested Limit (Note 4)	Design Limit (Note 5)	Typical	Tested Limit (Note 4)	Design Limit (Note 5)	
Accuracy (Note 7)	$T_A = +25°C$	±0.2	±0.5		0.2	±0.5		°C
	$T_A = -10°C$	±0.3			0.3		1.0	°C
	$T_A = T_{MAX}$	±0.4	1.0		0.4	1.0		°C
	$T_A = T_{MIN}$	±0.4	1.0		0.4		1.5	°C
Nonlinearity (Note 8)	$T_{MIN} \le T_A \le T_{MAX}$	0.18		0.35	0.15		0.3	°C
Sensor Gain (Average Slope)	$T_{MIN} \le T_A \le T_{MAX}$	+10.0	+9.9, +10.1		+10.0		+9.9, +10.1	mV/°C
Load Regulation (Note 3) $0 \le I_L \le 1$ mA	$T_A = +25°C$	0.4	1.0		0.4	1.0		mV/mA
	$T_{MIN} \le T_A \le T_{MAX}$	0.5		3.0	0.5		3.0	mV/mA
Line Regulation (Note 3)	$T_A = +25°C$	0.01	0.05		0.01	0.05		mV/V
	$4V \le V_S \le 30V$	0.02		0.1	0.02		0.1	mV/V
Quiescent Current (Note 9)	$V_S = +5V$, +25°C	56	67		56	67		µA
	$V_S = +5V$	105		131	91		114	µA
	$V_S = +30V$, +25°C	56.2	68		56.2	68		µA
	$V_S = +30V$	105.5		133	91.5		116	µA
Change of Quiescent Current (Note 3)	$4V \le V_S \le 30V$, +25°C	0.2	1.0		0.2	1.0		µA
	$4V \le V_S \le 30V$	0.5		2.0	0.5		2.0	µA
Temperature Coefficient of Quiescent Current		+0.39		+0.5	+0.39		+0.5	µA/°C
Minimum Temperature for Rated Accuracy	In circuit of *Figure 1*, $I_L = 0$	+1.5		+2.0	+1.5		+2.0	°C
Long Term Stability	$T_J = T_{MAX}$, for 1000 hours	±0.08			0.08			°C

Note 1: Unless otherwise noted, these specifications apply: $-55°C \le T_J \le +150°C$ for the LM35 and LM35A; $-40° \le T_J \le +110°C$ for the LM35C and LM35CA; and $0° \le T_J \le +100°C$ for the LM35D. $V_S = +5Vdc$ and $I_{LOAD} = 50$ µA, in the circuit of *Figure 2*. These specifications also apply from +2°C to T_{MAX} in the circuit of *Figure 1*. Specifications in **boldface** apply over the full rated temperature range.

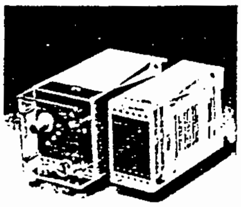
Note 2: Thermal resistance of the TO-46 package is 440°C/W, junction to ambient, and 24°C/W junction to case. Thermal resistance of the TO-92 package is 160°C/W junction to ambient.

Our complete range
Please ask for the catalogue or leaflet on equipment which is of interest.

Proximity Sensors
- for D.C. and A.C. voltage or according to DIN 19234 resp. NAMUR
- Inductive sensors in slot, cylindrical, rectangular or ring form Approved in EEx ia II C resp. in special protection classes (Ex) is G5, (Ex) is G5/Zone 0 and (Ex) s G5
- in safety version, TUV-approved (GL)
- Capacitive sensors in cylindrical and rectangular form
- Ultrasonic sensors



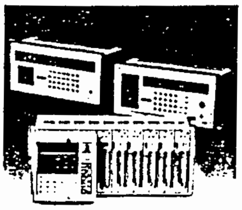
WE-System (construction follows DIN 43604)
- [EEx-i]-isolation units, transistor relays, transistor switching amplifiers
- units for speed measuring and monitoring, direction sensing
- special purpose: frequency divider, impulse divider, impulse adder, temperature controls etc.
- intrinsically safe D.C. current supplies
- Transformer isolated repeaters and drivers analoque



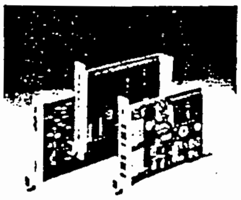
K-Series (in terminal compartment)
- [EEx-i]-isolation amplifiers, control circuit to DIN 19234 resp. NAMUR
- galvanically isolated coupling elements for D.C. and A.C. voltage

PEFUSAFE-System (in terminal compartment)
- shunt zener diode safety barriers
- transformer isolated barriers

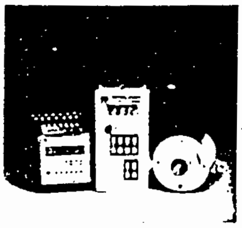
Programmable logic Systems
- controller CS-112, up to 112 in-or outputs
- positioning controller FA-200, 256 positioning steps
- timing controller FT-100, 24 outputs/128 set points
- timing controller FT-11, 8 outputs/set points setable



E-System (European Standard plug-in cards 100 x 160 mm)
- [EEx-i]-isolation amplifiers, control circuits to DIN 19234 resp. NAMUR
- Alarm annunciator system, alarm annunciators with first up facility, state indications
- Electronic logic and output elements, counting elements, time functions
- Programmable logic cards
- 19" rack mounted card frames, pre-wired
- Transformer isolated analogue repeaters and drivers



Digital Electronics
- for the explosion hazardous area
- counters with preselection and preliminary signals
- speed measuring with preselection and preliminary signal
- up-down counters with preselections
- counters with BCD inputs and outputs
- rotary pulse generators



Equipment with intrinsically safe control circuits is certified for use, by the appropriate bodies, in Germany, England, France, Switzerland, Austria, Italy, U.S.A. and Canada.

Pepperl+Fuchs · Special electronic units
Königsberger Allee 87
Postbox 310440
6800 Mannheim 31
West-Germany

Phone 0621/7505-1
Telefax 0621/785354
Telex 4-62138
Teletex 6211957

Process Measurement
419 3234

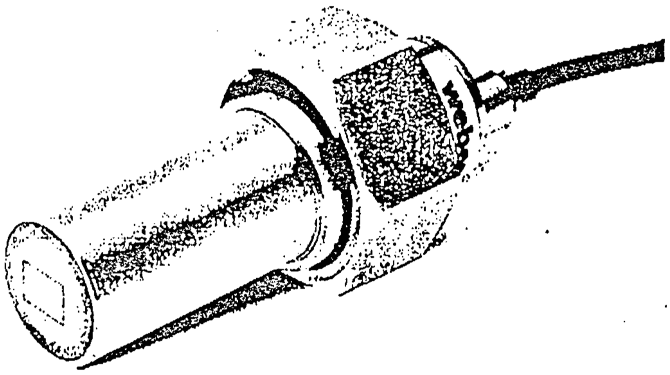
9.86

Part No. 13503

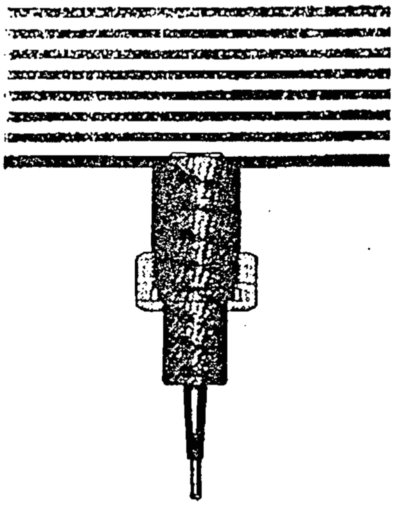
1988-12-05 15:48 WEIL GROUP JOHANNESBURG. 011 402 8241 P.02

weber flow-captor

captor



Self-contained Flow Meter, Sensor for all measurement and control applications, wide measurement range, non-intrusive sensing, linear voltage output, for all liquids, semi-solids and most corrosive media, no moving parts



Type 4113.30

The flow-captor type 4113.30 is a flow meter for industrial applications. The small, self-contained flow-captor is completely epoxy resin encapsulated and therefore suited for the harshest environmental conditions.

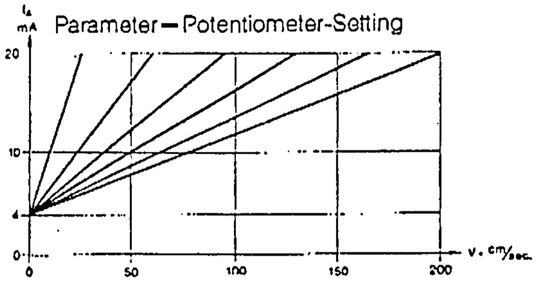
The sensor element is comprised of industrial ceramic, that is resistant to virtually all corrosive media. The sensor may be installed in any pipe fitting, allowing for non-intrusive flow sensing which does not obstruct the pipe diameter.

The newly developed operating principle for the measurement of flow, based on the calorimetric principle, provides for a wide measuring range.

At low flow rates, the measurement accuracy is considerably better than all other contending measurement technologies. The integration time is very small, even at low flow, such that this analog flow-captor is ideally suited for quick control loops.

Completely epoxy resin encapsulated, the flow-captor is extremely rugged, shock and vibration resistant.

Output current related to flow speed at various potentiometer settings.



Sensing Data:

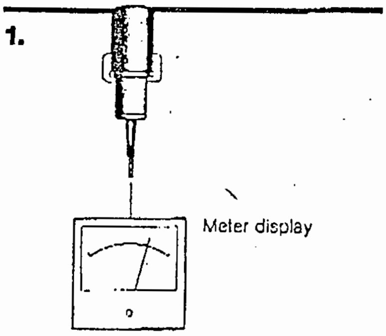
Medium	all liquids, pastes, semi-solids and most corrosive medias	
Measuring range	0 to 200 cm/sec (related to water), extended range with other media, calibrations possible.	
Linearity deviation	< 5 % (best fitting slope)	NO ACCURACY NEEDED.
Repeatability	< 2%	

Particulary at low flow conditions, the measurement accuracy is better than with any other comparable control technology.

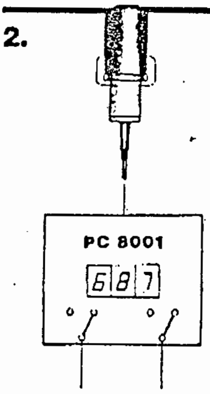
flow-captor Compact Flow Meter Type 4113.30

Application examples:

1.

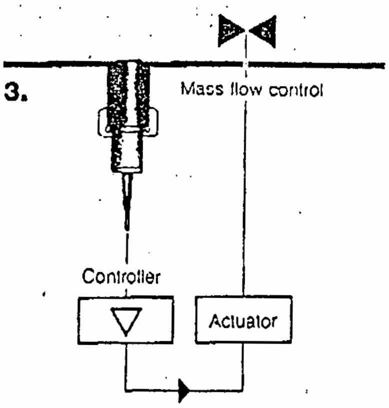


2.



Digital display on PC-captor with two additional relay outputs, applicable as 2-point controller.

3.



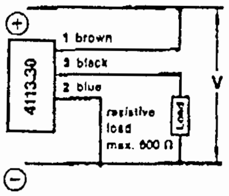
2 and 3 can be combined

Electrical Data:

Voltage supply	24 V DC	Current consumption max. 100 mA
Output current	4 to 20 mA	
Resistive load	0-600 Ohm	

Measurement range adjustment:
The two potentiometers protected by covering hubs, allow for the zero balancing and the adjustment of the measuring range by means of a small screwdriver. A color changing LED signalizes flow within the adjusted measuring range (green) or overflow (red).

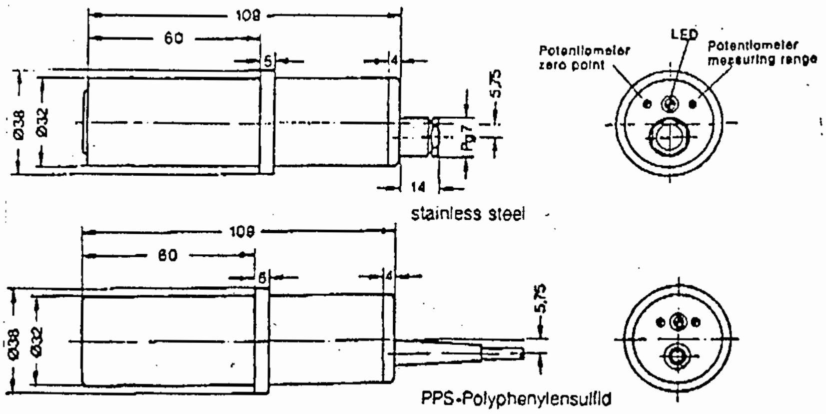
Connection diagram **4-20 mA current output**



Mechanical Data:

Material	Sensorhead	Housing
	Ceramic KER 221	stainless steel WN 4305 PPS-Polyphenylensulfid
Operating pressure	max. 30 bar, attention! not applicable under vacuum conditions	
Medium temperature range	-10° C to +80° C (14° F to 175° F)	
Ambient temperature	-10° C to +60° C (14° F to 160° F)	
Union fitting	R 1 ¼" SW 50 DIN 259 ISO 228	
Electrical connection	2 m moulded oilflex cable	
Protection standard	IP 65	
Weight	plastic approx. 230 g, stainless steel approx. 410 g	

Dimensions in mm



This flow-captor is also available in 25 mm Ø housing. (Type 4111.30)

weber
Sensortechnik GmbH · D-2201 Kollmar · Strohdeich 32 · Telefon: 0 41 28 / 591 · Telex: 218 326

BBC BROWN BOVERI **Kent Meters (South Africa) (Pty) Ltd**

Technical Specifications

11/5/89 R57-80 . 65-20 172-86

Classification			Size 3	Size 5	Size 7	
Nominal Bore		mm	15	20	25	32
PERFORMANCE						
Starts to register at about		ℓ/h	4	4	6	14
Minimum accurate registration ±2%		ℓ/h	24	24	32	68
Flows at 30 kPa pressure drop		kℓ/h	2	3	4,1	5,8
Flows at 100 kPa pressure drop		kℓ/h	3,7	5,6	7,5	11
Maximum recommended continuous flow		kℓ/h	2,8	3	4,6	6,8
Test pressure		MPa	2	2	2	2
Maximum water temperature		°C	50	50	50	50
Counter resets to zero at		kℓ	9 999	9 999	99 999	99 999

The group of white numbers in the counter (register) represent kilolitres and are used for periodic meter reading. The orange numbers represent litres and are intended to be used when checking the meter accuracy against a calibrated measure.

NET MASS						
Meter only		kg	1	1,3	2,4	3,6
Meter with connectors		kg	1,2	1,7	3	4,6
DIMENSIONS						
Length over body	A	mm	114	165	198	198
	B	mm	44	44	57	60
Length over connectors	C	mm	200	267	311	327
Meter body screwed ISO-R7 thread		mm	20	25	32	40
Connectors screwed ISO-R7 thread		mm	15	20	25	32

MATERIALS

Body – brass SABS 200 1972 Code 9A.

Chamber – graphited styrene

Counter – diakon

Number wheels – delrin

Gear wheels – nylon

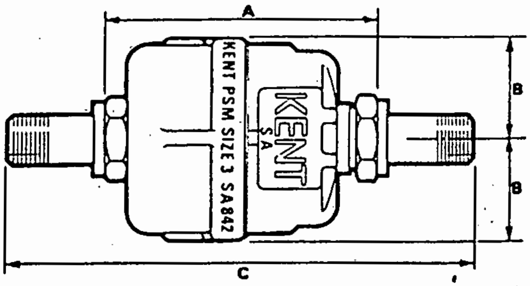
Spindles – nickel

The PSM, designed for the measurement of potable water, has a specially developed thermoplastic working chamber to ensure an exceptionally long working life. It is also highly resistant to chemically aggressive water whilst still retaining its high accuracy and reliability.

Standard Features

Semi-positive rotary piston of latest design which commences to register at extremely low flows and is accurate within plus or minus 2% throughout a wide range.

Counters and working chambers interchangeable between 15 mm and 20 mm meters.



Optional Features

Disc-type non-return, valve.

Normally supplied with connectors for iron pipe comprising union nuts and tailpieces screwed BSP.

Connectors for copper pipe by means of flared-type reducing pillar cock adaptor can also be supplied.

Approved in terms of Section 21 of the Trade Metrology Act and Regulations.

helman

57 0/83

14. SPECIFICATIONS

REAL TIME CLOCK	Better than 5 seconds/month
CALENDAR	3 digit Julian, 6 digit year-month-day
STATION ID	8 digit alphanumeric
KEYBOARD	Alphanumeric 30 pad membrane keyboard
DISPLAY	16 digit alphanumeric LCD display
THERMOCOUPLE CHANNELS	7 channels type T thermocouples
THERMOCOUPLE ACCURACY	±0.5°C -10°C to 50°C
SCAN PERIOD	Channels scanned once per minute.

LOG PERIOD	2 independent log periods setable from 1 minute to 24 hours
OUTPUT PROGRAMS	Instantaneous, totalled, average, maximum and minimum, time of max/min.
INTERNAL STORAGE	720 data points FIFO buffer.
OUTPUT DEVICE	Built-in solid state memory module recorder, serial output, telemetry link
POWER	4.8 to 6.2 volts powered by 4 D-cells, battery life >30 days. Dedicated battery channel and low battery flagging
ENVIRONMENTAL	-10 to +50°C 0 to 95% RH non condensing
SIZE	170 x 180 x 110 mm
WEIGHT	2.0 Kg without batteries

Appendix 3.4: The Experimental Method and Data Analysis

The following subsections give the backup information for the four series tests done. There is no backup data needed for the test on the array and so no Appendix 3.4.1.

3.4.2: Data Processing for the Honeywell and Baldor Motors

The raw data from the laboratory readings is given in the table below. The motor efficiency is given in the right-most column. This was calculated from the readings using the following formula where the units are given in the table.

EFF = (Speed.Torque)/(Voltage.Current) * (2*PI/60)

Table A3.1: Honeywell Motor

Voltage (V)	Current read mV	Current (Amps)	Torque (Nm)	Speed (rpm)	RAWEFF (%)
15.7	1.0	0.8	0.06	323	16.2
15.2	2.3	1.8	0.56	293	61.4
15.2	3.0	2.4	0.87	292	72.9
15.4	5.2	4.2	1.63	252	67.1
15.4	7.1	5.7	2.33	227	63.3
15.8	9.2	7.4	3.11	204	57.1
15.8	16.2	13.0	5.64	103	29.7
29.8	1.2	1.0	0.12	609	26.8
29.9	2.1	1.7	0.45	602	56.5
30.1	3.2	2.6	0.86	588	68.7
30.2	5.2	4.2	1.61	563	75.6
30.3	9.7	7.8	3.26	509	73.9
30.2	14.1	11.3	4.86	461	68.9

continued over page

Table A3.2: Honeywell Motor (continued)

Voltage (V)	Current read mV	Current (Amps)	Torque (Nm)	Speed (rpm)	RAWEFF (%)
45.4	1.2	1.0	0.12	954	27.5
45.8	3.0	2.4	0.78	937	69.6
45.5	4.9	3.9	1.50	897	79.0
45.9	7.4	5.9	2.40	869	80.4
45.9	9.0	7.2	2.98	844	79.7
45.4	13.9	11.1	4.73	768	75.4
61.0	1.5	1.2	0.18	1276	32.9
61.0	3.1	2.5	0.77	1247	66.5
60.5	5.1	4.1	1.50	1216	77.4
61.0	7.2	5.8	2.31	1185	81.6
60.7	8.8	7.0	2.87	1153	81.1
61.0	14.3	11.4	4.83	1086	78.7
75.5	1.5	1.2	0.18	1598	32.7
75.5	3.0	2.4	0.78	1564	70.5
75.3	5.2	4.2	1.57	1525	80.0
74.9	7.1	5.7	2.25	1488	82.4
75.0	8.9	7.1	2.90	1461	83.1
75.8	14.1	11.3	4.77	1397	81.6
91.0	3.5	2.8	0.92	1884	71.2
90.5	5.2	4.2	1.53	1837	78.2
90.4	7.1	5.7	2.23	1807	82.2
91.0	9.1	7.3	2.94	1784	82.9
90.7	13.8	11.0	4.64	1708	82.9

As described in the main body correlations were found to adjust this data to constant voltages and constant currents. The following graphs were used to find the form the correlations used. They show the relationships between the various parameters.

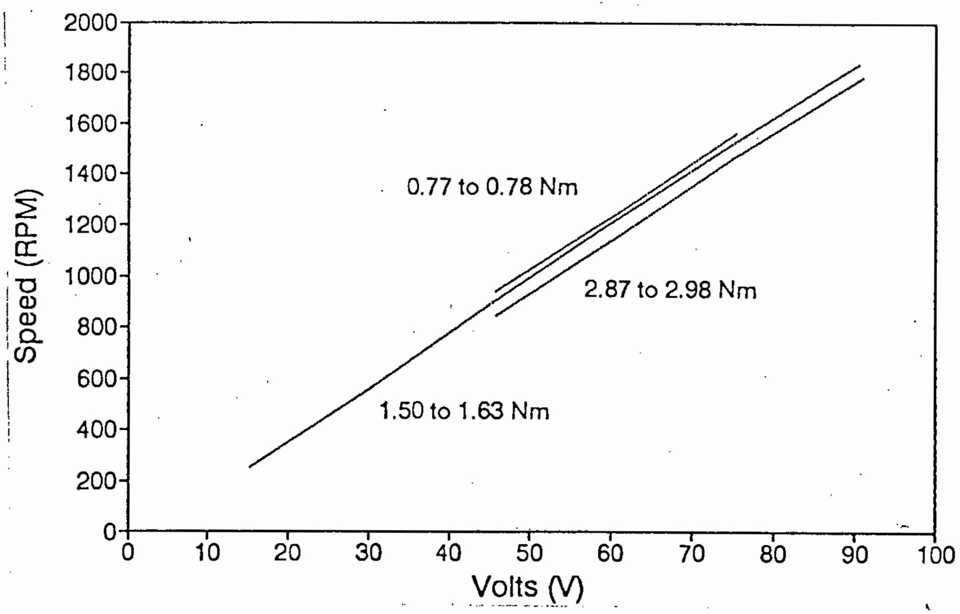


Figure A3.1: Speed vs Volts at constant Torque

The fact that the lines are straight shows that speed is proportional to voltage (as expected). And the lines are only shifted slightly by changing the torque so the dependence on torque is slight, but not negligible. So Speed can be related to Volts by the following equation:

$S = a.V + b.T + c.T^2 + d$ where a to d are constants

The following figure shows the relationship between Speed and Torque. It can be seen that Speed decreases slightly with increasing Torque. It also confirms the large dependence Speed on Voltage.

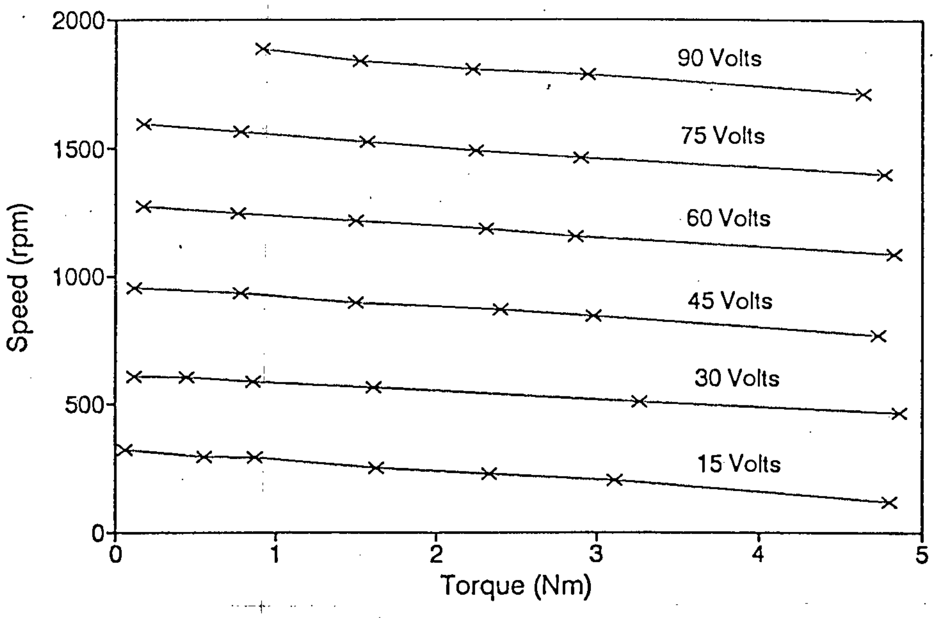


Figure A3.2: Raw Data: Speed versus Torque at all Voltages

Similar graphs can be used to find the form the equation for Current. Current is proportional to Torque with a very slight (but not negligible) dependence on Voltage. This is shown in the figure below:

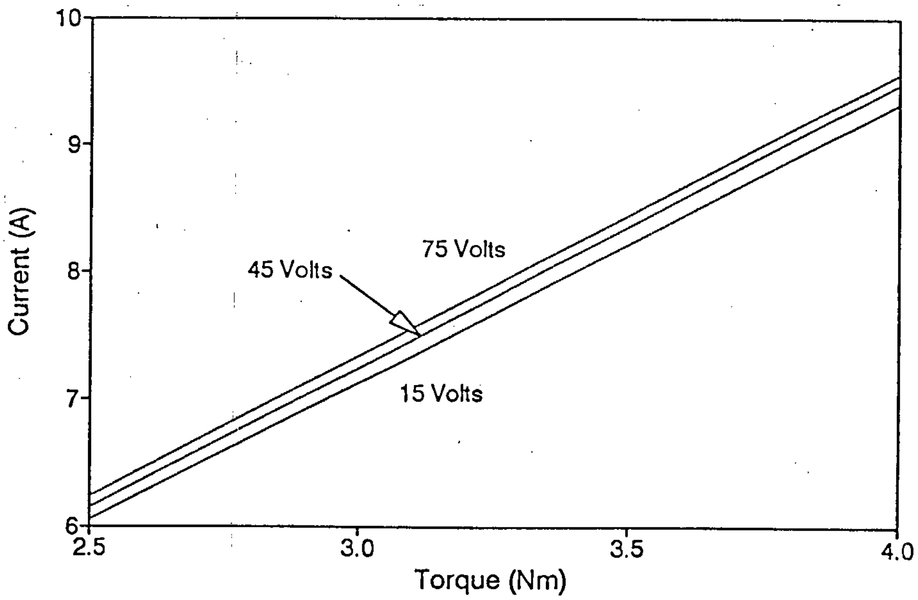


Figure A3.3: Current vs Torque at constant Voltage

Again the slight dependence on voltage cannot be assumed to be linear, so a square term is used for voltage. The form the correlation must then be:

$I = a.T + b.V + b.V^2 + d$ where a to d are constants

The experimental data was not read at constant Torque, so the data had to be searched to find readings with almost constant Torque. This was done so that the effect Voltage on the Current at constant Torque could be found. This is shown in the graph below.

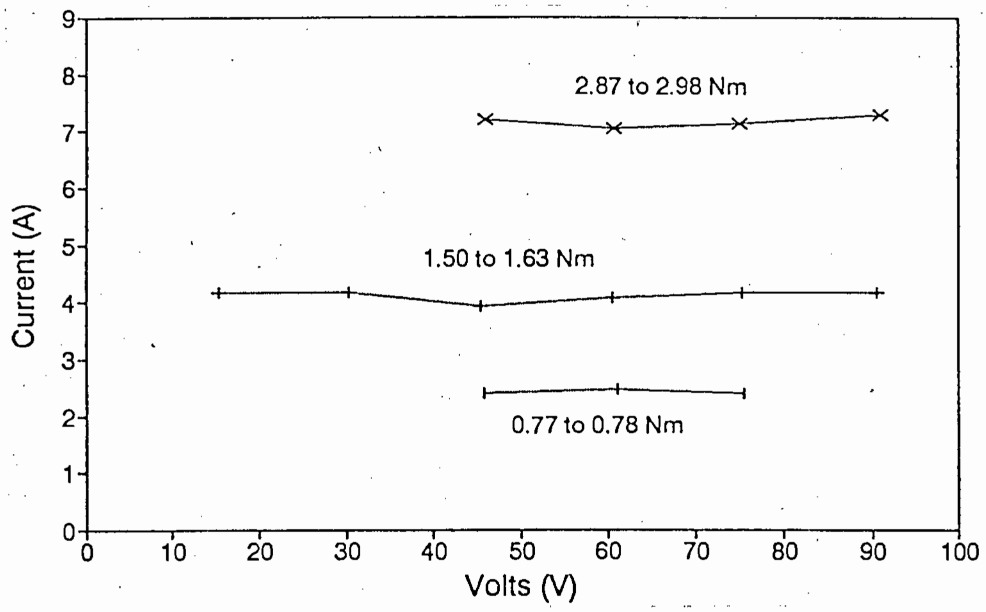


Figure A3.4: Raw Data - Current vs Voltage at constant Torque

The graph seems to indicate, as would be expected that Current and Voltage are independent. Nevertheless the terms for voltage in the correlation for current were not excluded as the coefficients would themselves account for their independence.

The raw data was then adjusted by the correlations found. Tables the adjusted data are given in Appendix 3.5.4.

3.4.3: The Accuracy of the Readings for the Test on the Two Power Maximizers

As mentioned in the main body each channel was checked by constant battery signal checks on each day of the test. These readings provided "fine tuning" - small changes to the normal calibration to suit that particular day. Throughout the tests channels were rechecked manually and the results compared with the MCS logger readouts.

The standard deviation of the discrepancies between the MCS logger readouts and the manual checks is given in the table below for each of the channels.

Table A3.3: The Reliability of the Readings

Channel	No of Batt Sig Checks	No of Man Checks	Std Dev of Error	Percent Std. Dev.	Correl Coeff
V_a	4	13	0.5 V	0.5%	0.9999
V_m	7	24	0.4 V	1.1%	0.9998
i_a	5	3	0.01 A	0.4%	0.9999
i_m	5	19	0.01 A	0.1%	0.9999
G	9	3	$6\ W/m^2$	1.2%	0.9990

Some data had to be discarded for some of the days (for example that for the Pump Mate maximizer). But the accuracy of the remaining data was very good. The highest standard deviation of error is 1.2% for the irradiance.

The correlation coefficients are for the correlations used to "fine tune" the channel calibration. These are good: the lowest is 0.999.

3.4.4: The Test for the Whole System over Half a Day

a) The accuracy of the data

The following table gives a summary of measurements of the reliability of the data collected for the whole system undisturbed over half a day.

Table A3.4: The Reliability of the Readings

Channel	No of Batt Sig Checks	No of Man Checks	Std Dev of Error	Percent Std. Dev.	Correl Coeff
Ta	5	3	0.1 °C	0.3%	0.9999
Tamb	4	3	0.1 °C	0.3%	0.9999
Va	3	5	0.2 V	0.2%	0.9999
Vm	3	6	0.8 V	1.2%	0.9990
ia	4	5	0.05 A	1.4%	0.9985
im	4	5	0.05 A	1.3%	0.9975
G	3	3	8 W/m2	1.1%	0.9871
Sp=f(Vm,im)		15	4 rpm	0.9%	0.9985
Q=f(Sp)		5	0.03 m3/h	1.3%	0.9947

The table shows that the reliability of the data was good. The standard deviations of the error in most channels is around 1% or below. The highest is 1.4% for the array current.

The correlations for pump speed and flow rate were found on this day. The correlation coefficients of 0.9985 and 0.9947 indicate that they model the behaviour of the pump well.

b) The Correlations and Formulae Used to Calculate Daily Energy Efficiencies

The process and necessity of computing the Daily Energy Efficiencies of the system are discussed in the main body. The equations and correlations used are given here.

For a standard solar day the irradiance follows a sine curve with time. For a 12-hour day (autumn and spring) this gives the following formulae:

G = Gmax * sin[(Time - 6 am) * PI/12 hours] where
Gmax = (PI/24) * I; and I is insolation in $Wh/m^2/d$

Gmax is the highest irradiance reached for that day. Its formula was derived by making the integral of the irradiance (G) over the day equal to the insolation (I) of the standard solar day. G is in power units; I in energy units.

Table A3.5: Correlations and Formulae for Energy Efficiencies

CORRELATION		COMMENT
P_a [W]	= 0.6122 * G [W/m^2] - 78.75	At 42 °C - Corr Coeff = 0.9971
PE_{pm}	= 0.0318% * P_a [W] + 78.7%	Above 355 W, PE_{pm} = 97.3%. See below
P_m [W]	= P_a [W] * PEpm	
i_m [A]	= 0.00177 * P_m [W] + 3.195	Except < 110 W, i_m = 9.68 A. See below
tau_m [Nm]	= 0.455 * i_m [A] - 0.316	Corr Coeff = 0.9998
s_m [rpm]	= 21.04 * V_m - 40.36 * tau_m -1.4	Corr Coeff = 0.9998
P fr mot	= tau_m [Nm] * s_m [rpm] * 2 PI/60	
PE_{tr}	= 93%	
s_p [rpm]	= PEtr * 1.74 * s_m [rpm]	1.74 is the pulley ratio
tau_p [Nm]	= 1.74 * tau_m [Nm]	
P to pump	= tau_p [Nm] * s_p [rpm] * 2 PI/60	
Q [m3/h]	= 0.002766 * s_p [rpm]	Corr Coeff = 0.9947
Head [m]	= 12.75 + 0.09561 * Q^1.75	The friction head depends on Q
P_{hyd} [W]	= 1000 kg/m^3 * 9.8 m/s^2 * Q [m^3/s] * H [m]	From theory

Note: PE in the above stands for Power Efficiency. The subscripts a, pm, m, tr and p denote the array, power maximizer, motor, transmission and pump respectively.

All except two of the above correlations were based on linear data and so straight lines modelled the behaviour well. But it was necessary to use two correlations to model the efficiency of the maximizer (PE_{pm}). And two were also necessary for the current to the motor (i_m). The need is illustrated by the following two figures. The variation of the maximizer efficiency with array power is shown below.

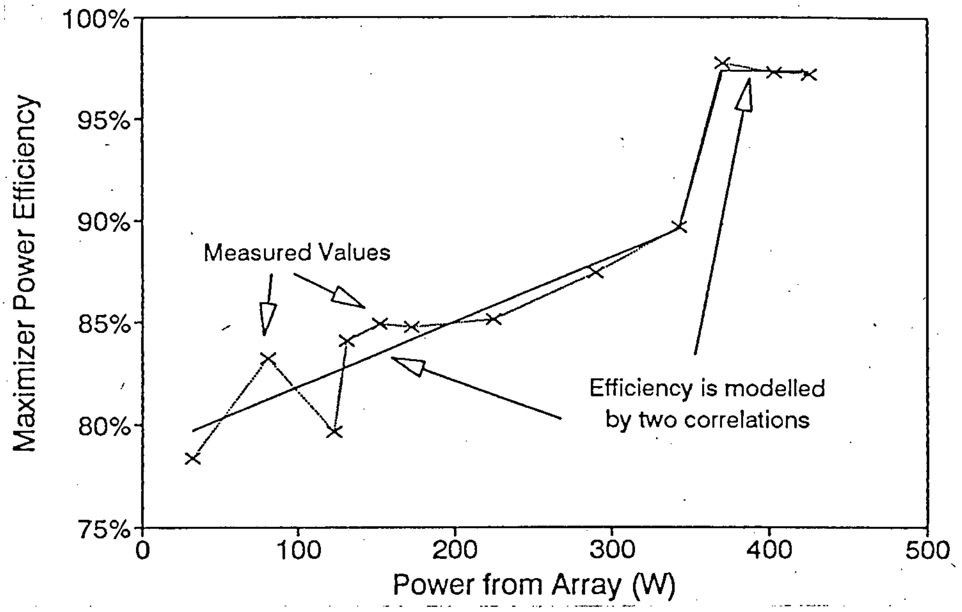


Figure A3.5: Maximizer Efficiency versus Array Power

The maximizer efficiency increases steadily until it goes into straight-through mode when it receives about 355 W from the array. At this point the efficiency increases to a constant 97.3%. So the efficiency is modelled in two stages as shown in the graph.

The variation of motor current with power to the motor is shown below.

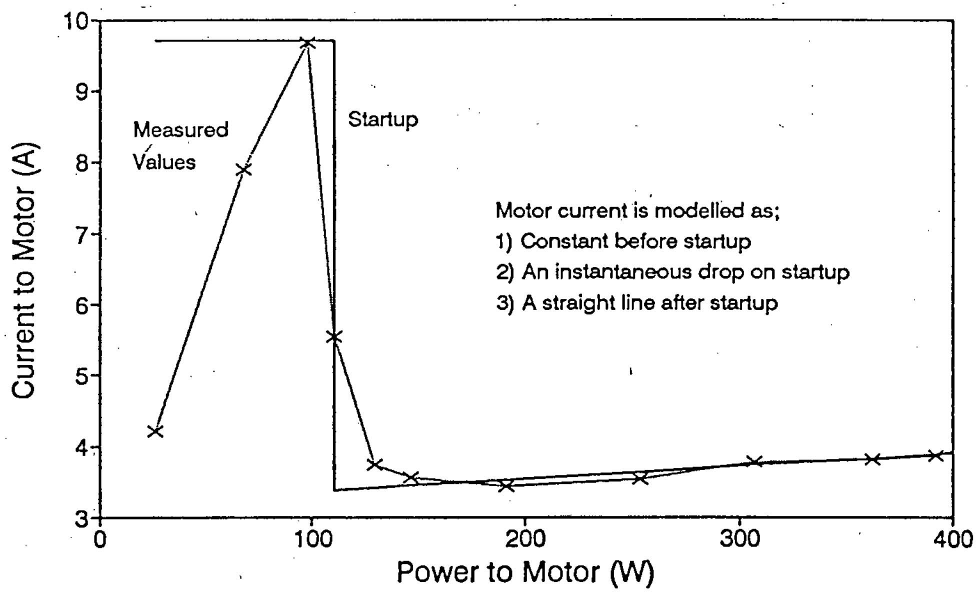


Figure A3.6: Motor Current versus Motor Power

It is necessary to model the motor current in two parts: before and after start-up. Before start-up it is possible to set the current to a constant 9.68 A (the current required to overcome starting torque). The torque is calculated from the current and it is only necessary to find out when the motor overcomes that starting torque.

When the power to the motor reaches 110 W the motor current drops sharply. This is modelled by an instantaneous drop as shown in the above figure. And from there the current increases slightly with increasing friction head (and consequently increasing torque). This is modelled by a straight line as shown.

Tables of all the processed results and the derived correlations are given in Appendix 3.5.1.

Appendix 3.5: The Results for Each Component

This section gives the background information for the "Results and Discussion" in the main body. The following subsections deal with each component in turn. There is no separate subsection on the pump itself as information was used from the test on the whole system and so information on the Mono Pump is in Subsection 3.5.1.

3.5.1: Results for the Whole System: Power and Energy Efficiencies

This subsection gives a summary of the processed results for the test on the whole system during one half-day.

The following are averages for the irradiances given. They are the readings for each channel.

Table A3.6: The Averaged Readings for Test of the Whole System over Half a Day

Date	Time	G (W/m2)	Ta (C)	Tamb (C)	Va (V)	Vm (V)	ia (A)	im (A)	Pa (W)
14/3/90	07:40	98	20.54	23.36	95.0	6.2	0.35	4.22	33
14/3/90	07:54	198	22.38	26.66	95.0	8.6	0.86	7.90	82
14/3/90	08:02	273	25.30	27.19	95.3	10.1	1.29	9.68	123
14/3/90	08:06	299	25.87	27.00	95.1	19.9	1.38	5.55	131
14/3/90	08:16	351	27.47	26.66	95.8	34.4	1.59	3.74	152
14/3/90	08:30	400	28.44	26.81	95.9	41.0	1.80	3.57	173
14/3/90	08:55	501	33.93	28.63	96.3	55.6	2.34	3.45	225
14/3/90	09:21	602	36.02	30.18	96.3	71.6	3.01	3.54	290
14/3/90	10:01	700	40.03	32.01	96.3	81.1	3.56	3.79	343
14/3/90	10:50	801	45.11	33.45	96.8	94.6	3.82	3.82	370
14/3/90	11:50	900	40.57	31.18	104.2	101.3	3.87	3.87	403
14/3/90	12:30	955	38.47	30.79	106.9	103.9	3.98	3.98	425
14/3/90	13:00	900	40.57	31.18	104.2	101.3	3.87	3.87	403

From the above the following variables were calculated in order to be able to calculate the efficiencies.

Table A3.7: Variables Calculated from the Readings

G (W/m^2)	Pm (W)	taum (Nm)	Sm (rpm)	taup (Nm)	Sp (rpm)	Sm/Sp	Flow (m^3/h)	Head (m)
98	26	1.68	0	7.28	0		0.00	12.55
198	68	3.35	0	7.28	0		0.00	12.55
273	98	4.16	0	7.28	0		0.00	12.55
299	110	2.26	327	3.95	170	1.92	0.47	12.60
351	129	1.41	666	2.46	352	1.89	0.97	12.64
400	147	1.32	808	2.30	428	1.89	1.18	12.66
501	192	1.24	1117	2.17	593	1.88	1.64	12.71
602	254	1.26	1451	2.21	771	1.88	2.13	12.75
700	307	1.37	1646	2.39	876	1.88	2.42	12.78
801	362	1.37	1929	2.40	1027	1.88	2.84	12.82
900	392	1.39	2069	2.44	1102	1.88	3.05	12.84
955	413	1.44	2120	2.52	1129	1.88	3.12	12.85
900	392	1.39	2069	2.44	1102	1.88	3.05	12.84

From the above the power into and out of each component was calculated for each irradiance.

Table A3.8: The Power into and out of Each Component

G (W/m2)	Psun (W)	Pa (W)	Pm (W)	Pout M (W)	Pin P (W)	Pout P (W)
98	468	33	26	0	0	0
198	945	82	68	0	0	0
273	1302	123	98	0	0	0
299	1424	131	110	77	70	16
351	1673	152	129	98	91	34
400	1909	173	147	111	103	41
501	2388	225	192	145	135	57
602	2868	290	254	192	178	74
700	3336	343	307	235	219	84
801	3816	370	362	277	259	99
900	4291	403	392	302	281	107
955	4554	425	413	320	298	109
900	4291	403	392	302	281	107

The power efficiencies for each component were calculated from the above:

Table A3.9: The Component Power Efficiencies Against Irradiance

G (W/m²)	PEa	PEpm	PEm	PEtr	PEp	PEsys	PEsub
98	7.09%	78.4%	0.0%	N/A	N/A	0.00%	0.0%
198	8.64%	83.2%	0.0%	N/A	N/A	0.00%	0.0%
273	9.44%	79.7%	0.0%	N/A	N/A	0.00%	0.0%
299	9.20%	84.1%	70.0%	91.4%	22.9%	1.14%	12.3%
351	9.07%	84.9%	76.0%	92.5%	37.0%	2.00%	22.1%
400	9.05%	84.8%	75.9%	92.7%	39.5%	2.14%	23.6%
501	9.43%	85.2%	75.5%	92.9%	42.2%	2.38%	25.2%
602	10.11%	87.4%	75.6%	93.1%	41.5%	2.58%	25.5%
700	10.27%	89.7%	76.6%	93.1%	38.4%	2.53%	24.6%
801	9.70%	97.7%	76.7%	93.2%	38.4%	2.60%	26.8%
900	9.40%	97.3%	76.9%	93.2%	37.9%	2.48%	26.4%
955	9.34%	97.2%	77.4%	93.2%	36.7%	2.40%	25.7%
900	9.40%	97.3%	76.9%	93.2%	37.9%	2.48%	26.4%

As described in Subsection 3.4.1 correlations were used to calculate the power into and out of each component at 15 minute intervals for standard solar days. These were then integrated to get the following energies into and out of each component.

Table A3.10: The Energy into and out of Each Component (Whr)

Insolation (kWh/m2/d)	FR SUN (Whr)	FR ARR (Whr)	TO MOT (Whr)	FR MOT (Whr)	TO PUMP (Whr)	FR PUMP (Whr)	VOLUME (m^3/d)
4.5	21471	1880	1613	1234	1147	449	12.69
5.0	23857	2178	1891	1452	1350	531	14.94
5.5	26243	2481	2210	1693	1575	623	17.42
6.0	28628	2783	2550	1944	1808	720	20.00
6.5	31014	3086	2865	2154	2003	802	22.16
7.0	33400	3388	3181	2379	2213	891	24.48

From these the daily energy efficiencies were calculated:

Table A3.11: Component Daily Energy Efficiencies for Standard Solar Days

Insolation (kWh/m²/d)	DEEa	DEEpm	DEEm	DEEtr	DEEp	DEEsys	DEEsub
4.5	8.76%	85.8%	76.5%	93%	39.1%	2.09%	23.9%
5.0	9.13%	86.8%	76.8%	93%	39.3%	2.22%	24.4%
5.5	9.45%	89.1%	76.6%	93%	39.5%	2.37%	25.1%
6.0	9.72%	91.6%	76.2%	93%	39.8%	2.51%	25.9%
6.5	9.95%	92.8%	75.2%	93%	40.0%	2.59%	26.0%
7.0	10.14%	93.9%	74.8%	93%	40.3%	2.67%	26.3%

The following table gives the energy lost in each component.

Table A3.12: The Energy Lost in Each Component

Insolation ($kWh/m^2/d$)	ARRAY (Wh)	POW MAX (Wh)	MOTOR (Wh)	TRANS (Wh)	PUMP (Wh)	USEFUL ENERGY
4.5	19591	267	379	86	698	449
5.0	21679	288	439	102	820	531
5.5	23762	271	517	119	952	623
6.0	25845	233	606	136	1088	720
6.5	27928	221	711	151	1201	802
7.0	30012	208	802	167	1321	891

If the energy coming from the array is taken as 100% the following table gives the percentage energy loss in each component of the subsystem.

Table A3.13: The Percentage of Array Energy Lost in Each Component of the Subsystem

Insolation ($kWh/m^2/d$)	POW MAX	MOTOR	TRANS	PUMP	USEFUL ENERGY
4.5	14%	20%	5%	37%	24%
5.0	13%	20%	5%	38%	24%
5.5	11%	21%	5%	38%	25%
6.0	8%	22%	5%	39%	26%
6.5	7%	23%	5%	39%	26%
7.0	6%	24%	5%	39%	26%

From the daily energy efficiencies correlations in terms of insolation for each component can be found. The efficiency of most components remains constant with head, but that of the pump varies markedly. For this reason the pump efficiency is correlated against head as well. The four columns on the right in the table below give an indication of the accuracy of the correlations.

Table A3.14: Correlations for the Component Daily Energy Efficiencies

Component	Offset	Insolation Coefficient	Head Coeff	4.5 kWh/m2/d		7.0 kWh/m2/d	
				Corr'n	Actual	Corr'n	Actual
Array	6.35%	0.552%		8.84%	8.76%	10.22%	10.14%
Maximizer	69.9%	3.49%		85.6%	85.8%	94.4%	93.9%
Motor	76.9%	-0.17%		76.1%	76.5%	75.7%	74.8%
Transm'n	93.0%			93.0%	93.0%	93.0%	93.0%
Pump	26.1%	0.40%	0.85%	39.0%	39.1%	40.0%	40.3%
System	0.04%	0.291%	0.051%	2.02%	2.09%	2.74%	2.67%
Subsystem	11.3%	1.18%	0.54%	23.6%	23.9%	26.6%	26.3%

Note: the units for Insolation in the correlation are kWh/m^2/d while those for Head are metres.

3.5.2: Results for the Array

a) Data which describes the operation of the array

The table below gives the correlations found by regression analysis. These model the behaviour of some parameters.

Table A3.15: The Correlations Used to Model Various Parameters

Correlation		Corr Coeff
V_{oc}	$= 6.034 \ln(G) - 0.43\ T_a + 101.1$	0.9469
i_{sc}	$= 0.006571\ G + 0.001\ T_a - 0.904$ (fence in)	0.9997
i_{sc}	$= 0.006877\ G + 0.001\ T_a - 0.716$ (no fence)	0.9978
$\mathrm{DEL}(V_a)$	$= 6.034\ \mathrm{DEL}(G) - 0.43\ \mathrm{DEL}(T_a)$ (from V_{oc})	
$\mathrm{DEL}(i_a)$	= as in i_{sc} but using DEL where $\mathrm{DEL}(i_a) = i_a' - i_a$	
T_a	$= T_{amb} + 0.0119 * G$ (simple but less accurate)	0.7752
T_a	$= 1.956\ T_{amb} + 0.0075\ G - 31.6$ (more accurate)	0.9774
P_{max}	$= 0.5512 * G - 69.24$ (with fence in, 42 C)	0.9975
P_{max}	$= 0.6167 * G - 81.67$ (without fence, 42 C)	0.9971
P_{max}	$= 0.6622 * G - 88.57$ (without fence, 25 C)	0.9971
P_{max}	$= 0.6224\ G - 1.646\ T_a - 19$ (without fence)	0.9939

The above correlations were used to adjust the data in the following four tables to an array temperature of 42 C and constant irradiances as shown. The adjusted data is marked by an apostrophe. For example, V_a is the array voltage at the read irradiance and array temperature (G and T_a), whereas V_a' is adjusted by correlations to the desired irradiance G′ and to $T_a' = 42$ C.

Table A3.16: The Array Operation with the Fence in and No Diodes

G′ (W/m2)	Ta (C)	G (W/m2)	Va (V)	Ia (A)	Va′ (V)	Ia′ (A)	Pa′ (W)
400	38.1	362	42.2	1.54	41.2	1.79	74
	37.9	358	61.6	1.48	60.5	1.76	107
	37.9	353	74.1	1.38	73.1	1.69	123
	37.7	355	75.8	1.45	74.6	1.75	130
	37.7	346	107.1	0.97	106.1	1.33	141
	38.1	345	116.0	0.15	115.2	0.51	59
	37.8	344	120.2	0.00	119.3	0.37	45
600	40.0	558	0.8	2.78	0.4	3.06	1
	40.4	562	65.0	2.64	64.8	2.89	187
	40.7	575	82.4	2.70	82.1	2.86	235
	39.6	583	88.3	2.73	87.5	2.84	249
	39.1	587	88.5	2.79	87.4	2.88	251
	40.2	569	98.2	2.38	97.8	2.59	254
	39.1	590	100.3	2.55	99.2	2.62	259
	40.6	576	102.8	2.28	102.5	2.44	250
	39.3	597	105.6	2.29	104.5	2.32	242
	39.6	601	122.1	0.00	121.0	0.00	0
800	49.1	809	1.6	4.49	4.6	4.42	20
	49.8	807	59.0	4.39	62.3	4.34	270
	48.6	805	74.8	4.30	77.6	4.26	330
	48.6	807	82.6	4.22	85.3	4.17	356
	49.7	805	94.5	3.87	97.8	3.83	374
	47.3	805	95.2	3.85	97.5	3.81	371
	47.3	805	96.2	3.82	98.5	3.77	372
	47.5	805	100.3	3.51	102.7	3.47	356
	47.8	803	100.9	3.47	103.4	3.44	356
	48.8	803	106.9	2.77	109.8	2.74	301
	49.7	799	120.2	0.00	123.5	0.00	0

Table A3.17: Array Operation with Fence in and Diodes in

G′ (W/m2)	Ta (C)	G (W/m2)	Va (V)	Ia (A)	Va′ (V)	Ia′ (A)	P_a′ (W)
200	36.7	184	25.8	0.80	24.0	0.91	22
	36.3	191	40.5	0.74	38.3	0.80	31
	36.0	210	66.7	0.75	63.8	0.68	44
	35.7	220	70.3	0.73	67.0	0.60	41
	35.5	209	81.0	0.68	77.9	0.63	49
	35.3	209	100.0	0.44	96.9	0.39	38
	35.1	203	105.3	0.39	102.3	0.38	39
400	34.9	379	0.8	1.79	0.0	1.93	0
	35.1	387	41.7	1.69	39.0	1.78	69
	34.8	393	55.4	1.69	52.4	1.74	91
	35.3	399	64.4	1.68	61.5	1.69	104
	37.0	413	89.8	1.64	87.5	1.56	136
	36.0	408	90.9	1.58	88.3	1.53	135
	37.0	425	100.1	1.64	97.6	1.48	144
	37.2	418	106.4	1.40	104.1	1.28	134
	38.5	436	120.9	0.00	118.8	0.00	0
600	40.7	609	1.1	3.30	0.4	3.24	1
	40.7	615	54.7	3.20	54.0	3.10	167
	41.7	624	76.9	3.20	76.5	3.04	233
	42.0	620	77.7	3.16	77.5	3.03	235
	42.0	629	89.6	3.14	89.3	2.95	263
	40.9	634	95.5	3.02	94.7	2.80	265
	40.9	640	102.5	2.75	101.6	2.48	252
	40.9	645	106.4	2.48	105.5	2.18	230
	41.1	647	122.0	0.00	121.1	0.00	0
800	50.9	795	1.1	4.51	4.9	4.53	22
	49.5	797	57.8	4.29	61.0	4.30	262
	48.9	797	73.3	4.20	76.2	4.21	321
	47.9	793	80.4	4.13	83.0	4.17	346
	47.7	793	93.4	3.82	95.9	3.86	371
	47.2	795	95.3	3.77	97.6	3.79	370
	47.5	797	99.6	3.52	102.0	3.53	360
	46.7	797	101.5	3.36	103.6	3.38	350
	46.9	793	106.7	2.79	108.9	2.83	308
	47.9	787	121.1	0.00	123.7	0.08	10

Table A3.18: Array Operation without the Fence but with the Diodes

G′ (W/m2)	Ta (C)	G (W/m2)	Va (V)	Ia (A)	Va′ (V)	Ia′ (A)	P_a' (W)
200	37.2	279	1.0	1.38	0.0	0.84	0
	37.4	272	58.4	1.15	54.6	0.66	36
	37.1	271	67.5	1.12	63.5	0.64	41
	36.9	267	86.2	1.00	82.3	0.55	45
	36.9	263	88.2	0.98	84.4	0.56	47
	Maximum Power Point				89.4	0.54	49
	36.9	260	93.8	0.95	90.1	0.54	48
	36.8	256	100.2	0.83	96.5	0.45	43
	36.8	248	116.6	0.00	113.1	0.00	0
400	38.9	451	0.8	2.42	0.0	2.07	0
	39.2	458	58.7	2.32	56.7	1.93	109
	39.8	463	76.7	2.28	74.9	1.84	138
	39.3	470	89.0	2.26	86.9	1.78	155
	39.6	477	94.1	2.24	92.0	1.71	158
	Maximum Power Point				92.5	1.72	159
	40.0	480	99.2	2.13	97.3	1.59	154
	39.3	487	110.0	1.45	107.6	0.85	92
	39.5	493	120.7	0.00	118.3	0.00	0
600	42.8	652	1.1	3.94	0.9	3.58	3
	41.8	657	65.0	3.81	64.3	3.42	220
	42.0	661	88.7	3.65	88.2	3.23	285
	43.2	666	93.8	3.55	93.7	3.09	290
	Maximum Power Point				93.3	3.11	290
	43.0	665	97.6	3.38	97.4	2.93	285
	41.8	659	100.6	3.23	100.0	2.82	282
	42.5	670	101.7	3.18	101.3	2.69	273
	43.7	673	105.7	2.79	105.7	2.29	242
	44.2	675	108.4	2.48	108.6	1.96	213
	43.2	681	122.0	0.00	121.7	0.00	0
800	47.4	787	1.1	4.82	0.0	4.90	0
	48.1	780	61.4	4.55	64.1	4.68	300
	47.4	783	77.6	4.46	80.0	4.57	366
	46.9	780	84.8	4.35	87.1	4.48	390
	Maximum Power Point				96.3	4.22	406
	46.4	776	96.5	3.95	98.6	4.11	405
	47.1	774	97.5	3.84	99.9	4.02	402
	47.5	770	101.1	3.56	103.7	3.76	390
	46.6	768	102.2	3.47	104.4	3.69	385
	47.4	766	107.3	2.81	109.9	3.04	334
	47.8	763	121.4	0.00	124.2	0.00	0

Table A3.19: The Array Operation without the Fence and without Diodes

G' (W/m2)	Ta (C)	G (W/m2)	Va (V)	Ia (A)	Va' (V)	Ia' (A)	P_a' (W)
200	39.6	283	32.1	1.30	29.0	0.74	21
	39.4	280	49.4	1.24	46.2	0.69	32
	39.1	278	70.7	1.17	67.5	0.64	43
	39.9	291	74.3	1.11	71.1	0.49	35
	38.8	275	93.7	0.74	90.4	0.23	20
	39.1	269	118.4	0.00	115.3	0.00	0
400	45.0	512	1.1	2.74	0.9	1.96	2
	43.9	520	68.2	2.63	67.5	1.81	122
	43.9	527	83.8	2.59	82.9	1.72	143
	42.6	531	98.0	2.40	96.6	1.50	144
	39.8	541	104.0	2.22	101.2	1.25	126
	40.8	534	108.8	1.77	106.5	0.84	90
	40.8	545	121.4	0.00	119.0	0.00	0
600	43.6	686	1.9	4.02	1.8	3.42	6
	43.1	689	68.0	3.98	67.7	3.37	228
	43.6	691	93.0	3.73	92.9	3.10	288
	42.5	694	96.2	3.61	95.6	2.96	283
	41.6	700	96.7	3.64	95.6	2.96	283
	43.6	693	98.6	3.50	98.4	2.86	281
	43.0	707	108.0	2.56	107.5	1.83	196
	42.9	709	122.1	0.00	121.5	0.00	0
800	47.5	809	1.6	4.94	3.9	4.87	19
	48.0	804	64.3	4.80	66.8	4.77	319
	48.0	806	81.2	4.65	83.7	4.60	385
	48.2	806	98.3	4.02	100.9	3.97	401
	48.2	806	99.6	3.92	102.2	3.87	396
	48.4	806	102.6	3.60	105.3	3.55	374
	47.7	805	103.5	3.58	105.9	3.53	374
	47.2	807	108.9	2.83	111.1	2.78	309
	47.4	805	121.5	0.00	123.8	0.00	0

And then the effect of array temperature on the i_a versus V_a graph was found by adjusting data at 800 W/m^2 to the following array temperatures:

Table A3.20: Array Operation with No Fence but with Diodes at 800 W/m2

Ta' (C)	Ta (C)	G (W/m2)	Va (V)	Ia (A)	Va' (V)	Ia' (A)	P_a' (W)
25	47.4	787	1.1	4.82	0.0	4.89	0
	48.1	780	61.4	4.55	71.4	4.67	333
	47.4	783	77.6	4.46	87.3	4.56	398
	46.9	780	84.8	4.35	94.4	4.46	421
	Maximum Power Point				102.9	4.23	435
	46.4	776	96.5	3.95	105.9	4.09	433
	47.1	774	97.5	3.84	107.2	4.00	429
	47.5	770	101.1	3.56	111.0	3.75	416
	46.6	768	102.2	3.47	111.7	3.67	410
	47.4	766	107.3	2.81	117.2	3.02	354
	47.8	763	121.4	0.00	131.5	0.00	0
40	47.4	787	1.1	4.82	0.0	4.90	0
	48.1	780	61.4	4.55	65.0	4.68	304
	47.4	783	77.6	4.46	80.9	4.57	370
	46.9	780	84.8	4.35	88.0	4.47	393
	Maximum Power Point				97.1	4.22	410
	46.4	776	96.5	3.95	99.5	4.11	408
	47.1	774	97.5	3.84	100.8	4.02	405
	47.5	770	101.1	3.56	104.6	3.76	393
	46.6	768	102.2	3.47	105.3	3.68	388
	47.4	766	107.3	2.81	110.7	3.04	336
	47.8	763	121.4	0.00	125.0	0.00	0
55	47.4	787	1.1	4.82	0.0	4.92	0
	48.1	780	61.4	4.55	58.5	4.70	275
	47.4	783	77.6	4.46	74.4	4.59	341
	46.9	780	84.8	4.35	81.5	4.49	366
	Maximum Power Point				91.2	4.21	384
	46.4	776	96.5	3.95	93.0	4.12	383
	47.1	774	97.5	3.84	94.3	4.03	380
	47.5	770	101.1	3.56	98.1	3.78	371
	46.6	768	102.2	3.47	98.8	3.70	366
	47.4	766	107.3	2.81	104.3	3.05	318
	47.8	763	121.4	0.00	118.6	0.00	0

To get a correlation for the power the array delivers the maximum power points for all conditions were found at 42 C. For the sake of accuracy the irradiance was not adjusted and was left as read. This data is given in the following two tables for the fence being both in and out. From this data the power efficiency of the array (PE_a) was calculated. The correlations for P_{max} = f(G) given in Table A3.15, page 336, were computed from the data below.

Table A3.21: The Efficiency of the Array with the Fence in at 42 C

G (W/m2)	Va′ (V)	ia′ (A)	Pa′ (W)	Corrl′n (W)	PEa (%)
126			0	0	0.0%
210	80.2	0.63	50.8	47	4.7%
350	90.2	1.42	127.8	124	7.4%
408	96.3	1.52	146.1	156	8.0%
580	94.5	2.57	243.4	251	9.1%
630	93.9	3.03	284.9	278	9.3%
795	95.6	3.85	367.9	369	9.7%
805	95.3	3.97	378.0	375	9.8%

Table A3.22: The Array Efficiency without the Fence at 42 and 25 C

	ADJUSTED TO 42 C					ADJUSTED TO 25 C				
G (W/m2)	Va′ (V)	ia′ (A)	Pa′ (W)	Corrl′n (W)	EFFa (%)	Va′ (V)	ia′ (A)	Pa′ (W)	Corrl′n (W)	EFFa (%)
132			0	0	0.0%				0	0.0%
260	92.8	0.94	87.4	79	6.3%	100.2	0.92	92	84	6.7%
275	78.7	1.05	82.9	88	6.7%	86.0	1.03	89	94	7.1%
470	94.5	2.18	205.6	208	9.3%	101.8	2.16	220	223	9.9%
530	97.0	2.43	235.7	245	9.7%	104.3	2.41	252	262	10.4%
665	95.0	3.51	333.8	328	10.4%	102.3	3.49	358	352	11.1%
693	95.8	3.69	353.9	346	10.5%	103.1	3.68	379	370	11.2%
774	95.9	4.05	388.5	396	10.7%	103.2	4.03	416	424	11.5%
806	95.2	4.39	417.6	415	10.8%	102.5	4.37	448	445	11.6%

From the correlations established from the above data the Daily Energy Efficiency of the array (DEE_a) was computed for various days:

Table A3.23: The Daily Energy Efficiency of the Array With No Fence

Insolation (kWh/m2/d)	DEEa for T_a' = 42 C	 25 C
4.5	8.75%	9.27%
5.0	9.14%	9.67%
5.5	9.46%	10.01%
6.0	9.74%	10.29%
6.5	9.97%	10.53%
7.0	10.17%	10.74%

b) The Effect of Array Temperature and Irradiance on the PPC

The ratio V_{max}/V_{oc} was established from the following table. This gives the position of the PPC.

Table A3.24: The Position of the PPC (No fence but Diodes in)

Irrad (W/m2)	Vmax (V)	Imax (A)	Pmax (W)	Voc (V)	Vmax /Voc
200	89.4	0.54	48.6	115.0	77.7%
400	92.5	1.72	158.7	119.2	77.6%
600	93.3	3.11	289.7	121.6	76.7%
800	96.3	4.22	406.1	123.4	78.1%
AVERAGE:	92.9				77.5%

From this data correlations for $P_a = f(V_a)$ were used to calculate the tracking efficiency of the array when various methods of tracking are used. The following table gives the results.

Table A3.25: The Tracking Efficiency of Various Methods of Tracking

Irrad	Va/Voc set to		Va set to constant voltages						
(W/m2)	80%	75%	85 V	88 V	90 V	92 V	95 V	100 V	107 V
200	98.6%	98.4%	97.0%	99.7%	99.9%	98.6%	93.1%	72.0%	8.4%
400	98.9%	99.0%	95.2%	98.0%	99.3%	100.0%	99.2%	91.5%	61.3%
600	98.8%	99.7%	95.9%	98.2%	99.2%	99.9%	99.8%	96.4%	82.5%
800	99.6%	99.2%	94.3%	96.7%	98.0%	99.0%	99.9%	99.1%	91.1%
AVERAGE:	99.0%	99.1%	95.6%	98.1%	99.1%	99.4%	99.0%	89.7%	60.8%

Note: the tracking efficiency (PE_{ppc}) is equal to P_a/P_{max} - the power the array is delivering divided by the maximum power it could deliver under those conditions (at the PPC).

For constant voltage tracking the best voltage (92 V) was chosen. Then the effect of changing the ambient temperature was examined:

Table A3.26: The Effect of Ambient Temperature on the Tracking Efficiency

Irrad (W/m2)	AMBIENT TEMPERATURE -15 C	-7 C	SET FOR	+7 C	+15 C
200	99.1%	100.0%	98.6%	94.7%	86.5%
400	97.2%	99.2%	100.0%	99.6%	97.2%
600	97.5%	99.1%	99.9%	99.9%	99.0%
800	95.9%	97.8%	99.0%	99.8%	100.0%
AVERAGE:	97.4%	99.0%	99.4%	98.5%	95.7%

Note: The "SET FOR" column is for the conditions at which the power maximizer is correctly set. The other columns are for temperatures at various other temperatures as shown.

c) The Effect of Shading on Array Output and the Use of Bypass Diodes

The data from experiments was brought to standard conditions of 50 C and 900 W/m^2 to make all the conditions comparable. The following two tables give the raw and adjusted data. Shortage of space made it necessary to codify the conditions of shading as follows. "BD" stands for the "bird dropping" size shade, whereas "B" stands for the larger full "block", which completely shades a whole cell. (B) stands for "only on the bottom row" whereas (B&A) stands for "below and above". So:

3 BD(B&A):	Three panels on the bottom row and three on the top had one cell each shaded by a small piece of cardboard (bird dropping size - coded BD).
1 B(B):	One panel on the bottom row had one of its cells covered by the larger size of shade (completely shading that one cell). 4 B(B) is the same but 4 cells are shaded.
4 B(B&A):	Four panels on the bottom row and four on the top had one cell each covered by the larger size of shade.

Table A3.27: Adjusting the Data to an Array Temperature of 50 C and Irradiance of 900 W/m2: for when the diodes are in

SHADING	Pmax (W)	Vmax (V)	Imax (A)	Ta (C)	G (W/m2)	Pmax′ (W)	V_{max}′ (V)	I_{max}′ (A)
NONE	472	95.0	4.97	42.0	900	456	91.6	4.98
3 BD(B&A)	417	94.9	4.39	47.3	888	420	93.8	4.48
1 B(B)	395	81.9	4.82	50.0	910	389	81.8	4.75
4 B(B)	217	81.8	2.65	50.9	914	213	82.1	2.60
4 B(B&A)	169	35.0	4.81	49.2	910	164	34.6	4.75

Table A3.28: Adjusting the Data to an Array Temperature of 50 C and Irradiance of 900 W/m2: for when the diodes are not in

SHADING	Pmax (W)	Vmax (V)	Imax (A)	Ta (C)	G (W/m2)	Pmax′ (W)	V_{max}″ (V)	Imax′ (A)
NONE	472	95.0	4.97	42.0	900	456	91.6	4.98
3 BD(B&A)	416	93.1	4.47	50.4	907	412	93.2	4.42
1 B(B)	286	67.3	4.25	47.4	889	287	66.3	4.33
4 B(B)	224	95.0	2.36	47.5	873	232	94.1	2.47
4 B(B&A)	28	77.5	0.35	46.0	839	30	76.2	0.40

The data above is summarized in the table below.

Table A3.29: The Effect of Diodes and Shading on Array Power at the PPC: (900 W/m2 and 42 C)

AMOUNT OF SHADING	DIODES IN Pmax	DIODES IN Shade/None	NO DIODES Pmax	NO DIODES Shade/None	NO DIODES/ DIODES IN
NONE	456	100%	456	100%	100%
3 BD(B&A)	420	92%	412	90%	98%
1 B(B)	389	85%	287	63%	74%
4 B(B&A)	164	36%	30	7%	18%
4 B(B)	213	47%	232	51%	109%

3.5.3: Full Processed Results for the Three Power Maximizers

a) Specifications of the Three Maximizers Tested

The specifications are as follows:

Maximizer type	Tracking Method	Pulsed Startup?	Voc max (V)	Pa max (kW)	Vm low cutout	Overspeed protection?	High Curr protected
Miltek	V_a set by installer	No	160	1.0	Yes	No	15 A
AERL	Tracks the PPC	15 second	160	1.4	Yes	Yes	28 A
Pump Mate	Tracks 80% of V_{oc}	High freq	110	0.9	?	Yes	15 A

Notes:

1. The Pump Mate is shown here for interest. It was tested but the results were discarded due to lack of accuracy.

2. The Miltek is designed and made locally for the Mono Pumps system. The AERL (Australian Energy Research Laboratories) MPPT is designed and made in Australia. It was supplied by Mono Pumps. The Pump Mate is designed in Britain and made locally. It was supplied by BP SA.

3. Startup: The Miltek maximizer only begins to operate when the array voltage has reached its preset value and so has a type of low voltage cut-out. The low voltage cut-out on the AERL is preset. In addition the AERL stores power over about 15 seconds and then gives a sustained high current pulse to aid startup. The Pump Mate has a high frequency pulse during start-up. This is not well-matched to a positive displacement pump (as it wasn't designed for one).

4. No motor overspeed protection was put in the Miltek maximizer as it is unnecessary if the correct motor is used. However Miltek has designed a more sophisticated maximizer which is available if the market warrants it.

The following tables give the complete results for each maximizer:

Table A3.30: Miltek Maximizer - Summarized Results

DATE	TIME	Ta (C)	Tamb	Va (V)	Vm (V)	Ia (A)	Im (A)	G (W/m2)	PEpm	Pa calc
14/3/90	07:40	20.54	23.36	95.0	6.2	0.35	4.22	98	78%	33
14/3/90	07:54	22.38	26.66	95.0	8.6	0.86	7.90	198	83%	82
14/3/90	08:02	25.30	27.19	95.3	10.1	1.29	9.68	273	80%	123
14/3/90	08:06	25.87	27.00	95.1	19.9	1.38	5.55	299	84%	131
14/3/90	08:30	28.44	26.81	95.9	41.0	1.80	3.57	400	85%	173
14/3/90	08:55	33.93	28.63	96.3	55.6	2.34	3.45	501	85%	225
14/3/90	09:21	36.02	30.18	96.3	71.6	3.01	3.54	602	87%	290
14/3/90	10:01	40.03	32.01	96.3	81.1	3.56	3.79	700	90%	343
14/3/90	10:50	45.11	33.45	96.8	94.6	3.82	3.82	801	98%	370
14/3/90	11:50	40.57	31.18	104.2	101.3	3.87	3.87	900	97%	403
14/3/90	12:30	38.47	30.79	106.9	103.9	3.98	3.98	955	97%	425
14/3/90	13:00	40.57	31.18	104.2	101.3	3.87	3.87	900	97%	403

Table A3.31: AERL Maximizer - Summarized Results

Using the 126 mm motor pulley

DATE	TIME	Ta (C)	Tamb	Va (V)	Vm (V)	Ia (A)	Im (A)	G (W/m2)	PEpm	Pa calc
20/3/90	7.40	16.84	18.43	59.7	5.1	0.66	6.47	112	84%	54
20/3/90	7.54	17.80	19.35	81.2	7.7	0.97	8.89	194	87%	91
20/3/90	8.05	19.65	20.30	92.0	37.3	1.47	3.62	309	100%	144
20/3/90	8.20	26.58	21.60	98.0	50.4	1.81	3.55	396	101%	182

Using the 151 mm motor pulley

DATE	TIME	Ta (C)	Tamb	Va (V)	Vm (V)	Ia (A)	Im (A)	G (W/m2)	PEpm	Pa calc
17/3/90	7.37	18.80	20.44	64.1	4.4	0.62	6.46	112	71%	50
17/3/90	8.06	23.33	21.98	91.5	9.3	1.44	9.47	303	67%	140
17/3/90	8.17	26.37	23.14	95.6	9.9	1.62	9.52	350	61%	155
17/3/90	8.45	33.39	25.39	95.6	38.0	1.85	4.45	394	96%	173
ALL		39.96	28.21	97.1	58.7	2.55	4.13	505	98%	197
13/3/90	15.09	38.66	29.95	97.0	74.5	3.40	4.44	612	100%	276
13/3/90	11.45	45.19	31.23	100.2	99.9	4.37	4.23	804	96%	366

Table A3.32: PUMP MATE Maximizer - Summarized Results

Ta (C)	Tamb	Va (V)	Vm (V)	Ia (A)	Im (A)	G (W/m2)	PEpm	Pa calc	Pa read	G corr1	G corr2
24.62	22.83	73.9	7.3	1.89	9.85	213	52%	140	168	318	378
24.88	22.16	79.3	8.1	2.16	9.04	287	43%	171	176	383	394
25.18	22.06	80.9	10.5	2.17	8.86	302	53%	175	183	392	408
34.77	34.88	83.6	22.5	2.11	2.62	328	33%	177	276	393	598
29.04	24.07	85.1	31.7	2.16	3.65	365	63%	184	300	409	649
42.02	29.75	84.3	86.9	4.64	4.46	885	99%	391	378	836	810

3.5.4: Full Processed Results for the Honeywell and Baldor Motors

These results are discussed in Subsection 3.5.4 of the main body. The method by which they were obtained is given in full in Appendix 3.4.2.

The readings were processed to give two tables: the first at six constant voltages, the second at seven constant currents. These tables are given below.

Table A3.33: Adjusted Data at Six Voltages

Volts' (V)	Current' (Amps)	Speed' (rpm)	Torque (Nm)	Effic. (%)
15	0.8	308	0.06	16.2
15	1.8	289	0.56	61.4
15	2.4	288	0.87	72.9
15	4.2	244	1.63	66.7
15	5.7	219	2.33	62.6
15	7.4	187	3.11	55.2
15	13.0	86	5.64	26.2
30	1.0	613	0.12	26.7
30	1.7	604	0.45	56.5
30	2.6	586	0.86	68.7
30	4.2	559	1.61	75.5
30	7.8	503	3.26	73.7
30	11.3	457	4.86	68.7
45	1.0	946	0.12	27.5
45	2.4	920	0.78	69.7
45	3.9	886	1.50	79.0
45	5.9	850	2.40	80.2
45	7.2	825	2.98	79.5
45	11.1	760	4.73	75.2
60	1.2	1255	0.18	32.9
60	2.5	1226	0.77	66.5
60	4.1	1205	1.50	77.4
60	5.8	1164	2.31	81.5
60	7.0	1138	2.87	81.0
60	11.4	1065	4.83	78.5

continued on next page

Table A3.34: Adjusted Data at Six Voltages (continued)

Volts′ (V)	Current′ (Amps)	Speed′ (rpm)	Torque (Nm)	Effic. (%)
75	1.2	1587	0.18	32.8
75	2.4	1553	0.78	70.5
75	4.2	1519	1.57	80.0
75	5.7	1490	2.25	82.4
75	7.1	1461	2.90	83.1
75	11.3	1380	4.77	81.5
90	2.8	1863	0.92	71.3
90	4.2	1826	1.53	78.2
90	5.7	1799	2.23	82.2
90	7.3	1763	2.94	82.9
90	11.0	1693	4.64	82.8

Table A3.35: Adjusted Data at Seven Currents

Current (A)	Voltage (V)	Power (W)	Effic. (%)
1	15	15	18.3
1	30	30	27.9
1	45	45	28.9
1	60	60	27.2
1	75	75	25.9
1	90	90	--
2	15	30	62.7
2	30	60	63.2
2	45	90	62.0
2	60	120	57.7
2	75	150	62.5
2	90	180	--
3	15	45	71.0
3	30	90	71.8
3	45	135	75.3
3	60	180	72.3
3	75	225	75.9
3	90	270	73.3

continued on next page

Table A3.36: Adjusted Data at Seven Currents (continued)

Current (A)	Voltage (V)	Power (W)	Effic. (%)
4	15	60	66.0
4	30	120	74.8
4	45	180	79.4
4	60	240	76.9
4	75	300	79.2
4	90	360	77.6
6	15	90	62.8
6	30	180	--
6	45	270	79.9
6	60	360	81.1
6	75	450	81.6
6	90	540	82.5
7	15	105	55.9
7	30	210	77.6
7	45	315	80.5
7	60	420	81.1
7	75	525	83.6
7	90	630	82.9
11	15	165	48.3
11	30	330	67.0
11	45	495	74.1
11	60	660	79.0
11	75	825	78.8
11	90	990	82.8

APPENDIX 4

ECONOMIC EVALUATION

The information in the appendices maps directly onto that in the main body of the report - for example, Appendix 4.2 has information relating to Section 4.2 in the main body.

Appendix 4.1: Introduction

See main body. No backup information.

Appendix 4.2: Tables for the Base Case: Examining the Effect of Site Dependent Factors

For tables of the default conditions for the tables below, and for the assumptions used, see Section 4.1 in the main body of the report. The following abbreviations have been used in the tables below:

Init	Initial Costs
Run	Running Costs
Oper's	Operator's Wages
Maint	Maintenance Costs
Rep	Replacement Costs
Salvg	Salvage Value
Array%	The percentage the array contributes to initial costs
PMP%	The percentage the power maximizer, motor and pump costs together contribute to initial costs
BOS%	The percentage the Balance of System costs contribute to initial costs

4.2.1: The Effect of Average Water Demand and Peak Demand Factor

a) The Cost of Pumped Water (c/m3)

WATER		COST OF PUMPED WATER (c/m3)					
DEMAND	Petrol	Diesel	Pumps	PV	Pumps	ESKOM	Pumps
(m3/day)	Pumps	Normal	Best	Normal	Best	Normal	S1
3	38	47	44	107	46	87	10
6	25	27	24	72	34	44	5
9	21	20	18	60	28	30	4
12	19	17	14	53	24	22	3
15	18	15	12	49	22	18	3
30	15	11	8	39	17	10	2
90	13	9	6	34	13	4	1

b) The Effect of Peak Demand Factor

Peak		COST OF PUMPED WATER (c/m3)					
Demand	Petrol	Diesel	Pumps	PV	Pumps	ESKOM	Pumps
Factor	Pumps	Normal	Best	Normal	Best	Normal	S1
1.1	38	47	44	77	40	87	10
1.3	38	47	44	95	42	87	10
1.5	38	47	44	100	43	87	10
1.83	38	47	44	107	46	87	10
2	38	47	44	110	47	87	10

c) The Effect of Average Daily Water Demand on the Cost of Energy (c/kWh)

WATER		THE COST OF POWER (ELEC EQUIV c/kWh)					
DEMAND	Petrol	Diesel	Pumps	PV	Pumps	ESKOM	Pumps
(m3/day)	Pumps	Normal	Best	Normal	Best	Normal	S1
3	520	643	600	1447	624	1185	138
6	344	369	330	979	462	598	74
9	285	277	240	814	373	402	53
12	256	231	195	724	328	305	42
15	238	204	168	664	299	246	36
30	203	149	114	524	235	130	24
90	175	124	78	464	176	53	17

d) The Cost per Member per month

WATER DEMAND (m3/day)	COST PER MEMBER (c/person/month) Petrol Pumps	Diesel Pumps Normal	Diesel Pumps Best	PV Pumps Normal	PV Pumps Best	ESKOM Pumps Normal	ESKOM Pumps S1
3	70	87	81	195	84	159	19
6	46	50	44	132	62	80	10
9	38	37	32	109	50	54	7
12	34	31	26	97	44	41	6
15	32	27	23	89	40	33	5
30	27	20	15	71	32	17	3
90	23	17	10	62	24	7	2

e) Life Cycle Costs

WATER DEMAND (m3/day)	LIFE CYCLE COSTS Petrol Pumps	Diesel Pumps Normal	Diesel Pumps Best	PV Pumps Normal	PV Pumps Best	ESKOM Pumps Normal	ESKOM Pumps S1
3	8,393	10,382	9,680	23,369	10,076	19,134	2,230
6	11,097	11,901	10,650	31,623	14,907	19,313	2,391
9	13,802	13,419	11,619	39,414	18,078	19,492	2,552
12	16,506	14,938	12,589	46,744	21,163	19,670	2,713
15	19,210	16,457	13,559	53,611	24,162	19,849	2,874
30	32,731	24,050	18,406	84,610	37,871	20,973	3,908
90	84,596	59,849	37,799	224,527	85,271	25,452	8,032

f) Break-down of the Life Cycle Costs

PV "normal case"

WATER DEMAND (m3/day)	BREAK-DOWN OF LIFE CYCLE COSTS PV "normal case" Init	Maint	Rep	Salvg	%age of Initial Costs Array%	PMP%	BOS%
3	75%	14%	11%	0%	28%	15%	32%
6	80%	10%	10%	0%	39%	14%	27%
9	82%	8%	9%	0%	46%	12%	24%
12	84%	7%	9%	0%	49%	12%	23%
15	85%	6%	9%	0%	52%	12%	22%
30	87%	4%	8%	0%	56%	11%	20%
90	91%	1%	8%	0%	63%	10%	17%

PV "best case"

WATER DEMAND	BREAK-DOWN OF LIFE CYCLE COSTS						
	PV "best case"				%age of Initial Costs		
(m3/day)	Init	Maint	Rep	Salvg	Array%	PMP%	BOS%
3	79%	17%	5%	-1%	29%	32%	18%
6	87%	11%	4%	-2%	38%	24%	24%
9	89%	9%	3%	-2%	47%	21%	21%
12	91%	8%	3%	-2%	52%	19%	19%
15	93%	7%	3%	-2%	56%	18%	18%
30	96%	4%	2%	-3%	66%	15%	15%
90	99%	2%	2%	-3%	74%	14%	12%

Diesel "normal case"

WATER DEMAND	BREAK-DOWN OF LIFE CYCLE COSTS				
	Diesel "Normal Case"					
(m3/day)	Init	Run	Oper's	Maint	Rep	Salvg
3	67%	10%	20%	3%	0%	0%
6	58%	17%	20%	5%	0%	0%
9	52%	23%	19%	6%	0%	0%
12	46%	27%	19%	8%	0%	0%
15	42%	31%	18%	9%	0%	0%
30	29%	42%	17%	12%	0%	0%
90	12%	51%	14%	14%	9%	0%

Diesel "best case"

WATER DEMAND	BREAK-DOWN OF LIFE CYCLE COSTS					
	Diesel "Best Case"					
(m3/day)	Init	Run	Oper's	Maint	Rep	Salvg
3	71%	6%	22%	2%	0%	-1%
6	65%	11%	22%	3%	0%	-1%
9	60%	16%	22%	4%	0%	-1%
12	55%	19%	22%	5%	0%	-1%
15	51%	22%	22%	6%	0%	-1%
30	38%	33%	22%	8%	0%	-1%
90	18%	48%	22%	12%	0%	-0%

Petrol Pump

WATER DEMAND	BREAK-DOWN OF LIFE CYCLE COSTS Petrol Pumps					
(m3/day)	Init	Run	Oper's	Maint	Rep	Salvg
3	22%	23%	25%	7%	25%	-2%
6	17%	35%	21%	10%	19%	-2%
9	13%	42%	18%	12%	15%	-1%
12	11%	47%	17%	14%	13%	-1%
15	10%	50%	15%	15%	11%	-1%
30	6%	59%	12%	17%	6%	-1%
90	4%	68%	10%	13%	5%	-0%

ESKOM normal tariff

WATER DEMAND	BREAK-DOWN OF LIFE CYCLE COSTS ESKOM normal tariff					
(m3/day)	Init	Energy	Meter	Maint	Rep	Salvg
3	17%	1%	84%	0%	0%	-1%
6	17%	2%	83%	0%	0%	-1%
9	16%	3%	82%	0%	0%	-1%
12	16%	4%	81%	0%	0%	-1%
15	16%	5%	81%	0%	0%	-1%
30	16%	9%	76%	0%	0%	-1%
90	17%	21%	63%	0%	0%	-1%

ESKOM S1 tariff

WATER DEMAND	BREAK-DOWN OF LIFE CYCLE COSTS ESKOM S1 tariff					
(m3/day)	Init	Energy	Meter	Maint	Rep	Salvg
3	92%	7%	0%	0%	0%	0%
6	86%	13%	0%	0%	0%	0%
9	81%	19%	0%	0%	0%	0%
12	76%	24%	0%	0%	0%	0%
15	72%	28%	0%	0%	0%	0%
30	59%	41%	0%	0%	0%	0%
90	40%	60%	0%	0%	0%	0%

4.2.2: Total Head

a) The Cost of Pumped Water (c/m3)

Total	COST OF PUMPED WATER (c/m3)						
Head	Petrol	Diesel	Pumps	PV	Pumps	ESKOM	Pumps
(m)	Pumps	Normal	Best	Normal	Best	Normal	S1
7	33	45	43	78	39	87	10
13	38	47	44	107	46	87	10
30	53	55	49	131	73	88	11
60	79	69	57	173	105	90	13

b) The Cost of Energy (c/kWh)

Total	THE COST OF POWER (ELEC EQUIV c/kWh)						
Head	Petrol	Diesel	Pumps	PV	Pumps	ESKOM	Pumps
(m)	Pumps	Normal	Best	Normal	Best	Normal	S1
7	833	1125	1073	1965	981	2191	248
13	520	643	600	1447	624	1185	138
30	313	324	286	769	427	520	66
60	234	203	167	507	309	265	38

c) The Cost per Member per month

Total	COST PER MEMBER (c/person/month)						
Head	Petrol	Diesel	Pumps	PV	Pumps	ESKOM	Pumps
(m)	Pumps	Normal	Best	Normal	Best	Normal	S1
7	60	81	78	142	71	159	18
13	70	87	81	195	84	159	19
30	97	101	89	239	132	161	20
60	145	126	103	315	192	165	23

d) Life Cycle Costs

Total	LIFE CYCLE COSTS						
Head	Petrol	Diesel Pumps		PV Pumps		ESKOM Pumps	
(m)	Pumps	Normal	Best	Normal	Best	Normal	S1
7	7243	9779	9331	17081	8528	19052	2156
13	8393	10382	9680	23369	10076	19134	2230
30	11652	12090	10670	28650	15892	19368	2441
60	17402	15105	12418	37797	23019	19780	2812

e) Break-down of the Life Cycle Costs

PV "normal case"

Total	BREAK-DOWN OF LIFE CYCLE COSTS						
Head	PV "normal case"				%age of Initial Costs		
(m)	Init	Maint	Rep	Salvg	Array%	PMP%	BOS%
7	67%	19%	14%	0%	24%	20%	23%
13	75%	14%	11%	0%	28%	15%	32%
30	78%	11%	10%	0%	36%	14%	28%
60	82%	8%	9%	0%	45%	13%	25%

PV "best case"

Total	BREAK-DOWN OF LIFE CYCLE COSTS						
Head	PV "best case"				%age of Initial Costs		
(m)	Init	Maint	Rep	Salvg	Array%	PMP%	BOS%
7	75%	20%	6%	-0%	18%	37%	20%
13	79%	17%	5%	-1%	29%	32%	18%
30	88%	11%	3%	-2%	41%	23%	23%
60	92%	7%	3%	-2%	55%	19%	19%

Diesel "normal case"

Total	BREAK-DOWN OF LIFE CYCLE COSTS					
Head	Diesel "Normal Case"					
(m)	Init	Run	Oper's	Maint	Rep	Salvg
7	71%	6%	22%	2%	0%	0%
13	67%	10%	20%	3%	0%	0%
30	57%	19%	18%	5%	0%	0%
60	46%	31%	14%	9%	0%	0%

Diesel "best case"

Total Head (m)	BREAK-DOWN OF LIFE CYCLE COSTS Diesel "Best Case" Init	Run	Oper's	Maint	Rep	Salvg
7	74%	3%	23%	1%	0%	-1%
13	71%	6%	22%	2%	0%	-1%
30	65%	13%	20%	3%	0%	-1%
60	56%	22%	17%	6%	0%	-1%

Petrol Pump

Total Head (m)	BREAK-DOWN OF LIFE CYCLE COSTS Petrol Pumps Init	Run	Oper's	Maint	Rep	Salvg
7	26%	14%	29%	4%	29%	-2%
13	22%	23%	25%	7%	25%	-2%
30	16%	38%	18%	11%	18%	-1%
60	11%	51%	12%	15%	12%	-1%

ESKOM normal tariff

Total Head (m)	BREAK-DOWN OF LIFE CYCLE COSTS ESKOM normal tariff Init	Energy	Meter	Maint	Rep	Salvg
7	17%	1%	84%	0%	0%	-2%
13	17%	1%	84%	0%	0%	-1%
30	17%	2%	83%	0%	0%	-1%
60	16%	4%	81%	0%	0%	-1%

ESKOM S1 tariff

Total Head (m)	BREAK-DOWN OF LIFE CYCLE COSTS ESKOM S1 tariff Init	Energy	Meter	Maint	Rep	Salvg
7	96%	4%	0%	0%	0%	0%
13	92%	7%	0%	0%	0%	0%
30	84%	15%	0%	0%	0%	0%
60	73%	26%	0%	0%	0%	0%

Subsection 4.2.3: Critical Daily Insolation

a) The Cost of Pumped Water (c/m3)

Critical Insolation (kWh/m2/d)	COST OF PUMPED WATER (c/m3)						
	Petrol Pumps	Diesel Normal	Pumps Best	PV Normal	Pumps Best	ESKOM Normal	Pumps S1
4.5	38	47	44	110	47	87	10
5	38	47	44	107	46	87	10
5.5	38	47	44	106	49	87	10
6	38	47	44	104	49	87	10
6.5	38	47	44	90	49	87	10
7	38	47	44	89	49	87	10

b) The Cost of Energy (c/kWh)

Critical Insolation (kWh/m2/d)	THE COST OF POWER (ELEC EQUIV c/kWh)						
	Petrol Pumps	Diesel Normal	Pumps Best	PV Normal	Pumps Best	ESKOM Normal	Pumps S1
4.5	520	643	600	1488	634	1185	138
5	520	643	600	1446	619	1185	138
5.5	520	643	600	1432	659	1185	138
6	520	643	600	1409	661	1185	138
6.5	520	643	600	1220	663	1185	138
7	520	643	600	1210	667	1185	138

c) The Cost per Member per month

Critical Insolation (kWh/m2/d)	COST PER MEMBER (c/person/month) Petrol Pumps	Diesel Pumps Normal	Best	PV Pumps Normal	Best	ESKOM Pumps Normal	S1
4.5	70	87	81	200	85	159	19
5	70	87	81	195	83	159	19
5.5	70	87	81	193	89	159	19
6	70	87	81	190	89	159	19
6.5	70	87	81	164	89	159	19
7	70	87	81	163	90	159	19

d) Life Cycle Costs

Critical Insolation (kWh/m2/d)	LIFE CYCLE COSTS Petrol Pumps	Diesel Pumps Normal	Best	PV Pumps Normal	Best	ESKOM Pumps Normal	S1
4.5	8393	10382	9680	24023	10244	19134	2230
5	8393	10382	9680	23340	9987	19134	2230
5.5	8393	10382	9680	23116	10638	19134	2230
6	8393	10382	9680	22748	10665	19134	2230
6.5	8393	10382	9680	19696	10709	19134	2230
7	8393	10382	9680	19530	10767	19134	2230

e) Break-down of the Life Cycle Costs

PV "normal case"

Critical Insolation (kWh/m2/d)	BREAK-DOWN OF LIFE CYCLE COSTS PV "normal case" Init	Maint	Rep	Salvg	%age of Initial Costs Array%	PMP%	BOS%
4.5	77%	12%	11%	0%	30%	15%	31%
5	73%	14%	13%	0%	26%	15%	31%
5.5	69%	16%	16%	-1%	22%	15%	31%
6	66%	17%	17%	-0%	20%	15%	31%
6.5	56%	22%	22%	0%	20%	17%	20%
7	54%	24%	22%	0%	18%	17%	19%

PV "best case"

Critical Insolation (kWh/m2/d)	BREAK-DOWN OF LIFE CYCLE COSTS						
	PV "best case"				%age of Initial Costs		
	Init	Maint	Rep	Salvg	Array%	PMP%	BOS%
4.5	81%	16%	5%	-1%	31%	32%	18%
5	78%	18%	5%	-1%	28%	32%	18%
5.5	70%	18%	15%	-3%	23%	30%	17%
6	67%	20%	16%	-2%	20%	30%	17%
6.5	64%	21%	16%	-2%	18%	30%	16%
7	62%	23%	16%	-1%	16%	29%	16%

4.2.4: Distance to the ESKOM grid

Distance to Grid (km)	COST OF PUMPED WATER (c/m3) AT 3 M3/D						
	Petrol	Diesel	Pumps	PV	Pumps	ESKOM	Pumps
	Pumps	Normal	Best	Normal	Best	Normal	S1
0.2	38	47	44	107	46	44	10
0.4	38	47	44	107	46	55	10
0.6	38	47	44	107	46	66	10
1	38	47	44	107	46	87	10
3	38	47	44	107	46	197	10

4.2.5: Number of ESKOM consumers connecting simultaneously

Number of Consumers in Area	COST OF PUMPED WATER (c/m3)						
	Petrol	Diesel	Pumps	PV	Pumps	ESKOM	Pumps
	Pumps	Normal	Best	Normal	Best	Normal	S1
1	38	47	44	107	46	175	10
3	38	47	44	107	46	87	10
5	38	47	44	107	46	70	10
15	38	47	44	107	46	52	10

4.2.6: Number of Consumers sharing one account

Number of Consumers per Account	COST OF PUMPED WATER (c/m3) Petrol Pumps	Diesel Normal	Pumps Best	PV Normal	Pumps Best	ESKOM Normal	Pumps S1
1	38	47	44	107	46	87	10
2	38	47	44	107	46	51	10
4	38	47	44	107	46	32	10

Appendix 4.3: Tables for the Sensitivity Analysis

For tables of the default conditions for the tables below, and for the assumptions used, see Section 4.1 in the main body of the report. For abbreviations used in the tables below see Appendix 4.2.

4.3.1: Assumptions Affecting All Pumps

a) Project Length

Project Length (years)	COST OF PUMPED WATER (c/m3) Petrol Pumps	Diesel Pumps Normal	Diesel Pumps Best	PV Pumps Normal	PV Pumps Best	ESKOM Normal	Pumps S1
5	58	110	98	288	112	138	26
10	44	77	70	177	74	115	18
20	38	47	44	107	46	87	10
30	31	43	38	88	36	73	10

b) Real Discount Rate (at 3 m3/day)

Real Discount Rate	COST OF PUMPED WATER (c/m3) AT 3 M3/D Petrol Pumps	Diesel Pumps Normal	Diesel Pumps Best	PV Pumps Normal	PV Pumps Best	ESKOM Normal	Pumps S1
0%	56	57	51	121	51	129	11
3%	44	50	46	112	48	101	10
5%	38	47	44	107	46	87	10
10%	28	42	40	98	43	65	10

Real Discount Rate (at 30 m3/day)

Real Discount Rate	Petrol Pumps	Diesel Pumps Normal	Diesel Pumps Best	PV Pumps Normal	PV Pumps Best	ESKOM Pumps Normal	ESKOM Pumps S1
	COST OF PUMPED WATER AT 30 M3/DAY (c/m3)						
0%	23.0	15.4	11.3	41.4	17.1	14.2	2.2
3%	17.6	12.5	9.4	39.6	17.3	11.1	1.9
5%	14.9	11.0	8.4	38.6	17.3	9.6	1.8
10%	10.5	8.5	6.8	37.0	17.2	7.1	1.5

4.3.2: Assumptions Affecting only PV Pumps

a) PV System Efficiency

PV System Efficiency	Petrol Pumps	Diesel Pumps Normal	Diesel Pumps Best	PV Pumps Normal	PV Pumps Best	ESKOM Pumps Normal	ESKOM Pumps S1
	COST OF PUMPED WATER (c/m3)						
2%	38	47	44	109	46	87	10
3%	38	47	44	95	46	87	10
4%	38	47	44	74	46	87	10
5%	38	47	44	69	46	87	10
6%	38	47	44	67	46	87	10

b) PV Unit Capital Costs

PV Cap Costs (R/Wp)	Petrol Pumps	Diesel Pumps Normal	Diesel Pumps Best	PV Pumps Normal	PV Pumps Best	ESKOM Pumps Normal	ESKOM Pumps S1
	COST OF PUMPED WATER (c/m3)						
30	38	47	44	59	46	87	10
40	38	47	44	70	46	87	10
60	38	47	44	92	46	87	10
80	38	47	44	113	46	87	10

c) PV Panel Price

PV Panel Price (R/Wp)	COST OF PUMPED WATER (c/m3)						
	Petrol	Diesel Pumps		PV Pumps		ESKOM	Pumps
	Pumps	Normal	Best	Normal	Best	Normal	S1
9.7	38	47	44	88	46	87	10
11.6	38	47	44	90	46	87	10
14.5	38	47	44	93	46	87	10
18	38	47	44	97	46	87	10
24	38	47	44	103	46	87	10

4.3.3: Assumptions Affecting only Diesel Pumps

a) Diesel System Efficiency (at 3 m3/day)

Diesel System Efficiency	COST OF PUMPED WATER (c/m3) AT 3 M3/DAY						
	Petrol	Diesel Pumps		PV Pumps		ESKOM	Pumps
	Pumps	Normal	Best	Normal	Best	Normal	S1
6.0%	40	49	44	107	46	87	10
7.4%	38	47	44	107	46	87	10
9.0%	37	47	44	107	46	87	10
12.6%	35	45	44	107	46	87	10
20.0%	33	44	44	107	46	87	10

Diesel System Efficiency (at 30 m3/day)

Diesel System Efficiency	COST OF PUMPED WATER (c/m3) AT 30 M3/DAY						
	Petrol	Diesel Pumps		PV Pumps		ESKOM	Pumps
	Pumps	Normal	Best	Normal	Best	Normal	S1
6.0%	17.1	12.1	8.4	38.6	17.3	9.6	1.8
7.4%	15.0	11.0	8.4	38.6	17.3	9.6	1.8
9.0%	13.4	10.2	8.4	38.6	17.3	9.6	1.8
12.6%	11.3	9.1	8.4	38.6	17.3	9.6	1.8
20.0%	9.4	8.1	8.4	38.6	17.3	9.6	1.8

b) Diesel Pump Price (at 30 m3/day)

Diesel Pump Price (R/l)	COST OF PUMPED WATER (c/m3) AT 30 M3/D						
	Petrol Pumps	Diesel Pumps		PV Pumps		ESKOM	Pumps
		Normal	Best	Normal	Best	Normal	S1
0.71	11.4	9.1	7.3	38.6	17.3	9.6	1.8
0.95	13.2	10.0	7.8	38.6	17.3	9.6	1.8
1.20	14.9	11.0	8.4	38.6	17.3	9.6	1.8
1.45	16.7	11.9	9.0	38.6	17.3	9.6	1.8

c) Fuel Escalation Rate (at 3 m3/day)

Fuel Escalation Rate	COST OF PUMPED WATER (c/m3) AT 3 M3/DAY						
	Petrol Pumps	Diesel Pumps		PV Pumps		ESKOM	Pumps
		Normal	Best	Normal	Best	Normal	S1
0%	37	47	44	107	46	87	10
2%	38	47	44	107	46	87	10
4%	38	47	44	107	46	87	10
8%	40	48	45	107	46	87	10

Fuel Escalation Rate (at 30 m3/day)

Fuel Escalation Rate	COST OF PUMPED WATER (c/m3) AT 30 M3/DAY						
	Petrol Pumps	Diesel Pumps		PV Pumps		ESKOM	Pumps
		Normal	Best	Normal	Best	Normal	S1
0%	13.7	10.3	8.0	38.6	17.3	9.6	1.8
2%	14.2	10.6	8.2	38.6	17.3	9.6	1.8
4%	14.8	10.9	8.4	38.6	17.3	9.6	1.8
8%	16.1	11.6	8.8	38.6	17.3	9.6	1.8

Appendix 4.4: The Method of Calculation (LCC) - Spreadsheet Formulae

a) The Formula for Present Value

Present value was calculated using the @PV(payment,interest,term) function in the Quattro spreadsheet. This works most easily for annual expenses. The method used for each category of expenses is dealt with below.

a) Initial Costs: no discounting necessary - simply the sum of all the initial expenses.

b) Running Costs: using the formulae described in Appendix 4.5 an annual average running cost is calculated. Then the arguments for the @PV function are simply: "payment" = annual cost, "interest" = discount rate, "term" = project life.

c) Maintenance Costs: see "running costs".

d) Replacement Costs: replacement costs occur at the end of the lifetime of a component and so cannot be reduced to annual costs. Instead the lifetime of the component is regarded as the basic unit. To do this the interest rate needs to be compounded over the lifetime of the component. For a lifetime of 10 years and real discount rate of 5%, the "interest" = 1.05^{10}-1. A further modification is necessary to deal with the number of replacements. If a component has a lifetime of 9 years and the project life is 20 years, a simple formula would calculate that it should be replaced two years before the end of the project (which is unreasonable). Instead it is assumed that each component can make it to 1.5 times its normal lifetime if the project is about to end.

e) Operator's Wages: see "running costs".

f) Salvage Value: the salvage value is calculated from the initial cost of the component and so does not need to be brought to its present value. Its formula is given below.

b) The formula for Salvage Value

The formula used for salvage value is a small adaptation of the Double Declining Balance method. The adaptation is that 7% of the Capital Cost is subtracted from the Salvage Value. This gives the following formula:

Salvage Value = Cap Cost * Dep Rate^{year} - 7% * Cap Cost
where:
Cap Cost = Component Capital Cost
Dep Rate = (1 - 2/Component Lifetime)
Year = Years of lifetime spent

If the normal Double Declining Balance formula is used, the Salvage Value at the end of the component lifetime comes to between 7 and 10% of the initial capital cost. However, it is considered more realistic if the value of the component drops 7% on purchase, and the salvage value at the end of its life is nearly zero. The graph below shows the effect of this adaptation - as well as the relatively quick drop in Salvage Value at the beginning of project life due to the use of the Double Declining Balance formula.

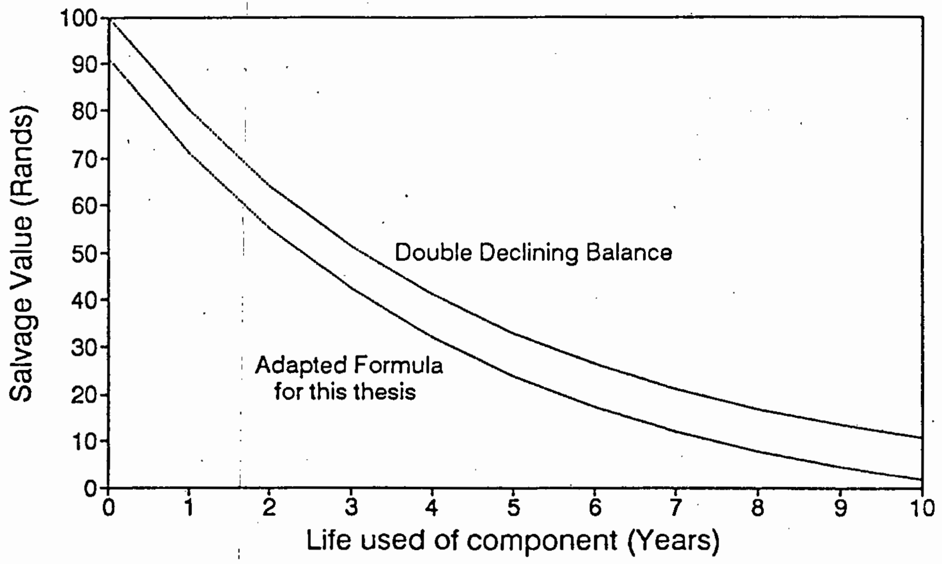


Figure A4.1: The Decline in Salvage Value with Time

Appendix 4.5: The Validity of the Assumptions Used

This section contains the most important formulae and correlations used to compute the Life Cycle Costs of the three methods of pumping. It contains relevant backup information for Section 4.5 in the main body. Each pumping method is dealt with in turn.

4.5.1 Assumptions for Photovoltaic Pumps

a) Capital Cost

System Efficiency

Normal case: The system and component efficiencies were based on those measured in the field for the technical evaluation (see Chapter 3).

The efficiencies of most components varied linearly with insolation and so straight lines correlations were used to be able to predict their efficiencies at any insolation considered. The efficiency of the pump itself was dependent on head. This was accounted for by an extra term in the correlation for pump efficiency. The table below gives the coefficients of the correlations for each component. The four columns on the right indicate the accuracy of the correlations by comparing their predictions with actual values.

Table A4.1: The Correlations Used For Component Efficiencies

Component	Const	Insolation Coefficient	Head Coeff	4.5 kWh/m2/d		7.0 kWh/m2/d	
				Corr'n	Actual	Corr'n	Actual
Array	6.35%	0.552%		8.84%	8.76%	10.22%	10.14%
Maximizer	69.9%	3.49%		85.6%	85.8%	94.4%	93.9%
Motor	76.9%	-0.17%		76.1%	76.5%	75.7%	74.8%
Transm'n	93.0%			93.0%	93.0%	93.0%	93.0%
Pump	26.1%	0.40%	0.85%	39.0%	39.1%	40.0%	40.3%
System	0.04%	0.291%	0.051%	2.02%	2.09%	2.74%	2.67%
Subsystem	11.3%	1.18%	0.54%	23.6%	23.9%	26.6%	26.3%

Note: the units for Insolation in the correlation are kWh/m^2/d while those for Head are metres.

Best Case: See the main body.

Component Cost Correlations

Normal Case: The correlations for the prices of each component were based on the following data which was supplied by Mono Pumps for the components they generally use.

Table A4.2: Component Prices Supplied by Mono Pumps (April 1990)

Component		Rands (ex GST)
Miltek Maximizer	(1 kW)	1164
Miltek Maximizer	(2.2 kW)	1840
Baldor DC Motor	(0.37 kW)	1400
Baldor DC Motor	(0.75 kW)	1825
Baldor DC Motor	(1.5 kW)	3300
Mono Pump SW4L	(4 m^3/h)	812
Mono Pump SW12L	(12 m^3/h)	1426

Balance of system costs: The above costs comprise the bulk of the system cost. But it is necessary to account for labour and transport to install the system, for mounting frames, fencing and an alarm to deter theft of the panels. These costs comprise the "Balance of System Costs". The table below shows that for the pump at Sondela the Balance of System costs were 27% of the total costs - much higher than all the component costs except that of the array.

Table A4.3: Breakdown of Original Costs for Sondela System

Component	Cost (1990 R)	% of Total
16 PV panels	17168	59
Miltek 1 kW maximizer	1267	4
0.75 kW Motor	1520	5
SW4L pump	1436	5
Balance of System costs	7768	27
TOTAL:	29159	100

So the Balance of System (BOS) costs are about 27% of the total system costs. However, it is necessary to be able to calculate them for a system of any size. Only some of the components of the BOS costs will be dependent on the size of the system.

The table below gives a breakdown of the major components of the BOS costs and an estimate of their size dependence.

Table A4.4: Breakdown of the Balance of System Costs

Component	Cost (1990 R)	%age of Total	% Size Dependence
6 Days Labour	2371	26	10
Fencing	1664	18	15
Mounting Structure for panels	507	6	5
Transport, Mounting, Alarm etc	4512	50	0
TOTAL:	9054	100	30

Note: A "% Size Dependence" of 10% for labour means that 10% of the total BOS costs are dependent on size due to labour.

About half the Balance of System Costs is independent of size. Labour is weakly dependent on size. As labour comprises 26% of the BOS costs, possibly 10% of the BOS costs can be considered to be size dependent due to labour. Another 20% of the BOS costs is size dependent due to the fencing and the mounting structure for the panel. Thus in total 30% of the BOS costs are size dependent. Mono Pumps has examined these figures and is is satisfied with their accuracy. So the correlation for BOS costs was based on a size dependence of 30%.

PV panel price: the panel price was based on the following prices quoted by Optitron for Arco panels in April 1990.

Table A4.5: Arco PV Panel Prices: April 1990

Module Code	Wp	For <20 Panels Retail	R/Wp	For 20-59 Panels Retail	R/W_p
M 55	53	R 1,504	28.4	R 980	20.9
M 58	48	R 1,307	27.2	R 852	20.1
M 75	47	R 1,268	27.0	R 826	19.9
M 65	42	R 1,242	29.6	R 811	21.8
G 4000	30	R 719	24.0	R 468	17.6
Average			28.0		20.1

Note: all prices include 13% GST. They were obtained in April 1990.

A straight line correlation for the R/W_p price of the panels was used: from 28 R/W_p at 1 panel to 20 R/W_p for 40 panels. These two figures are the average prices for the two sets of prices shown.

Best case: The best case assumed that the BOS costs are half those of the "normal case".

Comparing the three most established pumps: The table below gives the figures found for the Mono Pump for the correlations described above. Prices and efficiencies for the BP Solarspring and the Solar Jack are also shown. This data was used to plot the graph in the main body comparing the correlations for the normal and best case against the Solarspring and the Solar Jack.

The "best case" was based on the solar pumps presently marketed in South Africa. Specifications for each pump and current prices (July 1990) were obtained from the manufacturers. From these the best head was found for each pump. The following table shows the efficiencies and costs of all of these pumps at their best heads.

Table A4.6: Efficiencies and Costs of Solar Pumps: for "best case"

Make[1]	Wp	HEAD (m)	PRICE[2] (R)	BOS (R)	TOTAL (R)	m3/d	R/(m4/d)	Subsys Eff.[3]	System Eff.[3]	U.C.C (R/W_p)
BP (2)	80	20	8,997		8,997	2.02	222	34.0%	3.03%	112
BP (3)	120	20	10,328		10,328	3.58	144	40.1%	3.57%	86
BP (4)	160	35	11,792		11,792	3.23	104	47.5%	4.23%	74
MONO (2)	80	45	5,196	7,541	12,737	1.08	261	40.9%	3.64%	65
MONO (6)	240	45	9,649	8,304	17,953	3.25	123	40.9%	3.64%	40
MONO (16)	640	45	20,782	10,211	30,993	8.66	80	40.9%	3.64%	32
MONO (30)	1200	45	36,369	12,880	49,249	16.24	67	40.9%	3.64%	30
JACK (1)	48	50						29.6%	2.63%	
JACK (2)	96	50	6,215		6,215	1.00	124	35.1%	3.12%	65
JACK (2)	120	50	6,780		6,780					56

1. The "BP" in the above is the Solarspring made by BP Ltd. The "JACK" is the Solar Jack marketed by Allpower. The figures in brackets give the number of panels - a better indication of size, however, is the W_p rating in the next column.

2. Prices include 13% GST. No installation costs are included for the BP or JACK. The installation costs of the Mono Pump are under BOS costs.

3. Efficiencies are at 4.5 kWh/m^2/d - approximately the critical insolation for Durban. The efficiencies shown are at the ideal head of each pump, so that they can all be compared on an equal footing.

Pertinent Formulae

The following formulae are needed to calculate capital cost. First the hydraulic energy required per day is calculated as follows:

$$\text{Hyd E} = \frac{(10\ \text{m.s}^2 * \text{Water Vol l/d} * 1\ \text{kg/l} * \text{Head m})}{3600\ \text{s/hr}}$$

Then the system efficiency (found via the correlations described above) is used to calculate the W_p rating of the array:

$$\text{Array } W_p = \frac{(\text{Hyd E [Wh/d]/EFFsys}) * (41\ W_p)}{(I_c\,[\text{Wh/m}^2.\text{d}]) * (0.873*0.390)\ \text{m}^2}$$

Then the system capital cost is calculated from system size from the correlations for unit capital costs (R/W_p).

b) Replacement Costs: Component Lifetimes

See the main body.

c) Maintenance Costs

A fairly thorough break-down of the maintenance costs is given in the main body. The following table gives the charge rates that were used to calculate these.

Table A4.7: Charge Rates for Calculating Maintenance Costs

Quantity	Value
Charge for time	45 R/hr
Charge for travel	50 c/km
Distance	90 km return
Motor repairs	R 200

Hours Pumped per Day

It is necessary to know the number of hours pumped per day in order to calculate both the maintenance costs and replacement costs.

However, finding a formula to estimate the number of hours a PV pump works on average during the year is not easy. This is because it depends on a number of unknown factors: a) the average number of hours per day when the irradiance is higher than the start-up irradiance, b) the variation of the ratio of irradiance to water demand over the year and c) whether the owners turn the pump off when enough water has been pumped.

For simplicity the number of hours pumped per day was made equal to the insolation of the design month (I_c). For example for a site with 5 kWh/m^2/d insolation in its design month, the pump will work an average of 5 hours per day for the whole year. This approach is justified below.

An obvious first approach would be to get the average irradiance profile for a site for the whole year. Then the average number of hours the pump works per day can be taken as the number of hours for which the average irradiance profile is greater than the start-up irradiance. However, this approach is erroneous. For example, if the irradiance profile gives 500 W/m^2 for the site between 11 and 12 in the morning, then one would assume the pump would pump for this whole hour each day of the year (assuming a start-up irradiance of 270 W/m^2). But half the hours that contributed to this average of 500 W/m^2 may be sunny at 800 W/m^2 and half of them cloudy at 200 W/m^2. In this case the pump will only work for half the time on average during this hour.

So another approach is used. This has the following steps:

a) The number of hours per day that the pump will work on a sunny day during the design month is calculated.

   For example, for Durban, the design month is September as it has the lowest insolation for the year of 4.7 kWh/m^2/d. (This is for a tilt angle of 30° which is the same as the latitude of Durban). An average irradiance profile for September shows that the irradiance is above the start-up irradiance of 270 W/m^2 for 8 hours a day. For arguments outlined above, the time spent pumping on a sunny day is likely to be longer - say 9 hours (out of the 12 daylight hours).

b) The average number of hours pumped per day during the design month is calculated from the ratio of the average number of sunlight hours during that month to the average number of daylight hours.

For example, records for Durban show that on average 7.2 hours per day are sunny in September (of the 12 daylight hours). So the average number of hours pumped per day in September is 5.4 (= 9 hours/day for a sunny day * 7.2/12).

c) The average for the whole year is found by dividing by the ratio of the insolation averaged for the whole year to that average for the design month. This is based on the assumption that the demand for water is either the same during the summer or it drops. So the pump will be used less on average during the rest of the year than during the design month.

For Durban the average insolation for the whole year is 5.03 kWh/m^2/d: that is 1.07 * that for September. So the average hours pumped during the whole year would be 5 hours per day (= 5.4 hours/day for September / 1.07).

d) The pump will most likely work proportionally longer hours in areas with higher levels of insolation. The figure of 5 hours pumped per day is so close to the figure for the critical insolation of 4.7 kWh/m^2/d that it is assumed equal. So for a site with critical insolation of 6.5 kWh/m^2/d it is assumed the pump will work 6.5 hours per day on average.

4.5.2 Assumptions for Diesel and Petrol Pumps

The following table gives the constants and conversion factors used in all the sections.

Table A4.8: Constants and Conversion Factors Used in Formulae

Constant or Conversion factor	Value
Calorific Value of Diesel	42.4 MJ/kg
Calorific Value of Petrol	44.1 MJ/kg
Specific Gravity of Diesel	0.848
Specific Gravity of Petrol	0.741
Conversion factor for Power	0.746 kW/HP
Gravitational acceleration	9.8 m/s^2
Density of water at room temperature	1000 kg/m^3

a) Capital Costs

Maybe put here the data on the correlations used. Have I given all the costs in the main section? Altitude derating table or graph?

b) Running Costs

To calculate the running costs it is necessary to calculate the engine efficiency, the pump efficiency and the fuel price.

Engine Efficiency:

Optimum Efficiency: The optimum efficiency of 30% was obtained from manufacturer's specifications for the Lister SR1 diesel engine. They give a fuel consumption of 1.16 l/hour at 1500 rpm when the power output of the engine is 3.7 kW. So the optimum efficiency is given by:

$$\text{EFFopt} = \frac{3.7\ \text{kW} * 3600\ \text{s/hr}}{1.16\ \text{l/hr} * 0.848\ \text{kg/l} * 45{,}000\ \text{kJ/kg}}$$

Scaling for real efficiencies: The optimum efficiency was then scaled by a factor, K, to get the actual efficiency of the engine, EFFdies. K was found as a correlation of two parameters: i) the hours run per session (HRS), ii) the capacity factor which is the actual engine load divided by full load (CF). The capacity factor (CF) also accounts for the speed of the engine (which is the third factor which affects engine efficiency).

The effect of time run per session: The efficiency of the engine when it first starts operating is low because much of the diesel's energy goes into heating the engine to its running temperature of 130 °C. The magnitude of this effect was calculated using the mass of the engine and the heat capacity of steel and assuming that 20% of the energy of the diesel is lost through the exhaust. The following graph shows the results for an engine at full load.

The effect of capacity factor: the losses due to low capacity factor and speed were based on measurements by Kenna (1987).

The equations which accounted for these two losses were then used to generate the following table. Linear regression was then used to find correlations from this data.

Table A4.9: Output from Model Dealing With Time per Session and Capacity Factor

Mins per Session	Capacity Factor		
	33%	80%	97%
5	4.9%	11.6%	11.9%
10	7.9%	16.7%	17.1%
15	9.9%	19.5%	19.9%
20	11.3%	21.3%	21.8%
25	12.4%	22.6%	23.0%
30	13.2%	23.5%	24.0%
40	14.4%	24.8%	25.2%
50	15.3%	25.6%	26.1%
60	15.9%	26.2%	26.6%
90	17.1%	27.2%	27.7%

The correlation found for the factor, $K = EFFdies/EFFopt$, is:

$$K = 0.112 * \ln(HRS) + 0.537 * CF + 0.35$$

where: HRS is the average hours run per session, and
CF (the capacity factor) is the actual load over full load.

A graph showing the effectiveness of this method is given in the main body.

Hourly Fuel Consumption HFC [l/hr]:

The running expenses are then calculated from the hourly fuel consumption, HFC, which is calculated from the engine efficiency found above as follows:

$$\text{HFC [l/hr]} = \frac{\text{kW out of engine} * 3600\ \text{s/hr}}{\text{EFFeng} * 0.848\ \text{kg/l} * 42{,}400\ \text{kJ/kg}}$$

Pump Efficiency

The pump efficiency for the VE 32C centrifugal pump connected to the diesel engine was calculated from figures read off graphs supplied by the manufacturers. The formula for pump efficiency is as follows:

$$\begin{aligned}\text{EFFpump} &= \text{Hydraulic Energy out / Energy in from engine}\\ &= (\text{Mass of water lifted} * g * \text{Head})/\text{Energy in}\\ &= \frac{(\text{FLOW RATE m}^3/\text{hr} * 1000\ \text{kg/m}^3 * 10\ \text{m.s}^2 * \text{HEAD m})}{(\text{POWEReng [kW]} * 1000\ \text{W/kW} * 3600\ \text{s/hr}) * \text{EFFtrans}}\end{aligned}$$

where: POWEReng is shaft power from the engine
EFFtrans is the transmission efficiency

This formula was used to calculate the figures in the following table for the pump at a head of 13 metres (from specifications).

Table A4.10: Pump Efficiency vs Power and Flow: 13 m Head

kW in	m3/h	EFFpump
0.2	0.0	0%
0.4	3.4	22%
0.6	7.2	40%
0.8	10.7	50%
1.0	13.8	53%
1.2	16.6	52%
1.4	18.9	48%
1.6	20.9	42%
1.8	22.5	37%
2.0	23.7	31%

The default efficiencies of the pump were chosen as:

Fuel Price:

The table below gives forecasts from four different sources. All of the prices have been brought to 1990 US$ by the table of US Consumer Price Indexes which follow. Also the EEC and CERG predictions were for North Sea Brent crude oil. This was scaled by a factor of (17.5)/20 to make it equivalent to Dubai Crude.

Table A4.11: Four Forecasts of Dubai Crude Oil Price (1990 US $/bbl)

PREDICTION	1990	1992	1994	1996	1998	2000	2002	2004	2006	2008	2010
AECI - High	19.8	19.8	19.8	19.8	19.8	19.8	19.8	19.8	19.8	19.8	19.8
AECI - Central	15.8	15.9	15.8	15.8	15.8	15.8	15.8	15.8	15.8	15.8	15.8
AECI - Low	13.2	13.2	13.2	13.2	13.2	13.2	13.2	13.2	13.2	13.2	13.2
EEC - High	45.8	49.0	52.2	54.5	55.8	57.2	58.6	59.9	61.3	62.7	64.1
EEC - Central	30.3	32.3	34.2	36.2	38.1	40.0	42.0	43.9	45.9	47.8	49.8
EEC - Low	22.9	22.9	22.9	22.9	22.9	22.9	22.9	22.9	22.9	22.9	22.9
CERG - High	51.9	55.5	59.4	63.5	67.9	72.6	75.8	79.0	82.4	86.0	89.7
CERG - Central	44.3	48.9	54.0	59.6	65.8	72.6	75.3	78.0	80.8	83.8	86.8
CERG - Low	36.0	39.3	43.0	46.9	51.3	56.0	58.8	61.6	64.6	67.7	71.0
CHEM SYS - High	21.0	22.9	25.1	27.4	29.9	32.7	32.7	32.7	32.7	32.7	32.7
CHEM SYS - Central	16.2	17.6	19.2	20.9	22.8	24.8	24.8	24.8	24.8	24.8	24.8
CHEM SYS - Low	11.3	12.3	13.3	14.5	15.7	17.0	17.0	17.0	17.0	17.0	17.0

The following table, which includes the US CPI index, was used to bring all the above prices to 1990 US$. This table has all the data used for currency conversions.

Table A4.12: Historical US Inflation Rate and CPI

PARAMETER	1983	1984	1985	1986	1987	1988	1989	1990[1]
US CPI	92.6	96.6	100.0	101.9	105.7	109.9	115.2	119.0
US $/R	0.899	0.695	0.456	0.441	0.491	0.442	0.382	0.389
SA R/US$	1.11	1.44	2.19	2.27	2.04	2.26	2.62	2.57
SA CPI	77.1	86	100	118.6	137.7	155.4	178.2	193.9

1. This is for the first quarter in 1990 only.

Source: IFS, 1990.

The following correlations were used to find the In Bond Landed Cost (US c/l) at the coast in South Africa from the Dubai Crude Oil price (US $/bbl) (Stelna, 1990: pers. comm.). These correlations work with January 1987 currencies.

IBLC 98 Octane [US c/l] = 0.7907 * Dubai [$/bbl] + 4.0351
IBLC Diesel [US c/l] = 0.8456 * Dubai [$/bbl] + 2.8557

The IBLC price was then converted to current SA c/l using the present exchange rate (2.70 R/$) and converted to a pump price using the following break-down (SASOL, 1989).

The IBLC price at present forms 39% of the reef pump price for high octane petrol and 42% of that for diesel (Olivier, 1990: pers. comm.). The present coastal pump price is 93% that of the reef. These figures were used to convert the IBLC price to coastal pump prices for 98 Octane petrol and for diesel.

Other Formulae

The combined efficiency is the product of the engine, transmission and pump efficiencies.

Hours pumping per day:

$$\text{HRS/DAY} = \frac{\text{WATER FLOW RATE l/hr}}{\text{GARDEN AREA ha * WATER RQD l/ha/day}}$$

Average Daily Running Cost:

RUN COST (R/day) = HRS/DAY * HFC [l/hr] * DIESEL PRICE R/l

c) Maintenance costs

See main body.

d) Replacement costs

See main body.

e) Operator's wages

See main body.

4.5.3 Assumptions for Electric Pumps (connected to ESKOM)

a) Capital Cost

See main body

b) Running Cost - Energy Charge

To calculate the energy charge one need the hours pumped per day and so the flow rate:

1. Water Flow Rate (l/hr):

The hydraulic power is equal to the power output of the pump. So:

(rho * g * Water Flow * H) = Pump W rating * EFFsys
Therefore:

$$\text{FLOW [l/hr]} = \frac{(\text{Watt rating} * \text{EFFsys})}{(\text{rho} * g * \text{Head})}$$

$$= \frac{(\text{Watt rating} * \text{EFFsys} * 3600\ \text{s/hr})}{(1\ \text{kg/l} * 10\ \text{m/s}^2 * \text{Head m})}$$

The system efficiency is assumed to be 56% - based on a motor efficiency of 80% and a pump efficiency of 70%. These are high because working from Eskom both the motor and pump can operate under their design conditions.

2. Hours pumped per day:

HRS/DAY = WATER RQD [l/d] / FLOW [l/hr]

3. Energy charge (R/month):

Energy Charge [R/m] = Pump kW rating * HRS/DAY * 30.4 day/month

c) Replacement Costs

See main body.

d) Maintenance Costs

See main body.

APPENDIX 5

SOCIAL EVALUATION

Appendix 5.1: Introduction

See main body. No backup information.

Appendix 5.2: The Responses to the 1990 In-Depth Interview

The following is the interview administered in April 1990. The questions and my introductory comments are in bold. Their answers are in normal type.

Overall Structure:

1. Introduction
2. Personal Details
3. Feelings about the garden
4. Feelings about the pump
5. Feelings about possible solutions to problems encountered
6. Comparing petrol and PV pumps - extra for treasurer.
7. Feelings about the organization and togetherness of the garden
8. Perceptions about most important problems in the area
9. Questions for Mrs. Mdluli only

1. INTRODUCTION

Overall purpose of project:

- **We know the pump works**
- **But it is different in the field - we want to gauge practical problems.**
- **And we want particularly to see whether it is suitable to the community - to get your opinions about the pump. It is for this reason that I am doing the interview.**

Please be honest:

* I have selected a few people to get well-thought out opinions
* I have tried to get varying opinions - therefore I want your opinion not what others think
* With this information we will decide whether we will recommend this pump is installed in other gardens. Therefore don't be kind to this pump because you don't want to hurt my feelings: we don't want to saddle other gardens with a second best. And I am not advocating this type of pump. You would in fact ruin my work if you didn't give an honest opinion.
* If you don't understand my question please ask for clarification
* If there is something important which I don't ask about please tell me it

Permission to use tape recorder:
* Tape recorder will help me remember your replies, and help me ask for translation if I do not fully understand. It will also mean I don't need to write everything down.
* Please don't fear - only I and maybe my translator will use the tapes. Nobody else will have access to them.
* Are you happy? If so, please forget it exists

Expectations:
* We are asking for knowledge. Nothing will happen directly because of this interview. If you want to follow up a good idea tell me and maybe something will be done about it. And what you say will certainly not affect how much you pay for the pump - it is already paid for.
* I expect the interview will take 1.5 hrs. There are eight sections and I will tell you as we pass each one.

2. PERSONAL DETAILS:

Name:	1) Mrs Princess Mdluli 2) Mrs Mavis Nene 3) Mrs S Mkhize
Age:	Mrs Mdluli: 49 Mrs Nene: 37 Mrs Mkhize: 64
Office:	Mrs Mdluli: Chairperson Mrs Nene: Treasurer

Mrs Mkhize: No position

Ever held office?
Mrs Mdluli: She has been chair since 1985
Mrs Nene: She has been treasurer since 1989
Mrs Mkhize: She was secretary from 1986 to 1987. And treasurer from 1987 to 1989.

Length of time in garden:
Mrs Mdluli: Since the beginning - 1983
Mrs Nene: Since the beginning - 1981
Mrs Mkhize: Since 1982

How many in your family (that rely on the food):
Mrs Mdluli: 12
Mrs Nene: 8
Mrs Mkhize: 12

People who earn different amounts of money mostly think differently about the cost of something. Some of the questions we ask are about which pump you would choose at different prices. Therefore, if you don't mind could you please tell us what the income of your immediate family is:

Mrs Mdluli: She doesn't know how much her husband earns. But she gets R 120 a month from him for groceries. Nobody else is working at the moment in her family.
Mrs Nene: She doesn't know how much her husband earns. But she gets about R 140 a month from him for groceries. None of her children are working at the moment.
Mrs Mkhize: Her children are married and they stay at home. But none of them tell her how much they earn. She gets money for groceries from her husband.

I will check whether this money includes pensions, migrant labour remittances etc.

3. FEELINGS ABOUT THE GARDEN:

What do you feel about the garden (free answer):
Mrs Mdluli: Very positive about it.
Mrs Nene: It helps a great deal.
Mrs Mkhize: She likes it a lot.

Could you get by without it?

Mrs Mdluli: No, they couldn't really cope. Before the garden was established they scraped by but ate far less nutritiously.

Mrs Nene: No. They struggled beforehand and did not eat well.

Mrs Mkhize: No. They did not have enough to eat beforehand.

What proportion of your weekly food comes from the garden?

Mrs Mdluli: A big proportion. She uses a lot of vegetables and salads. If she had to buy this food in the shop it may cost her R 60 a month. (She spends R 120 a month on groceries so this comes to one third in monetary terms).

Mrs Nene: A big proportion. If she had to buy all the food that she got from the garden she may have to pay R 10 or 20 per month. (She spends R 140 per month on groceries).

Mrs Mkhize: A lot. If she had to buy all the vegetables that she gets out of the garden it would cost her a lot of money - maybe R 90. If she had to sell all the vegetables in her garden (not eating any), she would make much money - maybe R 1000 per month.

Do you still need to buy some vegetables?

Mrs Mdluli: A little - only when a particular vegetable is not yet ripe in the garden.

Mrs Nene: No.

Mrs Mkhize: A little - only vegetables which our not in her garden at the time.

Do you have enough for your family or would you prefer more?

Mrs Mdluli: Yes - she is still able to sell to others.

Mrs Nene: Yes.

Mrs Mkhize: Yes - she sells the excess.

Do you sell vegetables much?

Mrs Mdluli: Yes, a little.

Mrs Nene: Yes, she makes maybe R 3 a month.

Mrs Mkhize: Yes, she makes maybe R 30 a month.

Why? Because of the money you get, to help the others?

All: To help others, not because they need money.

Do you give some away?

All: Yes.

What are the biggest problems of the garden (free answer):

Mrs Mdluli: There are now no problems because now they have water.

Mrs Nene: No problems. Maybe the lack of health of the women, which means that they struggle to work.

Mrs Mkhize: No problems.

My Suggestions:

Water: getting it regularly to the garden

All: Getting water is now no problem.

Pump: breaking down

All: It has given no problems.

Reticulation system: taps breaking down and pipes bursting

All: The pipes and taps no longer give problems.

Pests:

All: They give a little trouble, but they can be fixed with pesticides.

Cost of seeds:

Mrs Mdluli: Yes a little bit. The prices are always rising.

Mrs Nene: Yes. Sometimes not all the seeds take root, and so she needs to replant.

Mrs Mkhize: Not a problem.

Cost of fertilizers:

Mrs Mdluli: A bit of a problem - the prices are rising.

Mrs Nene: Not really.

Mrs Mkhize: No.

Need for advice or knowledge:

Mrs Mdluli: There is a continual need for advice and the help that the Agricultural Officer provides. It was OK when Mr Mdlolo was there but he has left and not yet been replaced.

Mrs Nene: No problem.

Mrs Mkhize: Advice is always needed. The advice was good when Mr Mdlolo was there.

Organization of the garden - difficulty making decisions:

Mrs Mdluli: There is a problem now because the Agricultural Officer has left.

Others: No problem.

4. FEELINGS ABOUT THE PUMP

How important is it that there is a pump in the garden? (Free answer)

Mrs Mdluli: Very important because they no longer have to carry water. You have heard how much they complain if there is no water for a few days.

Mrs Nene: Very important - the women were tired from carrying water.

Mrs Mkhize: Very important. Before she came to the garden at 4 am in the morning to carry water (she had two plots at that stage). Now she can come down at any time and there is water.

Mr Mdlolo: Very important because the members get enough water for irrigation. Also they are not strained by carrying water - it is very heavy work.

Would you be part of the garden if you knew that you would have to carry water?

Mrs Mdluli: Yes. They need the food.

Mrs Nene: No. It saps your strength.

Mrs Mkhize: Yes. They must eat.

How many people share this opinion?

Mrs Mdluli: About 3/4 of the gardeners would stay.

Mrs Nene: About 10 or 20 out of the 43 would stay.

Mrs Mkhize: Most would stay.

Do you enjoy working in the garden if the pump is working well?

Mrs Mdluli: She enjoys the work very much.

Mrs Nene: Yes.

Mrs Mkhize: Very much so.

And if there is no pump?

Mrs Mdluli: It is hard work. But yes she does because it is necessary.

Mrs Nene: No.

Mrs Mkhize: Yes. She likes the garden so much, she will enjoy it even if the pump is not there.

Why is the pump important to you? (free)

All: First of all because it saves their strength and effort, and secondly because it saves time.

Do you think that you are getting more vegetables in your garden than before because of the pump?

Mrs Mkhize: Yes.

Mrs Nene: No, she gets the same amount as before but with less time and effort.

Mrs Mkhize: Yes. Look at the cabbages - they are much bigger than before.

Mr Mdlolo: Yes.

How much do you think these extra vegetables would cost if bought at the shop?

Mrs Mdluli: She now thinks that if she sold all her vegetables (and ate none) she would get about R 100 per month. Before she would have made about R 60. So the extra vegetables are worth about R 40 per month.

What do feel about this particular (solar) pump (free):

Mrs Mdluli: It is very important that it is a solar pump because there are no expenses and no petrol needs to bought.

Mrs Nene: She likes it a lot. When it is cloudy or raining the pump does not work but this is no problem as she does not need to water.

Mrs Mkhize: She does not know other pumps. This is pump is fine - it works well and gives no problems.

Do you feel apprehensive about future problems or confident that they can be solved?

Mrs Mdluli: She is concerned that there may be problems because I will no longer be around. I told her that before I left I would leave her with a paper giving my advice of what to do in the event of problems and giving the necessary phone numbers.

Mrs Nene: Yes she is concerned because I will be leaving. I told her I would leave a paper with my advice.

Mrs Mkhize: She feels that they will be able to resolve problems which arise.

Mr Mdlolo: The problems can be solved - even in the future.

5. SOLUTIONS TO THE PROBLEMS OF THE PUMP

In this section I will be asking your feelings about money. Do you prefer to work in Rands or pounds?
(Many people still work in pounds. One pound is equal to R 2. In the Zulu version all prices were put in both currencies and the one they preferred was used.)

After this year the insurance from UCT lapses. So if the pump is washed away or panels are stolen there will be no insurance unless the garden organizes it. So we would like your opinion as to in how much danger the pump is and whether our methods of protection are adequate.

a) Flooding?

Do you think the pump now is safe from flooding?

Mrs Mdluli: Yes. The array is definitely safe from floods. The actual pump is grouted to the rock but goes into the water. This is most likely safe, but the cause of a little concern.
Others: Yes. There is no problem.

Do think that it will stay safe for the next 20 years

Mrs Mdluli: See last question.
Others: Yes.

b) Theft?

The pump is at the moment protected by bits of metal welded over the ends of panels and a bar locked in over the middle of the frame. This makes it difficult but not impossible to remove. In fact one was removed - although the bar was not in place at the time. There is also an alarm that will sound if any of the panels are removed. This will protect the panels if the people in the area respond. It may give trouble over the next twenty years (the lifetime of the panels) and so may be turned off.

Do think that these methods of protection are enough?

All: Yes they are enough.

If not what would you recommend?

All: Question not asked as they all felt the protection was adequate.

Imagine that you are from another garden which has decided to buy a PV pump. Would you pay the following prices for each of these? (Note there is no possiblility that you will be asked to pay as the protection for this garden has been bought.)

Welded barriers and the bar in middle at R 6 per person once?

Mrs Mdluli: Yes. They want to keep the pump in tact.
Mrs Nene: Yes. Once off expenses are OK.
Mrs Mkhize: Yes.

Alarm system at R 9 per person once off?

Mrs Mdluli: No. Although she said this she later changed her mind when choosing which methods to use to make a comprehensive protections system.
Mrs Nene: Yes.
Mrs Mkhize: Yes.

If Sondela had to pay R 11 per person once off to electrify the fence around the array would you recommend they do?

Mrs Mdluli: Yes.
Mrs Nene: Yes.
Mrs Mkhize: Question was not asked.

Would you use all of the methods or which ones would you choose in order to be economical?

All: They would choose the alarm and the welded bits of metal which would come to R 14 per person once off. These are in fact the methods of protection in use at the moment.

c) Vandalism:

Two panels were stoned in January last year. Each panel costs about R 1000 at the moment:

Who do you think did it?

Mrs Mdluli: It is difficult to say. It is unlikely that it was children. It was probably social misfits - possibly the people who came back about three weeks later and stole half the PV modules.
Mrs Nene: Could have been older children but was most likely adults who enjoy causing trouble and destroying what is good.

Mrs Mkhize: Most likely adults - trouble causers.

Why did they do it?

Mrs Mdluli: Who knows - probably jealousy: they don't like to see others doing well.
Mrs Nene: Probably jealousy.
Mrs Mkhize: Probably jealousy.

What are the chances that the panels will get stoned again in the next 10 years by the following people?

By small children on purpose?

Mrs Mdluli: Not likely.
Mrs Nene: Possible.
Mrs Mkhize: Possible.

By small children by mistake?

Mrs Mdluli: Possible.
Mrs Nene: Possible.
Mrs Mkhize: Possible.

By thieves if they can't steal?

Mrs Mdluli: Possible. These are the most likely people.
Mrs Nene: Possible.
Mrs Mkhize: Possible.

By the "comrades"?

Mrs Mdluli: Possible but not likely.
Mrs Nene: Could be.
Mrs Mkhize: Could be.

What are the possible solutions to vandalism? (Free)

Mrs Mdluli: They could put small gauge netting wire over the PV modules so that it is difficult to hit them with stones. She also agreed with my suggestion that it may help to talk to the children at school to tell them the cost of the PV modules.
Mrs Nene: No suggestions. She agreed about talking in the schools.
Mrs Mkhize: They could put netting wire over the array. Also talking at the schools may help.

<u>d) All risks:</u>

It is possible to guard against all risks. There are three options I would like to discuss.

The one option is insurance. If you pay insurance this will cost each member R 2 per month. If there is a disaster like a flood, or theft, or stoning then the insurance will pay out. However, the insurance subtracts R 1000 from what it pays. One panel now costs about R 1000. So if one panel is stoned you will get nothing out of the insurance. If three panels are stoned you will get two back. If the whole pump is destroyed - eg. by a flood - you will get the whole thing back except for one panel. So insurance is a lot of help if there is a major disaster but not much help for small setbacks. The pump will still work with fewer panels - but it will just pump a little less water. Insurance also takes about 3 or 4 months to pay.
Would you recommend that Sondela buys insurance at R 2 per person per month?

Mrs Mdluli: No. The gardeners could not afford that amount on top of the R 2 they already pay for seed and fertilizer.

Mrs Nene: No, it is too much.

Mrs Mkhize: Yes, she would be prepared to pay that amount to protect the pump.

The other option is to put 40 c/month aside in a bank account. This has the advantage that if nothing happens then you still have the money in the bank and you can do something with it or you can share it out again. Also, if something happens you can use that money quickly to get the pump going again - there is no waiting. But on the other hand if a big disaster happens soon then you may not have yet saved enough money and you would not be able to replace the pump. However, you may have saved enough to buy a cheaper pump eg an electric pump. If you put 40 cents per person per month aside you will have R 240 at the end of one year and R 1200 in the bank at the end of five years. Do you think this method is better or worse than insurance?

Mrs Mdluli: This method is better because the money stays with them. They would be prepared to pay 40 cents per month or even maybe R 1.

Mrs Nene: This method is better - if insurance is bought the money disappears.

Mrs Mkhize: This method is better.

The third option is the use of a medicine man. This was done on a solar pump in Lesotho which had repeatedly been stoned. Apparently after that there were no problems. Is this a good method?

Mrs Mdluli: (Some laughter.) Where would they be able to find somebody to do this? She does not think that there are people in this area who know how. She herself does not believe in these "medicines". The method may be effective, but only if people saw that it worked - if somebody touched the pump and was affected as predicted.

Mrs Nene: (Some laughter). They do not know where to get the medicines or who would do it for them. She does not have much faith in this method.

Mrs Mkhize: I did not ask this question.

e) Breaking of the reticulation system

Every now and again the piping has a hole put into it or children steal the rubbers from inside the taps. This means that the water is either not pumped or cannot be used. How big a problem is this?

Mrs Mdluli: This has not been a problem recently. The Assistant Agricultural Officer knows how to deal with this and so there is no problem.

Others: I felt there was no need to continue asking.

6. COMPARISON BETWEEN DIESEL AN PV PUMPS

In this section I want your opinion about whether you would prefer a diesel or PV pump. Please remember that we want to know the truth. I will not be offended it you say you would prefer the other types of pumps. The purpose of my study is to find out which one is best for people like you.

Also, the pump at Sondela is already paid for. What you say here will not affect what you pay for the pump. We just want to see what another garden would be likely to decide if it had your experience.

If you were now to choose between a PV pump, a diesel pump or any other type of pump which one would you choose?

Mrs Mdluli: She would choose a PV pump because it does not involve any work. There is no need to put in diesel or to service it.

Mrs Nene: She does not know other types of pumps so cannot choose. This one however works well.

Mrs Mkhize: PV pump. She knows that it works and does not give problems. She has no experience of other pumps and so would choose what she knows.

Mr Mdlolo: I would choose the solar pump because it has a guarantee of 20 years, and it doesn't need to be serviced as a diesel pump does.

Now I want to give you some of my ideas about the advantages and disadvantages of each to see what you think is important.

a) Start-up: PV pumps start on their own when the sun comes up. So they will be left on most of the time and only switched off when there are problems. On the other hand the diesel pump will need to be filled with diesel and oil and then started run for four hours once a week.

Who would start and stop the pump and fill it up with diesel and oil?

All: A member of the garden. It would not be too difficult to find somebody willing.

Would you be prepared to do this job?

All: Yes

Would the person who started the pump be paid by the garden?

Mrs Nene: No. They are all in it together and should share that work.

Mrs Mkhize: Yes. If it is a member of the garden it will not be necessary to pay much - maybe R 30 per month.

How much of a problem is the starting of the pump, and filling it with diesel and oil?

All: Not too much of a problem.

b) Purchase of fuel: Solar needs no diesel and oil. For a diesel pump approximately 25 litres of diesel will need to be bought once a month. If no money is collected, then the pump will not work.

How would the diesel be collected?

Mrs Mdluli: There is a problem at the moment because they have no Agricultural Officer (AO) at the moment. He may agree to carry diesel using the government bakkie. They may need to walk 40 minutes to the bus stop, catch a bus (costing R 3-00 return) to the garage and then walk back with a 25 litre container of diesel. This would probably take a whole morning. There is a further problem at the moment. The neighbouring ward through which they would normally go is UDF controlled whereas they are Inkatha controlled. They would not be able to go through it at the moment and may have to go to Pietermaritzburg to get diesel.

Mrs Nene: It would be a big problem. There is no AO. They would need to carry it on their heads (as above).

Mrs Mkhize: They would need to carry the diesel on their heads. The AO would not agree as it is the government vehicle and he has other work. Arguments could easily arise about whose turn it is to carry diesel. It would be most likely that a few ended up doing the work - as has been the case with buying seed and fertilizer.

Mr Mdlolo: It is not advisable to carry petrol by bus, as it could be used to burn somebody. The government vehicle is in short supply - kilometer limits. Maybe twice a month he could use it for diesel.

How much of a problem is it to be sure that money will be available for diesel every month?

Mrs Mdluli: It is a problem. They would not be able to be sure. There may be no money.

Mrs Nene: This could well cause big problems.

Mrs Mkhize: There is unlikely to be a problem here. Members will pay because they want water.

Mr Mdlolo: It is a big problem because some members may start defaulting on payment.

If you were to buy the PV pump through installments each member of the garden would need to pay about R 1-70 per month for the next 20 years. This would be agreed to beforehand. If the garden stopped paying, some of the panels would be taken back by Mono pumps - depending on how long you have paid for. If you paid for 10 out of the 20 years half of the panels would be taken back. Do you think some members of the garden would stop paying their monthly sum for the PV pump seeing as it seems to be working for nothing?

Mrs Mdluli: If they agreed to it before hand there should be no problem. But R 1-70 is high if they pay it for that time and some of the members may be strained.

Mrs Nene: Probably OK but some members may give problems.

Mrs Mkhize: There should be no problem. If the garden stops paying then they lose some modules. So if they want water they will pay.

If some members were slack would it be possible to force them to pay in some way?

Mrs Mdluli: The other gardeners would stop them using the water from the taps.
Mrs Nene: They would be asked to leave the garden.
Mrs Mkhize: They would leave the garden.

If a member did not pay, are there enough people who would like to join the garden if there is a working pump who would take their place?

Mrs Mdluli: Yes, there are enough people who are keen.
Mrs Nene: Yes.
Mrs Mkhize: Indeed there are many people who would like to join.

Do some members ever not pay the money for seeds and fertilizers?

Mrs Mdluli: It does not often happen.
Others: Question not asked - Mdluli's response satisfactory.

What is done to them?

Mrs Mdluli: They are not given seed to plant or fertilizer.

c) Maintenance: For the diesel pump one major service would be necessary a year.

Would the pump be maintained locally or in town?

All: In town. There are no local skills in maintenance - even simple maintenance. "All" includes Mdlolo.

The solar pump would need to be maintained once every two or three years. It may be possible to train the assistant agricultural officer to identify where the problem is and take that component into Pinetown. Somebody, maybe the assistant AO would have to check that the filter at the bottom of the pump does not silt up, maybe once a month. If there were a big problem Mono Pumps would need to be phoned and it might take a little time for them to come to fix the pump?

Do you think that diesel or PV is going to be less trouble to maintain?

All: The PV pump would be less trouble.

How important is this difference?

All: It is important.

So let us summarize:

- **The PV pump will be left running unless there is a problem. The diesel pump needs to be filled with diesel and oil and then run for four hours once per week.**

- **Money must be collected for both pumps. For the PV pump a fixed amount must be collected from each member as agreed before the pump is installed. For the diesel pump the same could be the case. But diesel will need to be bought for the diesel pump regularly (maybe 25 litres per month). If enough money is not collected from the gardeners both systems will not work well.**

- **The diesel pump will need a major service once a year. If it breaks down somebody will need to organize its repair. The PV pump should go without problems for two or three years. If there is a problem then Mono pumps will have to be contacted. The costs for the maintenance in both cases will be paid out of the kitty from the money which is brought in each month.**

d) Now, which one would you prefer, if you needed to put the following amounts of money in the kitty each month to pay for the pump. This money includes all the costs: the pump itself, the protection of the pump, the maintenance, replacement costs, and fuel for the diesel pump.

Diesel vs PV

1) Normal: 85 c/month vs Normal: 170 c/month

Mrs Mdluli: After much thought - she would choose PV.

Mrs Nene: Hard to choose - but she would choose PV because of the trouble involved in fetching the diesel monthly.

Mrs Mkhize: PV pump is higher quality - better to go for it even if it is more expensive.

2) High: 110 c/month vs Low: 90 c/month

All: From the decisions above, it is obvious they would go for PV.

3) Low: 65 c/month vs High: 270 c/month

Mrs Mdluli: She couldn't really come to a decision. R 2-70 is very high and the gardeners can't really afford it. But she still wanted the advantages of PV. No decision.

Mrs Nene: No decision. She said that there would be different opinions among the gardeners depending on how much they earned and so the garden would be divided. She would not decide herself.

Mrs Mkhize: She would choose the PV pump. If you buy quality it lasts. If you go for the cheapest you will get problems.

How important is money as a criterion?

All: It is important.

e) For both PV and diesel pumps each member of the garden will need to contribute an agreed amount of money per month. This will be kept by the treasurer and used when there are breakdowns or problems.

Is R 1-70 per month too much to pay for the benefits of the pump?

All: This question was not asked as they all put the extra profit of the pump above R 1-70 per month, and they indicate how much they think it is worth by what they regard as acceptable monthly contributions.

f) Other ways of financing the pump:
The pump saves you time and effort.

How much time does the pump save you a day?

Mrs Mdluli: It used to take her about one hour to fill the a drum of water at her plot (44 gallon or about 200 litres). She does not know how many drums she used per week. But when they were using a lot or water, she sometimes needed to fill two drums - otherwise one. If the garden used 5000 litres per day during the winter months (as I measured), she would save herself maybe and average of 40 minutes a day. She now spends just 1 hour in the garden.

Mrs Nene: It took her just less than an hour to fill a drum.

Mrs Mkhize: It took her two hours to fill the two drums for the two plots she had at that stage.

If this pump provides more water than is being used would you like to keep the same size plot or would you have the time to farm another plot across the road?

Mrs Mdluli: She would like to get another plot of the same size as her present one. Not many people would want to. She has the time and she could sell these vegetable for profit. There are many people who would like to buy. The only problem in getting this scheme going across the road is that there is no AO - and they need his help.

Mrs Nene: No, she does not have the energy to farm another plot.

Mrs Mkhize: She would like to get two extra plots the same size as her present one. (She did at one stage have two plots in the present garden, but then gave her one to another person). She enjoys gardening a lot and there is profit in it. If there is water available then there is no problem.

Would you farm fruit or vegetables?

Mrs Mdluli: She has heard that fruit gets stolen. She would farm only vegetables.

Mrs Mkhize: She would farm both.

Are there lots of people in the area who would want to buy your excess produce?

Mrs Mdluli: Yes, there are many people who would buy.

Mrs Mkhize: Yes, and she would also sell in the locations.

If you sold all of this extra food would you make more than the R 1-70 per month that the pump costs?

Mrs Mdluli: R 100 per month for a plot the same size

Mrs Nene: R 10 to 20 per month.

Mrs Mkhize: R 90 per month.

I would like to work out how much money the garden makes for you and compare that to other methods of making money. Imagine that the local shop were to offer you a job. You would not have to spend much time getting there or money on transport. You would start work at 7-30 and finish at 4-30 with one hour for lunch. How much money a day would you work for?

Mrs Mdluli: The going rate for piece work is R 5 per day, so she would settle for that. This comes to 60 cents per hour.

Others: Question not asked.

The lowest wages you would work for comes out to .... c/hour. If you could make this money by a craft at your home where you worked in your spare time, what amount of profit per hour would you settle for?

Mrs Mdluli: She can't put a figure to it, but craft work pays better than this 60 cents per hour. But there is quite a bit of work involved, buying the material, and then trying to sell the end product. In the garden she sells produce while she works and knows she would find no problem in selling the produce.

Mrs Mkhize: There is money is craft work, but she does not have an interest in it. She enjoys working in the garden a lot.

Do you have much time for this type of work?

Mrs Mdluli: She has time. But she does not do it because she does not have a machine.

Mrs Mkhize: If she wanted to do it she would do it in the evening and work on the garden in the day.

Are there many men in the area who would like to work but cannot get work?

Mrs Mdluli: Yes there are many - possibly 25% of the men cannot get work.

Mrs Nene: Yes, many men cannot get work.

Mrs Mkhize: Yes, many.

Are there many women in the area who would like to work but cannot get work?

Mrs Mdluli: Yes, many. Possibly 50% of the women who want work cannot get work. None of her daughters are now working and two of them have matric certificates.

Mrs Nene: Yes, many. Even those with matric cannot get work.

Mrs Mkhize: Yes, many.

Do some people who are out of work not try to find work because the wages are too low?

Mrs Mdluli: No, half a loaf is better than none.

g) Hand pumps:

Have you ever used a hand pump?

All: None of the women had any experience with hand pumps so this line of questioning was dropped.

Mdlolo: No.

I think that hand pumps are probably cheaper than other types of pumps to buy and to run and there will probably be less problems with maintenance. Do think a garden may choose this type of pump for these reasons?

Mdlolo: Yes

Imagine that a hand pump was bought at Sondela. Would you be able to share out the work evenly or would some people be lazy?

Mdlolo: There could be problems but they would probably be intermittent.

Would it be better to buy a diesel pump and share out the expenses rather than sharing out the work of the hand pump?

Questions for the treasurer:

Do you think that you will succeed in organizing the expenses of both the PV and diesel pumps i.e. expenses to repair the pumps and replace components when necessary?

Mrs Nene: There should be no problem in organizing finances.

Or would you like the help of an organization like INR of KFIC?

Mrs Nene: Question not asked - she saw no problem.

Let us say that the motor of the PV pump will need to be maintained after three years. This may cost R 400. Do you think that the gardeners would prefer to pay R 8 each at the time the repair is necessary or would they prefer to put aside 20 cents each per month into the kitty so that the money is there when needed?

Mrs Mdluli: She felt that putting aside 20 cents a month is preferable - but some other members may prefer the lump sum.

Mrs Nene: Putting aside 20 cents a month is preferable - the members will not feel it as much.

To pay for repairs and replacements for the PV pump will cost each member about 45 cents per month. Do you think that they will agree to put this aside?

Mrs Mdluli: Yes, they would agree to this amount.

Mrs Nene: Yes, they would agree.

At the moment how much does each member of the garden contribute per month?

Mrs Nene: R 2 per person per month for seeds, fertilizers, pesticides and any other expense. As she is new to the job she is unable to give a break down.

Mrs Mkhize: As a past treasurer. Pesticides and fertilizer are fairly expensive. The seeds are not too bad.

7. ORGANIZATION AND TOGETHERNESS OF THE GARDEN

Do you feel that most problems in the garden are discussed properly or are some members frustrated and not being heard?

Mrs Mdluli: Problems are discussed adequately. No problems.

Do you feel that the garden is able to organize itself to solve difficult problems?

Mrs Mdluli: With the help of the AO they can solve difficult problems.
Mrs Mkhize: The garden has no problems in solving its problems.

If you are on the committee:
Do you enjoy being on the committee?

Mrs Mdluli: She likes the work but she is now tired - she has been chairperson for seven years. She hopes to stop at the end of this term of office.
Mrs Nene: She has been treasurer for one year. She will not carry on as they take turns.

Are there enough people offering themselves for election?

Mrs Mdluli: Not really. They are not keen on the responsibility and work.
Mrs Nene: No, the others do not want to be on the committee.

8. DEVELOPMENT NEEDS

What are the main problems you face in this area (free)?

Mrs Mdluli: The fighting (between UDF and Inkatha) is destroying everything good. Unemployment is a big problem. And they have recently been told that they will no longer have the use of the government tractors in the coming spring - and they do not know what they will do.
Mrs Nene: There are few needs. They have churches, schools, and now bridges and good dirt roads. They need electricity in the houses and eventually piped water. The current fighting is a major problem.
Mrs Mkhize: The lack of employment is a major problem. Then the fighting and the consequent hunger of the people - food and property are destroyed and work lost.

THAT IS ALL! THANK YOU VERY MUCH!!!

9. QUESTIONS FOR MRS MDLULI ABOUT THE RUNNING OF THE INTERVIEW

In general how did it go? Fine - no problems.
Is the tape recorder likely to put the others off? No.
Is it OK to ask about income? Question not asked because I did not perceive it was likely to be a problem.
Was the interview too long? No, it is necessary for me to get good results.

Appendix 5.3: Social Profile of the Area and Garden

5.3.1 Profile of Mpumalanga District

See main body: no back-up information.

5.3.2 The Garden

Irrigation Suitability Report by Raymond Auerbach (INR)

SOIL CHARACTERISTICS

The two pits examined have similar agricultural features and reflect a simple topographical transition from higher to lower positions on the catena. Both confirm the suitability of the soils for irrigation.

Pit A is the Cleveland series of the Griffin soil form, and Pit C (the lower soil pit), is the Doveton series of the Hutton form.

The infiltration rate in the centre of the garden (sample B) was measured to be 11.06 mm/hr at field capacity. A maximum application rate of 10 mm/hr is thus indicated for irrigation.

The Available Water Content was determined and found to be 163mm/m soil.

The soil's Dry Bulk Density is 905 kg/m3 (0.905 g/ml).

Taking rooting depth for vegetables to be 450 mm, Profile Available Water Content= 73.35 mm.

Allowable Depletion % (35% clay) = 50%

Thus only 37 mm of water may be lost between Field Capacity and the next irrigation cycle.

Each irrigation should thus apply 37 mm at a maximum of 10 mm/hr.

RAINFALL, EVAPORATION, AND IRRIGATION INFORMATION (mm)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Rain	130	92	97	58	31	11	16	28	46	72	94	84
A pan	148	128	131	97	74	60	68	94	111	121	122	146
Nett	-18	-36	-34	-39	-43	-49	-52	-66	-65	-49	-28	-62
CrReq	65	78	81	84	90	94	99	113	110	96	73	109

Since the nett area of the garden is approx 1 ha, crop requirement in m3 would thus be ten times the CrReq figure.
This is a maximum figure, assuming that the whole garden is planted at all times. Practically, it would be safe to work on a water requirement of 40,000 l per day, as long as water is applied with a can or hose. As soon as sprinklers are used, a safety factor of 50% should be introduced (ie 60,000 l/day).
At present, only a fraction of the optimum water requirement is being provided, and the gardeners appear reluctant to increase water use significantly.

SOIL FERTILITY REPORT

	(all these units in mg/kg).							KCl
Sample description	P	K	Ca	Mg	Na	Zn	Acid sat.	pH
Pit A (above gdn)	8	95	2089	469	0	1.0	1%	5.7
Sample B (in gdn)	12	109	792	221	0	2.4	4%	4.9
Pit C (below gdn)	9	78	1117	303	0	3.6	1%	5.4

Pits A and C were dug above and below the garden to examine soil profiles, and sample B was taken from a point in the upper region of the garden. It is interesting to note that Calcium and pH are considerably lower in the cultivated sample, and acid saturation is correspondingly higher, indicating a probable decrease in organic matter. This should be rectified by using kraal manure and mulching techniques as well as a standard type fertilization programme. This should include a basal dressing of 300 kg/ha Langfos, 400 kg/ha kraal manure (both worked in before planting), 600 kg/ha 3.2.1 (30) at planting, and top-dress with kraal manure or Limestone Ammonium Nitrate.

SOIL CONSERVATION

Probably the most important planning feature which should be attended to is the provision of adequate run-off control.
At the very least three contour drains should be constructed.
Positions for these drains have been indicated to Mr Gosnell.
I note that although the original recommendations were made in July, no progress has been made to date (August) with run-off protection.

I feel that the Institute's credibility will be endangered if we have organized a radical change in management such as the introduction of irrigation without providing the necessary guidelines on soil conservation.

In fact, I believe that we should go further in refusing to intervene in future <u>until</u> suitable conservation measures have been taken, and that attention be given ahead of time to planning, including such details as where workers will stay and for how long; what back-up and equipment will be required; and what community training will be needed to utilize the newly introduced technology.

Raymond Auerbach 26/8/87.

The table for rainfall, evaporation and irrigation information was adapted as follows by inserting measured rainfall figures for that year.

Table A5.1: Actual Rainfall, Evaporation, and Irrigation Information

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Rain	54	60	120	35	0	10	10	74	331	72	73	50
A pan	148	128	131	97	74	60	68	94	111	121	122	146
Nett	-94	-68	-11	-62	-74	-50	-58	-20	220	-49	-49	-96
CrReq	141	110	58	107	121	95	105	67	0	96	94	143

The Profitability of Sondela Community Garden: Information provided by Mr Mdlolo, agricultural officer of Nyavu Ward

1. Background Information

Garden membership:	46
No of plots:	46
Size of plots:	180 m^2

Each plot is divided into six sections of 30 m^2 each. So in each season six crops are grown. A plot may be used for two different crops in a year, but this is not done regularly. Different crops are grown each year in order to rotate them. Crops commonly grown are: cabbages, tomatoes, beetroot, spinach carrots, potatoes, onions, butternut, beans, egg plant, peas, cauliflower.

2. Estimates of Profitability

The following six crops were used to estimate the average profit made during a year. (Other crops may be planted in other years). In addition to the six winter crops butternut is included as a summer crop.

Each crop effectively uses a whole section for a whole year because of the maturation period. Each section has 6 rows (1 meter apart); and each row is 5 meters in length.

a) Cabbages: There are 72 heads of cabbage per section. This is worked on six rows of 12 heads per row (40 cm spacing). The price of a cabbage is R 1-25 per head?

b) Spinach: There are 96 plants per section (16 plants per row). A bunch consists of 10 leaves and sells for 50 cents. There are 150 leaves per section and so 15 bunches - which gives R 7-50 per harvest. Once a leaf has been cut it will regenerate in two months, meaning that there are effectively three harvest in the 6 months during which the spinach is grown. So the annual income is R 22-50.

c) Tomatoes: There are 72 tomato plants per section (12 plants per row at 40 cm spacing). Each plant produces 7 fruit over the whole season. And 6 fruit make a kilogram. And one kilogram sells for R 3.00.

d) Onions: 150 tubers per section (25 per row at 20 cm spacing). On average 6 tubers weigh one kilogram - so the yield is 25 kg. The selling price is 2.50 R/kg.

e) Potatoes: There are 66 plants per section (11 plants per row at 45 cm spacing). The average yield per plant is 7 tubers, giving a total yield of 462 tubers. The total weight of this yield is 46.2 kg (10 tubers per kilogram). The selling price is 3 R/kg which gives an annual yield of R 138-60.

f) Carrots: Each section produces 60 bunches of carrots (10 per row). One bunch of carrots weighs 1 kg and sells for R 2-50. So the annual yield from carrots is R 150.

3. Summary Table

The following table summarizes the above.

Crop	Units produced	R/unit	Kilograms	R/kg	R/section
Cabbage	86 heads	1.25			108.00
Spinach	54 bunches	0.50			27.00
Carrots	72 bunches	2.50			180.00
Tomatoes	86 plants		20	3.50	252.00
Onions	180 tubers		25	2.50	62.50
Potatoes	554 tubers		55	3.00	166.32
Butternut	36 butternuts		36	1.29	46.44
Total annual profit per garden member (180 m^2 plot)					660.26

Note: the prices of the first three crops are given in R/unit - for example Rands per head of cabbage or per bunch of carrots. The other crops are priced per kilogram and so the mass of the product is estimated.
Source: Mr Mdlolo, agricultural officer for Nyavu ward.