Declaration

The accompanying research project report entitled: “**Solar Powered Well Pump: Electrical System Design”** is submitted in the third year of study towards an application for the degree of Bachelor of Engineering in Mechanical Engineering at the University of Bristol.

The report is based upon independent work by the candidate. All contributions from others have been acknowledged at the start of the report. The supervisors are identified at the start of the report. The views expressed within the report are those of the author and not of the University of Bristol.

I hereby declare that the above statements are true.

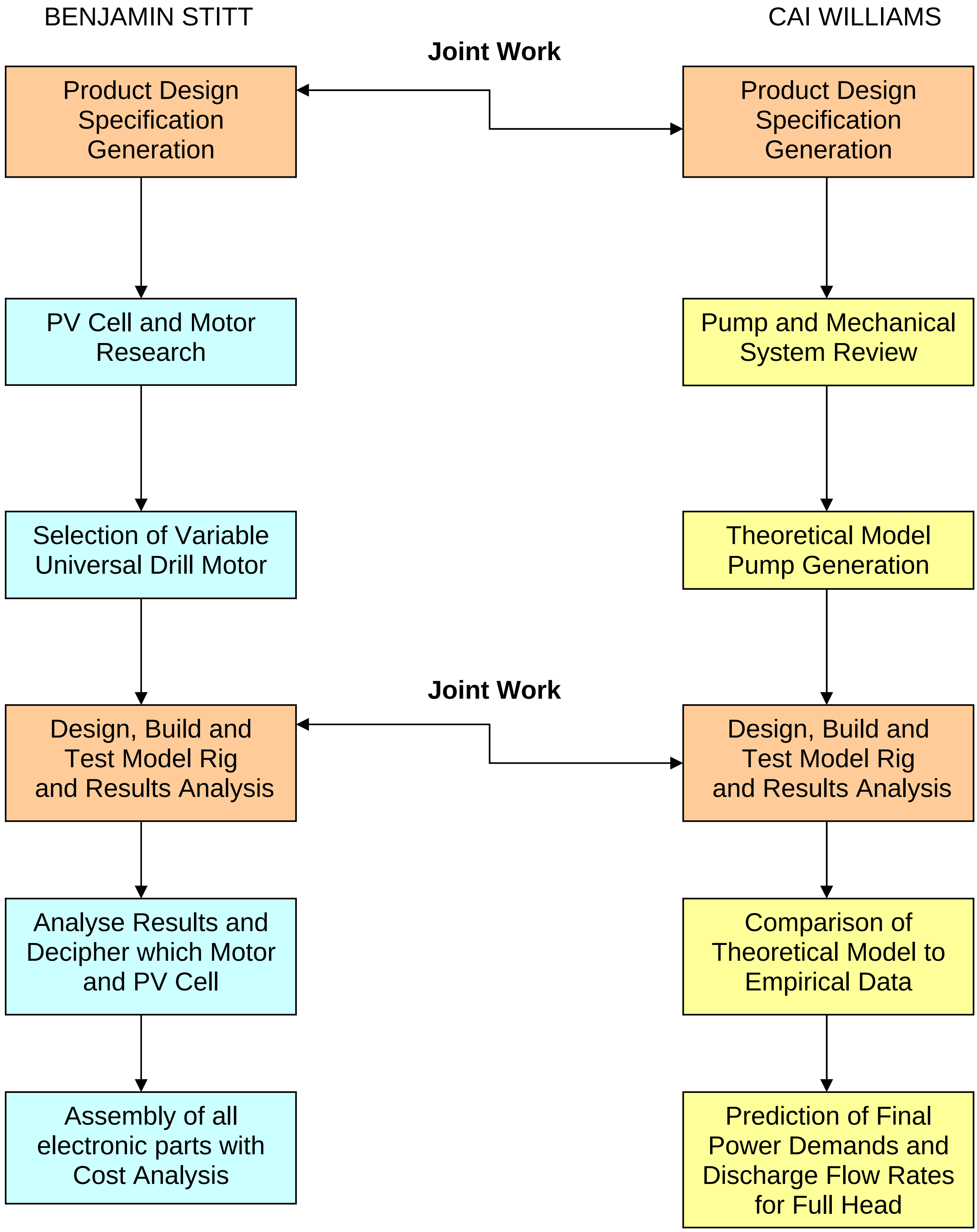
Name: Benjamin Stitt
Date:

Acknowledgements

The author wishes to acknowledge the vital role of supervisor Dr. Booker and the technical staff in the workshop and hydraulics laboratory, particularly that of the electrical department. The combined expertise provided an indispensable resource and without which this project could not have been completed. Cai Williams’ significant preliminary research was also central in launching this project, and his practical skills were continuously appreciated throughout.

Project Title: Solar Powered Well Pump: Electrical System Design

Work Distribution



Project Supervisor: Dr. J.D. Booker

Summary

This report covers the initial steps of improving an already existing and proven water-pump, by operating it with the use of solar power. Mono-Pumps already have a popular solution, with a solar powered pump costing £2000 to £5000. However, this is for a comparatively wealthy market with a budget much greater than most can afford in Africa. Therefore the main restriction of this project is keeping the cost as low as possible, around £500.

The existing pump, known as the elephant or rope washer pump, was manufactured at one-third scale in the University laboratories. The current build specifications were modified so as to incorporate the electrical system and methods of taking readings of Torque, Flowrate, Rope Speed and Power Input. The electrical system consisted of a DC Power Pack and Universal Motor that could mimic the output power created by a Solar Panel. Initially research was carried out on just PV Module and Motor options, finding equilibrium between efficiency and cost. However, it became apparent that without the use of energy storage, large portions of the solar panels harnessed energy would be wasted. Further research was then carried out on the option of integrating a battery into the electrical system.

The expensive inclusion of energy storage had its effects on the overall price, but keeping to the original budget was very difficult. With this report as a guideline, further work should reveal options closer to the £500 mark. For now the prices range from the smallest and simplest design at around £900, to a very effective water pump with back-up battery power costing around £1800. The smaller system could be in sight of a family market, and the larger system has great potential for small communities such as schools and hospitals. This project has also unveiled a more effective method of selecting components that ensures best value for money.

Notations & Subscripts

v = Rope Velocity (ms^{-1})
D = Diameter (m)
r = Radius (m)
F = Tensional Force (N)
g = Gravitational Constnt (ms^{-2})
I = Current (A)
V = Voltage (V)
L = Length (mm)
l = Litre (cm^3)
P = Power (W)
t = Time Period (s)
$T(\tau)$ = Torque (Nm)
ΔL = Spring Extension (mm)
η = Efficiency (%)
ω = Rotational Velocity (rad/s)
MR = Motor Rating (W)
(S) = Standard Error
(r) = Correlation Coefficient

x_T = Tachometer
x_W = Pulley Wheel
x_S = Shaft
x_{wtch} = Stopwatch
x_O = Output
x_I = Input
x_G = Gearbox
x_M = Motor
x_{Ttl} = Total
x_{Sp} = Spring
x_{pix} = Number of Pixels
x_{mm} = Number of Millimeters
x_{max} = Maximum
x_{min} = Minimum

Contents

1. Introduction

1.1 Background

There are places in Africa, South America, and across the world where millions of poverty stricken people suffer from one main problem – hunger. The availability of food is something that most of the western world takes for granted, but those in such deprived areas face a constant uphill struggle to survive. Figure 1 shows one of the luckier children. The less fortunate people must grow their own crops to feed themselves. However, food requires sufficient water to grow, and when droughts hit, their invaluable supplies run short and the farmers are left with nothing. With global warming causing serious climate change, the droughts are becoming a more and more frequent occurrence and the problem pleads attention.

Figure 1 – Water essential to human survival [1]

Why is a Solution Necessary? [2]

→ *Every year 15 million children die of hunger*

→ *Nearly every 2 seconds someone dies of hunger*

→ *Malnutrition is implicated in more than half of all child deaths worldwide - a proportion unmatched by any infectious disease since the Black Death*

→ *It is estimated that some 800 million people in the world suffer from hunger and malnutrition, about 100 times as many as those who actually die from it each year.*

[1]

Figure 2 – Simple pump systems help ease the shortage

There are many existing hopeful 'solutions' or projects that aim to help recover water all year round. See pump in Figure 2. But after extensive research contact was made with Bobby Lambert, ex-CEO of Registered Engineers for Disaster Relief (Red-R), who offered a task that involved converting an existing water pump into a solar powered pump and hence making it automatic. The reasoning behind the idea is to free up time that would otherwise be required to pump sufficient volumes of water to tend a small agricultural plot. This time can then be spent on, amongst other tasks, irrigation and education. The design is aimed to be purchased by a single family, and so a key criterion is keeping the cost to an absolute minimum.

The new system would deliver the following benefits: [3]

- *Improved family nutrition through economically viable household food production*
- *Improved health associated with sufficient clean water*
- *Improvements in household economics through sale of irrigation produce*
- *Improved opportunities for education & other economic activities through reduction in labour required for food production & water collection*
- *Improved electricity availability for domestic and small community use*
- *Enhanced attractiveness of solar power as a viable energy source, through adding another level of economically viable functionality*
- *Improved environment through reduced soil erosion associated with well watered soil*

1.2 Aims & Objectives

Aims: Design, build, and adapt an existing water pump to be run on solar power alone, keeping cost to an absolute minimum. Generate a PDS and energy balance for the electrical system. Demonstrate final component selection and mechanical integration with energy optimisation.

Research: Research and investigation of variables for major electrical system including PV cell, power tracker, energy store, motor and power controller.

> *Panel Selection:* The panel must provide sufficient power to run the motor everyday under standard African climate. It must also withstand the harsh environment Africa can present, but staying as inexpensive as possible.
>
> *Motor Selection:* The motor must work continuously to provide sufficient water every day in the same tough environment. Performance and cost must be balanced with the PV modules ability to harness power to form an efficient but inexpensive system.

Simulation: Motor and panel selection should be based upon experimental loads obtained using a model pump. If possible, an actual solar panel should be used to prove the experimental model results are the same when working from sunlight alone.

1.3 Research Methodology

The electrical part of the solar pump system relies heavily on using the mechanical model to acquire necessary readings. The results can then become the specifications of each component, to be later analysed using supplier catalogues. This meant a continuously close relationship with the mechanical section, where my partner Cai Williams and I worked together to build the model. It was considered necessary that a Gantt chart should be created for both parts. This way, structuring the project and understanding necessary deadlines is clear. The collectively created Gantt chart can be found in the appendix.

To manage the shared work, a shared folder was created across the University network. Here model dimensions and results could be easily viewed or modified. Contact was kept very regular with exchanged numbers, emails and meetings inside and outside of University. To guide the progress of the report and keep tasks on schedule an implementation plan was devised:

Implementation Plan

Problem Statement: Selection of most Efficient and Inexpensive Electrical System

Restrictions: Budget of £500

Specific Steps	Completion Date
1. Research PV technology – then specific panels and costs,	10/07
2. Research Motor types – interpret the most suitable and find costs,	10/07
3. Research design of existing washer pump,	10/07
4. Create ways of imitating motor and panel performances,	11/07
5. Build and test model pump with electrical system,	02/08
6. Extract results and form product specifications,	02/08
7. Contact companies for price ranges,	03/08

8. Find optimum panel and motor combination, 03/08
9. Select components, 03/08
10. Create cost analysis diagram for complete setup, 03/08

Resources Required:

People – Contacts within motor and solar panel industry, and charity companies such as Pump Aid and Solar Aid would be useful but not essential. Bobby Lambert already positioned for continuous advice if required.

Facilities – Access to Internet and tools in laboratories essential. Workspace in Hydraulics Laboratory to assemble model pump.

Funds – University allows budget per student, sponsorship required if final components are to be bought.

Materials: Testing model covered by budget, further investments by sponsorship.

Contact: Tutor and partner meetings at least every week, regular emails and calls.

Selection Process

To ensure the most suitable solution can be found, it is useful to have a design selection method. The diagram in Figure 3 is a simplified version of Phal and Beitz's model of a design route.

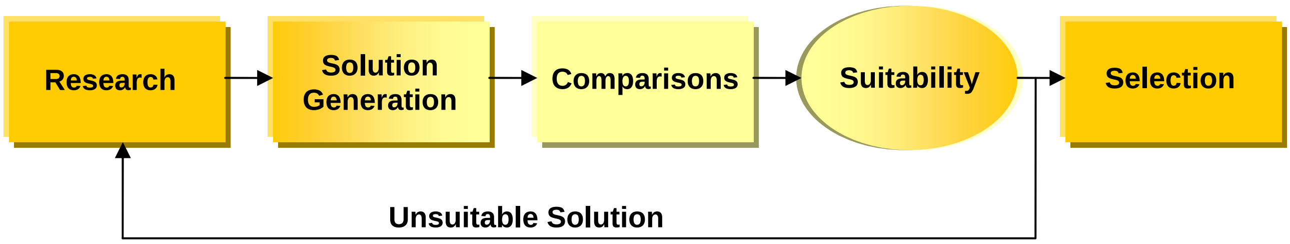


Figure 3 – Selection Flow Diagram [4]

By continually referring to these steps, it can be warranted that the best possible design has been found. Throughout this project each problem will be soundly researched so as to understand the options and generate a solution. These solutions can then be compared and a decision made on the overall suitability. However, if the solution is found to be unsuitable, more ideas and concepts will have to be generated, a process repeated until the right solution is established.

1.4 Summary of Chapters

- → Chapter 2, *Research* ~ Thorough component research on Motors and how PV modules work, the types available and how to select the most appropriate.
- → Chapter 3, *Design & Development* ~ Techniques and materials used in manufacturing the test model including CAD models and work distribution.
- → Chapter 4, *Experimental Methodology* ~ The process of acquiring results from the test model and how each value is obtained as accurately as possible.
- → Chapter 5, *Results & Analysis* ~ Overview of the results obtained and initial thoughts on

their impact on component choice.

→ Chapter 6, *Discussion* ~ Calculation and accumulation of results used in component selection, cost analysis of system and comparisons.

→ Chapter 7, *Conclusions & Future Work* ~ Final thoughts, problems encountered and recommendations for future work.

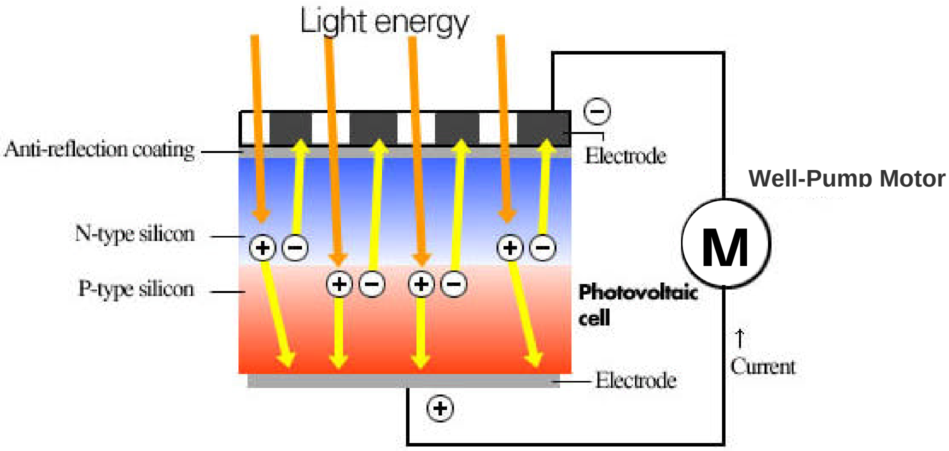
2. Electrical System Research

2.1 Photovoltaic (PV) Cells

2.1.1 How they Work – Photons to Electrons

Photovoltaic Cells, or Solar Panels, are almost all made with the same basic element – Silicon. The properties of Silicon, when stripped of all impurities, make an ideal neutral platform for the transmission of electrons. However, because Silicon has no positive or negative charge, it could not generate electricity in Solar Panels on its own.

To create a charge, p-type semiconductors are made by doping Silicon with a small amount of Group 3 elements such as B, Al, In, and Ga. Then a thin layer of an n-type semiconductor is converted by diffusing in a Group 5 element such as As, P or Sb. When combined, as illustrated in the diagram of Figure 4, the p-type and n-type layers create a p-n junction which has an electric field across it.



[5]

Figure 4 - Illustration to demonstrate how a PV cell creates a current.

The Sun emits many different particles of energy, but specifically for Solar Panels – Photons are released. When angled correctly, photons bombard the n-type silicon layer and give more energy to electrons. With sufficient energy, the electrons are freed and can jump into the conduction band, and if available, will follow an external circuit. This freeing of electrons also creates positive 'holes', which move in the opposite direction as shown in Figure 4, and it is the motion of both these charges that causes the current to flow.

2.1.2 Types of Cell [6]

Several categories of Solar Panel are available. It is important that each is evaluated sufficiently, so the best panel for the unique requirements and environment is selected:

Amorphous: These Solar Panels are manufactured by depositing a thin film of silicon (2μm) onto a sheet of another material such as steel. The panel has poor efficiency compared to the other available forms, roughly half, but this is gradually improving as more suppliers look to this alternative. The attraction of amorphous panels is the low manufacturing cost.

Mono-Crystalline: The cost per watt for a Mono-Crystalline cell is comparatively expensive, mainly due to the slow, inefficient manufacturing process. Here a single crystalline seed is positioned in liquid silicon and then drawn out. The reasoning behind this extensive method is high energy efficiencies ranging from 14-18%.

Polycrystalline: The less expensive crystalline option, where manufacturing is simpler and relatively quick. The process involves pouring liquid silicon into block that are subsequently sawed into plates. However, during solidification, crystal structures of varying sizes are formed with boundaries that generate defects. These defects mean a lower cell efficiency ranging from 13-15%.

The previous types of cell are the most commonly known and collectively they can fulfil most requirements. However there are numerous other, more specific types of Solar Cell that should be taken into consideration.

Thin-Film Cell: These cells use much less material in manufacture than the other examples. This has two advantages in its lower price range and flexibility. The bendable properties aid transportation and consequently can improve security.

Concentrator Cells: These are by far the most efficient solar cell. Using optic technology to concentrate the sunlight onto a small area can create efficiencies up to 37%. However, the high efficiency cells will often be hundreds of times more expensive than the standard crystalline cells, making them fairly unpopular.

Multi-Junction: Standard silicon cells are best at converting red and infrared light into electricity. However, the sun emits blue and ultraviolet light too, which can be harnessed by Multi-Junction cells. This gives the highest efficiencies of up to 40.7%, but again a very high price range due to the multiple materials and complex manufacturing process.

2.1.3 Solar Efficiency [6]

As the size of the panel is not restricted, the efficiency of the type of cell is not central to the final panel decision. With size however, comes high expenses, and so the choice of panel will come down to which ever is most cost efficient – a small panel with high efficiency or a large panel with low efficiency. The efficiency of converting photons into electrons, or Photoconversion efficiency, is not dependant on the solar radiation. As can been seen from the graph in Figure 5, the efficiency reaches an acceptable rate of 85% before 300W/m².

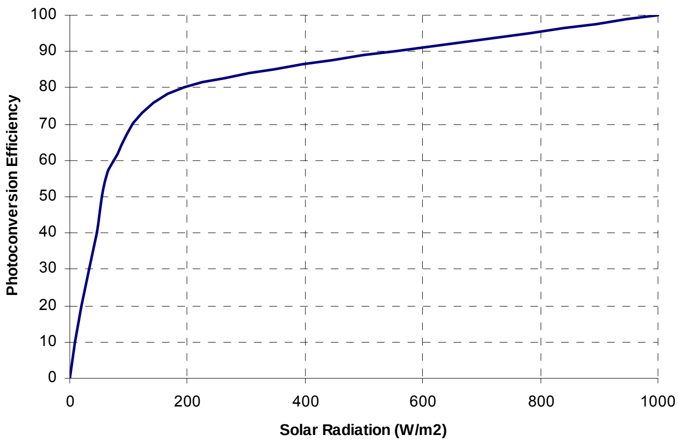


Figure 5 - Efficiency against Solar Radiation [6]

It can also be seen that the efficiency at 500W/m² is almost the same at 1000W/m². Essentially this means the conversion efficiency on a sunny day is the same as on a cloudy day. It can be said then, that the power output of a solar panel is directly proportional to the irradiance levels, and not efficiency. This means selection can be based on irradiance levels alone.

2.1.4 Irradiance [7]

An important factor in selecting a sufficiently powerful solar panel is how much sunlight or irradiance it will actually receive in the environment for this prototype – Tanzania.

The Sunbird European Commission website has a program that gives us around 10 years worth of records on the irradiation in Dodma:

A monthly irradiation levels graph was retrieved from program and can be viewed in Figure 6.

The graph demonstrates how unlikely it is for the radiation to drop below 5800kWh/m²/day. The dry season usually hits Tanzania from December to February, and so it is important to know the irradiance on an average day in these months:

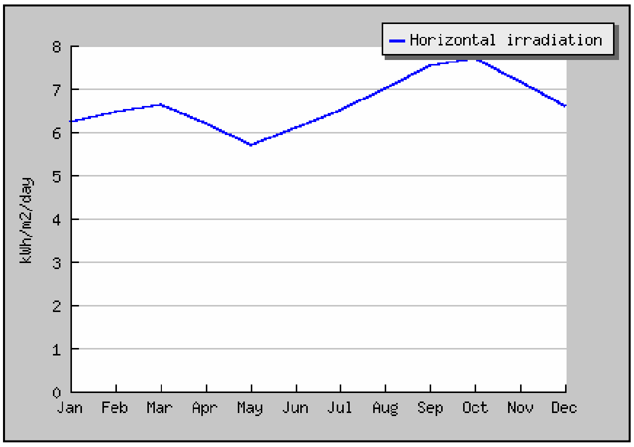


Figure 6 - Yearly average of horizontal radiation in Tanzania [7]

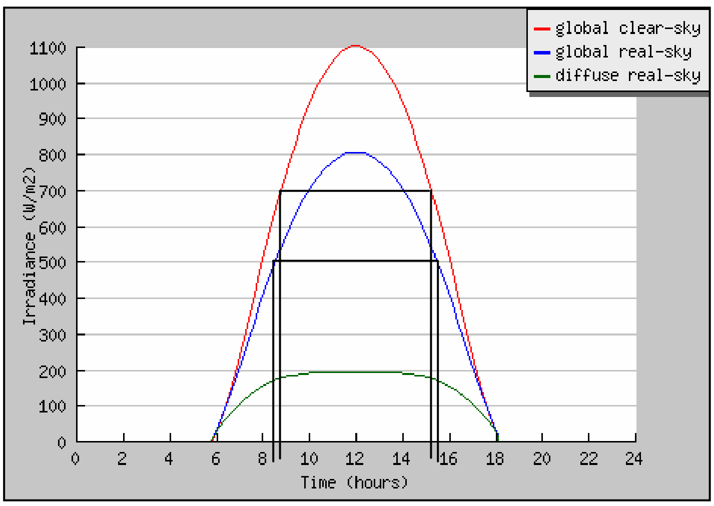


Figure 8a - Irradiance levels on an average day in January in Tanzania [7]

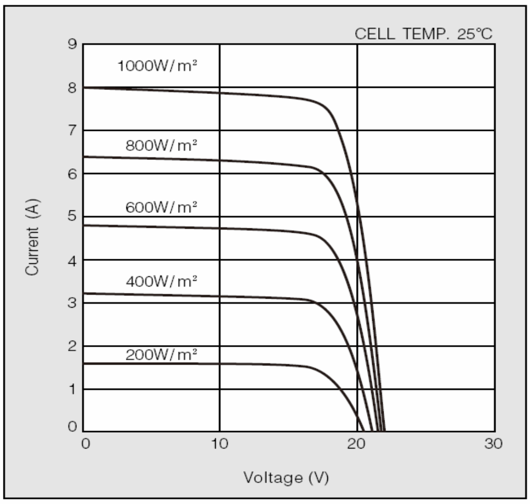


Figure 8b - Current-Voltage characteristics of Photovoltaic Module KC130TM at various irradiance levels. [8]

Figure 8a shows that it is possible to get 500W/m² of irradiance for around 7 hours a day in global real-sky, and 700W/m² in clear-sky. This can then be directly correlated to Figure 8b, the I-V characteristic curves for an example 130W solar panel.

At 500W/m², there is around 4 Amps and up to 17 Volts available, which amasses to 68 Watts in total. Different size and power modules will produce different amounts of power in the said conditions.

2.1.5 Angle

To achieve the best possible radiation level, the panel must be perpendicular to the sun rays. There are many ways of doing this, however for now, as costs are limited, we will assume the panel is constantly horizontal to the earth and will therefore receive rays at an inclination before and after midday. All the data obtained from the Sunbird European Commissions website assumes this.

2.1.6 Selecting the Right Cell

To find out which panel is most suitable, two things must be known. Firstly, the loads and rotational speed of the pump when delivering the minimum water quantity of 1000 litres, and how long this takes. Secondly, what motor and gearing is chosen that will reach these rates adequately and what power that motor requires. Then, taking into account the worst case radiation available and over how many hours it is emitted for, a solar panel can be selected by comparing its I-V curves to the power it must deliver, as illustrated above in Figure 8.

This project has specific aims and specifications, which limit the choice of solar cells if it is to be successful. Although it is possible to broaden the specifications, this should only be done if absolutely necessary – as major changes will seriously affect the budget. When selecting the type of solar cell to use, the following points should be taken into consideration:

→ Minimum Cost
→ Availability in Africa and Worldwide (supplier)
→ Security
→ Size
→ Future Cost

Minimum Cost: This is one of the most important factors in deciding the right solar panel. The target market will be spending anything from 3 to 10 years of their earnings to buy the system, and cannot afford to be stretched any further. This immediately rules out Concentrator and Multi-Junction Cells.

Worldwide Availability: To aid financial economization, supplying the panels through transportation should be kept to a minimum. It is also beneficial to support local companies, and introduce the system to them. Several emails were made, and the project now has contacts from Dodma and Arusha in Tanzania. The contacts are through supplying companies Umeme Jua and

African Energy respectively. There is also contact with Solar Century, a UK based company keen to be part of the project.

Security: Unfortunately, theft in the places where we intend to integrate this system is a common occurrence and must be considered in this project. There are several options for each type of panel, the most simple being a secure lock on the casing of each panel. The casing can then be fixed next to the pump. This is not full proof, but the only other option, which can still be available, is carrying the large panel back to the owner's home.

Size & Power: The Company selected must be able to supply a panel of sufficient size and power for use with the pump. It may also be necessary to find companies that produce custom designs, or at least one that produces a panel power closest to the pumps demands.

Future Costs [6]: Although the cost of PV modules is still quite high, trends show significant drops since they first came into production. Knowledge of this trend will help predict the final price of the solar pump system, and hence give an indication of the projects plausibility. Figure 9 demonstrates the gradual price fall since the 1960's. The future looks promising although some recent surveys suggest a plateau will come into effect soon.

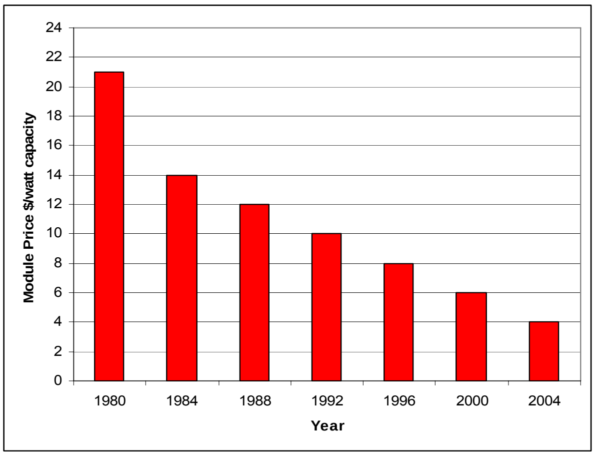


Figure 9 - Module Price Trends

2.2 Motor

2.2.1 Important Considerations

As the motor is a vital part of this project, it is very important its selection evolves around the project aims. Hence there are several areas that should be closely inspected before selection:

→ Rational motor type selection process
→ Sufficient power and torque to run pump
→ Correct gearing (and other options)
→ Environmental concerns
→ Maintainability and Availability
→ Cost

2.2.2 Motor Types [9]

There are many different motors in production today, but not so many that can work in coherence with a solar panel. PV cells produce a Direct Current, which with the right equipment can be transformed into the more common Alternating Current. However, this transformation is a costly addition and so only a motor that runs from DC should be selected. This immediately rules out Stepper motors and Induction motors. The remaining practical choices:

Permanent Magnet Motor: DC motor, low volts, power range under 3kW, very good power-to-weight ratio, no speed control, poor durability due to brushes wearing out, comparatively inexpensive motor. Brushes are easy and cheap to replace. Speed control could be an issue.

Series Wound (Universal Motor): DC or AC motor, 10 – 400V, range from 10W to 100's Watts, good power-to-weight ratio, no speed control, brushed (easier maintainability), inexpensive. Brushes are easy and cheap to replace. Speed control could be an issue.

Synchronous (Permanent Magnet Brushless Servo Motor): AC or DC via drive, 10W to 2000W, has speed control, excellent reliability – little to no maintenance, expensive motor. Drive adds extra cost, as does the reliability factor.

2.2.3 Sufficient Power & Torque

The pump will generate a torque whilst raising the water, and there will be a set speed for this to happen – too fast and damage can occur, too slow and the water will not reach the full height of the pipe. Readings of the Force and RPM will be made during testing. These values can then be used to identify the most suitable motor.

2.2.4 Gearing

The nature of motors, unless custom-made and thus expensive, is to have quite a fast RPM. However, the required RPM of the pump is likely to be quite low. Gearing can transmit this high rotational speed to a more practical slow speed. It is possible to purchase motors with built in gearing, and the prices range. It is also feasible to create your own gearing outside of the motor using a series of different size wheels or cogs to gradually scale down the initial RPM. This option is often cheaper, but less efficient.

2.2.5 Environmental Concerns

Motor efficiencies vary with the surrounding temperatures. In most cases, this is not an issue, but as the pump will be operated in very warm countries, the temperature should be taken into consideration when calculating the final motor to use.

2.2.6 Maintainability & Availability

As with the other components of this system, it is desirable to have a maintainable motor. This means if there should be a problem with the motor, instead of a family going without water for a long period of time before a professional turns up to fix the problem, they can do it themselves. This also requires the motor parts, such as brushes, to be accessible to every pump owner.

2.2.7 Cost

The less money the motor requires, the more money is available for other essential components such as the solar panel. This means the Synchronous motor is likely to be out of range. However, it is necessary to find a careful balance between cost, availability, reliability and maintainability.

2.3 Additional Options

2.3.1 Energy Storage – Battery

Photovoltaics are intermittent sources of power, only working during good daylight hours. If the load and requirements of the pump exactly meet the modules power production, then there should be no need for energy storage. However, it is likely that the pump will need to work in low levels of irradiance. Therefore, in high levels of irradiance, if the motor is to stay at the same speed, much of the energy captured will go to waste. The solar pump system could benefit from energy storage, but only if the expense is feasible. For many owners, the addition of energy storage can come at a later date, after the initial purchase when they can afford to spend more.
The most suitable method of energy storage is through the use of an electrochemical battery.

2.3.2 Maximum Power Point Trackers (MPPT) [10]

MPPT's seek the 'knee' found on graphs, like in Figure 10, illustrating the I-V characteristics of a PV module. This knee represents the largest quantity of power that can be drawn from the solar panel in a particular level of irradiance;

$$P_{max}(W)=I_{max}(A)\times V_{max}(V) \quad \textbf{(1)}$$

Installing a MPPT will ensure the owner will always get the most out of the module. However, these devices are expensive and usually only used when absolutely necessary, like in the UK where the sun is limited!

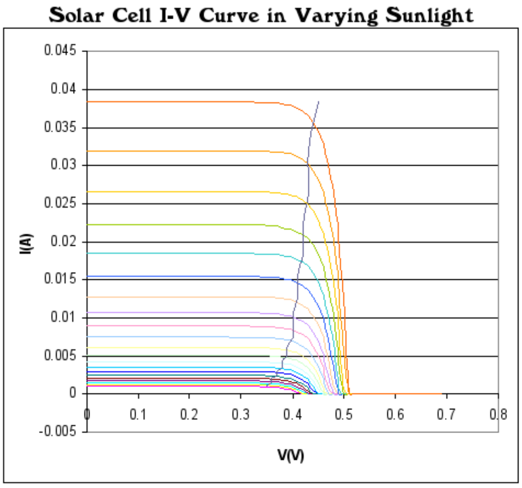


Figure 10 - Thin blue line hits each knee to find max power [10]

2.4 Summary

The preceding chapter generates a decent understanding of the fundamental components used in this project and briefly covers several other possible additions. When coming to the discussion section, this knowledge will make motor and panel selection a more structured affair.

3. Design & Development

3.1 Modelling the Rope Washer Pump

As stated before, the electrical system is aimed at developing an existing pump, creating huge advantages for farmers in irrigation time and ease. To identify the correct components it is necessary to empirically determine values of certain characteristics of the rope pump, such as the load in the rope and rotational speed, which can then be matched with product specifications.

As the pump has been in existence for some time, it was possible to get scattered information from previous builders or owners. Through this information and after extensive research into other existing well pumps, it was possible to create a Product Design Specification.

3.2 Product Design Specification (PDS)

The PDS, as seen in Table 1, was created for both Mechanical and Electrical sections of the project.

PRODUCT DESIGN SPECIFICATION	
Performance	The pump will need to be powered primarily by solar power but with a fail safe capability to be driven manually.
	The pump will need to provide between 1000 and 5000 litres of water per day to irrigate an area of 0.1 of a hectare, which is sufficient to provide food for one family.
	The water will need to be pumped from an operating depth of 10m and supplied though a simple surface irrigation system (pipe with holes in) 20m long with a minimum 40mm diameter.
	The electricity from the solar panel will be potentially also required for lighting, battery charging and low power uses.
	The package will also need to be put together with security in mind as theft may be a problem in the target areas
Environment	The package is designed to fit into the social, economic, agricultural, hydrological and environmental circumstances in large parts of rural Eastern Africa and other semi arid areas.
	Where water scarcity is a major constraint on food production
	Where modest amount of groundwater is available within 30 metres of the surface
	Where there is poor access to electric or other sources of power
	The specific operating climate of Tanzania may be designed for as this is where the field trials will take place
Product Life Span	Aim at a minimum of 15 years allowing for minor maintenance work, considering that the package is designed to be self financing over a potential 10 year period
Life in Service / Duty Cycle	Expected to be in use constantly during day light hours as well as up to 1 hour of manual use a day during peak dry season which may be up to 150 days a year
Target Costs	Must be kept to an absolute minimum, with a target of £500
Quantity	We are focused on the prototype
	The long term intention however is for the production several thousand
Maintenance	It is essential that the package is maintainable using basic artisan skills (with the exception of the photo-voltaic cells)
Marketing	We are not concerned with marketing
Packaging	None
Size and Weight Restrictions	The package will be assembled by a few trained individuals without any specialist lifting equipment.
Shipping	The package will be assembled on or in close proximity the target site
Manufacturing processes	It is essential that the package is as simple to fabricate as possible (using basic light engineering and welding shop technology) and to minimising the number of electrical components.
	The packages will be manufactured one at a time
	The photovoltaic cells and motor will be bought in
Materials	Made using readily available materials in the target location
Safety	Serious consideration must be given to the fact that the package will be used by untrained individuals and sometimes by children

Table 1 – Complete PDS for Solar Powered Well Pump.

The PDS and building information were enough to construct a third scale model of the Washer Pump. Both mechanical and electrical sections required data from the model, so where possible the work was split, and assembled together upon completion of each part. Table 2 below shows each individual's responsibilities during design, build, and assembly of the third scale washer pump.

Ben Stitt	Cai Williams	Joint
Power Pack	Rope	Calibrated Water container
Drill Motor	Washers	Small Wheel
Electrical wires	Pipe & supporting	Threading of Rope
Ammeter/ Voltmeter	Shaft	Water Flow (Bin bags)
Support Girders	Large Wheel	
Bearings	Spring	
Bottom Guide		

Table 2 - Distribution of work during design, build and assembly of third scale model

3.3 CAD Model of Rope Washer Pump

Figure 11 shows the most important annotated parts of the third scale model pump. Ideas11 complete file can be found on attached compact disc.

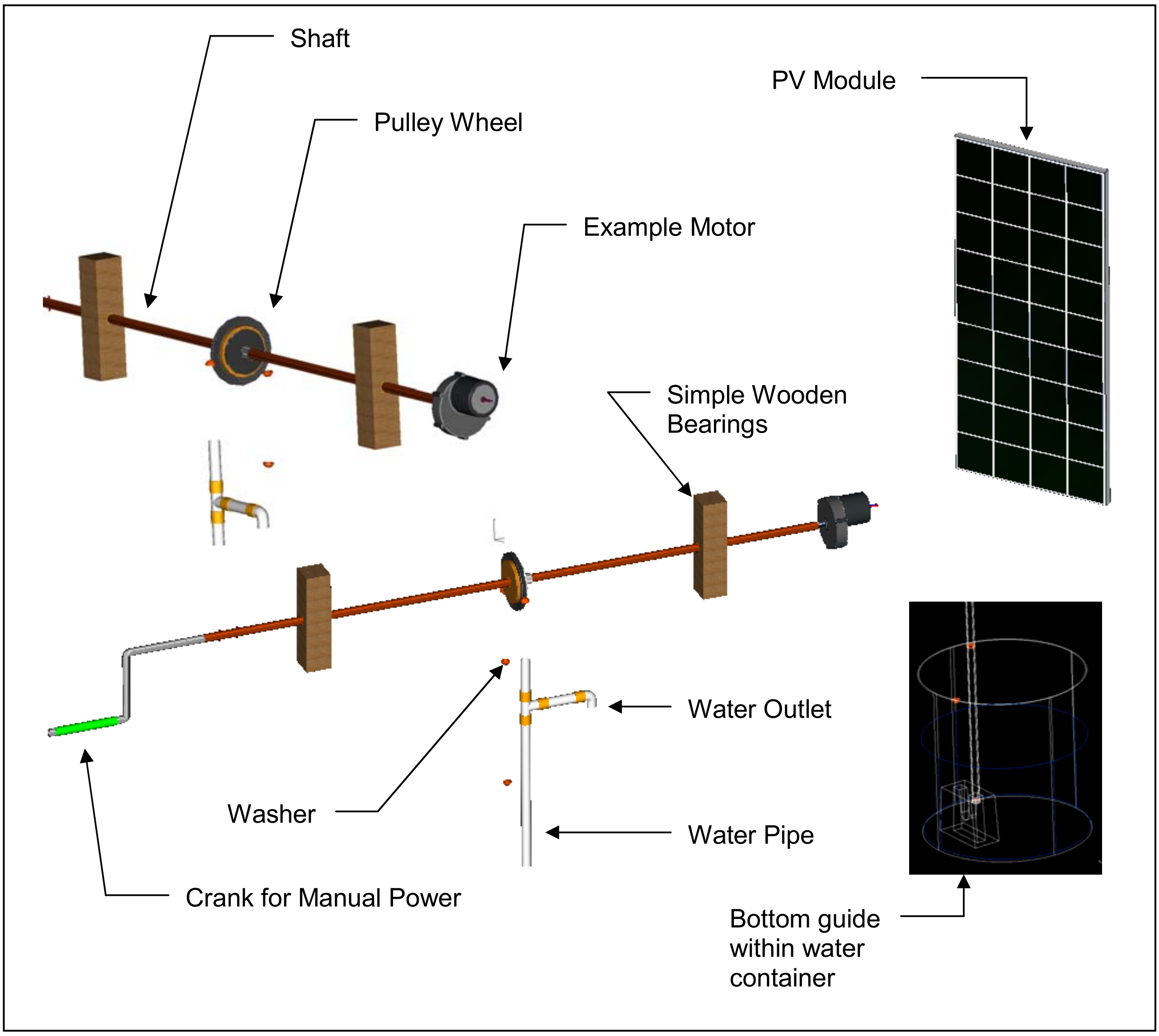


Figure 11 – CAD models of fundamental parts of one third scale solar pump.

3.3.1 Electrical Components

Implementation of Universal Motor: The correct motor cannot be selected without knowing the minimum Torque, Power and RPM required for a 10m Well Pump. To obtain this data from experimentation, it was decided that an inexpensive Universal Motor with sufficient power could be used. A Silverline handheld drill, Figure 12, was purchased and rigged directly to the wheel shaft. The structural support can be seen in Figure 16.

The drill was used because its characteristics meant any power of up to 200W could be applied for short periods without damage, and the input power of current or voltage would be directly proportional to torque and RPM respectively.

Figure 12 – Silverline Drill Purchased as Universal Motor [11]

The drill could be made to act like the perfect motor. The downsides include the drills poor efficiency, and its design would not allow for prolonged periods of use, such as over 10 minutes.

Power Pack: There was little choice in power packs as there were very few available that would be powerful enough to run the drill and pump. The final pack selected could produce 600 watts of power through a maximum of 20 volts and 30 amps.

Ammeter & Voltmeter: To ensure the power pack digital display was accurate, during the preliminary tests an ammeter and voltmeter were connected which did not enlighten any imprecision.

3.3.2 Supporting Girders & Bearings

The hydraulics lab consists of many elevated I-Beam girders that can withstand huge loads. This was perfect for structuring the shaft around, see Figure 13. Two steel and one aluminium 600mm brackets were cut and secured to one I-Beam, two to accommodate the shaft bearings and the last to support the drill. Before assembly the two steel brackets had 4 holes drilled, two for beam support and two for bearing connection. The aluminium bracket also had two holes drilled for beam support at one end, while the other end had the drill securely strapped to it.

Figure 13 - Shaft supported by series of brackets and girders.

3.3.3 Bottom Guide

The guide currently used for the rope washer pump is a concrete cast design as illustrated in the CAD images. However, acquiring the exact mould and a relatively small amount of concrete was impractical. Instead, scrap metal was used to form an effective structure that limited any

Figure 14 – Heavy duty bottom bracket – experimental purposes only.

chance of rope or washer catching and was also heavy enough to sit at the base of the water container and withstand the rope loads without support. Figure 14 shows the complete structure. As the metal tubing within the structure was bolted, it could later be possible to experiment with different materials with varying coefficients of friction.

3.3.4 Calibrated Water Container

It was not possible to obtain a large enough calibrated container for the rope pump to empty, so instead, to improvise, a white meter rule was securely fitted to the inside of a 50L bin. The bin was then filled using a litre measuring jug. With every 2 litres, the level of water in the bin was permanently marked to act as a calibration.

3.3.5 Small Pulley Wheel

The pulley design was mimicked from Bobby Lamberts original Rope Washer Pump handbook. In consistency with using the limited materials available in Africa, the wheel is made simply from two circular wooden slabs, a simple metal support and parts of an old tyre; Figure 15 is an Idea11 CAD model of the small pulley wheel. The metal support in the project design differs from the actually type used, but was easy to have manufactured in the labs. An old tyre is cut around the circumference on both sides, the two rings are then flip around and clamped to each other using the wooden slabs. This causes the tyre to form the v-shape as seen in the CAD image. The tyre creates sufficient friction with the rope to pull water up the tubing. The first wheel had a diameter of 300mm but due to this size caused too much torque for the motor to cope with. Consequently the smaller 150mm wheel was built.

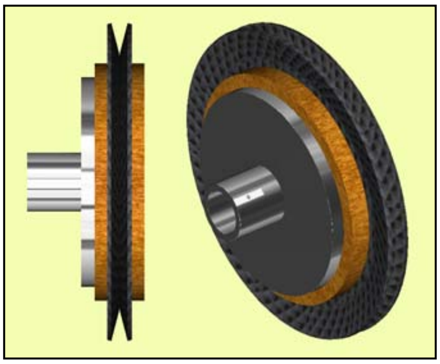


Figure 15 - CAD model of second pulley wheel design

3.3.6 Imitation of the PV Module

As with the motor, the exact specifications of the PV Cell will be a consequence of model testing. To determine what the panel output should be, a 600W DC power pack was connected to the drill. The power output could then be controlled with the adjustable current and voltage knobs. In contrast the power pack could also be set so the drill can draw any amount of power. Here the power pack will simply display the current and voltage required to run the pump.

3.4 Safety Consideration

It is essential to thoroughly asses every hazard the project is involved with. Either removing the hazard completely or ensuring the risk is as small as possible keeps health and safety standards high. Specifically, all the electrical components must be as far from the water as possible and shielded from any splashes. It is also important never to work alone in the laboratory, and take extra care when working at height. On each day, persons must be signed in and out of the Hydraulics Laboratory register.

Complete pictures all the components built and assembled can be found on the Compact Disc included.

3.5 Summary

This chapter overviews the methods and techniques used to manufacture a one-third scale well pump. Throughout, CAD models and images are used to demonstrate the design and build, with safety a constant concern.

4. Experimental Methodologies

4.1 Method

In order to know what size PV Cell is required to work the pump, it is necessary to identify two important factors. Step by step pictures of the pump can be found on the included CD.

4.1.1 Solar Panel

Firstly, it is essential to distinguish the performance of the solar panel in the African environment with regards to the daily solar radiation and the cells efficiency. This information will be extensively difficult to obtain practically, as for one you must invest in either a range of solar panels, or commit to a particular type of solar cell, and buy in bulk to experiment with. The other major issue is how the weather in Africa is somewhat different to the weather in the UK, where it is intended that the initial experimentation will be completed.

4.1.2 Power Required to Run Motor

Secondly, it is necessary to know what the minimum required output of the solar panel needs to be. This is so the selection of solar panel can incorporate its cost, where only the minimum amount can be spent to ensure the most efficient and economical specifications.

The initial problem can be easily found through comparing different panel's performance and efficiency, which is supplied on the manufacturer's websites, with recordings of previous years solar radiation values observed in Africa that can also be found on the Internet.

The output performance required can be obtained through knowing what current and voltage is being drawn from the motor, or calculating what torque and rpm is required of the motor. This is where laboratory experimentation is required.

4.1.3 Summary of Technique

By constructing a third scale model of the water pump and trialling several pipe lengths and diameters, it should be possible to determine what size motor is required for the full scale pump.

The model will be used to obtain, for a specific rpm, values for the current and voltage drawn, rope tension and flow rate. A minimum of 5 readings will be taken for each pipe length, of each pipe diameter, to gain averages and reduce sampling errors. The pipe lengths to be tested are specified by half the 0.7m washer spacing, this should aid finding a scaling function for torque and flow rate. This function can then be used to predict values for a full 10m head. The greatest height will be 2.8m, enough space for exactly 5 washers. 0.35m will be cut from this maximum for each subsequent test. The pipe internal diameters will be 19mm and 36mm as these are the dimensions currently used in the already existing rope washer pumps.

Power supplied to the drill will be varied until steady conditions are found. The rope velocity can then be recorded and kept constant throughout the experimentation. Tension can be found using a spring balance in the loop of the rope, and the flowrate through displacement over time taken. Further details of each measurement are described below.

4.2 Electrical Readings

4.2.1 Power

The power is the product of current and voltage as read from the power pack display during each test. As the only power pack found could not have voltage and current adjusted simultaneously, the current was kept constant, but only after a suitable RPM was obtained.

The drill is mounted and trigger locked full on to ensure the transformer has no effect on the output power.

Figure 16– drill mounted to crossbeam for fuller shaft support

4.2.2 RPM

It is important to know about any rope slippage on the wheel during testing. To get this comparison, the shaft speed will be measured separately to the rope speed. The shaft RPM will be measured using a tachometer. The tachometer wheel will be held against the shaft whilst in rotation and the speed will be converted through basic scaling calculations:

Rope speed can be found by multiplying the tachometer rotational speed in seconds by the radius of the pulley wheel times the ratio of the tachometer radius to the shaft radius.

To find the tachometer rotational speed in seconds:

$$\omega_T = \frac{\pi}{30} RPM_T \quad \textbf{(2)},$$

Where, $RPS = \frac{RPM}{60}$ **(3),** and $\omega = RPS \times 2\pi$ **(4).**

Then to find radius and ratio:

$r_W = \frac{D_W}{2}$, and $\frac{D_T}{D_S}$ (**5), (6),**

The rope speed is then:

$v = \omega_T \times r$ **(7),**

This becomes:

$$v = \frac{\pi}{30} RPM_T \frac{D_W}{2} \frac{D_T}{D_S} \quad \textbf{(8).}$$

Therefore if the shaft RPM is 120, the rope speed is 1 m/s – which is the suggested speed.

4.3 Speed

The rotational speed can be kept constant through timing one complete circulation of one single part of the rope and directly calculating the speed by:

$$speed = \frac{dist.}{time} \Rightarrow v = \frac{L}{t} \qquad \textbf{(9)}$$

It should be intentioned that the rope speed stays as close to 1m/s as possible throughout the testing. Keeping the speed constant allows easier manipulation of the remaining data. So if the rope is 7300mm in length, the motor will be adjusted so a complete rotation takes as close to 7.3 seconds as possible, the power readings will only be taken after this time has become constant.

4.4 Torque

The Torque can be obtained by measuring the force in the rope using just the bare spring from the Spring Balance force gauge in Figure 17. A spring's extension can be measured directly through its length-to-diameter ratio. This is because the diameter of the spring does not alter with extension, and as the spring is circular, the diameter can be read as a width from any angle. This means a photo of the spring can be taken from any distance during testing and then later analysed to interpret the extension. In turn this can then be compared to the calibration of the original spring balance of whence it came. To ensure the calibration is still the same, tests are done on the spring with known weight masses and the extension measured. The results of this test can be compared to the calibration and can be found in the appendix.

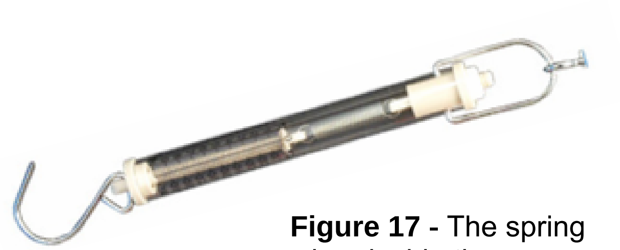


Figure 17 - The spring when inside the calibrated casing [12]

Once the force is obtained, the torque for each test is calculated through: $T = \frac{FD_W}{2}$ **(10)**

4.5 Flowrate

The Flowrate will be obtained by measuring the quantity of water displaced from the bin where the pipe end and bottom guide rest. As the bin had no markings, it was necessary to scale it. This was simply done by marking a white ruler and using a measuring jug to adjust the water height every 2 litres, as seen in Figure 18.

Once this was done, bin liners where taped up around the top section of the pipe, where the water departed. The bin liners then direct the water into a separate bin, so as to not affect the collecting bin.

Figure 18 - Red lines - 2 litres; Green -10

4.6 The Procedure

The simple directions applied to cover each measurement successfully for each test with just two people. The blue text represents the second person:

1. Turn Power on,
2. Allow time for water-flow to become constant/ linear,

3. Record water height and start stopwatch 1,
4. Take time for one complete rope rotation (second stopwatch)
5. Use tachometer to find shaft speed max and min,
6. Continuously take photos of spring as it passes whiteboard (clarity)
7. Stop stopwatch 1 when 20L is displaced
8. Record current and voltage – turn off power
9. Record what number photos represent that test and max/ min RPM
10. Repeat 5 times for each length to gain average result

4.7 Summary

Experimental Methodologies shows the procedures used to gather each necessary reading from the experimental model and the alterations required to make these readings possible and accurate.

5. Results & Analysis

During the experimentation, some tests had one or two recordings missing. This could be due to a stopwatch failure, or camera failure amongst others. It was ensured that for each length, at least 5 complete readings were obtained for each diameter. However, if each photo was analysed after every single test, the progress would have been too slow for the time scale allowed. Therefore, the photos were left until after testing was complete. Once at least 5 complete recordings were obtained for each length and diameter, an average of each variable was calculated. Full results and a short film of the pump at work can be found on the included Compact Disc.

5.1 Head

The head of water stayed constant for each different length of pipe, it was calculated approximately by: *Head = Pipe length – distance from pipe end to 5L mark for 19mm and 10L mark for 36mm*

5.2 Electrical Power & Mechanical Power

As torque is directly proportional to speed, the current was made constant once 1m/s was established. During each test the maximum and minimum voltage drawn was recorded from the power pack, and then an average was found for each of these. The product of this average voltage and the constant current gave the power drawn for each of the 5 tests. The overall power for each length was then obtained through the average of each of the 5 tests.

The mechanical power was deduced by multiplying the torque by the radius of the pulley wheel. The graph shown in Figure 19 illustrates the electrical and mechanical power used for each test and the equations of each line of best fit. The increase in gap between mechanical and electrical power with the 36mm pipe suggests a fairly large motor efficiency drop as the head is increased. In comparison the efficiency of the motor stays quite constant for the 19mm pipe. This maybe because the lower toques did not push the motors ability and limits as much as the higher torques of the 36mm pipe did.

The R² represents the square of the correlation coefficient. Rooting this value gives an idea of the level of confidence to be had with the results. For the 36mm pipe, 0.87 is very high for the electrical power; however, 0.46 for the mechanical is relatively low. This questions the original thought on motor efficiency.

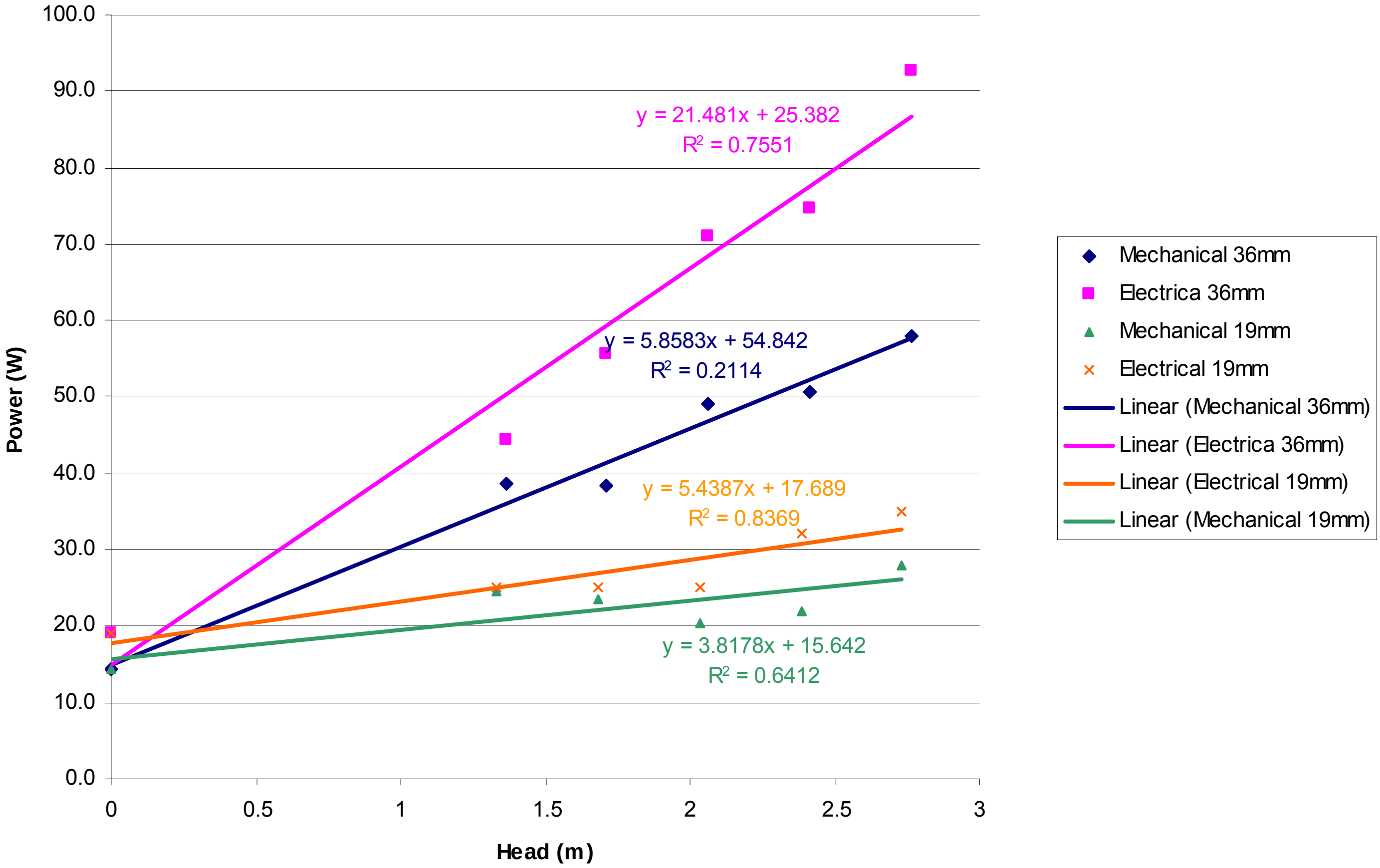


Figure 19 – Graph displaying Power against Head, illustrating model characteristics

5.3 Rope Velocity

Both shaft rpm and rope speed were measured for each test. For the shaft rpm, a max and minimum were recorded and averages found between them. For the rope speed, an average was taken for the stopwatch times of the 5 tests to get an overall average speed of the rope for each length.

The rope slip could then be calculated through subtracting the rope speed measured through the tachometer from the rope speed measured with the stopwatch:

$$slip = v_{stpwtch} - v_T \qquad \textbf{(11)}$$

A percentage of speed loss was the found using;

$$\%\ loss = \frac{Ave.\ slip}{v_{stpwtch}} \qquad \textbf{(12)}$$

The results showed 13% loss for the 36mm pipe and 5% for the 19mm. Although slip must be eliminated to ensure power is not wasted, these percentage losses are quite small and should not affect the results too greatly.

5.4 Flow Rate

The average flow rate was calculated through dividing the volume of water displaced by the time it took. This was repeated for each of the 5 tests on each length. The average flowrate for the 36mm pipe was 0.611 l/s and 0.107 l/s for the 19mm pipe diameter. To calculate how long it would take for the minimum or maximum quantity of water to be delivered in minutes:

$$Time\ (\text{min}) = \frac{Quantity\ of\ Water\ (l)}{Flowrate\ (l/s) \times 60} \qquad \textbf{(13)}$$

This means that using the 36mm pipe, the minimum 1000 litres of water can be delivered in just 28 minutes, and 155 minutes or 2 hours 36 minutes with the 19mm pipe. The sunlight hours in Africa are far greater than these times, so the flowrate is definitely sufficient.

5.5 Torque

Each photo taken looked similar to Figure 20, where the bright background aids the clarity of the spring. After the spring was calibrated, a graph of force applied against extension was plotted, as seen in Figure 21. From the line of best fit, an equation is formed so the force can be estimated at any extension length. The equation of the line of best fit is:

Extension (mm) = (15.38 x Force (N)) + 22.69

Rearranging to find the Force:

Force = (0.06216 x Extension) – 1.478

The Extension of the spring can be found with PhotoDraw by determining the ratio of pixels to millimetres and multiplying it by the extension seen in number of pixels:

$$\Delta L_{Sp(mm)} = \frac{D_{Sp(mm)}}{D_{Sp(pix)}} \times \Delta L_{Sp(pix)} \qquad \textbf{(14)}$$

Figure 20 – Clear image of the force of water acting on the spring

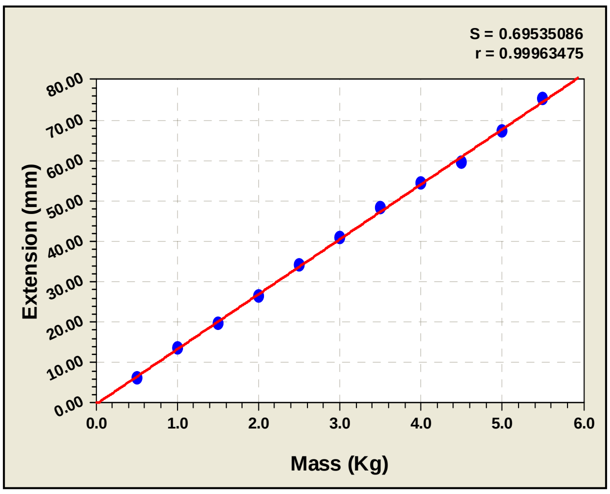


Figure 21 (right) – Graph of spring extension against force applied. The correlation coefficient (r) is very high; indicating the equation for the line of best fit can be relied upon.

5.6 Trial of example Solar Panel

The Electrical Department were able to loan two Solar Shell RSM75 PV modules to test after the experimental results were obtained. The aim of using these panels was to prove the pump and electrical system could really work powered by sunlight alone. The panel was set up on the Queens Library roof (Figure 22), and with long thick wires to minimise resistance, connected to the drill. The measured power output of the panels reached up to 125W in 560 W/m² of irradiance. This was sufficient power to work the pump at a small height of 2.8m. The harnessed power can be calculated theoretically through using the irradiance graph in Figure 23. This information was recorded on the day the panel produced 125W and was obtained through the Bristol City Council Air Quality website. Unfortunately, due to the age of the solar modules, no I-V curve could be found. However, if compared to a similar module, it can be seen that at 600W/m², about 2.5 amps is produced from each module and at about 25 volts. This correlates exactly to the power readings obtained:

(2.5A x 2) x 25V = 125W

Figure 23 – Trials of 150W PV Module on Queens Library Terrace

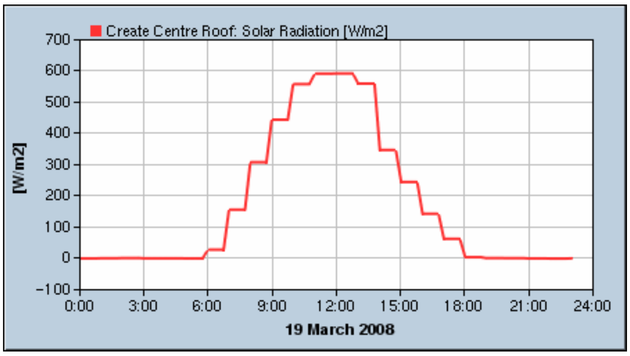


Figure 22 – Irradiation Levels in Bristol on the 19th March 2008 [13]

5.7 Summary

This chapter collects and analyses the results obtained from each set of readings. Using averages for accuracy, graphs are created to give a better idea of the existing forces in a full scale model.

6. Discussion

The initial aim of this project was to analyse the possibility of attaching a solar panel and motor system to the already existing rope washer pump. The results produced should give a general idea of what size and power each component will need to be. The following sections analyse the graphs created for the 3m pump such that motor and panel size predictions can be made for the full 10m scale.

6.1 Selection of Motor

Before the best solar panel can be chosen it is necessary to know what power it needs to provide the motor to operate the pump successfully. Therefore a sufficient motor must be selected first. As stated in the research section, a decision on the motor will be made through the required torque it must provide and the RPM it must continuously output with this applied load. The suitability of the motor type will also come under consideration.

Through the experimentation it was deduced that there is a minimum and maximum speed for the pump to work at. Too slow and the water seeps quickly past the washers back down the tube, and too fast the rope starts to slip on the pulley wheel. After several tests it was decided that 1m/s gave the fasted flowrate without slip.

6.1.1 Gearing

At 1m/s it can be calculated that the shaft speed is close to 120 r.p.m. See **4.2.2** for formula. DC motors commonly have rpm's from 2000 – 3000rpm, unless custom made which is very expensive. Therefore, gearing of some method is required. It would be possible to use extra pulley wheels and have external gearing constructed around the pump. The ratio of the wheel attached to the motor to the wheel attached to the shaft would need to be around 20 to 1. This is possible, and could be cheaper, but will be assessed in more detail next year. Instead, for the purpose of this project only, it will be assumed that gearing is required within the purchased motor.

So, the selection of motor will be based on this rpm and the predicted torque for a pump with 10m of head. To ensure the torque predictions are correct, we can compare the power of the chosen motor (after efficiency drop) to the predicted mechanical power of the pump at 10m.

Two pipe diameters were used and each one will be analysed separately and compared in the conclusion.

6.2 Large Pipe Motor

Using Curve-Expert, the equation for the line of best fit in Figure 24 is;

$$y = 1.375 + 1.071x.$$

The equation can be used to predict the torque with 10m head, which is 12.1 Nm.

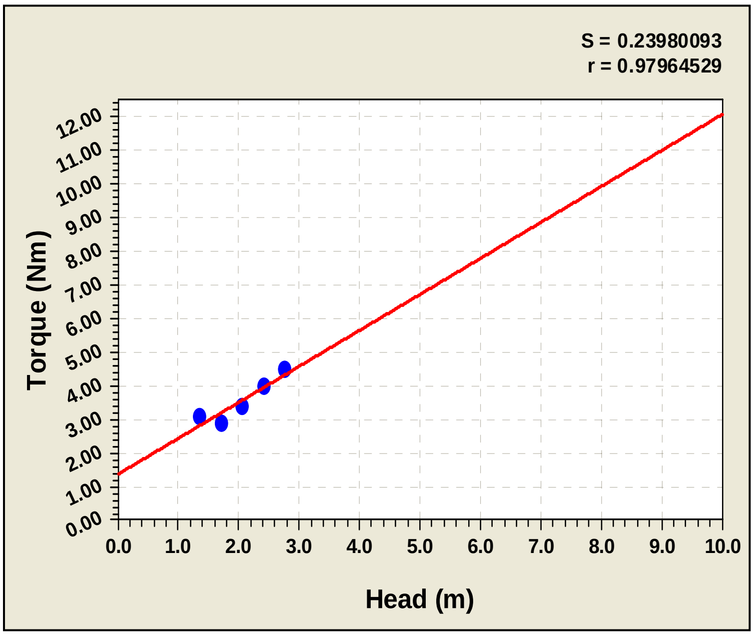


Figure 24– Graph to represent results, and line of best fit, of measured torque against the height of head in the 36mm diameter pipe.

6.2.1 Accuracy

Curve Expert 1.5 automatically gives a standard error (S) and correlation coefficient (r) for the input results, these combined give an estimate of the confidence levels that can be assumed.

The results for the 36mm diameter pipe produced a relatively accurate line of best fit. With such a high correlation coefficient of nearly 0.98, and low standard error of around 0.24, there can be a lot of confidence that the predicted torque with 10m of head is correct.

6.2.2 Safety Factor

It is important that the chosen motor does not fail. If it did, the owner could have wasted up to 10 years worth of wages, and this will seriously affect the survival of the family. Therefore it is necessary to incorporate a safety factor for the torque required. Safety factors vary from machine to machine, but as this is a low risk application (mechanically) and cost has a huge impact, the safety factor will be relatively low at 1.5. The required motor torque then becomes 18Nm.

6.2.3 Motor Specifications for Large Pipe

The resulting motor specifications are now:

- Gearing to achieve 120rpm
- 18Nm
- Inexpensive
- DC
- Maintainable

Initially it was planned to hopefully find manufactures in and around Africa. However, this proved exceptionally difficult to do without having a direct contact out there. For the preliminary work, a motor will be chosen from a UK company.

6.2.4 Parvalux Selection

RS-Components usually advertise several companies' products and compare them in one list. However, all the DC motors around these specifications came from the same manufacturer – Parvalux. Their slogan: Reliability – Worldwide – Customisable.

The Parvalux website takes you through several stages to find the ideal motor:

Type of Motor: Previous research shows that a Permanent Magnet DC Motor has the most preferred characteristics for this application. It is one of the least expensive and easy to maintain.

Gearbox [14]: The minimum rpm without a gearbox for a PM motor is 1500, making a gearbox essential. The following gearboxes were available:

- Worm and Wheel
- Inline Double Reduction
- Multi-Spur
- Inline Multi-Spur

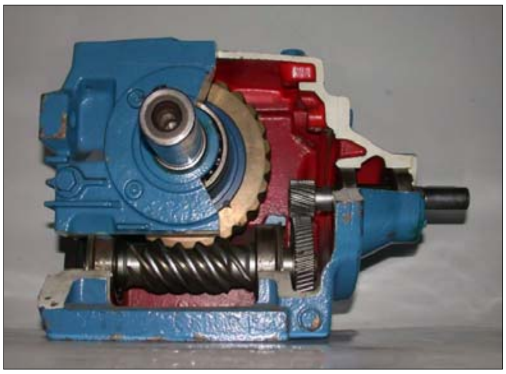


Figure 25 – Cut-out section of Worm & Wheel Gearbox [14]

The simplest and most efficient gearing mechanism is the Worm and Wheel. The large wheel driven by the worm gear also produces high torques, but at a much lower rpm, the most sensible choice. There are still several types of Worm and Wheel gearbox to choose from, but only one had the ability to output over 17Nm of torque; The 'Giant Single Worm and Wheel', as seen in Figure 25.

Final Product [14]: In selecting a final motor and gearbox configuration, it is important to ensure the motor rating could establish 120rpm with 18Nm of Torque. To ensure sufficient power Parvalux provide the data shown in Table 3, indicating the required ratio to achieve a desired torque and rpm. As can bee seen, 120rpm does not exactly reach 18Nm. After contacting Parvalux it was discovered the website is still displaying the old readings. The new models would indeed reach 18Nm at 120rpm with the 25:1 ratio. This leaves a motor rating of 337W, with product identification PM95-G.

Gearbox Specification Motor Speed 3000 r.p.m.		PM 95 G Motor Rating 337 watts
GEARBOX	FINAL	OUTPUT TORQUE (Nm)
RATIO	RPM	COMPOSITE
75:1	40	30
60:1	50	29
50:1	60	27
30:1	100	18
25:1	120	16
12 1/2:1	240	10

Table 3 – Parvalux provided method for finding motor rating, ratio and rpm.

Voltage, Current & Efficiency [15]: Due to the nature of solar panel power output, having a 12V motor would not be an efficient way of getting the most power from the panel as possible. As the 'knee' (Figure 10) is over 20V, it is sensible to select the 24V motor, otherwise to achieve sufficient power; a very large current would be required. Below are the formulas for calculating the total efficiencies and Output Power for the motor and gearbox system. The following Table 4 gives the final properties of the chosen motor.

Output Power; $P_O = \frac{T \times RPM}{60} \times 2\pi$ **(15),**

Efficiencies; $\eta_G = \frac{P_O}{MR}$ **(16),** $\eta_M = \frac{MR}{P_I}$ **(17),** $\eta_{Ttl} = \frac{P_O}{P_I}$ **(18).**

Code	Current	Voltage	Total Input	Torque	RPM	Total Output	Gearbox Eff	Motor Eff	Total Eff
PM95-G	17.6A	24V	422.4W	18.5Nm	120	232.5W	69%	80%	55%

Table 4 – Calculated properties of the PM95-G DC Motor.

Expenditure [15]: For further testing, it may be desirable to purchase a single motor and gearbox combination. However, in the future, when mass production of the pump and solar panelled system is a possibility, many more will be desired and hence the price will fall. So for future reference:

- Cost of one PM95-G = £268.98.
- Cost of over 1000 PM95-G = £70.40 per motor.

6.3 Small Pipe Motor

The equation for the line of best fit in Figure 26 is ***y = 1.482 + 0.050x***. The predicted torque with 10m head is then 1.98Nm.

6.3.1 Accuracy

It is obvious from the graph that the 19mm results were not nearly as consistent as they were for the 36mm. The correlation coefficient is very low at 0.32, suggesting the results obtained should not be relied upon. It would appear that the torque for the 19mm pipe is almost staying constant at around 1.7Nm, however, the points still managed to create a basic line of best fit. The reason behind the constant results could be because the rope diameter was unchanged from the 36mm pipe. This meant that the proportion of volume taken up by the rope was much greater in the 19mm pipe than in the 36mm pipe. Therefore, the volume taken up by water was much less in the smaller pipe diameter and also changed a lot less with different pipe lengths. This also meant that other slight changes to the experimentation (adjusting bottom guide etc), made a much larger impact to the results as they would have done with the 36mm pipe. Although inaccurate, these results can still provide a basic idea of how much power a motor would require to run the pump with the 19mm pipe diameter.

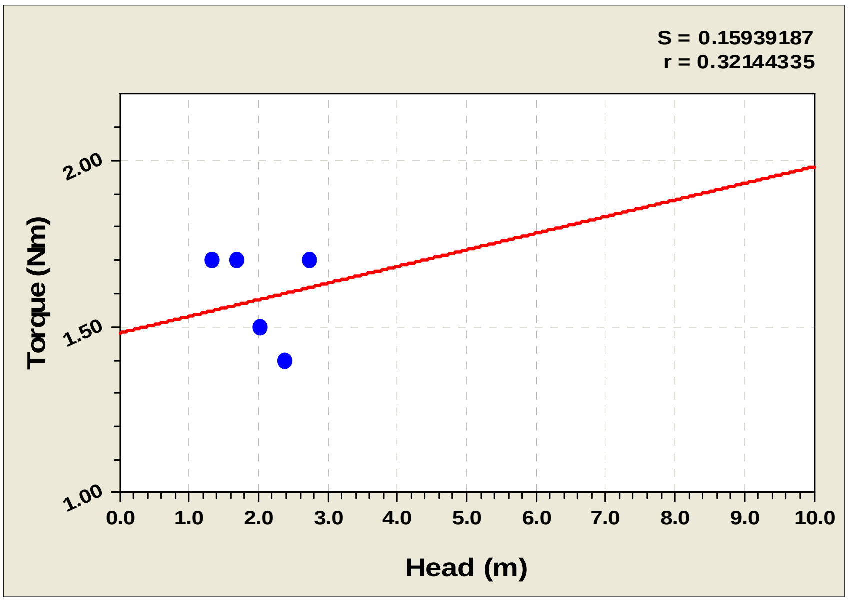


Figure 26 - Line of best fit through measured torque against the height of head in the 19mm diameter pipe.

6.3.2 Safety Factor

Due to the very poor accuracy of these results it is sensible to assume a much larger safety factor is required. With a safety factor of 3, there can be much more confidence that the pump will run at 10m.

6.3.3 Motor Specifications

The resulting motor specifications are now:

- Gearing to achieve still 120rpm
- 1.98Nm x 3= 5.94Nm
- Inexpensive
- DC
- Maintainable
- Power around 160W

Again, for preliminary work, Parvalux will be used to select the initial motor and gearbox combination.

6.3.4 Parvalux Selection

The type of motor to select remains unchanged, as the qualities required from the motor are unchanged. However, the gearbox will need re-evaluating using the provided data in Table 5.

Gearbox[14]: The Worm and Wheel gearing is still the best choice, but now the torque is much less and so Giant is no longer required. Instead the torque and rpm fall in the range of *25 - 970 R.P.M. / 0.3 - 11.8 Nm,'* which correlates to the *'Medium (Base Pad) Single Worm & Wheel (MB)'* on the Parvalux website.

Gearbox Specification Motor Speed 3000 r.p.m.		PM 50 MB					
		CONT		1 Hour		15 MIN	
		Motor Rating 155 watts		Motor Rating 200 watts		Motor Rating 280 watts	
GEARBOX	FINAL	OUTPUT TORQUE (Nm)					
RATIO	RPM	COMPOSITE	BRONZE	COMPOSITE	BRONZE	COMPOSITE	BRONZE
60:1	50		7.9		7.9		7.9
48:1	62		7.9		7.9		7.9
40:1	75		8.8		11.3		11.8
36:1	83		8.0		10.3		11.8
33:1	91		7.8		10.0		11.8
30:1	100	7.2			9.3		11.8
25:1	120	6.5			8.4		11.5

Table 5 - Parvalux provided a method for finding motor rating, ratio and rpm.

Final Product [14]: To be safe, the motor with the largest power rating should be selected, and again the data tables show how with a 25:1 ratio, 120 rpm can be achieved with a continuous load of 6.5Nm. The 'composite' column refers to the material of the gears. For both gearboxes bronze is available but at a much higher cost and actually displays disadvantages for this application. So the motor and gearbox power rating is 155W, and has product identification code PM50-MB.

Voltage, Current & Efficiency: As most solar panels of the size needed for this project have output voltages well above 16V, it is still sensible to select a 24V motor. Parvalux provide a figure for the current required, for the PM50-MB, to achieve maximum torque which is 9.4A. To find the efficiencies, the same formulas can be used from section **6.2.4**, as shown in Table 6 below.

Code	Current	Voltage	Total Input	Torque	RPM	Total Output	Gearbox Eff	Motor Eff	Total Eff
PM50-MB	9.4A	24V	225.6W	6.4Nm	120	80.4W	52%	69%	36%

Table 6 - General properties of the chosen motor for the 19mm pipe pump.

Expenditure [15]: The same cost analysis applies for the 19mm diameter pipe. Prices were obtained through customer services at Parvalux.

- Cost of one PM50-MB = £141.20.
- Cost of over 1000 PM50-MB = £43.75 per motor.

6.4 Solar Panel Selection

Now that the wattage required to power the two motors is known, a solar panel for each pipe diameter can be selected. However, as water is such a necessity, the pump is required to work everyday. This means the panel must have an output sufficient to power the motor everyday, including overcast days. Therefore each panel should be chosen with a much higher power output than will normally be needed. This signifies a need for energy storage (as when it is sunny – there will be excessive watts produced). However, there is another option. On cloudy days, when the pump will not work, it will be hand powered. This implies that the point and aims of the projects have been missed, but because Africa has such a sunny environment, there will be very few days in the year where the pump will not work – and the money saved through not having an oversized panel may make it the better option.

The graph in Figure 6 of research section **2.1.3** suggests the lowest horizontal radiation comes in May. Figure 27 below displays the irradiation levels on an average day in May – the worst case scenario, and in October – the best case but also when drought is most likely to hit.

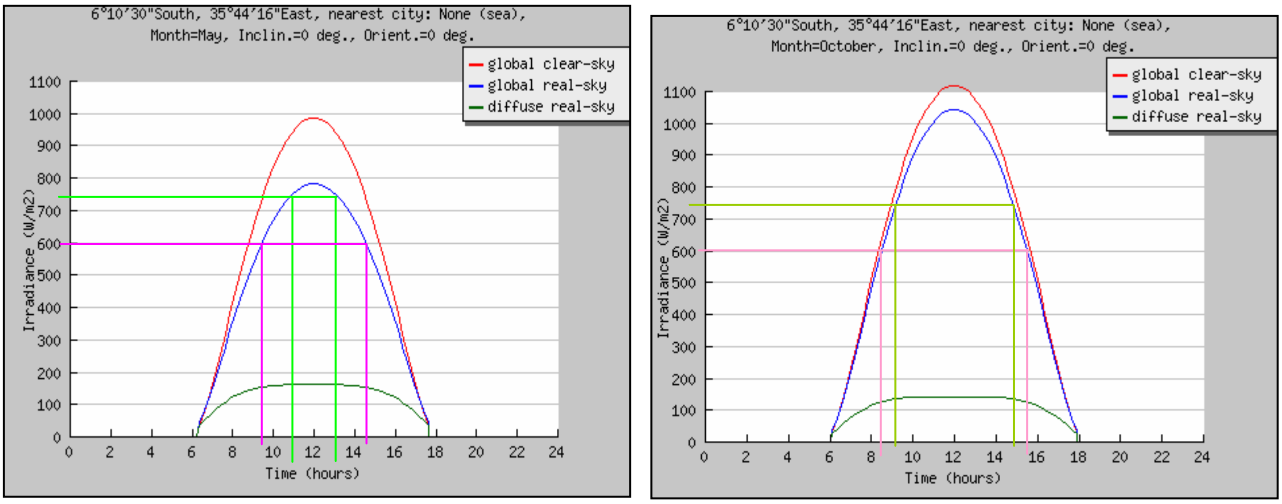


Figure 27 – Irradiation Levels in May (left) and during the drought season, October (right) [7]

Diffuse real-sky is the sunlight reflected off objects on earth onto the solar panel; Global real-sky is the irradiation received by the panel on a cloudy day; and Global clear-sky is the irradiation levels that can be expected if there are absolutely no clouds. Our base readings, then, should be taken from Global real-sky on the worst day, as this is the worst the panel will be receiving.

However, there is still the minimum quantity of water per day to be guaranteed. With reference to the PDS, this is 1000 Litres. To calculate how many hours of pump use will be needed, the flowrate for each pump will be required.

6.5 Solar Module for Large Pipe

The average flowrate for the 36mm pipe is 0.611 litres per second. Therefore, the time taken to pump 1000 litres will be 1636.7 seconds, which is about 27 minutes. This is very fast, and somewhat unnecessary for a small family. Though there may still be a use for it in small communities, bearing in mind that in 6 hours, 13200 litres can be pumped.

If the pump was indeed required to deliver only 1000 litres, a solar panel could be chosen that can power the 422W motor with 750 W/m² of radiation. This is because on the worst case scenario day, there will be 750 W/m² for at least 27 minutes, as shown by the bright green line in Figure 43.

This though would be a large waste of money. Instead a panel could be chosen that will produce 422W with much less irradiation, closer to 600 W/m², as illustrated by the bright pink line. Now the pump will use the daylight hours more productively and deliver 5 hours worth of use. For both cases on a better day in October, the useful hours will increase massively to nearer 7 hours at 600 W/m² (15400 litres), and 5 hours at 750 W/m² (11000 litres).

The reason for having a more powerful solar panel is to get more for your money, because despite paying more, the water displacement is much larger. The previous paragraph is summed up in Table 7 below:

Panel Rating	Irradiation level that will power motor	Hours of Use on a bad day	Water displaced	Cost of Panel
2x260W	750 W/m²	2	4400 litres	£800
3x260W	600 W/m²	5	11000 litres	£1200

Table 7 – Finding Equilibrium between Price and Efficiency [16, 17]

From Table 7, it can be calculated that for 2.5 times the water production, you are paying only one and half times more money.

6.5.1 Panel Suppliers [16-20]

There are several companies in the UK and Tanzania that can supply panels and there are 4 main manufactures; Suntech, Sharp, Kyocera, and BP Solar. These are compared in Table 8. There are other smaller companies, but these cannot offer the same range and prices.

Supplier	Manufacturer	Range	Location
Solar Century	Suntech/ Sharp/ Sunpower	15 - 260W	UK, Spain, France
African Energy	Suntech/ Photowatt	20 - 165W	Africa Only - ship from every continent to provide the most efficient delivery channels.
Umeme Jua	Kyocera	50 - 130W	Tanzania, Africa
MonoPumps	BP Solar	150W - 1800W	World Wide

Table 8 - Comparison of Companies and Manufactures Available [16-20]

The 36mm pipe pump will require 422W of power. To achieve maximum torque, it is essential enough current reaches the motor. As can be seen in Figure 28, at 500 W/m² only about 4 Amps will be produced, therefore to get over 17 amps, five panels will need to be joined in parallel.

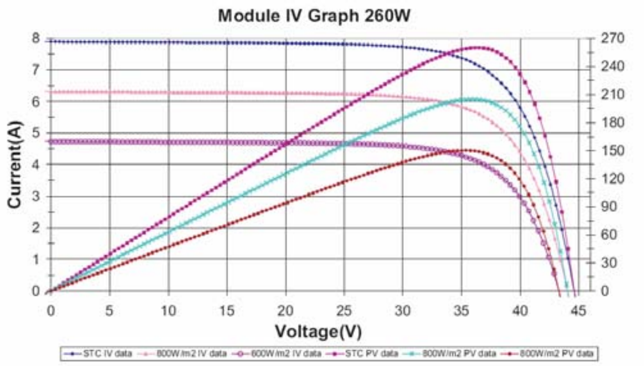


Figure 28 – IV characteristics of a large 260W Solar Panel.

Panel	Manufacture	Power (W)	Number required to achieve 17A at 24V	Actual power achieved at 600W/m	Cost per panel	Total Cost	Type
STP130 S-12/Tb	Suntech	130	4.88 (5)	432W	£540	£2,700	Mono
STP130-12/Tb	Suntech	130	4.88 (5)	432W	£540	£2,700	Poly
STP200 S-18/Ub	Suntech	200	3.66 (4)	480W	£808	£3,232	Mono
KC130G HT -2	Kyocera	130	5.49 (6)	456W	£480	£2,880	Poly
KC175G HT-2	Kyocera	175	4.00 (4)	422W	£647	£1,294	Poly
ND-N2ECUF	Sharp	142	5.49 (6)	461W	£350	£2,100	Multi
ND-167U1Y	Sharp	167	4.7 (5)	450W	£676	£3,380	Multi
BP3125	BP Solar	125	4.62 (5)	456W	£448	£2,240	Poly
BP3165	BP Solar	165	5.49 (6)	660W	£566	£3,396	Poly

Table 9 - Comparisons of solar panel options for the 36mm pipe and the respective prices. [8, 18, 20, 21]

The IV curves of some solar panels over 100W, like Kyocera, are very similar on the y-axis. This means that despite larger panels producing much higher voltages, they are not necessary to achieve high currents. In fact, because the motor is 24V, there is no need to have a panel that can produce 40V. So instead many smaller sized panels can be joined in parallel to achieve the same necessary power for much less money.

Table 9 compares not only the different manufactures prices, but also the type of cell – mono-crystalline or polycrystalline, the number of panels required, the total power produced with this number of panels, and the total cost of buying what is necessary. The table assumes the panel will produce enough power at 600W/m², and the data is calculated from the individual IV curves of each panel as can be found through the manufacturer's websites.

6.6 Solar Module for Small Pipe

The average flow rate for the 19mm pipe is 0.107 litres per second. This is much slower than the 36mm pipe, but it also uses much less power. The time now taken to pump the minimum 1000 litres becomes 9345.8 seconds, which is 2 hours 36 minutes.

The droughts usually come when the temperature is highest and hence the irradiation at its peak. At this time, the water is most valuable and is heavily required to keep the crops from dying over such a tough period. Fortunately, pumping water to the 5000 litres a day mark will become, at this time, much closer. As can be seen in Figure 43, the graph to the right resembles one of these days during a possible drought. Unlike in May, 600W/m² is now available for 7 hours a day. If a panel was chosen that can power the motor with just 600W/m², then in 7 hours, 2700 litres can be pumped.

6.6.1 Panel Suppliers

With a 19mm pipe diameter the pump will require a 226W motor. With this motor, 9.4 amps of current will be required to ensure the maximum torque is established. The same principles of combining panels apply for the 19mm as they did for the 36mm. Therefore, the data in Table 10 below again compares the manufacturers and the number of panels required to achieve 9.4 amps and 24 volts. The base irradiation level will be kept at 600W/m² because of the slow flow rate. It will now take longer to achieve the minimum 1000 litres, and so daylight hours must be used productively.

Panel	Manufacture	Power (W)	Number required to achieve 17A at 24V	Actual power achieved at 600W/m	Cost per panel	Total Cost	Type
STP085S-12/Bb	Suntech	85	4.27 (5)	264W	£331	£1,655	Mono
STP130S-12/Tb	Suntech	130	2.7 (3)	250W	£540	£1,620	Mono
STP200S-18/Ub	Suntech	200	1.95 (2)	230W	£837	£1,674	Mono
STP200-18/Ub	Suntech	200	1.95 (2)	230W	£837	£1,674	Poly
KC130GHT - 2	Kyocera	130	2.75 (3)	245W	£480	£960	Poly
KC175GHT-2	Kyocera	175	2 (2)	225W	£647	£1,294	Poly
ND-123U1	Sharp	123	3.83 (4)	235W	£322	£1,288	Multi
ND-N2ECU	Sharp	142	2.92 (3)	230W	£370	£1,110	Mulit
ND-200U1	Sharp	200	2.03 (2)	224W	£483	£966	Multi
BP3125	BP Solar	125	2.47 (3)	274W	£448	£1,344	Poly

Table 10 - Comparisons of solar panel options for the 19mm pipe and the respective prices.[8, 18, 20, 21]

6.7 Energy Storage

As can be seen from the 'Actual Power achieved at 600W/m²' column in both tables, there will be wasted energy created with this light intensity. This also means that with higher light intensities even more energy will be wasted. The most sensible solution would be the integration of a battery into the system. With the correct circuitry, the load from the motor will draw all the energy it requires, and the remaining power produced by the solar panel will be put to charging a battery.

6.7.1 The Circuit

The circuit must include a diode to ensure the battery does not push current back to the panel when the motor stops. It would also be desirable to include a switch so the motor can be run by the battery when the panel is unavailable. There are of course many other additions that could make the circuit

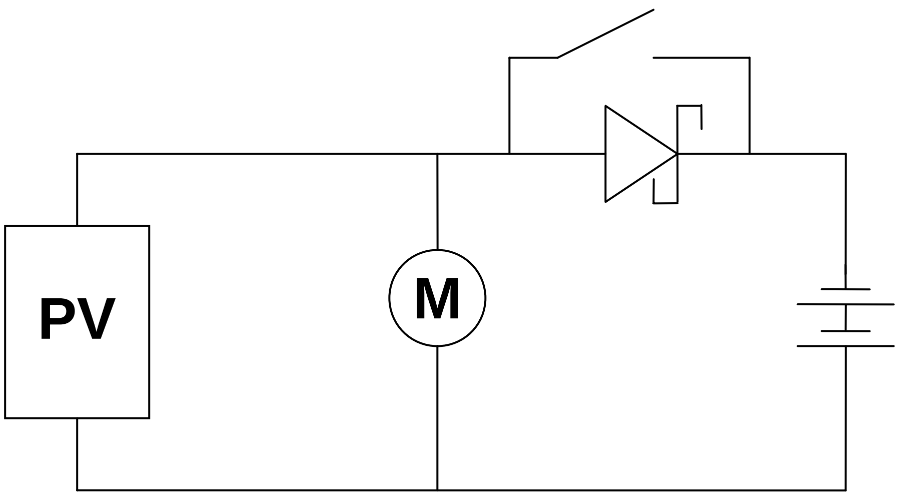


Figure 29 – Solar Module Circuit including Battery

better, but the diode and switch are the essentials, keeping cost to an absolute minimum.
With the circuit in Figure 29, the PV cell will primarily power the motor, but when there is excess power being created, it will also charge the battery. When the battery is charged, it can either be removed from the circuit and used for other appliances, or it can be used to power the motor if the panel is being repaired, or at night.

6.7.2 The Battery [22]

The battery stores energy in an electrochemical form, and is a very common method of energy storage as electricity is such a versatile type of power. There are a few essential characteristics required from the battery, mainly the ability to be deep-cycle charged, where the battery is suitable for repeated full charge and discharge cycles. There are many types of battery, but the most commonly used are displayed in the table below. Comparing characteristics in Table 11 will help identify the best choice.

Type of Battery	Positives	Negatives
Lead-Acid	High performance-over-cost ratio.	Least energy density by weight and volume.
Nickel-Cadmium	Half the weight, longer deep-cycle life, and more temperature tolerant than Pb-acid	Degrades if not used. Not so environmentally friendly.
Nickel-Metal Hydride	Improvement in energy density over NiCd. Negligible memory effect (does not degrade).	Less capable of high peak power, high self-discharge rate, damaged easily with over-charging.
Lithium-Ion	3 times energy density of Pb-acid. Higher cell voltage. Lower manufacturing cost.	Thick electrodes required and so more expensive than NiCd. Requires elaborate circuitry.

Table 11 - Comparing deep-cycle batteries on the market [6]

Through process of elimination it can be seen that a Lead-Acid battery would be most suitable. Lithium-Ion will be too expensive for this application, Nickel-Metal Hydride discharges very easily and has poor durability, and Nickel-Cadmium is not environmentally friendly and degrades if not used regularly. The downsides to having a battery are the necessary expenses. The battery can be seriously damaged if over charged. To prevent this, either a close eye must be kept on the 'guideline' charge level, or a regulator should be added to the system.

For the 36mm pipe, two batteries would be required, each costing up to £148, and the regulator around £95. The 19mm pipe would require similar prices. However, if the battery was not used to power the motor, a much smaller and cheaper option could be found. In the UK, batteries can be found for around £60 that will run for up to 6 hours until recharging is needed, but a regulator would still be required, costing around £70. Batteries and regulators can be found from companies in Africa and Tanzania, and are likely to come at a cheaper rate – further research should unfold the true expense necessary.

6.7.3 Diode [23]

The diode prevents the fully charged battery pushing current back into the solar panel which could cause serious damage (discharge-protection). The switch around the diode effectively removes it so the motor can be run off the battery. The most commonly used diode in solar systems is the Schottky. They are usually inexpensive and so it is just a matter of selecting a suitable model that will take the maximum current and voltage found in the system. The diode will create a slight voltage loss, but this would be negligible.

36mm: Max I = (no. panels x max current) = 4 x 8 = 32A, Max V = panel max = 35V

19mm: Max I = 3 x 8 = 24A, Max V = 26V

RS-components: 36mm requires a *Schottky barrier diode, STPS6045CPI 60A* at £6.49 each.

And the 19mm requires a *Dual Schottky barrier diode MBRB2560 30A* at £1.27 for 5.

7. Conclusion & Future Work

7.1 Large Pipe

Most of the prices were found from a British website; however there are many websites and suppliers that offer many variations in price. There are also the contacts in Tanzania who offer panels after shipment to Africa, which is of course slightly more money.

7.1.1 Panel Selection

The obvious option for the 36mm pipe is the Kyocera KC175GHT-2. The characteristics of this panels IV curve show that with 4 panels in parallel, at exactly 600W/m², there will be 422W of power produced. The lack of wasted energy and small number of panels compared to other option subsequently means the price is the lowest at £1,294.

This panel comes with an aluminium protective case which should keep the harsh environment at bay, as well as provide a means of security. Each panel has a life-time warranty of 20 years.

7.1.2 Total Cost

Where possible, prices were obtained for single component purchase and for purchases of over 100. This presents a more realistic total price as shown in Table 12.

Component:	**Panels**	**Motor**	**Batteries**	**Diode**	**Regulator**	**Total**
Cost of one:	£1,294	£270	£150	£7	£95	£1,816
Cost of multiple:	*£1165*	£70	*£135*	£4.87	*£86*	*£1461*

Table 12– Sum of total electrical system for prototype purchase and mass-production purchase. Italics are assumed discounts.

Where the cost of multiple components was unknown, a 10% discount was assumed, just to get a better idea. These prices could be due a fall if module costs continue their price trend, however, it is too unpredictable to take into account at this stage.

7.1.3 Conclusion

In terms of delivering 1000 to 5000 litres of water a day, this system exceeds expectations. From Table 13 it can be seen around 11000 litres can be produced on the worst case scenario day. However, it is obvious that the price is far too great for a single family. The initial aim of £500 is far out of reach with the predicted price about triple the target price. This electrical system could still have potential in larger communities though. Where more water is required, and more money is available, perhaps in schools and hospitals or small villages.

System	Total Cost	Water Provided on Bad Day	Cost per Litre a Day
36mm	£1816	11,000 L	17p
Multiple 36mm	*£1461*	11,000 L	13p
19mm	£1232	1,930 L	64p
Multiple 19mm	*£1026*	1,930 L	53p

Table 13 – Cost of One Litre per Day

7.2 Small Pipe

7.2.1 Panel Selection

For the 19mm diameter pipe, the best panel option would likely be the cheapest. In this case the Kyocera KC130GHT-2 and the Sharp ND-200U1 stand out. Although the Kyocera is slightly less, it is likely that once shipped to Africa, or purchased from Tanzania, the prices will be very similar. The table in section **6.6.1** gives a broad idea of the relative panel costs compared to each other. Either option has advantages and disadvantages; it is know the Kyocera is available in Tanzania, but 3 panels would be required – usually result in higher costs for wires etc. The Sharp is definitely around in the UK, and fewer panels are needed, but the manufacturer may not have any contacts in Africa. Either way the price looks to be around £960 in total.

This panel also comes with an aluminium protective case which should keep the harsh environment at bay, as well as provide a means of security. Again the panel has a life-time warranty of 20 years.

7.2.2 Total Cost

Table 14 outlines component prices found from UK websites.

Component:	Panels	Motor	Battery	Diode	Regulator	Total
Cost of one:	£960	£141	£60	£1.27	£70.00	£1,232
Cost of multiple:	*£864*	£44	*£54*	£0.84	*£63.00*	*£1,026*

Table 14 - Price of buying one system, and the price of buying multiple systems. Italics are assumed discounts.

Again 10% discount was allowed for unknown prices.

7.2.3 Conclusion

Although much less expensive than the 36mm piped pump, the 19mm still doubles the target price. Therefore it would still only be a realistic choice for the wealthier families, of which are few. Again there may be a market for this pump around schools and hospitals, or maybe a very larger family. However, this project can be expanded and further research is likely to show more ways of cutting the cost. Money could be saved in the choice of solar panels, or in a less expensive and more efficient motor.

Without the inclusion of a battery, each pump could be significantly cheaper as illustrated in Table 15.

System	Cost with Batteries	Cost Without Batteries
36mm	£1816	£1564
Mulitple 36mm	£1461	£1235
19mm	£1232	£1101
Mulitple 19mm	£1026	£908

Table 15 – Price comparison with and without energy storage.

This may be an initial solution for some families, who can consider purchasing the battery in the next few years after the basic panel and motor have been invested in. This way they will not spend all there money at once and risk much less.

7.3 Comparison

Before the project started, a questionnaire was filled in for another solar pump company by the name Mono Pumps. The details of the same PDS for this project were passed on and Mono Pumps responded with a solution. The 'Solar Drip System' offered had a peak flowrate of 0.153 L/s, this is just slightly more than the 19mm pipe in this project and can produce 3864 litres in 7 hours. The 19mm pipe will only deliver 2696 litres in the same time. However, the downside to the Mono Pumps model is the cost. At £2080 per pump, the expense required is almost doubled, and the system does not come with a battery that can be used for other applications. The Solar Drip System is also an enclosed design, so if any damaged occurred – it would be very difficult to repair locally. Although this project and Mono Pumps are not in competition, it is obvious that our system has huge potential and with a little more work can become a real solution to the water crisis in Africa.

7.4 Future Work

When work resumes on this project, there are several areas that should be assessed first. The problems encountered in this first experimentation must be reviewed and hopefully removed. With the following variables and problems removed, a consistent set of results can be created for the 19mm pipe.

7.4.1 List of Improvements to be considered

- Drill
  - Fluctuations when drill is hot – due to efficiency drop
  - Trigger – unnecessary resistance and complexity
  - Only designed for short bursts – now a more suitable motor can be purchased

- Power pack
  - Automatically switched to voltage mode if current very low – makes life difficult
  - Not very accurate (to 1dp) – maybe unavoidable
  - Voltage varied a lot – also due to drill fluctuation (change of motor should avoid this)
  - Could not adjust both I and V simultaneously – difficult to imitate PV module
  - Copper wires – this project considered these losses negligible

- Wheel (large and small)
  - Initially too large – created too higher torque for motor (choose better motor)
  - Very heavy – needs to be more like actual wheel used
  - Slip limit speed – greater diameter would reduce slip
  - Profile and material large factors in effecting slip

- Bottom bracket
    - Could not use concrete - Metal rusted, should mould concrete guide for accuracy
    - Inconsistent positioning created unpredictable friction levels - secure

- Bearings
    - Not constant application of grease – friction would vary
    - Wood – simple replacement?

- Spring balance (tension readings)
    - Initially too large to fit smoothly through pipe
    - Difficult to read as inside pipe!
    - Eventually opted to take apart spring balance and use just spring – this required photos for comparisons and calibrations – photos were poor quality
    - Ensure spring doesn't catch and stretch pass max yield

- Other prototype issues
    - Measuring flowrate – splashing meant volume measure may not have been perfect
    - Tachometer varied a lot – also due to drill speed variations
    - Impossible to have speed at exactly 1m/s – replace drill!
    - Time limited for doing more tests
    - Small washers smaller than knots! Pins required? – thinner rope should be used
    - Small diameter – rope way to thick – inefficient, when doubled only just fitted through pipe – unrealistic

7.4.2 Progression & Recommendations

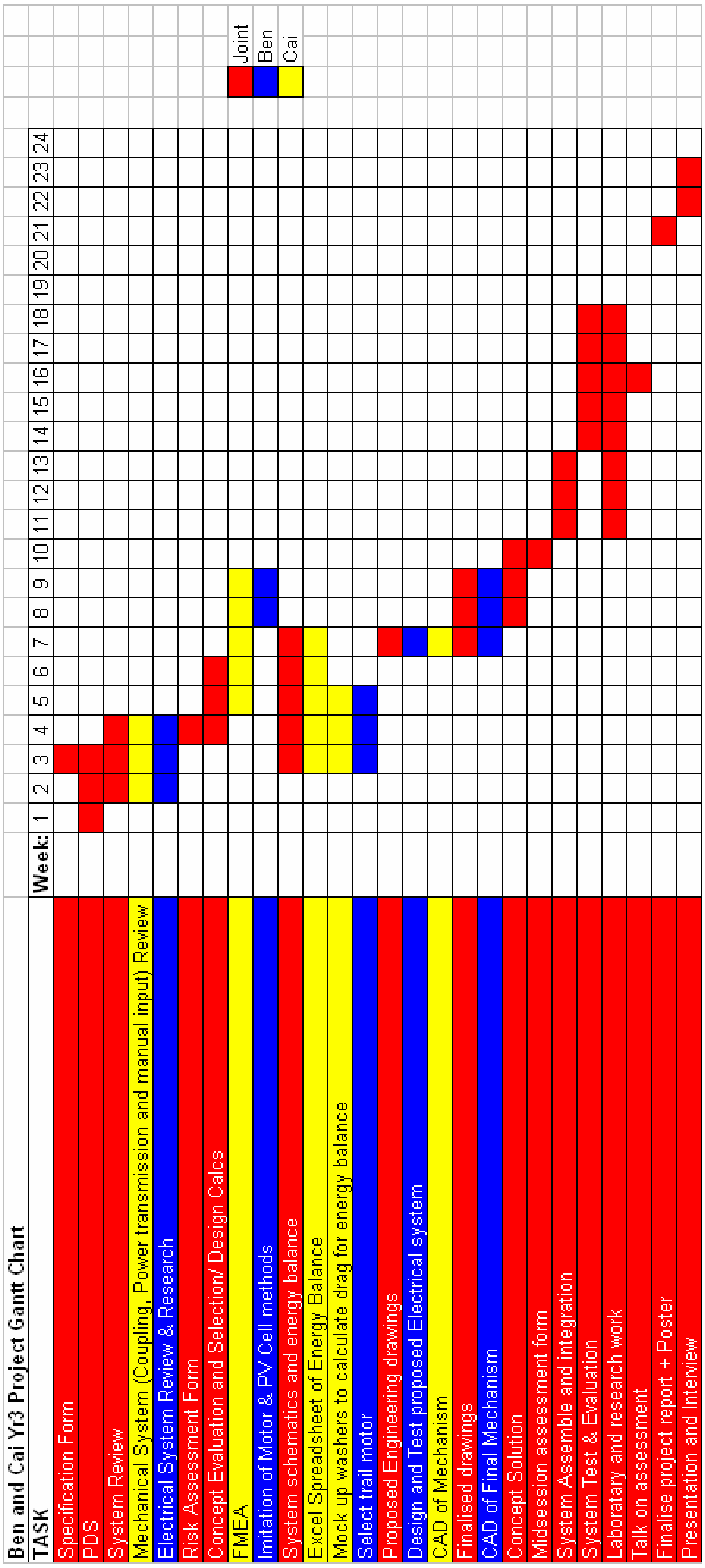
The next step is removing the inconstancies mentioned above, and then trialling the pump with preferably more diameters and longer lengths. If an exact full scale model of the pump in Africa can be made, then the test results can be analysed with very high confidence. This could lead onto better diagrammatic demonstrations, such as a Failure Modes and Effects Analysis (FMEA). From these results, and using this reports information, money can be confidently invested in a motor that will definitely work.

With testing different diameter pipes, a dimension may be found that matches motor and solar panel properties better, so the flowrate is sufficient over a period of time that allows the panel to exert enough power without being too large and expensive.

More research is also required to find the most suitable battery. It has got to the stage where official pricing and availability should be analysed. New products on the market may be useful, but are likely to be very expensive.

This project has made it apparent that the component selection process, similar to Phal and Beitz's model, would perhaps be more efficient if run backwards. Instead of finding all the relevant loads and then creating specifications for a motor and panel; the panel should be purchased first in relation to the money available. From the panels most suitable level of power output a motor can then be selected that matches this level. Then using the motors known torque and rpm rates, a model pump can be built that will not exceed these limits. Altering the mechanical components such as the size of pulley wheel and pipe diameter can reduce the torque required. This method should save a considerable amount of money, and would likely find the best equilibrium between cost and efficiency.

Appendix – Gantt Chart



Results Chart (Averages and Dimensions only)

L_{rm} (Rising Main Length) (m)	2.885	2.535	2.185	1.835	1.485	0
H (Head Ave) (m)	2.733	2.383	2.033	1.683	1.333	0
I (Current) (A)	5.6	5.3	4.8	4.8	4.7	3.7
V (Voltage Average) (V)	6.4	5.8	5.0	5.2	5.3	5.2
Max Elec Power per length (W) exc.dry	**37.04**	**33.20**	**25.88**	**26.01**	**26.11**	**20.2**
Min Elec Power per length (W) exc.dry	**33.00**	**31.13**	**24.18**	**24.33**	**23.82**	**18.0**
Ave Elec Power per length (W) exc.dry	**35.02**	**32.16**	**25.03**	**25.17**	**24.96**	**19.1**
t_r (Rope Rotational Time) (s)	5.82	6.51	7.37	7.07	6.68	6.56
Rope Velocity (m/s)	1.24	1.11	0.98	1.02	1.08	1.10
Ave rope speed per length (m/s)	**1.23**	**1.20**	**1.00**	**1.05**	**1.07**	**1.11**
Shaft Speed ave (RPM)	120	110	90	100	105	110
Rope slip velocity ave (m/s)	0.0559	0.0231	0.0912	0.0340	0.0443	0.0146
Rope Slip (%)	5%	2%	9%	3%	4%	1%
Total Time (s)	82.50	85.60	129.30	103.80	97.00	
Flow rate (l/s)	0.121	0.117	0.077	0.096	0.103	0.000
Ave FR per length (l/s)	**0.120**	**0.131**	**0.082**	**0.097**	**0.102**	**0.000**
Flow rate ideal (l/s)	0.352	0.315	0.278	0.290	0.307	0.312
Picture Number	2959	3011	3037	3067	3087	3145
Spring Width (pix)	10	10	10		11	
Spring Length (pix)	38	35	33		38	
Spring Aspect Ratio	3.8	3.5	3.3	#DIV/0!	3.5	
Force (N)	26.0	22.3	19.8	#DIV/0!	21.7	17.2
Torque (Nm)	1.94	1.66	1.48	#DIV/0!	1.62	1.28
Force Ave (N)	26.0	18.0	19.8	24.8	22.2	15.6
Ave Force per length (N)	**22.8**	**18.3**	**20.4**	**22.5**	**22.3**	**17.5**
Torque Ave (Nm)	1.9	1.3	1.5	1.8	1.7	1.2
Ave Torque per length (Nm)	**1.7**	**1.4**	**1.5**	**1.7**	**1.7**	**1.4**
Mechanical Power (W)	32.3	19.9	19.4	25.3	24.0	17.2
Ave Mech Power per Length (W)	**27.9**	**22.0**	**20.4**	**23.6**	**24.5**	**14.3**
Delivered Power Max (W) per L	**3.3**	**3.1**	**1.7**	**1.6**	**1.4**	
Delivered Power Min (W) per L	**3.2**	**3.0**	**1.6**	**1.6**	**1.3**	
Delivered Power Ave (W) per L	**3.3**	**3.1**	**1.6**	**1.6**	**0.3**	
Pump Mechanical Efficiency Max per L	**12%**	**14%**	**8%**	**7%**	**6%**	
Pump Mechanical Efficiency Min per L	**12%**	**14%**	**8%**	**7%**	**5%**	
Pump Mechanical Efficiency Ave per L	**12%**	**14%**	**8%**	**7%**	**1%**	
Motor Efficiency Max per L	**85%**	**71%**	**85%**	**97%**	**103%**	
Motor Efficiency Min per L	**75%**	**66%**	**79%**	**91%**	**94%**	
Motor Efficiency Ave per L	**80%**	**68%**	**82%**	**94%**	**98%**	**75%**
Total Efficiency Max per L	**10%**	**10%**	**7%**	**7%**	**6%**	**0%**
Total Efficiency Min per L	**9%**	**9%**	**6%**	**6%**	**5%**	**0%**
Total Efficiency Ave per L	**9%**	**9%**	**7%**	**6%**	**1%**	**0%**
Volumetric Eficiency per L	**34%**	**42%**	**30%**	**34%**	**33%**	

Constants

Density of Water (kg/m3)	998.2	998.2	998.2	998.2	998.2	998.2
Gravitational Constant (m/s2)	9.81	9.81	9.81	9.81	9.81	9.81
Rope Length (m)	7.224	7.224	7.224	7.224	7.224	7.224
Rope Diameter (m)	0.008	0.008	0.008	0.008	0.008	0.008
Pulley Diameter (m)	0.149	0.149	0.149	0.149	0.149	0.149
Big Pipe Diameter (m)	0.03642	0.03642	0.03642	0.03642	0.03642	0.03642
Medium Pipe Diameter (m)	0.03050	0.03050	0.03050	0.03050	0.03050	0.03050
Small Pipe Diameter (m)	0.01900	0.01900	0.01900	0.01900	0.01900	0.01900

Guide Diameter (m)	0.08908	0.08908	0.08908	0.08908	0.08908	0.08908
Tachometer Diameter (m)	0.03178	0.03178	0.03178	0.03178	0.03178	0.03178
Shaft Diameter (m)	0.02510	0.02510	0.02510	0.02510	0.02510	0.02510
Null Spring Length (m)	0.02960	0.02960	0.02960	0.02960	0.02960	0.02960
Length 0kg extension (mm)	29.60					
Length 0.5kg extension (mm)	35.92					
Length 1kg extension (mm)	43.24					
Length 1.5kg extension (mm)	49.34					
Length 2kg extension (mm)	56.10					
Length 2.5kg extension (m)	63.72					
Length 3kg extension (mm)	70.72					
Length 3.5kg extension (mm)	77.86					
Length 4kg extension (mm)	83.94					
Length 4.5kg extension (mm)	89.10					
Length 5kg extension (mm)	96.98					
Length 5.5kg extension (mm)	105.00					
Length 0.5kg ave extension (m)						
Average extension for 0.5kg (m)	0.00685	0.00685	0.00685	0.00685	0.00685	0.00685
Spring Width (m)	0.01736	0.01736	0.01736	0.01736	0.01736	0.01736

An expanded results table including all averages and formula used can be found on the Compact Disc provided. Colour coding used to distinguish important readings in analysing.

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