Appendix 5

Technical Report

Power control, thermodynamics and PV panels

SOWTech eCook stove

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Preface

Context

This appendix covers three topics regarding the cooking power topics relating to the project.

There are three discreet topics covered below, but they all pertain to providing the power needed for cooking which is derived from the solar energy.

- *The development and use of a Power Optimisation Device. A means to control and optimise the PV power derived from the panel*
- *The thermodynamic calculations which formed the basis of the power requirement*
- *A brief account of the PV panel specification issues options identified during the procurement of PV in Malawi.*

This work was undertaken as part of a programme called Modern Energy Cooking Services-Technology Research for International Development (MECS-TRIID) managed by Loughborough University and funded by DFID. The objective of this initiative was to fund research into developing new solutions and approaches which may improve the performance and delivery of modern energy cooking services, and which will provide tangible and impactful benefits.

These appendices have been written to provide a full account of the work undertaken so that it may be disseminated and shared. The report includes pictures and diagrams explaining what has been undertaken but the technical text has been kept to a minimum. The account seeks to convey the areas where things have not gone according to plan as well as those that we are pleased to report, so that the full learning experience can be passed on.

The structure of the report

The work will be described as a series of discreet work packages with each package having a section which describes the what problem or challenge is being investigated. We see the path to our objective being achieved through a series of hurdles which needs to be overcome. These “hurdles” could also be referred to as steps on a pathway, or experiments, or research topics or tasks. In this report we will call them “tasks”. Following the statement of each task there will be an account of the work undertaken. The work undertaken will contain a brief description of what was done. This is then followed by a short conclusion and comment on the implications arising from that work. The Implications may be conclusions or outcomes from research, further questions to be addressed or decision regarding what to do next.

The aim is to make these accounts short and discreet so that they are easier to cross reference and to make it as easy as possible for the reader to follow the evolution of the project.

TASK 1:- BUILDING A CONTROLLER TO OPTIMISE PV POWER OUTPUT

Introduction

Heat is the energy which is needed to cook food. The source of the energy to be used in this project is solar power captured by photovoltaic (PV) panels. Prior work by others had used diodes to convert the electricity from solar panels to heat. This approach was reviewed by our technical consultants who concluded that the method of preference for this project would be the use of resistive wire to generate the heat. Both approaches have similar technical merits but the primary reasons for this choice was cost of production at scale and the reduced risk of failure due to reducing the number of parts and connections.

In order to optimally use power from a PV panel some form of controller is needed to manage the amount of current drawn from it. If this demand is not managed and too much or too little is taken from the panel it causes the system performance to be compromised. The task is to devise the best method to achieve this power control at an affordable cost.

Work undertaken

The first step in taken was a review of existing devices to determine if an appropriate unit was readily available. No "off the shelf" equipment was judged to be available that was basic enough or cheap enough to justify buying. The next step was to specify and design a unit that would meet the requirements of the project. The requirements included the following:

- *suited to provide power to the heaters being planned*
- *suited to PV panels that are readily available in Africa*
- *suitable for construction in Africa with low cost components*
- *additional capability of charging mobile phones*

The technical consultants to the project developed plans for such a unit based on a double sided printed circuit board with through hole components. The description used for this design was "technology from the 1960's and could be built by school children". The key point about the design is that it does not use modern methods of manufacture which require complex factory based equipment. It is acknowledged that "in quantity" the printed circuit boards and components would probably come from China, but the assembly of the units could be undertaken in somewhere like Africa without recourse to sophisticated manufacturing facilities.

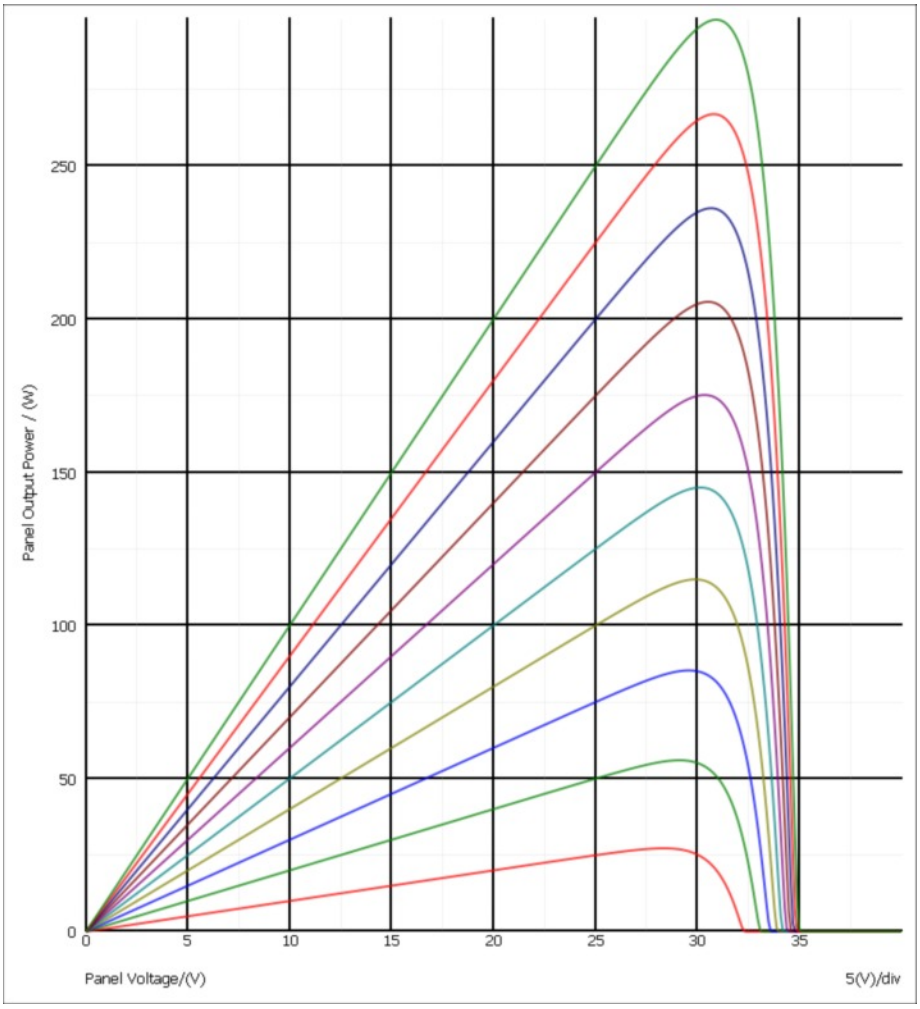
The efficiency of the circuits designed are estimated to be better than 97% efficient with overall system efficiency being greater than 90%. Improvements would be possible with more design cost and complexity.

The design of the circuit is to function in a manner similar to that used by Maximum Power Point Tracking (MPPT) controllers.

This is the design built into the majority of inverters tied to the grid. It enables the panels to work at maximum efficiency no matter what the environmental conditions. The MPPT controller works by adjusting the current drawn out of the panel so that the panel's "maximum power point" is maintained.

In the case of our project the principle is similar to the MPPT controllers used on grid/battery projects. However, in our project, the power is controlled by varying the average voltage delivered to the heaters so that a constant voltage on the panel is maintained, close to the maximum efficiency point.

The graph below shows a simulation of the PV performance at different levels of solar irradiation. From this graph it can be seen that the optimum power points on the panel are around 30V. Slightly higher in bright sunshine and lower at low light levels. The task of the Power Optimisation Devise is to maintain the panel voltage as close as possible to this optimum voltage. A true MPPT system would track the small variations, along with similar variations with temperature. However, for simplicity we use a constant voltage.



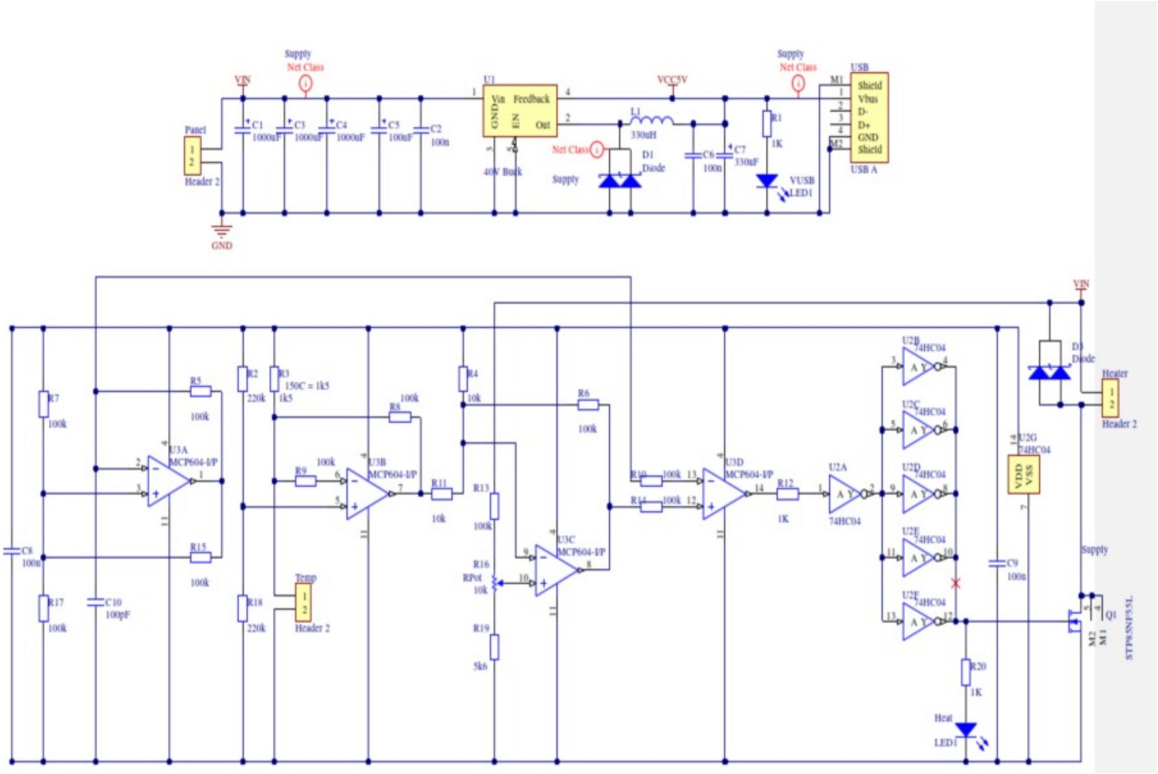
Using the resistive wire heaters and a controller means that there are no power variations to deal with as the heaters warm up, compared to the significant variation experienced with diode heaters.

Once the maximum desirable temperature is reached the power supply to the heater is reduced to maintain a constant temperature.

Part of the assumptions made regarding the project was the amount of power that we estimated was needed to provide the cooking function being sought. The conclusions were that we would use a PV panel with approximately 300W peak output. The thermodynamic calculations used to arrive at this are described in a separate task.

The design of the circuit is a resistive heater fed by a pulse width modulation (PWM) signal to match the average resistance to the current available from the solar panel. The circuit monitors the voltage on the panel and adjusts the PWM ratio and hence the right average current to maintain the desired voltage on the solar panel. The current is smoothed by a large capacitor. It had been hoped that the heater coil self inductance might be enough, but unfortunately it was not the case. The circuit consisting of a quad opamp and hex inverter is shown below

The design of the circuit to achieve this is reproduced below.



The circuit consists of:

- *A triangle wave generator based around U3A. A temperature error amplifier based around U3B, Temp is a 100k (at 25°C) thermistor. A voltage error amplifier based around U3C which measures the voltage on the solar panel . The solar panel working voltage is adjusted by varying R16.*

- *The voltage reference is shifted by the output from the temperature error amplifier, so the temperature control is achieved by moving the solar panel working voltage away from the optimum.*
- *The gain around U3C can be adjusted to provide 'super optimum' control of the solar panel voltage i.e. allowing the voltage on the solar panel to fall slightly as the current drops. We have only roughly optimised the gain.*
- *The voltage error signal is compared with the triangle wave by U3D to give the PWM signal which is cleaned up the logic invertors, U2 before switching Q1 which drives the heater. D3 is to prevent damage to the electronics by any inductance in the heater.*
- *C1-C5 are is the smoothing capacitors*

With respect to the design of this circuit it is similar to a preset MPPT circuit. The panel voltage is set by resistors/potentiometer. Whilst this can be close to optimum, PV panel temperature and operating light levels move so the optimum operating points vary slightly. However we estimate that this is only a few % efficiency loss. A future development of the unit could include a microcontroller to continuously optimise the operating point.

The control electonics run at 5V so using an underrated power supply unit allows simultaneous operation as a USB charger. The power supply unit can deliver 1.5 Amps to the USB socket.

One of the key design parameter for the unit is cost. The unit cost of the POD manufactured in bulk is very hard to estimate because costings are very sensitive to quantity orders and assembly costs. As a guide however, the unit costs of the prototype POD's components has been of the order of £5 unit. Given volume production the unit cost could be affordable for application within the target communities.

Having built the POD unit it was necessary to protect it. A ventilated box unit with apertures for wire input and outputs and the USB port was designed. The design also needed to allow for the two indicator LED lights to be seen outside the box. Two of these boxes were 3D printed for the project. The ventilation holes are important to ensure the components do not overheat. A secondary protection would also be required in a consumer version to prevent water ingress. The drawing of the POD case is shown below together with photo illustrations.

One of the constraints was the lack of sunshine for UK testing. In order to emulate the power from a PV panel a transformer was built which delivered 50V. The early trails of the POD were undertaken using this surrogate for the panel.

During one of these functional tests a clay heater panel was observed to heat to 200°C in 5 minutes with a resistance of 7.7 ohms (3 Ohms would be a more optimal value when the system is connected to a 30V Solar panel) so it was being powered by 325 watts.

Once in use in the field trials data was obtained with illustrates the control function of the POD. The following pages illustrate some graphs of the input and output voltages from the POD. It can be seen from the data due to the overcast conditions the maximum power output from the panels was rarely experienced. Further details of these particular trials are contained in the "Field Trial" appendix 7.

Conclusions

The development of the POD has been everything we sought. The unit is inexpensive, it could be constructed with basic facilities and modest skill levels.

The POD delivered controlled power to the heaters as can be seen on the graphs below. It did its job.

It was adaptable to different voltages with minor changes to potentiometer settings.

There are many ways the unit could be refined. For example, the POD could be adapted to serve two heater plates. One which can be used as a daytime hotplate specifically for achieving boiling temperatures and the other for heating the heat battery PCM material for slow cooking at times when sunshine is limited.

The POD can also be evolved to be able to automatically adjust or be user adjusted to solar panels optimised for different voltages.

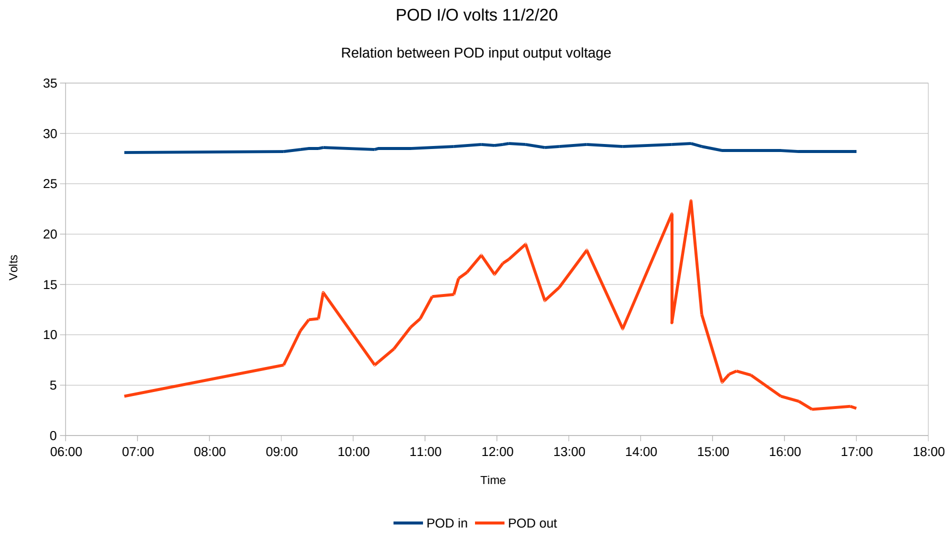
The unit has attracted the attentions of other developers in the field and a unit has been sent to Cal Poly in California to assist with their work in this field. The feedback received to date indicate it is working as required.

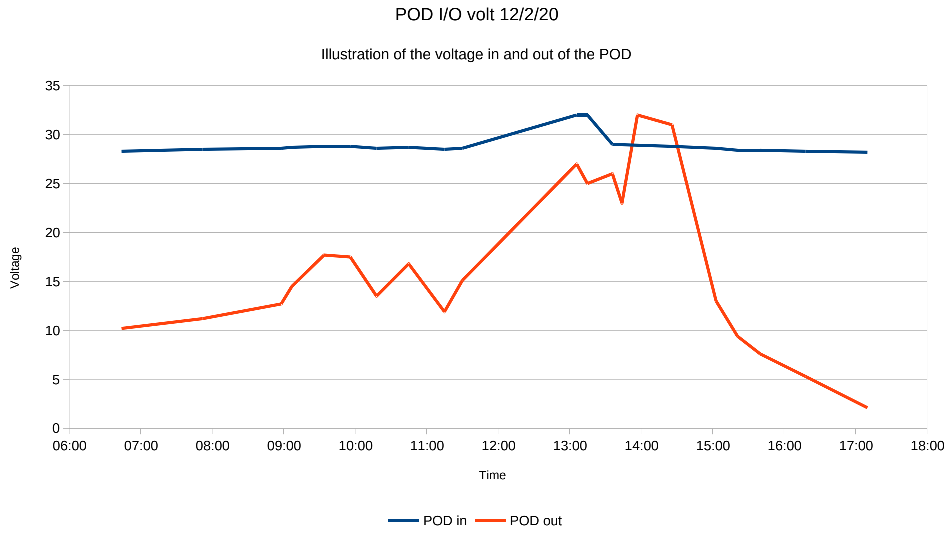
During development some operator errors caused the POD unit to be shorted-out by tinfoil. This led to damage to one of the components. Repairs to the POD were made by using a soldering iron to remove the damaged component and replacing it with a new one. This work was undertaken in a domestic UK kitchen using DIY tools. This experience suggests that repairs and maintenance will be achievable within the community, subject to suitable training and facilities being available.

There were a few minor issues with the current design during assembly. For example, the printed circuit board design had a couple of footprint errors which made it more difficult to assemble than it should have been. These can be rectified in any future builds through minor changes to layout.

The development of the POD is significant achievement of the project.

Graph illustration of POD controlled voltages





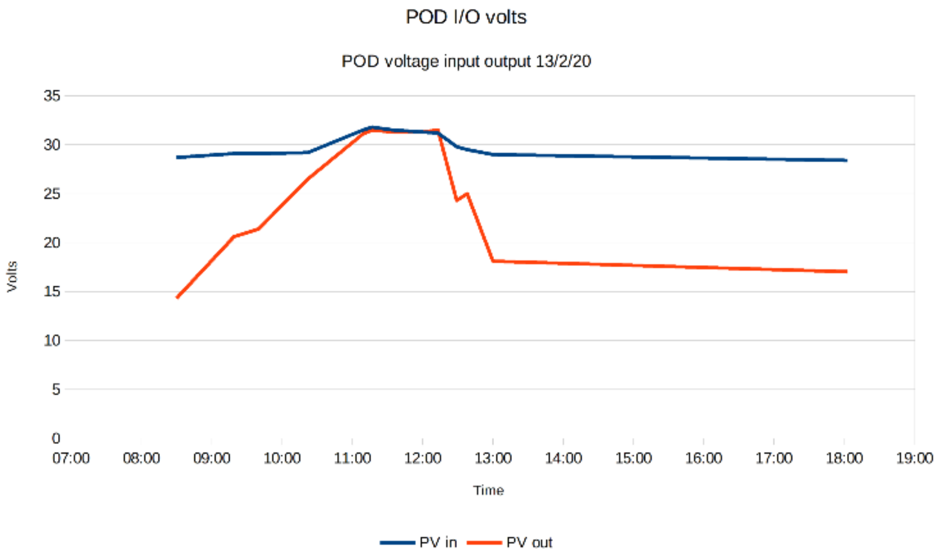
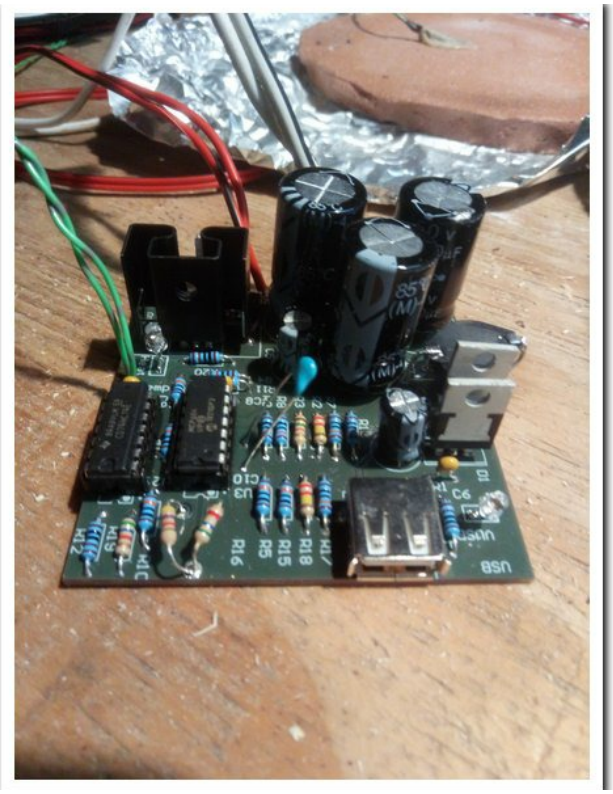
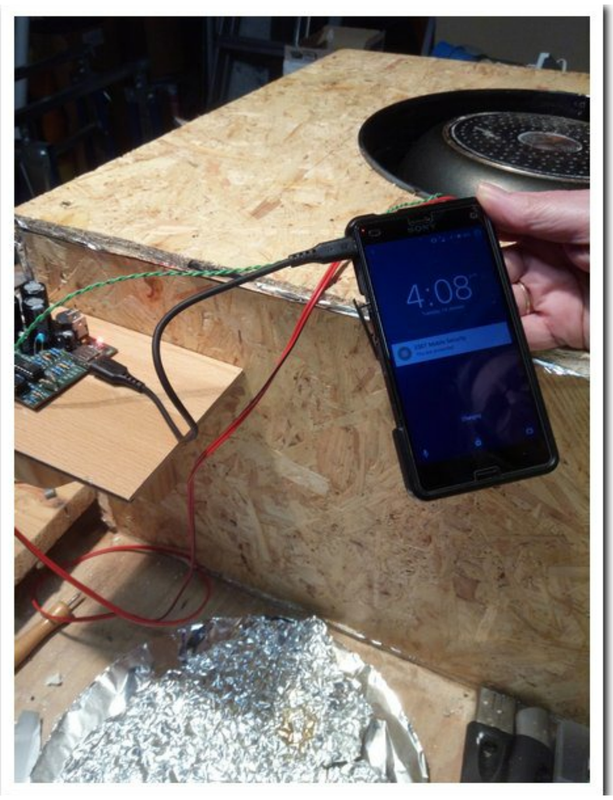


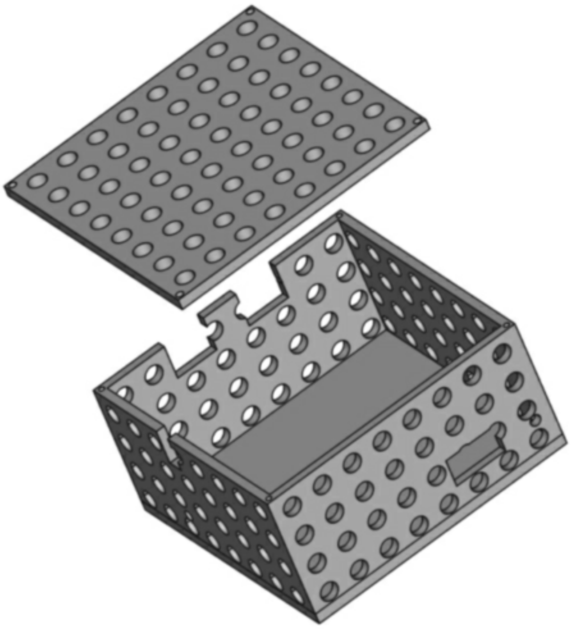
Photo illustrations of the POD



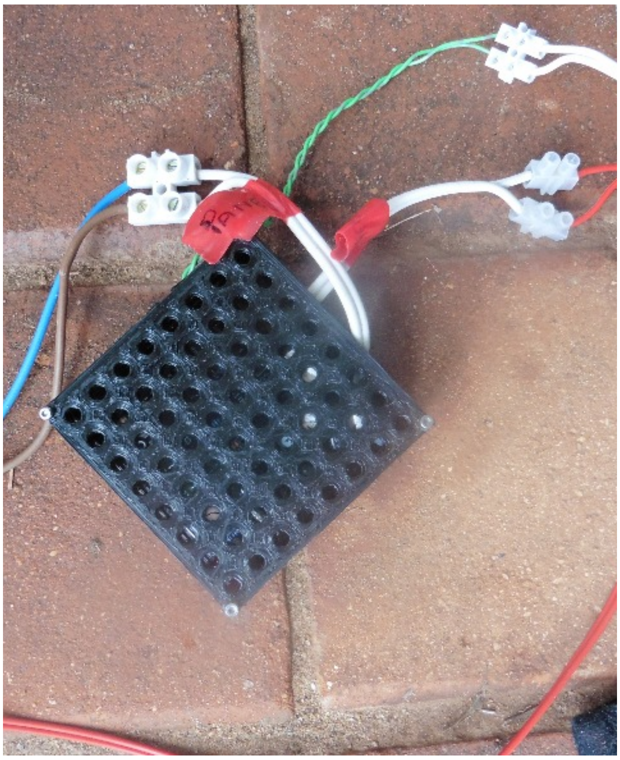
#1 Power Optimisation Devise (POD) assembled



#2 POD shown charging a mobile phone



#3 The drawing of the case to mount the POD for use. Weather protection not shown.



#4 Photo of the POD in use in Malawi

TASK 2:- THERMODYNAMIC CALCULATIONS

Introduction

One of the key design questions which had to be faced is just how big is the task. In other words what scale of cooker is required to meet the cooking expectations. Finding the long term answer to this question will be something which experience and circumstances will determine. There are many variables which cannot be readily determined will include heat losses from the cooker, the food to be cooked, the volume of food to be prepared. Nevertheless, this project had to prepare some best estimates of the cooking demand. This section illustrates the calculations that have been included and which formed the basis of the subsequent design.

Work undertaken

The factor which influenced the decision re the scale of the project was the power that a given type of solar panel could generate, so the maximum daily energy that a 300W PV panel could generate was estimated. This calculation was then down rated for loss of efficiency with age and sub-optimal conditions of operation. Having established what level of energy could be obtained this was then translated into the amount of water that could be boiled. This capability was then assessed to determine if it sounded realistic with respect to the possible heating requirement. The user-centred design work produced an indication of the cooking requirement. This process was undertaken on an iterative basis until a consensus was achieved within the team on the best guess for building the prototype.

The phase change material (PCM) of choice was Erythritol and the literature provided key thermodynamic information that was needed. This enabled a calculation to be made which determined the amount of PCM that the eCook stove would need have.

The calculations illustrated below show the detailed assumptions and calculations that were used.

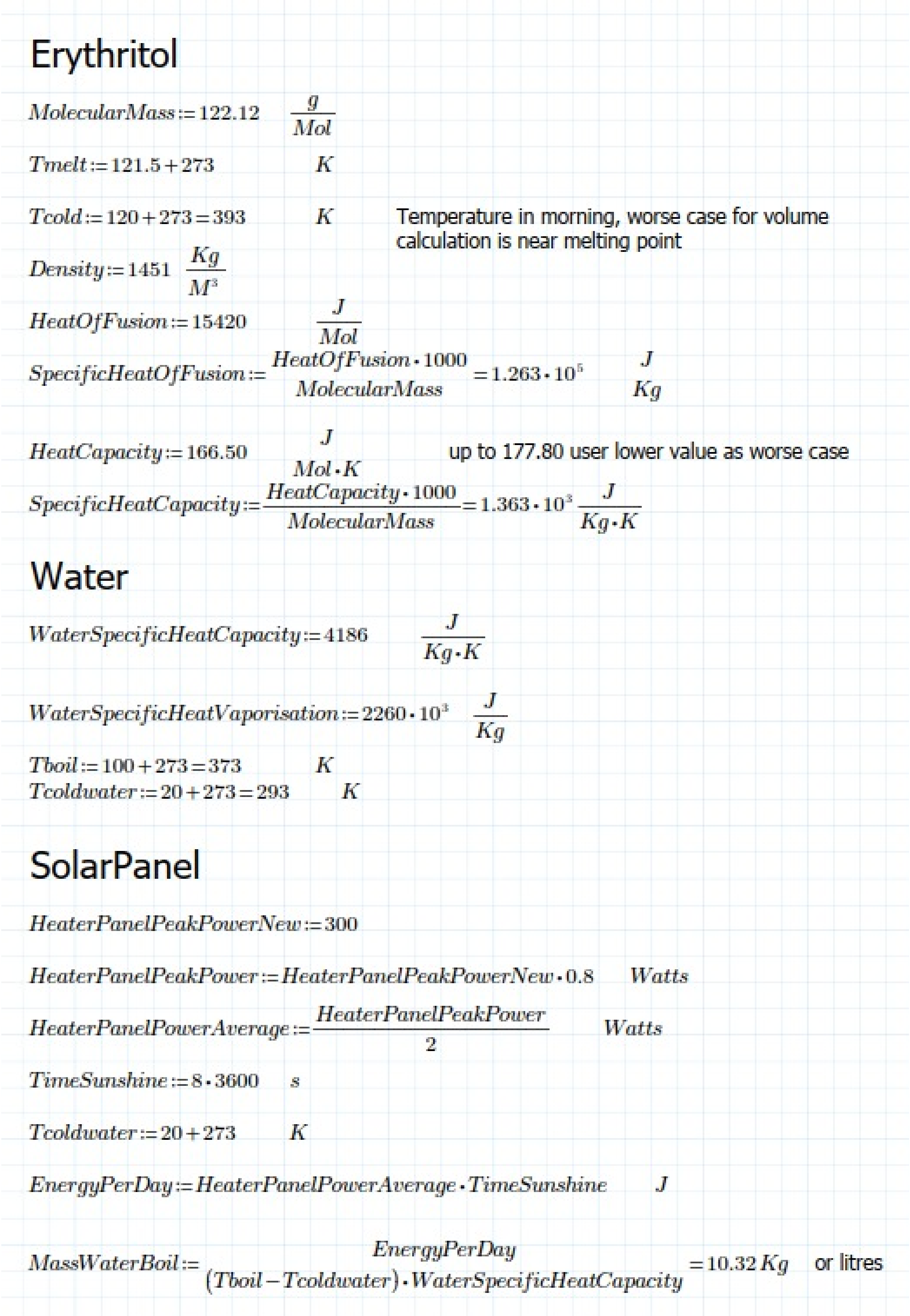
Conclusions

Given the assumptions used the practical implications were calculated as follows:

- *To store all the energy from a 300W panel would require a theoretical total of 27kg of PCM. This figure was discounted to 20 kg of PCM due to expected PV inefficiencies.*
- *This volume of PCM would have enough stored energy to bring 10 litres of water to 100°C from 20°C*

These calculations formed the basis for deciding on the volume of PCM to be used in the prototype eCook stoves.

Illustration of the Thermodynamic calculations



Erythritol

$MolecularMass := 122.12 \quad \frac{g}{Mol}$

$Tmelt := 121.5 + 273 \quad K$

$Tcold := 120 + 273 = 393 \quad K$ Temperature in morning, worse case for volume calculation is near melting point

$Density := 1451 \quad \frac{Kg}{M^3}$

$HeatOfFusion := 15420 \quad \frac{J}{Mol}$

$SpecificHeatOfFusion := \frac{HeatOfFusion \cdot 1000}{MolecularMass} = 1.263 \cdot 10^5 \quad \frac{J}{Kg}$

$HeatCapacity := 166.50 \quad \frac{J}{Mol \cdot K}$ up to 177.80 user lower value as worse case

$SpecificHeatCapacity := \frac{HeatCapacity \cdot 1000}{MolecularMass} = 1.363 \cdot 10^3 \ \frac{J}{Kg \cdot K}$

Water

$WaterSpecificHeatCapacity := 4186 \quad \frac{J}{Kg \cdot K}$

$WaterSpecificHeatVaporisation := 2260 \cdot 10^3 \quad \frac{J}{Kg}$

$Tboil := 100 + 273 = 373 \quad K$
$Tcoldwater := 20 + 273 = 293 \quad K$

SolarPanel

$HeaterPanelPeakPowerNew := 300$

$HeaterPanelPeakPower := HeaterPanelPeakPowerNew \cdot 0.8 \quad Watts$

$HeaterPanelPowerAverage := \frac{HeaterPanelPeakPower}{2} \quad Watts$

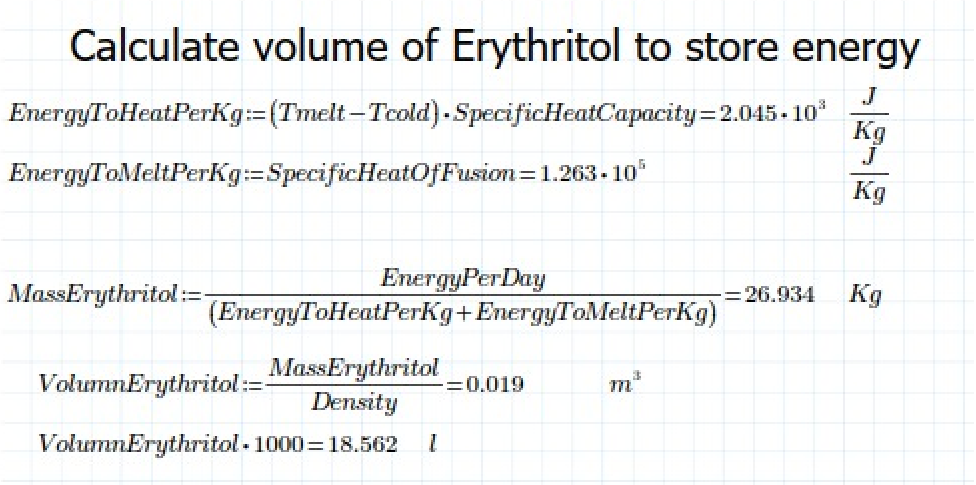
$TimeSunshine := 8 \cdot 3600 \quad s$

$Tcoldwater := 20 + 273 \quad K$

$EnergyPerDay := HeaterPanelPowerAverage \cdot TimeSunshine \quad J$

$MassWaterBoil := \frac{EnergyPerDay}{(Tboil - Tcoldwater) \cdot WaterSpecificHeatCapacity} = 10.32\ Kg$ or litres

Illustration of the Thermodynamic calculations cont



Calculate volume of Erythritol to store energy

$$EnergyToHeatPerKg := (Tmelt - Tcold) \cdot SpecificHeatCapacity = 2.045 \cdot 10^{3} \quad \frac{J}{Kg}$$

$$EnergyToMeltPerKg := SpecificHeatOfFusion = 1.263 \cdot 10^{5} \quad \frac{J}{Kg}$$

$$MassErythritol := \frac{EnergyPerDay}{(EnergyToHeatPerKg + EnergyToMeltPerKg)} = 26.934 \quad Kg$$

$$VolumnErythritol := \frac{MassErythritol}{Density} = 0.019 \quad m^{3}$$

$$VolumnErythritol \cdot 1000 = 18.562 \quad l$$

TASK 3:- SELECTION OF PV PANELS FOR TRIALS

Introduction

There are many different sizes and types of PV panel which are available on the market. This task was to determine which panel to buy and establish what was available in Malawi, the location of the field trials. This brief comment illustrates how this was approached and the reasons and options that were considered.

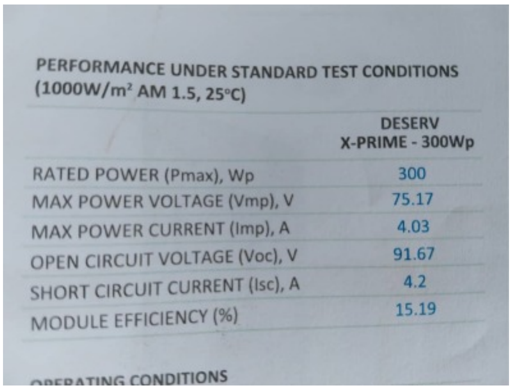
Work undertaken

One of our original partners in Malawi was a PV specialist. However, for reasons unknown to us and our other Malawi partners, they become uncontactable. However, we were able to pursue two other channels to resolve the issues. Firstly, a company supplying PV had approached us and provided an account of the equipment which he could provide. Details listed below for reference.

Secondly Aquaid Lifeline have previously purchased a number of PV panels for water pumping applications and their contact was able to offer suitable panels at a competitive rate. The MD of the business (Kim Gardner Jacobsen), expressed a keen interest to discuss the project with SOWTech so Dr Mullett met him during the fieldwork trip. The company is currently the main dealer for Grunfoss in Malawi and therefore they execute many PV powered pumping projects. The reason for his interest was that he had been involved in solar cooking trials earlier in his career when PV was far more expensive. He saw the potential and wanted to support the development of the concept. One of the practical ways in which this happen is through the dedicated import of PV panels from China. He currently imports PV panels for his existing business by container load, so doing the same for solar cooking would be a real option once it is known what is needed.

One supplier offered the following panel (see insert). However the voltage was above normal "safe" level and too high for the POD as built.

Other panels of 100W 18V and 100W 36V were also considered. These units could be arranged to work with the proposed system. An extract of the suppliers email is reproduced below to illustrate what is readily available in country and at what price.



PERFORMANCE UNDER STANDARD TEST CONDITIONS (1000W/m² AM 1.5, 25°C)

	DESERV X-PRIME - 300Wp
RATED POWER (Pmax), Wp	300
MAX POWER VOLTAGE (Vmp), V	75.17
MAX POWER CURRENT (Imp), A	4.03
OPEN CIRCUIT VOLTAGE (Voc), V	91.67
SHORT CIRCUIT CURRENT (Isc), A	4.2
MODULE EFFICIENCY (%)	15.19

OPERATING CONDITIONS

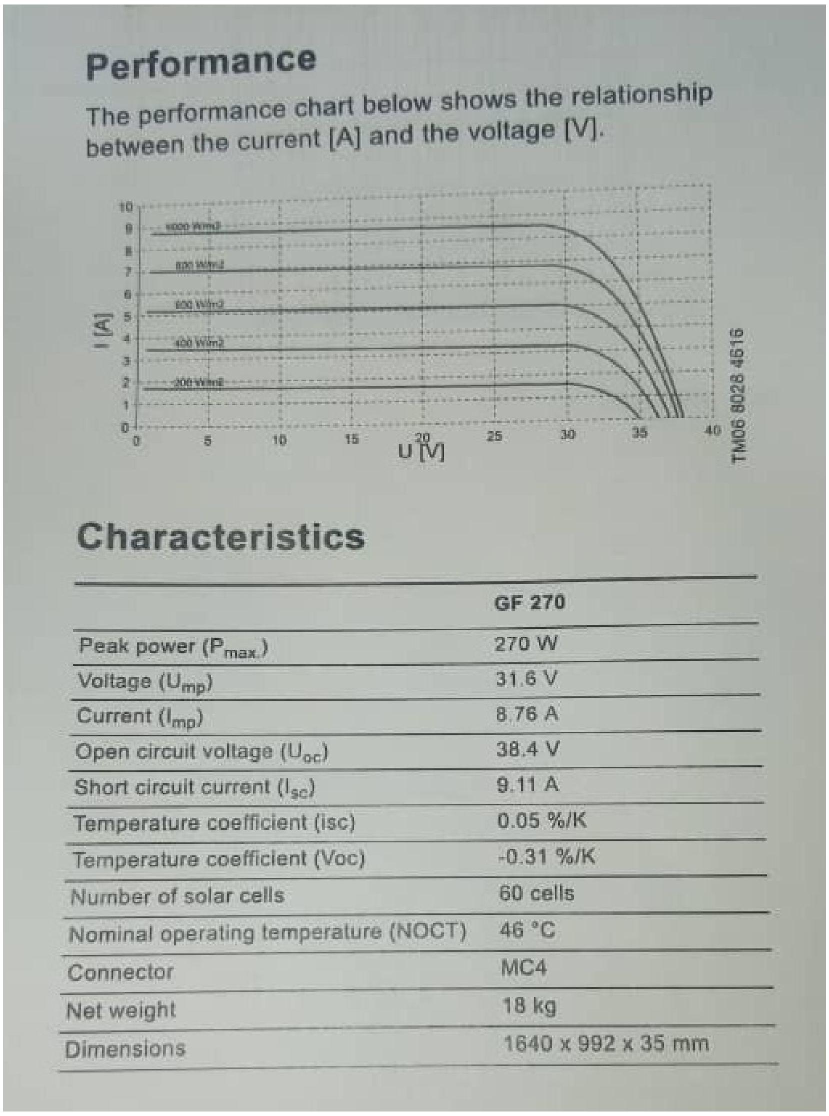
Extract of potential suppliers email *"The most prominent and high quality brand in Malawi so far is Enersol which is low voltage solar panels (100W, 18V,5.56A) and Aquasol which is high voltage solar panels(100W, 36V, 2.78A). The solar panels are very easy to buy as they come from South Africa, I have them in my shop and I sell 100W Enersol solar panels at K55,000 (57 GB pounds) and 100W Aquasol solar panels at K60,000 (63GB pounds). Please find attached datasheet for the solar panels mentioned.*

For this project, you might also need to consider solar panels supporting structure (aluminum type) which is about K80,000, (84 GB pounds). I am sure that the products (prototype) have build in batteries and charge controllers.

For other accessories, we can include DC cables 6mm which cost K1500 (1.57 GB pounds) per metre, MC connectors which is K4500 (4.7 GB pounds) per pair. Flexible conduit Ultraviolet (UV) adapted for outdoor use is k2500 (2.61 GB pounds) per meter, cable trunking is k2500 (2.61 GB pounds) per meter. We might also solar panel mounting screws, with rubber hole prug for sealing holes against rain water which cost K20,000 (20.89 GB pounds) per panel with 4 screws. I have all the necessary materials that might be needed for this project.

Conclusion

The panel chosen for use in the trial was 270W 31.6V. The specification of the panel which was readily available and competitive is given below. As the supplier offered two panels at a competitive rate, these were used in parallel during the project. This was helpful given the dull and overcast conditions experienced during the trials. Unfortunately, we had no option but to undertake our trials in the rainy season.



Performance

The performance chart below shows the relationship between the current [A] and the voltage [V].

Characteristics

	GF 270
Peak power ($P_{max.}$)	270 W
Voltage (U_{mp})	31.6 V
Current (I_{mp})	8.76 A
Open circuit voltage (U_{oc})	38.4 V
Short circuit current (I_{sc})	9.11 A
Temperature coefficient (isc)	0.05 %/K
Temperature coefficient (Voc)	-0.31 %/K
Number of solar cells	60 cells
Nominal operating temperature (NOCT)	46 °C
Connector	MC4
Net weight	18 kg
Dimensions	1640 x 992 x 35 mm