PERFORMANCE IMPROVEMENT OF PHOTOVOLTAIC PANELS THROUGH MITIGATION OF SURFACE TEMPERATURE COOLING AND DEBRIS REMOVAL

By

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FINAL REPORT

Submitted to the Mechanical Engineering Programme
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(Mechanical Engineering)

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CERTIFICATION OF APPROVAL

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Khairul Nazmi Bin Ahmad Majdi

A project dissertation submitted to the
Mechanical Engineering Programme
Universiti Teknologi PETRONAS
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Approved by,

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Project Supervisor

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TRONOH, PERAK

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CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

Khairul Nazmi Bin Ahmad Majdi

ABSTRACT

The photovoltaic (PV) power generation is an attractive renewable-energy option, which does not involve moving parts and can be implemented with a minimal operation and maintenance effort. The common problem which contribute to the reduction in the PV energy conversion efficiency and subsequently records a low overall performance, apart from high cloud coverage and high humidity levels, are surface temperatures and debris deposition. The purpose of this project is to study the effects of surface temperature cooling and debris deposition in order to optimise the performance of the PV panels. Two different PV modules are used in this experiment; conventional module and module with surface water cooling. The output variables to be compared with each module will be the temperatures, relative humidity, currents and voltages. The selected approach is to determine what factors affects the performance of the photovoltaic panels the most and how it can be overcome in order to improve the system. The intended scope of this project is to explore the studies carried out to improve the conversion efficiencies of solar PV's, in considering the thermal degradation due to the module surface temperature and surface depositions.

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CHAPTER 1 :
INTRODUCTION

1.1 Background Study

Photovoltaic's (abbreviated PV) is a direct way of converting solar radiation into electricity using semiconductors that exhibit the photovoltaic effect. It generates electric power by using solar cells to convert energy radiated from the sun into a flow of electrons. The photons of light exciting the electrons into a higher state of energy allows them to act as charge carriers for an electric current, this is termed the 'Photovoltaic Effect'.

Solar cells produce direct current electricity from sun light, which can be used to power equipment or to recharge a battery. The solar cells require protection from the environment and are usually packaged tightly behind a glass sheet. When more power is required than a single cell can deliver, cells are electrically connected together to form photovoltaic modules, or solar panels. A single module is enough to power low powered equipment, but for larger power consumption the modules must be arranged in multiples as arrays.

Due to the growing demand for renewable energy sources, the manufacture of solar cells and photovoltaic arrays has advanced dramatically in recent years. In order to improve the performance efficiency, it is required to study the effects of temperature cooling and debris removal of the photovoltaic panels. These factors can affect the efficiency of the panels and therefore yield better performance results. With the proper technique, it is hoped that from this project we can better understand how much effect it has on the overall performance.

1.2 Problem Statement

One of the common problems encountered by existing solar photovoltaic panels is the low energy conversion efficiency of the photovoltaic cells. Only a portion of the light energy that enters the cell is converted into electricity while the rest is converted to heat. The main factors that contribute to the decrease in efficiency are:

- Temperature

  Lowering the operating temperature of the photovoltaic module can increase its performance.

- Debris removal

  Dust deposition on photovoltaic module reduces the power generated. Considering the fact that PV cells already have low conversion efficiency, the accumulation of their surface will further reduce its overall efficiency performance wise.

1.3 Project Objectives

The objective of this project is to optimise the performance of the photovoltaic panels through measure of surface temperature cooling and debris removal. The objectives hoped to be achieved are as follow:

1. To investigate the effect of surface temperature cooling of the PV cells.
2. To simulate a model of how the debris accumulated on the PV cells would affect the power generated.
3. To study the impact of dust on PV system performance with respect to dust concentration and shade.

1.4 Scope of study

The input for this project will be obtained from the available equipments set-up in place at the UTP Weather Station. The variables that will be used are the temperatures, currents, voltages of each photovoltaic module (conventional module and the module with water cooling). The output would be by comparing the data obtained to prove our objectives. The selected approach is to determine what factors affects the performance of the photovoltaic panels the most and how it can be overcome in order to improve the system.

1.5 Relevancy of Project

This project is proposed to improve the performance of the photovoltaic panels through surface temperature cooling and debris removal. The reduction of surface temperature is known to increase the efficiency of the photovoltaic panels in order to produce higher electricity current. While the effects of debris on the surface of the module can block direct sunlight therefore affecting its efficiency performance wise.

1.6 Feasibility of Project

The study of temperature effects by cooling of the surface has already been proven based on previous researches. It is known that the photovoltaic modules are arranged in arrays with each solar cell connected with one another. Hence, it can be presumed that with debris on the panels it will affect the overall performance and its efficiency. The focal point of this project is to improve the performance by studying the effects of surface temperature cooling and debris removal of the photovoltaic modules.

The project is scheduled to be completed within two semesters. This can be accomplished successfully within the time period given that the individual responsible gives full commitment to obtained the desired result and also that the equipment set-up is in good working condition throughout the timeline.

CHAPTER 2 : LITERATURE REVIEW

2.1 Effects of Surface Temperature Cooling of Photovoltaic Panels

One of the main problems in using photovoltaic systems is the low energy conversion efficiency of the PV cells. As the operating temperature of the panel increases, the open circuit voltage of the PV cells drops therefore the power generated and its efficiency will decrease significantly (Korzadeh,A., 2009). In order to overcome this problem, it is necessary to reduce the operating temperature of the module.

To improve the system, the photovoltaic cells are cooled by providing water flowing on the panel. Water has the tendency to cool the cells temperature by absorbing the heat generated by the module during the day. By applying a thin film of water, it is known that water has a refractive index of about 1.3, which will improve the optical transmittance of PV cells. Due to the heat transfer by water, the temperature reduction is significant through cooling of the photovoltaic module.

$$\eta_{air}\,(1.0) > \eta_{water}\,(1.3) > \eta_{glass}\,(1.5)$$

In most panels, there is a layer of glass with a refraction index of 1.5. With a layer of water flowing on top of the photovoltaic module, it changes the reflected fraction of an incoming perpendicular ray from 4.4% to 2.0%. This will reduce the incoming impedance radiation which will allow for more intensity of the solar radiation. This effect is enhanced if the light is not perpendicular and becomes more important for wide incidence angles (Rosa-Clot M., 2010).

In addition to keeping the surface clean, water reduces reflection of the sunlight by 2-3.6%, and decreases cell temperatures up to 22°C. Comparing the conventional module and the module with water film, it is measured that there is an increase in electrical energy yield over the whole day by 10.3% (Krauter S., 2004). This is shown in Fig.1 below.

The disadvantages of using anti-reflective coatings for reducing the reflection loss are that these coatings are expensive and not durable. It has a tendency to absorb pollution and dust therefore coinciding with the need to improve the performance of the photovoltaic modules. The coatings will then need regular surface cleaning to avoid efficiency loss.

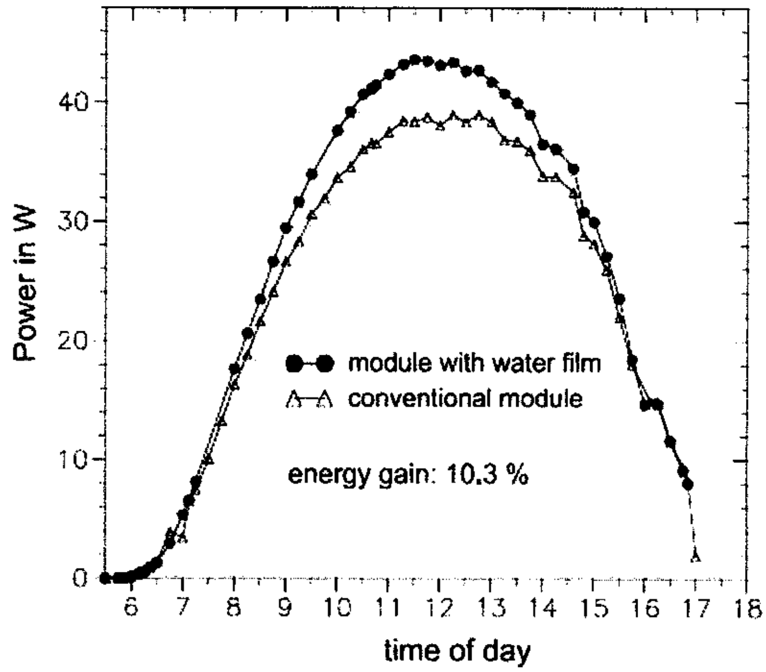

Figure 1: Comparison of output power of the PV modules

As expected, there is a gain in the performance of the photovoltaic module with water film compared to the conventional module. Not much change can be seen during the earlier time of day and towards the evening, but during the peak hours where there is high radiation of sunlight, the difference in energy gained can be seen significantly.

2.2 Effects of Debris on Photovoltaic Panels

Another factor that is known to affect the performance of the photovoltaic panels is the accumulation of debris/dust on the panels. In general, dust is a term which applies to minute solid particles with diameters less than 500 mm. It consists of particles in the atmosphere that arises from various sources such as soil dust lifted up by wind and pollution. Although it seems irrelevant, high attention should be paid on the fact that the air quality of our surroundings is polluted. High population concentration, rapid industrialisation and economic development of urban areas all over the world have caused significant degradation of the urban air quality.

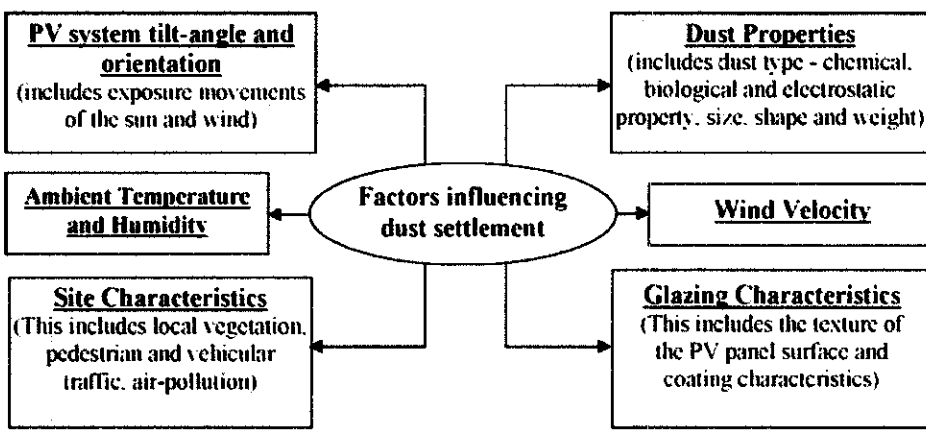

Figure 2: Factors influencing dust settlement

From Fig.2 above, the primary factors that influence the characteristics of dust settlement on photovoltaic systems are the property of dust and the local environment. The property of dust which includes the type, size, shape and weight is important to understand the type of accumulated dusts on the panels. Different types of dust will appear to have different effects on the performance of the PV modules. While the local environment comprises of specific surrounding factors which are influenced by human activities and weather conditions. Equally, the surface finish of the photovoltaic panel surface is also to be considered. A rough surface is more likely to accumulate dust if compared to a smooth one. The initial accumulation of dust would tend to promote further settlement of dust collection.

In general, horizontal surfaces would tend to accumulate more dust than inclined ones. This however is dependent on the wind movements where a low-speed wind pattern promotes dust settlement while a high-speed wind would, on the contrary, disperse dust settlement. Undergoing research to characterise the deposition of dust and their impact on photovoltaic system performance is limited, given the fact that it is a complex phenomenon and is influenced by varied environmental and weather conditions (Mani M., 2010)

It has been concluded that fine particulates significantly decrease the performance of photovoltaic cells, more so than coarser particles. Cement, the main building material which may often present in the atmosphere of urban areas has shown to reduce both the short circuit current and output power when deposited onto the surface of photovoltaic cells. This is due to the very small diameter of its particles. Carbon particulates, which are generated from combustion process and emitted from diesel engines among the different dusts used, have shown to result in the worst deterioration of performance of photovoltaic cells, and higher a loss in power output (El-Shobokshy M. S., 1993).

CHAPTER 3:
METHODOLOGY

3.1 Research Methodology and Project Activities

The planned research methodology of this project is compromised of five stages. The first stage will be the preliminary research for the project followed by the development of the experiment method. The third stage will consist of conducting the experiment itself. Once the experiment has been done, the results obtained will be analysed and further discussed. The final stage of this project will be the documentation of all that has been done and conclude whether the objectives have been met or not.

3.1.1 Preliminary Research Work

The objectives of this stage are to properly grasps and understand the basics of solar photovoltaic systems in general. This will be focused more on the collection of related data to the project. Research will be thoroughly done on information from available books, relevant journals and technical papers. The information obtained should be recorded for referencing in later stages. From the understanding of the problem, decisions will be made on the best and most feasible method to be performed for the project.

3.1.2 Development of Project Experiment

During this stage, the activities will include in deciding the variables to be later experimented to ensure that the objectives will be achieved. The variables that must be considered should allow space for improvement on the performance of the photovoltaic panels. This should include the temperature cooling and debris removal to improve the performance of the modules. The modus operandi of the experiment should be designed systematically. The tools and machineries needed should be identified. This should also be approved by the project supervisor.

3.1.3 Conducting Experimentation

Experiments will be conducted based on the objectives to be achieved. The investigation should be done to identify the gap for improvement of the photovoltaic module with respect to its efficiency. A successful experiment will achieve the objectives and should be capable to yield expected results in terms of the surface temperature cooling and debris removal. This will then be evaluated in the next stage.

3.1.4 Analysis of Results and Discussion

The results obtained from the experiment will be tabulated and compared with previous data results from relevant journals. This is to ensure that there will be a significant improvement in the performance of the photovoltaic module. The reliability of the results should also be evaluated to determine whether modification should be made to the procedure or the method itself. Should there be any improvements to be made, modifications will be implied.

3.1.5 Final Documentation

Once the results have been verified to be reliable, all activities and data will be compiled and documented along with the research and procedures of the experiment to meet the necessary requirements. This process will also be done continuously to avoid any valuable information left out. This must also be approved by the project supervisor.

*The flow chart of the research methodology is shown on the following page.

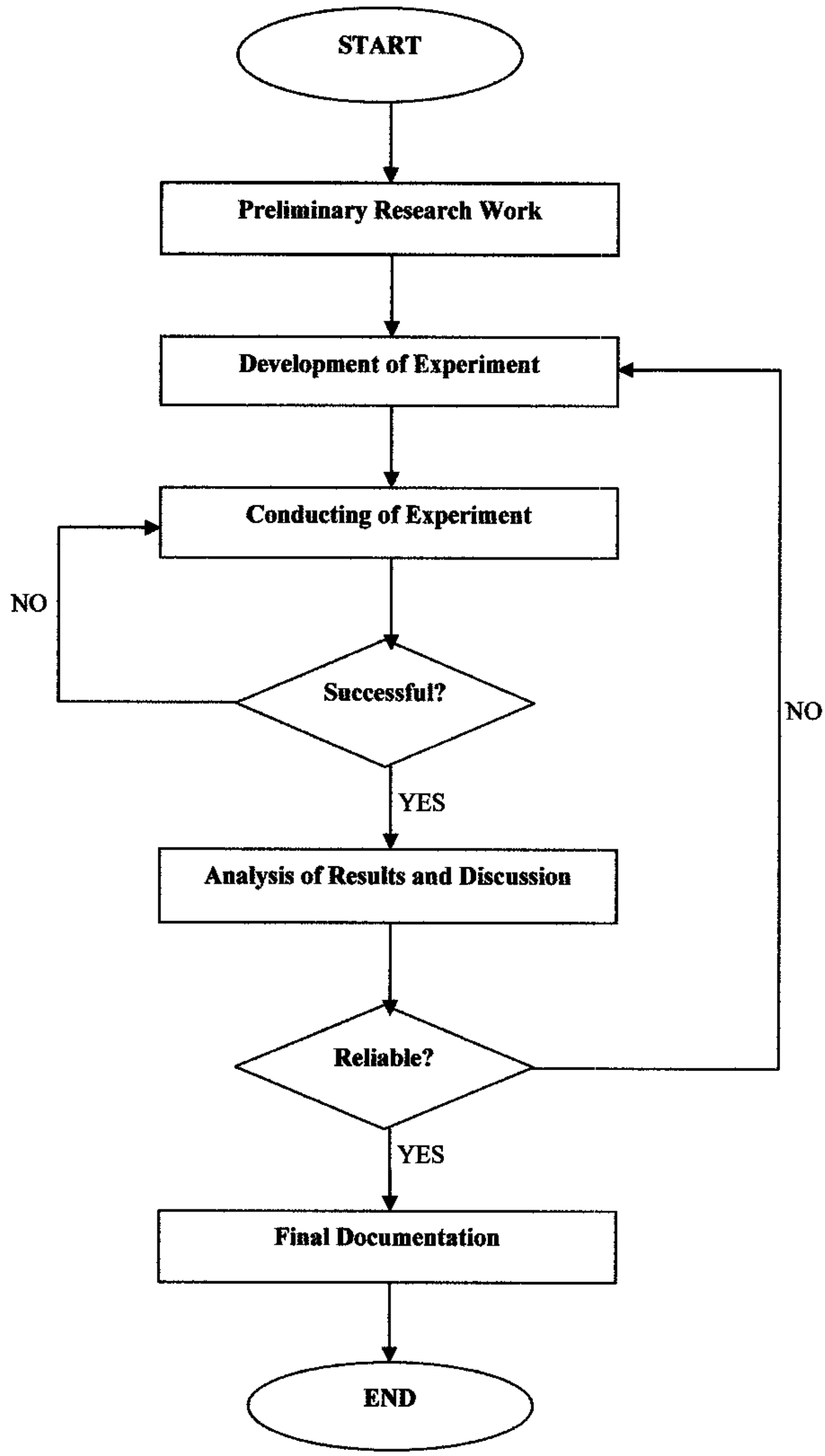

Figure 3: Flow Chart of Project

3.2 Tools Required

There are two photovoltaic modules readily available at the UTP Weather Station. One is with a thin film of water flowing on the surface of the panel while the other one is a conventional module. The data obtained is recorded using Pico Logger software which is placed at the site as well. The information recorded can be obtained via PC which can later be prepared into graphical form to be analysed.

3.3 Gantt Chart

3.3.1 First Semester

The Gantt chart below provides the timeline of the project for the first semester.

Table 1 : Gantt Chart for First semester

Activities/Week Number	1	2	3	4	5	6	7	Mid-Semester Break	8	9	10	11	12	13	14
Selection of project topic															
Briefing session															
Initial research work															
Submission of extended proposal						X									
Experiment Development (Preliminary)															
Proposal Defence									X	X					
Analysis of results (Preliminary)															
Submission of interim draft report														X	
Submission of interim report															X

X Suggested milestones
Process

3.3.2 Second Semester

The Gantt chart below provides the timeline of the project for the second semester.

Table 2 : Gantt Chart for Second semester

Activities/Week Number	1	2	3	4	5	6	7	Mid-Semester Break	8	9	10	11	12	13	14	15
Project work continues																
Submission of Progress Report									X							
Project work continues																
Pre-EDX												X				
Submission of Draft Report													X			
Submission of Dissertation (Soft bound)														X		
Submission of Technical Paper														X		
Oral Presentation															X	
Submission of Project Dissertation (Hard bound)																X

X Suggested milestones

Process

CHAPTER 4:
RESULTS AND DISCUSSION

4.1 Experimental Setup

The experimental setup to study the effects of surface temperature and debris accumulation on the module surface is carried out at the solar energy testing facility located at the UTP Weather Station. The experiments for the effects of debris accumulation and surface temperature cooling on the panel surfaces are carried out separately for obvious reasons. A schematic of the experimental set-up is shown below. Photos of the equipment setup for PV module with surface cooling are shown in the Appendix.

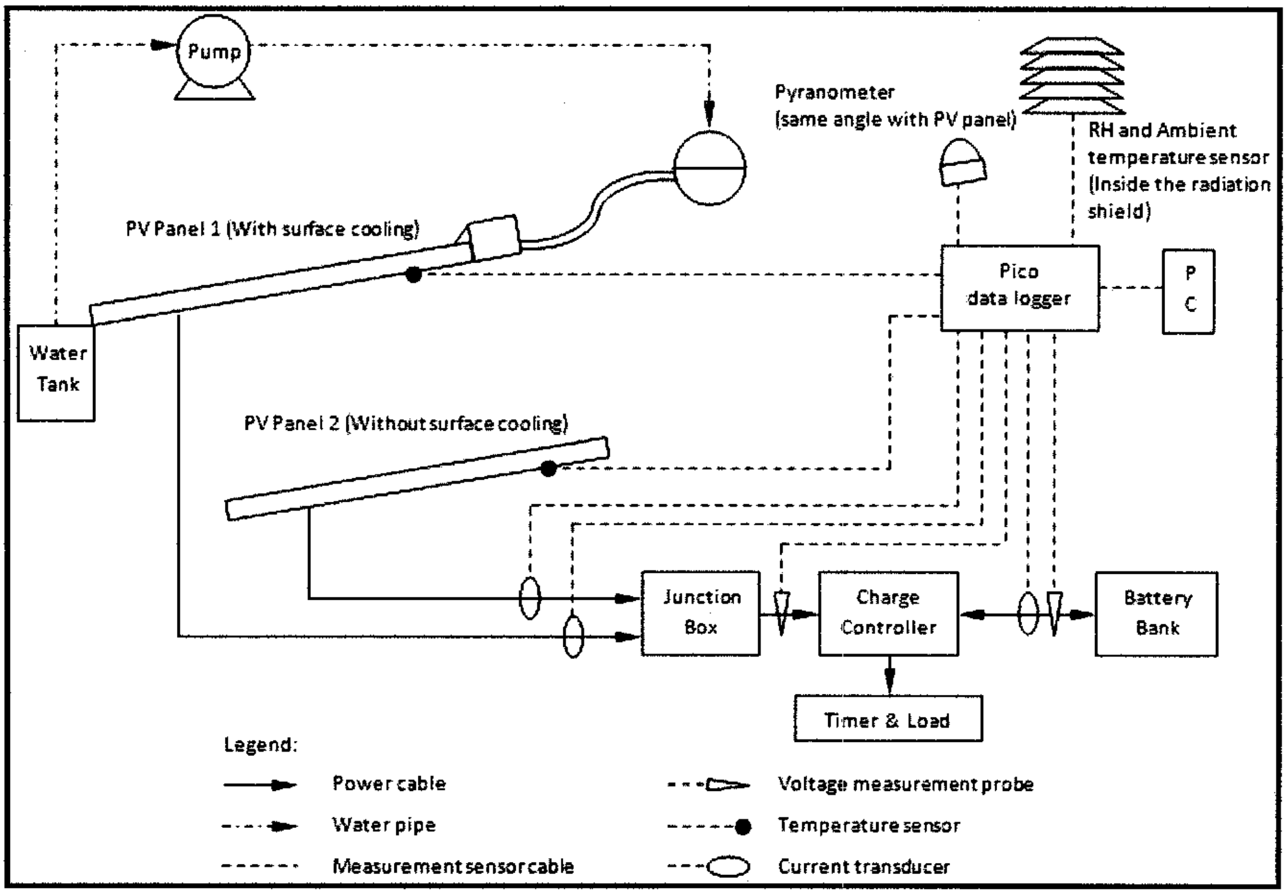

Figure 4 : Experimental setup schematic

The freestanding PV panel test rig consists of two poly-crystalline type PV panels; panel 1 (with surface cooling) and panel 2 (without surface cooling). Poly-crystalline PV panel is the most common type that is used for residential installations. Although the poly-crystalline PV panel's efficiency is lower than mono-crystalline, the price is cheaper and the overall performance ratio can be better during the diffuse solar radiation conditions (Carr,A.J., 2009). The specification of the PV panel is described in Table 2.

Table 3: PV panel specification

Description	Characteristic/Value
Type	Poly-crystalline Silicon
Nominal Peak Power (Pp)	50 Watt
Rated Voltage (Vr)	17.7 Volt
Rated Current (Ir)	2.8 Ampere
Open Circuit Voltage (Voc)	21.6 Volt
Short Circuit Current (Isc)	3.2 Ampere
Temperature Coefficient	-0.074 V/°C; +2.80 mA/°C
Number of modul in parallel	36
Company/Country of origin	Photon Solar - India

The cooling water that flows over the surface of the PV panel is supplied by 35W pump through a header and film levelling tubes. The water is collected by an open receiver tank and recirculated. The pump specification is described in Table 3.

Table 4: Pump specification

Description	Characteristic/Value
Power	35 Watt
Flow max	2200 litre/hour
Head max	1.7 meter

Weather and system parameters were monitored and recorded using Pico data logger and a PC. Monitored weather parameters are solar radiation, ambient temperature and relative humidity. System parameters are panel's temperature (1 and 2), PV panel's current output (1 and 2), current input and output to the battery, panel and battery voltage.

4.1.1 Additional Weather Station

Due to some unforeseen circumstances with the equipment set-up, an additional weather station is installed on site to further obtain results with regards to the surrounding weather data. This equipment is installed near location to the panels and is collected via wireless transfer of data from five different sensors to an indoor receiver. This equipment will collect indoor and outdoor temperature, wind speed, wind direction, humidity, barometric pressure, barometric pressure history, rainfall amounts, time and date. The readings are adjusted to be collected at intervals of every five minutes, this is to ensure that both equipments are running concurrently to avoid any misleading data.

From the data obtained, the wind speed and relative humidity can better explain the evaporation of water from the tank leading back to the levelling tubes. This additional data will be analysed to better support the conclusion later on.

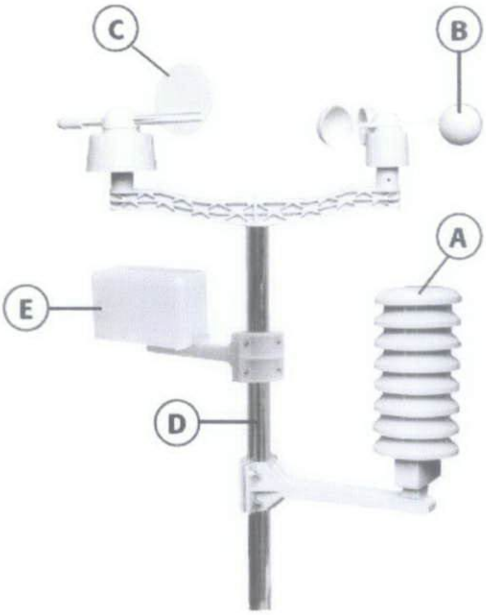

Figure 5 : Weather Station (radio controlled)

A – Transmitter (thermo-hygrosensor) including protective cap
B – Sensor for wind speed
C – Sensor for wind direction
D – Bracket
E – Rainfall gauge

4.2 Methodology

4.2.1 Surface Temperature Cooling

The first half of the project involves studying the effects of surface temperature cooling by flowing water on top of the panel surface. Water is known to be a cooling factor as it will absorb the heat generated by the module during the day through the process of heat transfer of water. The water is contained in a tank which will be pumped into the container above the module. It will then flow into the levelling tubes before flowing on top of the panel's surface and back into the water tank. This cycle repeats itself as the water is recycled.

The data is collected daily at an interval of every five minutes. Collection of data is necessary during the period of 8am until 5pm. This is the time period of which the data from both modules will be tabulated and analysed against each other.

4.2.2 Debris Accumulation

The second half of the project requires the simulation of debris accumulation on top of the panels to better understand the affects it has on the overall performance of the PV panels. Dust deposition on photovoltaic module reduces the power generated. Considering the fact that PV cells already have low conversion efficiency, the accumulation of their surface will further reduce its overall efficiency performance wise. The simulation of the debris accumulation will only affect the conventional module. This is due to the fact that the panel with water flowing will not allow the accumulation of debris on its surface.

The methodology to simulate the model of the debris accumulated on the PV panel is by covering the panel's surface with an opaque sheet, such as cardboard. In order to simulate the debris, the surface of the panel will be covered by percentage opening. The percentages will represent the amount of covered area from the debris accumulated. To obtain a sound relationship between the debris accumulated and how it affects the performance, a range of partial coverage of the surface area will be done. The intended range will be from 10%, 25%, 50%, 75% and full coverage of the surface area.

4.3 Calculation

Observation and analysis was carried out on experimental data. Standard Test Condition (STC) and actual PV panel efficiency can be calculated. PV panel efficiency at STC can be calculated from datasheet using Eq. 3-36 as follows:

$$\eta_{STC} = \frac{P_{PV}}{G_{STC} \cdot A_{PV}} \times 100\% \qquad (1)$$

η_{STC} is efficiency at STC (Irradiance (G_{STC}) = 1000 W/m^2 and 25 °C ambient temperature) and A_{PV} is the area of each module.

To calculate efficiency in actual condition Eq. 3-37 was used as follows:

$$\eta_{actual} = \frac{P_{actual}}{G_{actual} A_{total}} \times 100\% \qquad (2)$$

η_{actual} is actual efficiency, P is PV panel measured power output in Watt, G_{actual} is actual radiation received in W/m^2, A_{total} is total area of the PV panel.

PV panel efficiency measurement has been carried out and compared with PV panel efficiency calculated from the datasheet. According to the manufacturer's datasheet, P_{peak} of each module used in the experiment is 100 Wp and the area of each module (A) is 0.61mx0.655m = 0.39955 m^2, STC condition is test condition at 1000 W/m^2 of solar radiation level and 25 °C ambient temperature. PV panel's efficiency at STC is calculated from datasheet as follow:

$$\eta_{STC} = \frac{50}{1000 \times 0.39955} \times 100\% = 12.51\%$$

4.4 Analysis of Results

The results gathered from the PicoLog data logger is tabulated and shown in graphical form for ease of analysis. There are two parts to this analysis which is for the study of surface temperature cooling and the study of debris accumulation. A few experiments have been conducted, and the results obtained are shown in the figures below. Each result shows both the temperature of the PV module with surface cooling (Tcell 1) and the conventional module (Tcell 2) which is compared against the temperature of the air (Tair).

The graph plotted of Power against Time represents the power output obtained from both the PV modules. The module with surface cooling and the conventional module is labelled 'Power1' and 'Power 2' respectively. While the graph of Efficiency versus Time shows 'Efficiency 1' and 'Efficiency 2' plotted of the calculated efficiency values of the module with surface cooling and the conventional module respectively. The 'STC Efficiency' plotted represents the standard test condition of the PV panel from the manufacturers datasheet.

4.4.1 Study of Surface Temperature Cooling

The obtained data throughout the experiment was tabulated and compared against each other to select the best representation set of data to be elaborated. The highest 'Average Performance Improvement' was chosen for this method. This was calculated by averaging the overall performance improvement throughout the specified date. The set of data dated 17th August 2011 was selected as it had the highest 'Average Performance Improvement' at 31.3%. The table of selection of highest average performance improvement is attached in *Appendix (Table 6)*.

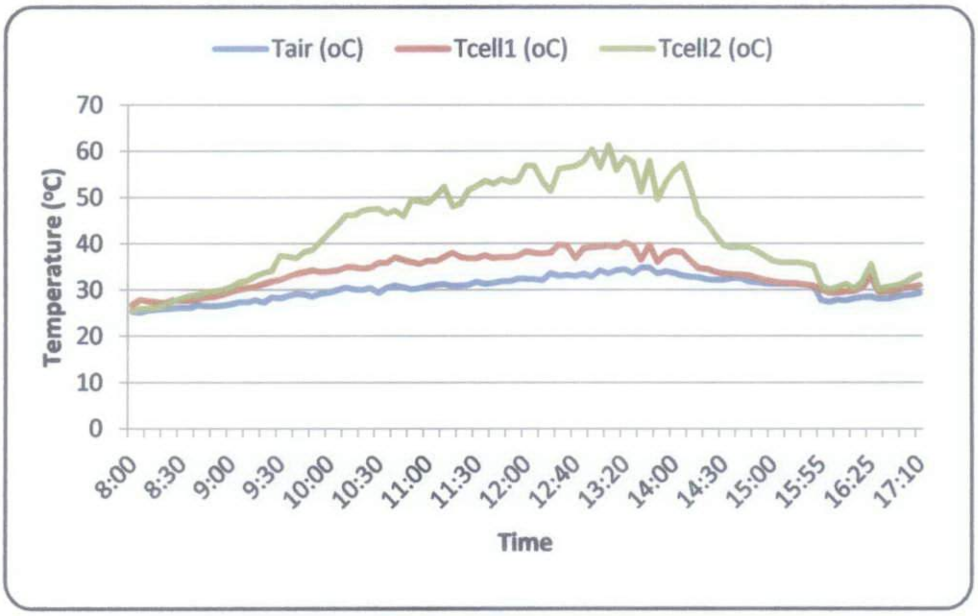

Figure 6: Measured PV panels and ambient temperature

From the graph shown above, it is clear that there is substantial difference in temperature on the PV module with surface cooling compared to the conventional module. It proves that the film of water flowing on the surface on the module does have an impact on its surface temperature measurement, thus reducing the temperature to near the ambient temperature of the air. Furthermore, from the reduction in temperature the value of efficiency of each panel also differs.

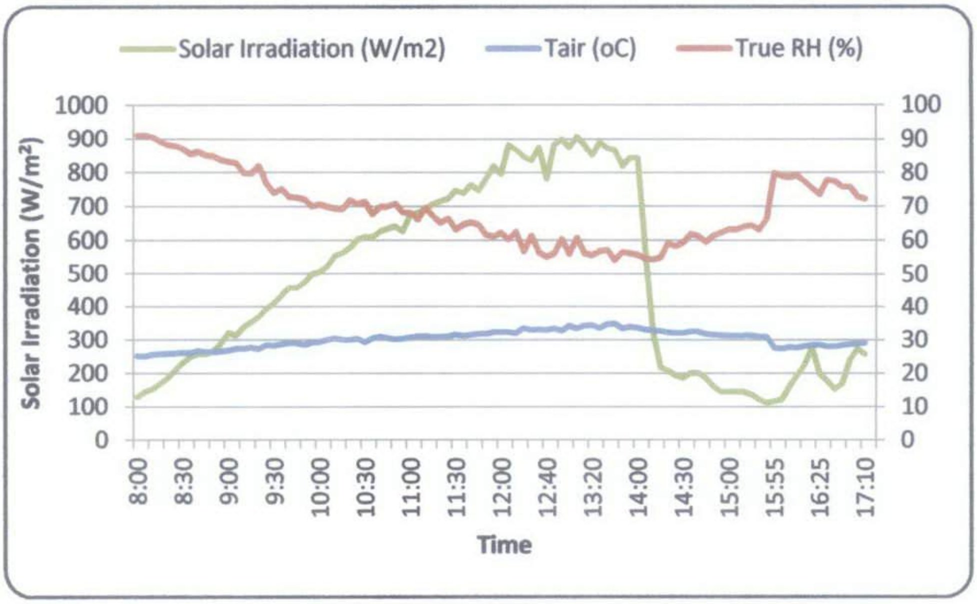

Figure 7: Measured weather parameter on 17th Aug 2011

Based on the weather parameters obtained, the relative humidity of the surrounding environment can be seen to be high (90%) during the early hours of the day and constantly reducing before it increases again after 2p.m. in the afternoon. The solar irradiation is highest during the peak sun hours from 11a.m. until 2p.m. On this day, the weather appeared to be slightly cloudy during the afternoon and later during the hours of after 2p.m., this explains the sudden drop in solar irradiation.

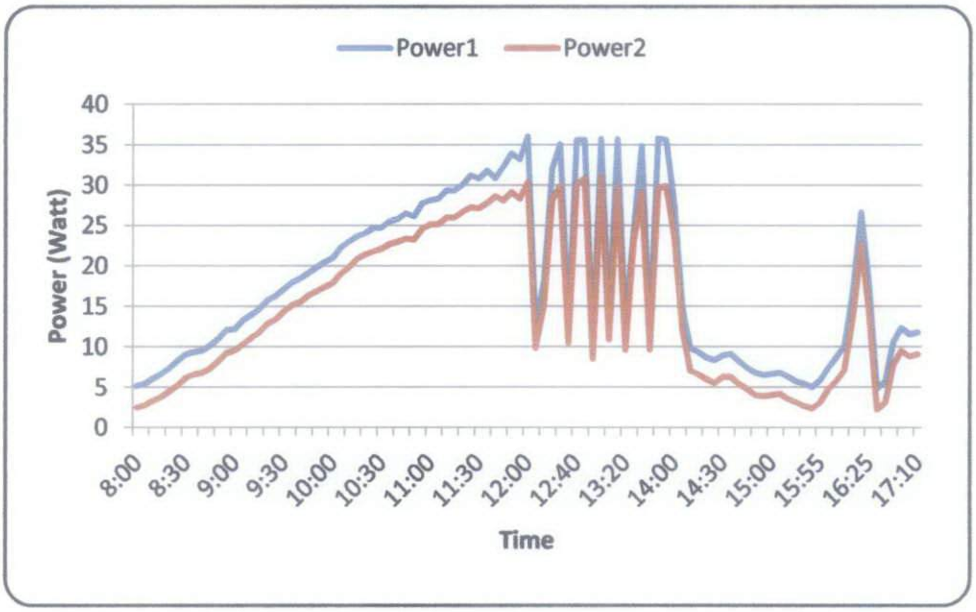

Figure 8: Measured PV panels output power

The power output of each panel is calculated by using the formula:

$$Power = Current \; x \; Voltage$$

Where the *current* is the value of current produced from each panel and the *voltage* is the amount of voltage supply produced by the panels combined at every five minutes interval.

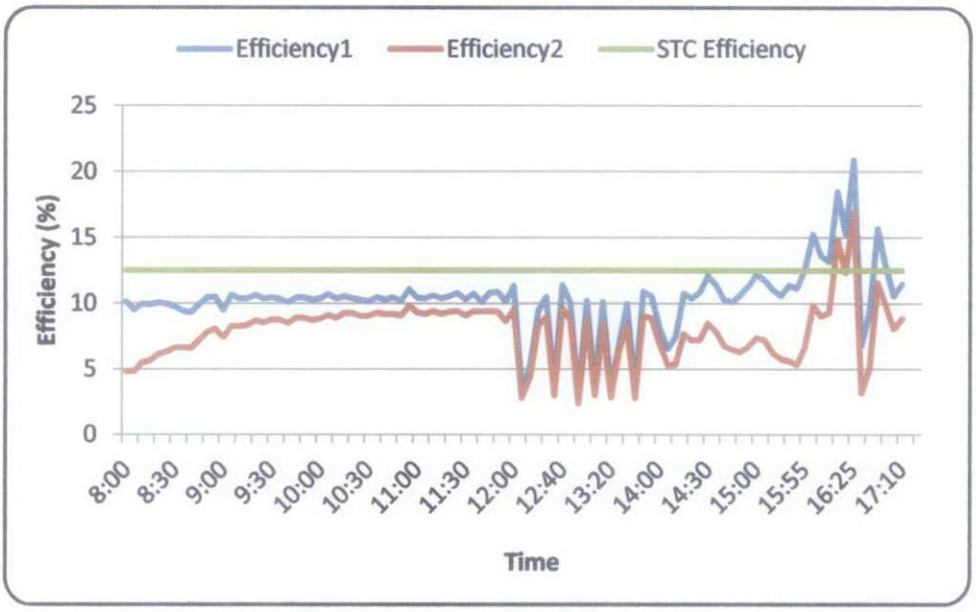

Figure 9: Comparison of Panel Efficiency

Using the calculations as shown in previous part 4.3, the Standard Test Condition (STC) of the panel is calculated to be 12.51%. According to the manufacturer's datasheet, P_{peak} of each module used in the experiment is 100 Wp and the area of each module (A) is 0.61m x 0.655m = 0.40 m^2, STC condition is test condition at 1000 W/m^2 of solar radiation level and 25 ^oC ambient temperature. The PV panel efficiency measurement has been carried out for both panels and is compared against each other. The PV panel efficiency calculated using values from the datasheet, provides the value of the STC efficiency. This is used to further express evidence that the efficiency of the PV module with water cooling is much higher compared to the conventional module. From Figure 9 as shown above, it can be seen that the panel with surface water cooling has a higher efficiency compared to the conventional module.

From the PV module with water cooling, a maximum power output of **45.7 W** and voltage of **16.2 V** was achieved under the operating temperature of 37°C, with low relative humidity of 56% and solar radiation of 843W/m^2. Current was measured to be **2.82 A** producing an efficiency of **14%**. The tabulated result is shown in *Appendix (Table 7).*

(PV Panel specifications: Power 50W; Voltage 17V; Current 2.94A)

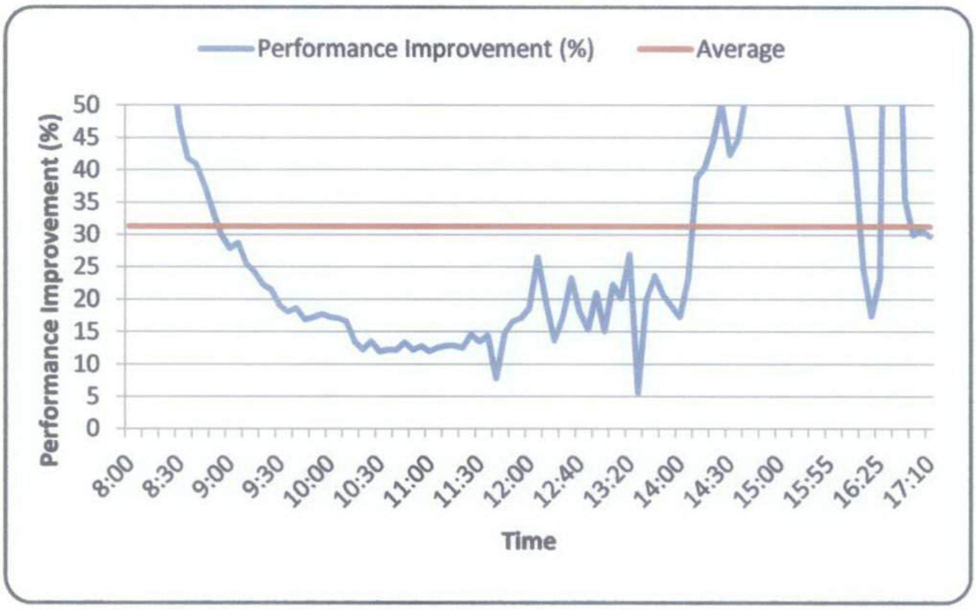

Figure 10: Performance improvement

During the peak operating hours of the day, which is from 11a.m. until 2p.m., the performance improvement by comparing the surface water cooling module with the conventional module can be distinguished. The method of calculating the performance improvement is done by using the following formula:

$$Performance\ Improvement(\%) = \frac{Power1 - Power2}{Power2}\ x\ 100\%$$

Where *'Power1'* is calculated from the module with surface cooling while *'Power2'* is calculated from the conventional module.

It can be seen that there is a positive improvement in the performance of the system. This proves that there is an improvement in efficiency with regards to the module with surface cooling.

From this study, the effects of ambient temperature, relative humidity and solar irradiation can be seen to vary the overall performance improvement of the photovoltaic modules. A PV module electrical power generation depends on its operating temperature. Most of the light energy shining on the PV cells is wasted as heat, by continually cooling the cell will result to lowering the operating temperature to near ambient temperature. This will reduce the amount of efficiency lost as solar cells work best at low temperatures. From the datasheet of the panel, the thermal degradation specification of the PV module is measured to be -0.074 V/°C. Therefore it proves that with the increase in operating temperature, the voltage output of the panel will decrease.

4.4.2 Study of Debris Accumulation

The study of debris accumulation requires the simulation of debris accumulation on top of the panels to better understand the affects it has on the overall performance of the PV panels. As previously mentioned, dust deposition on photovoltaic module reduces the power generated. The simulation of the debris accumulation will only affect the conventional module. This is due to the fact that the panel with water flowing will not allow the accumulation of debris on its surface.

The surface of the panels is partially covered using a cardboard. The study will analyse the results obtained from the partial coverage of the surface area of the panel. The percentages of covered area will represent the debris accumulated.

Experiment 1 : 8% Coverage (Bottom Left)

A piece of cardboard ***(17.5cm x 16cm)*** placed on the bottom left corner of the PV panel. Covered area of simulated debris is roughly ***8%*** of total area.

Note: Temperature sensor is directly below the area covered.

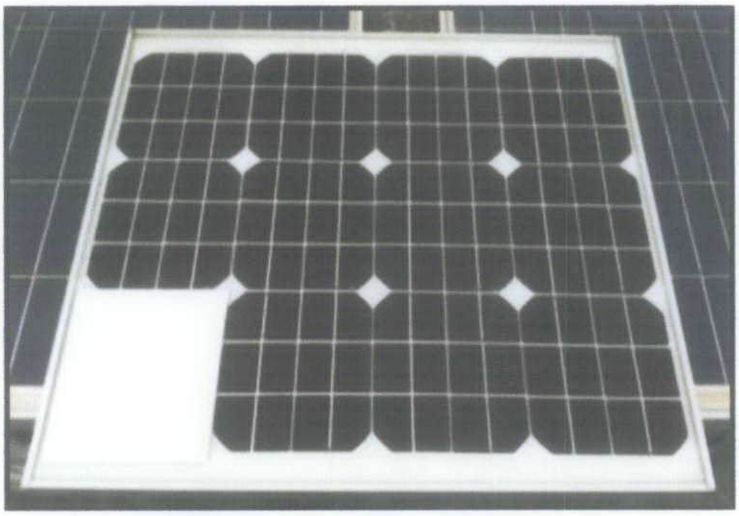

Figure 11 : Photo of Experiment 1 set-up

Figure 12 : Measured weather parameter on 6th December 2011

The above figure shows the measured weather parameter on the date of the experiment. It can be seen that during the afternoon hours from 11.30am until nearly 1pm, the solar irradiation declined. This was due to a cloudy followed by rainy weather.

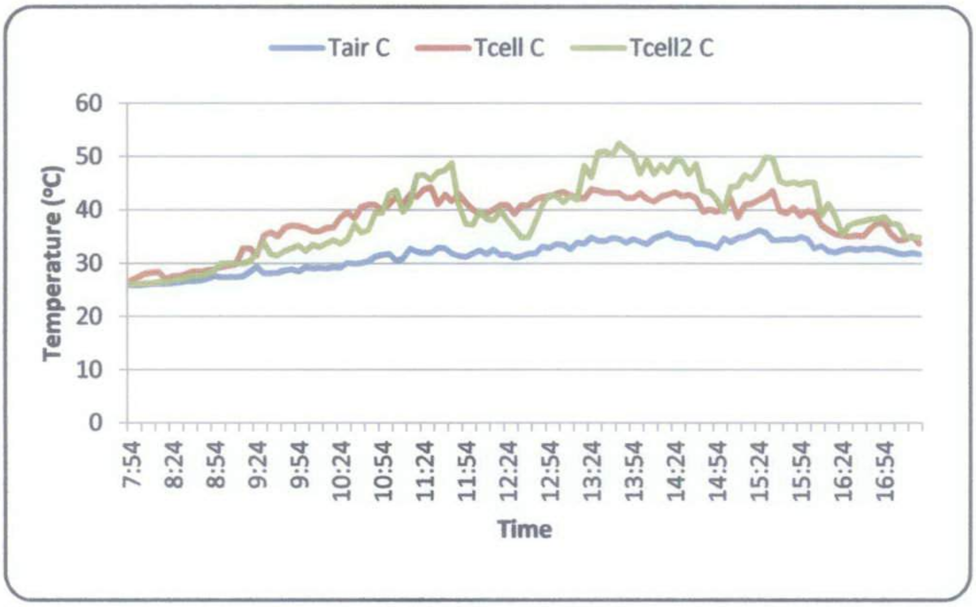

Figure 13 : Measured PV panels and ambient temperature

As explained earlier, it can be seen that there is drop in temperature of the panels due to the weather. Noticeably the temperature of the conventional module is cooler during the early hours of the day, which is due to the cardboard simulating the debris accumulation situated above the temperature sensor of the panel. Therefore, the cardboard acts as a second layer absorbing the heat. It provides the shade from direct transfer of heat from the sunlight onto the sensor itself. This is only present until the peak hours where the temperature of the sunlight can no longer be shaded by the layer of cardboard.

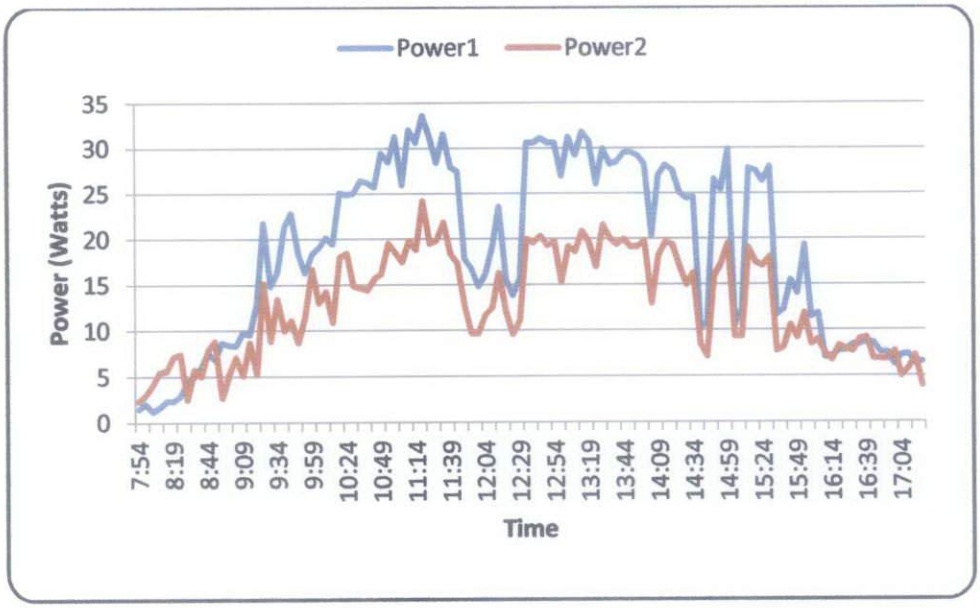

Figure 14 : Measured PV panels output power

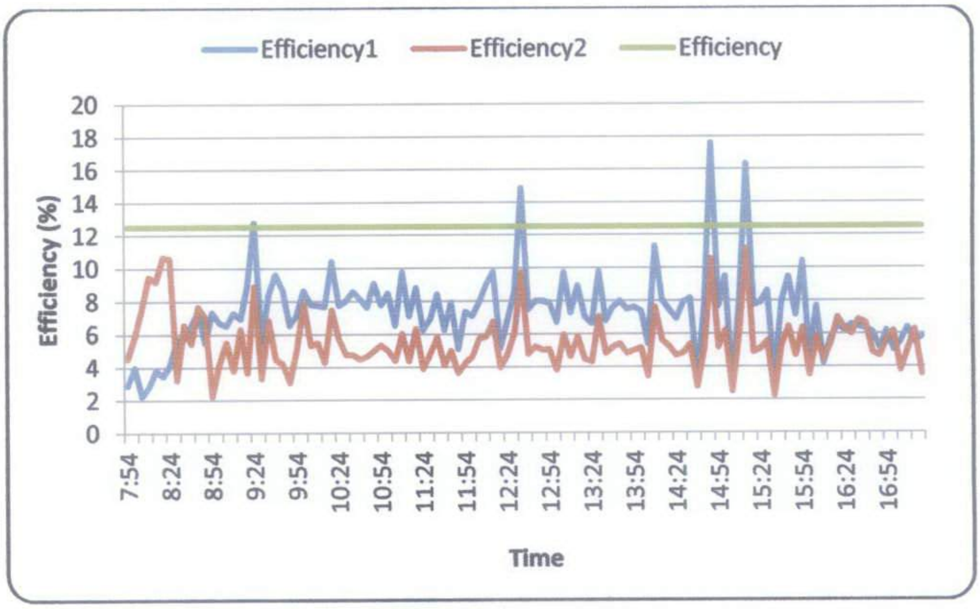

Figure 15 : Comparison of panel efficiency

Noticeably, the power output of the module with surface cooling is higher compared to the conventional module. The power output during the peak hours of the day can be seen to differ by almost 10Watts between the two panels. When comparing the efficiency of the panels, there is a significant reduction in the conventional module.

Experiment 2 : 8% Coverage (Top Right)

A piece of cardboard ***(17.5cm x 16cm)*** placed on the top right corner of the PV panel. Covered area of simulated debris is roughly ***8%*** of total area.

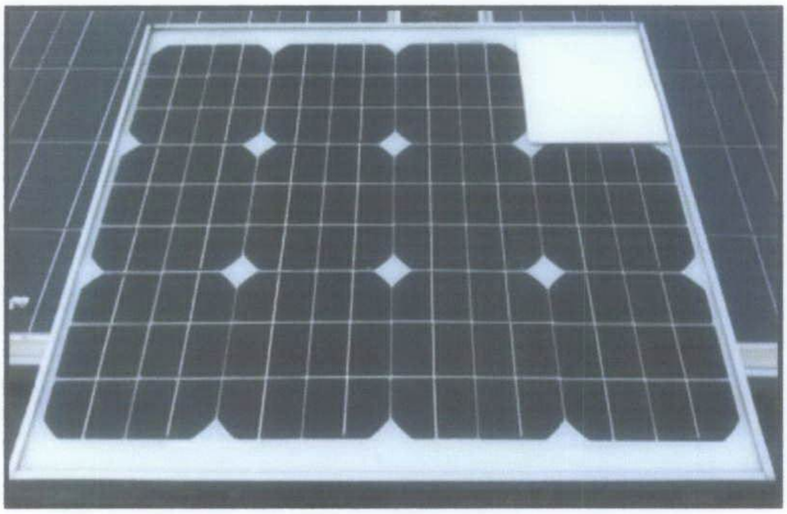

Figure 16 : Photo of Experiment 2 set-up

Figure 17 : Measured weather parameter on 8th December 2011

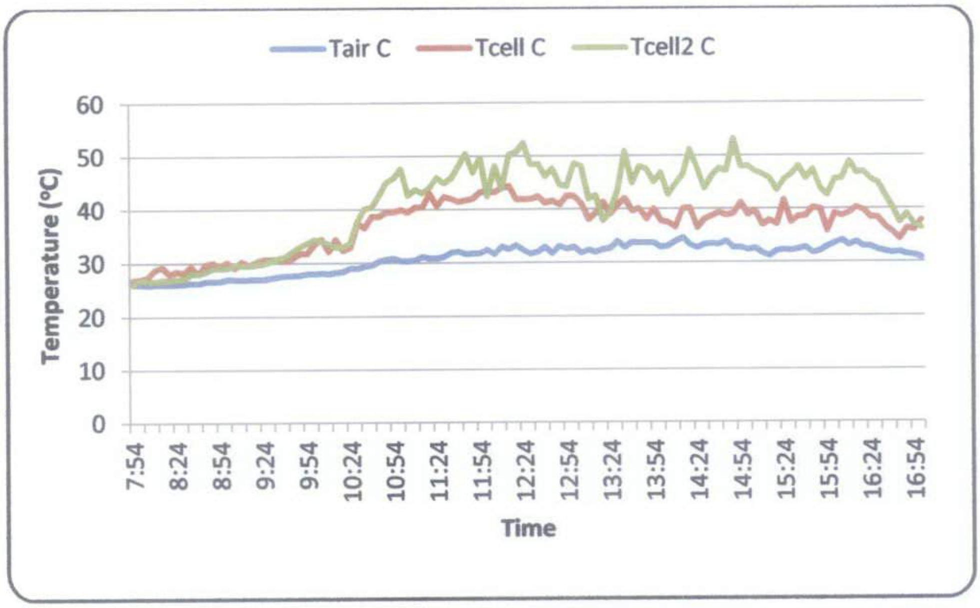

Figure 18 : Measured PV panels and ambient temperature

Based on the graphs plotted, it can be seen that the solar irradiation was low during the early hours of the day. The weather during the morning and shortly in the afternoon was slightly raining. This explains the drop in solar irradiation and temperature of the panels.

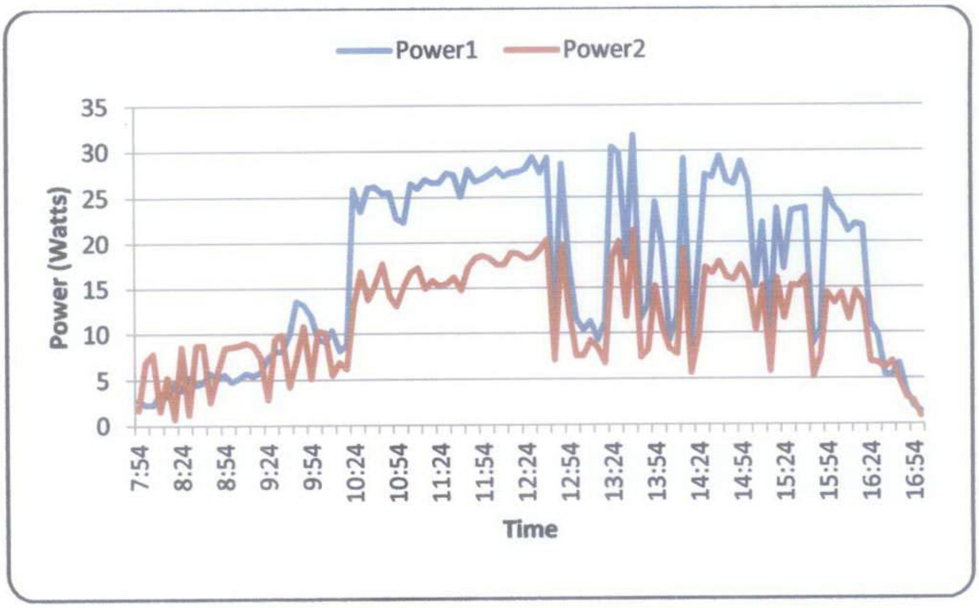

Figure 19 : Measured PV panels output power

It is noticeably that there is a power decrease in the power output from the conventional module. During the peak hours of the day, there is an estimated difference of more than 10Watts.

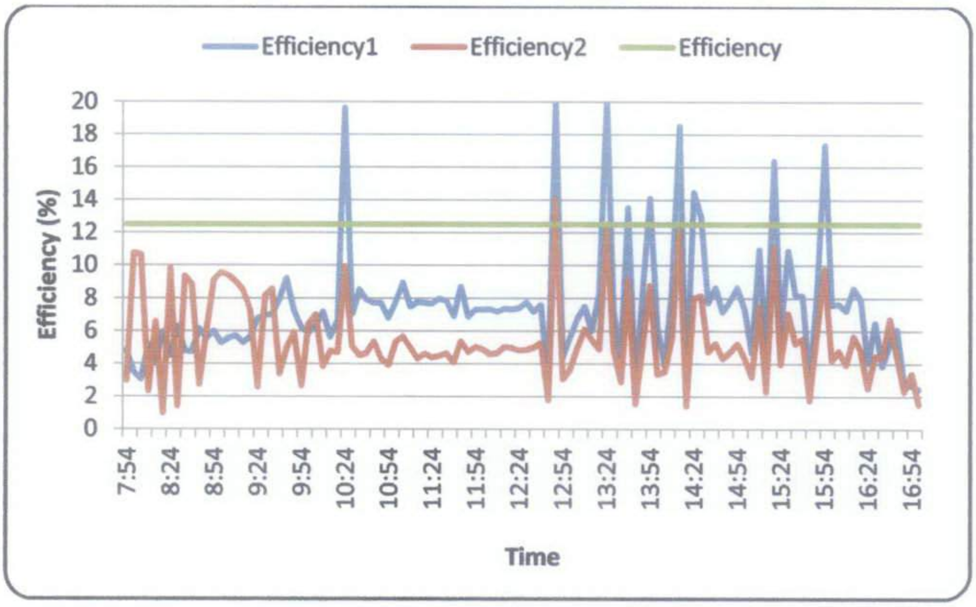

Figure 20 : Comparison of panel efficiency

By comparing the efficiency of the panels, it is notably seen that the conventional module with debris accumulated simulation has lower conversion efficiency when compared to the module with surface cooling.

Experiment 3 : 33% Coverage

Size of covered area is 32cm x 35 cm. The cardboard is placed on the bottom left corner of the PV panel. It is estimated that the covered area of the simulated debris is 33% of the total area. The cardboard is covering 4 cells.

Note: Temperature sensor is directly beneath the covered area.

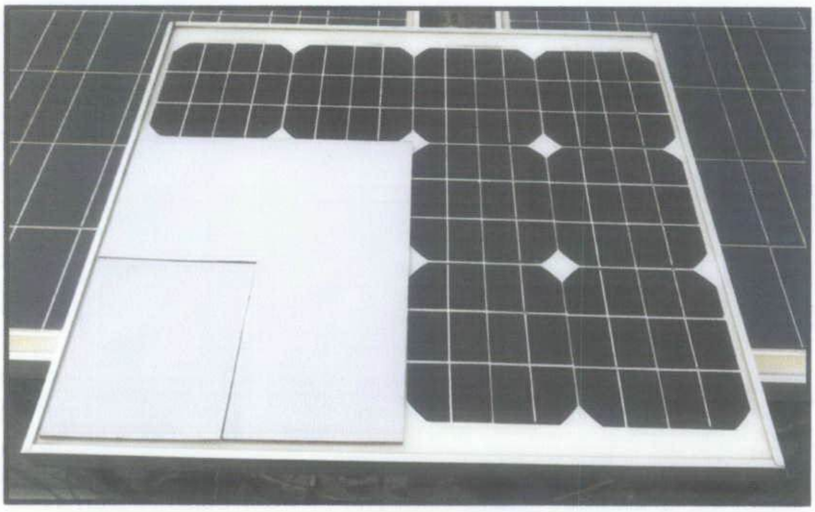

Figure 21 : Photo of Experiment 3 set-up

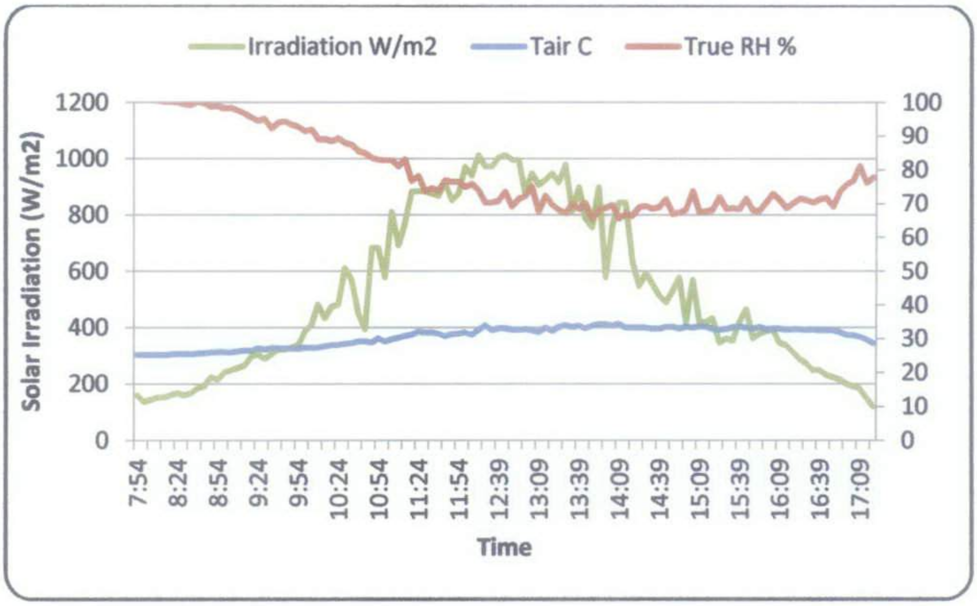

Figure 22 : Measured weather parameter on 9th December 2011

The weather data shows a fairly decent weather with high solar irradiation during the peak hours of the day. There was a slight rain during noon which explains the drop in solar radiation.

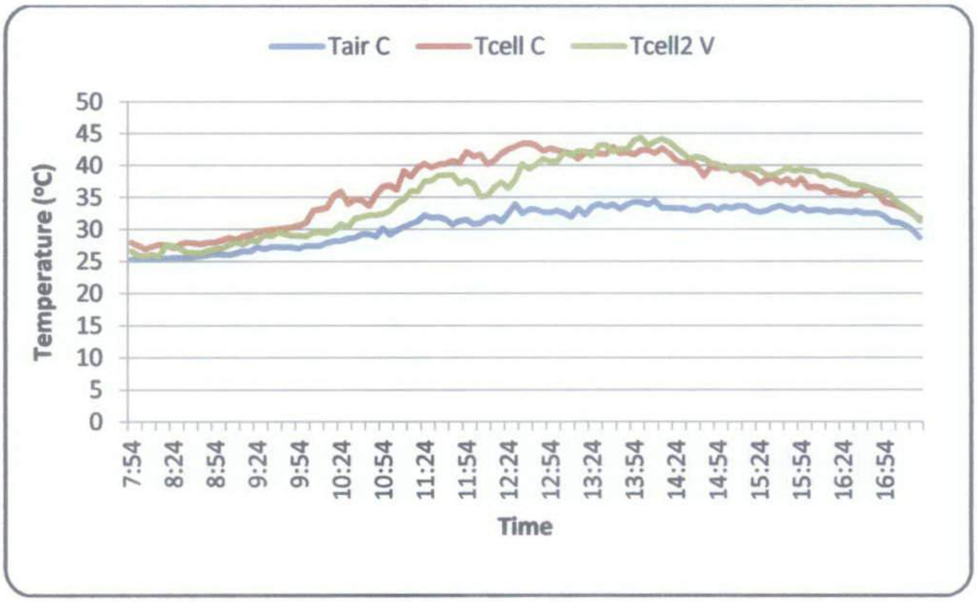

Figure 23 : Measured PV panels and ambient temperature

There is a slight difference in the temperature readings of both the panels during this experiment. This is due to the fact that the cardboard is placed directly above the temperature sensor which has affected the readings. It is notably that only during the afternoon that there is a slight increase in the temperature of the conventional module.

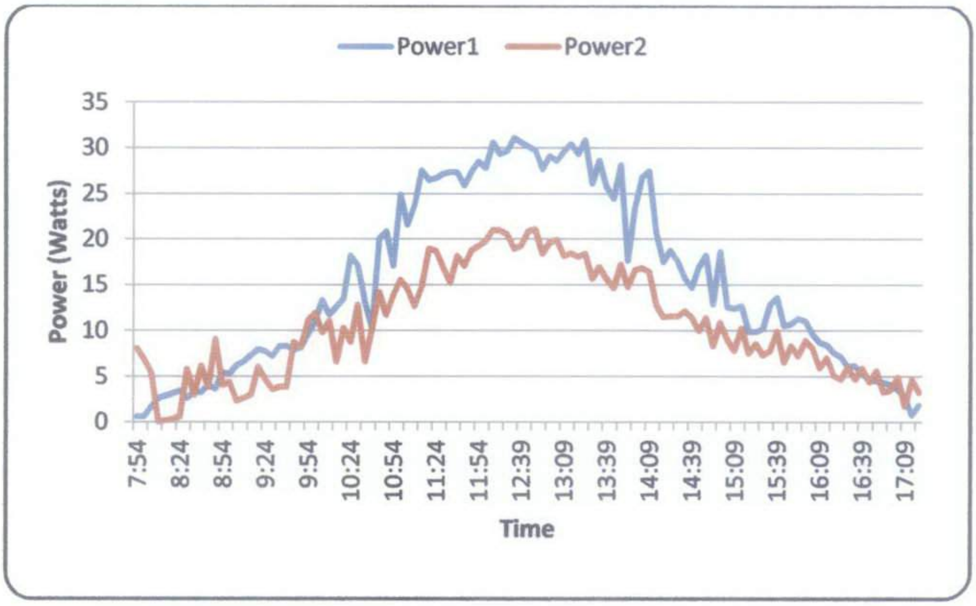

Figure 24 : Measured PV panels output power

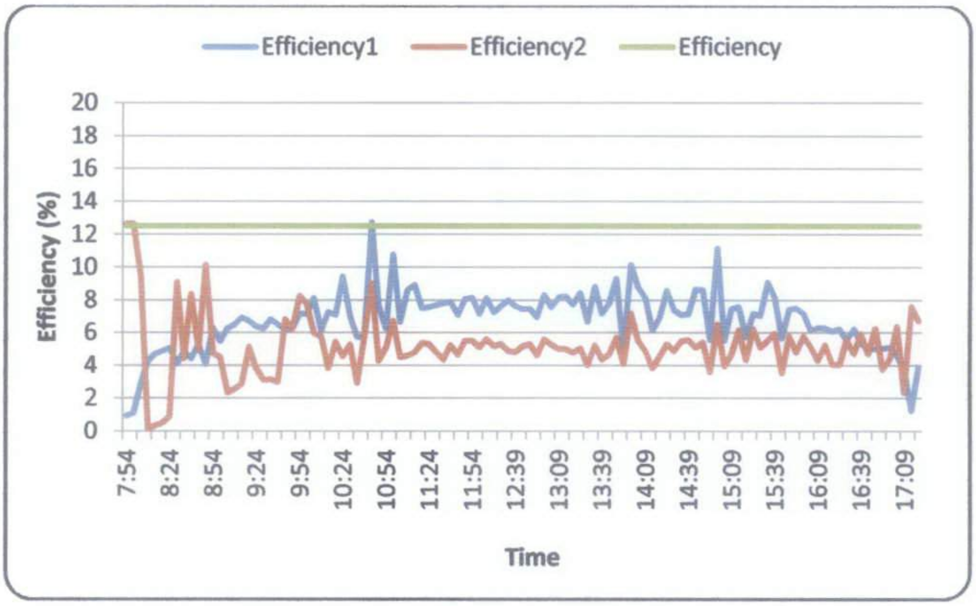

Figure 25 : Comparison of panel efficiency

During the peak hours of the day, there is a significant increase in power output from the module with surface cooling compared to the conventional module. This is due to the lower surface temperature of the module with surface cooling, and also the coverage area of the panel. With the debris simulation, it seems to have lowered the conversion efficiency hence reducing the overall power output of the panel.

Experiment 4 : 50% Coverage

A total of 6 cells are covered. The cardboard is placed to cover the whole of the right hand side of the PV panel. Size of cardboard covering the area is 32cm x 52.5cm. It is estimated that the covered area of the simulated debris is 50%.

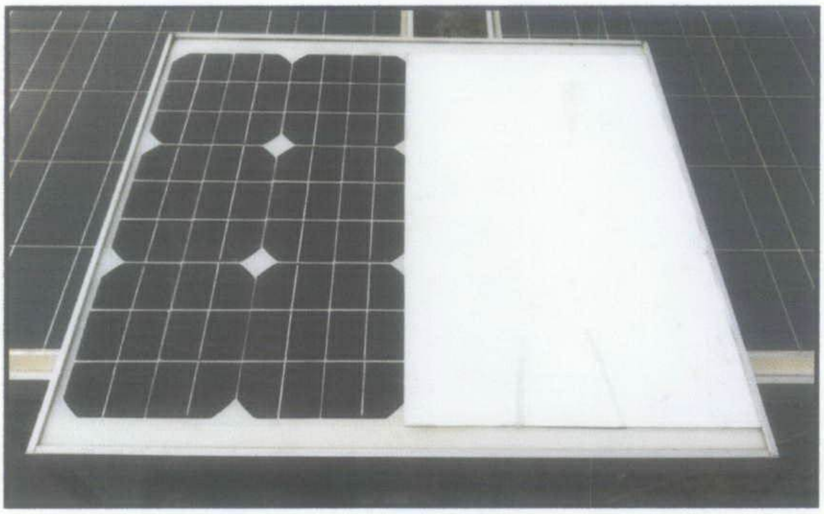

Figure 26 : Photo of Experiment 5 set-up

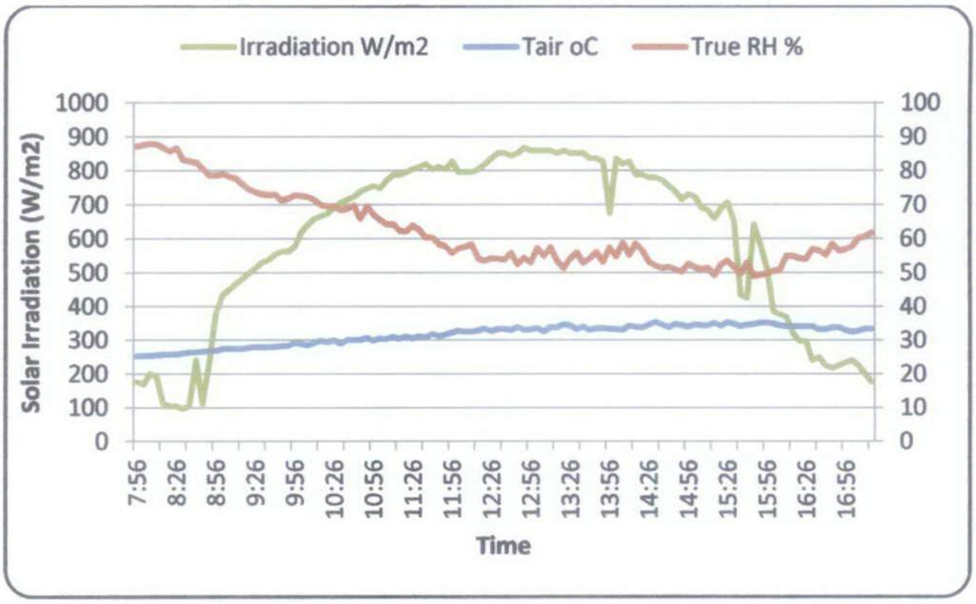

Figure 27 : Measured weather parameter on 26th December 2011

There was a slight cloudy and rainy weather during the early morning, which explains the drop in solar irradiation before increasing rapidly from 9a.m. Some casted clouds were seen also during the lunch hour and later during late afternoon.

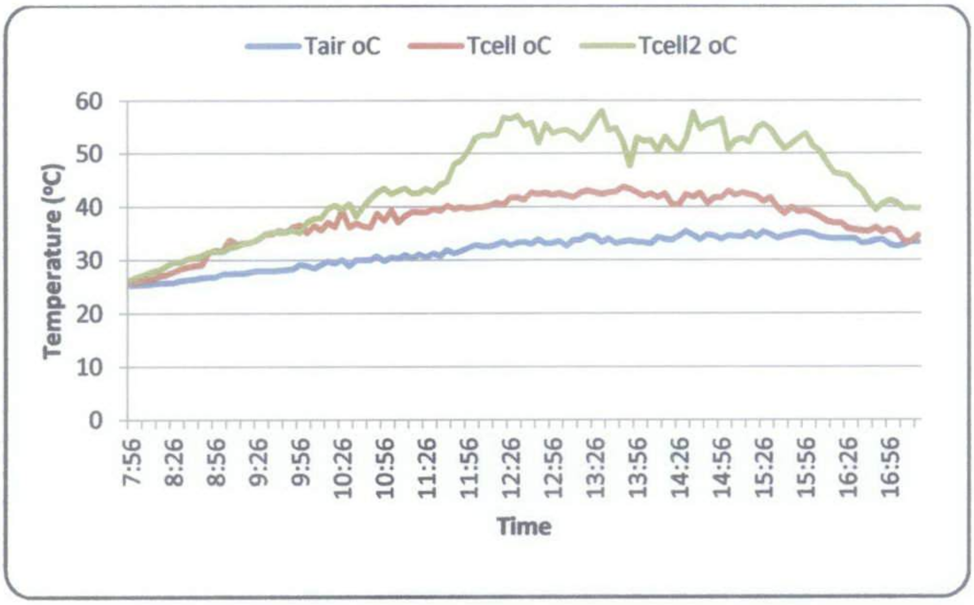

Figure 28 : Measured PV panels and ambient temperature

The temperature of the panels was evenly increasing during the morning due to the slightly ill weather. Once the solar irradiation had increased, it can be seen that there was a more significant difference between the temperatures of the panels.

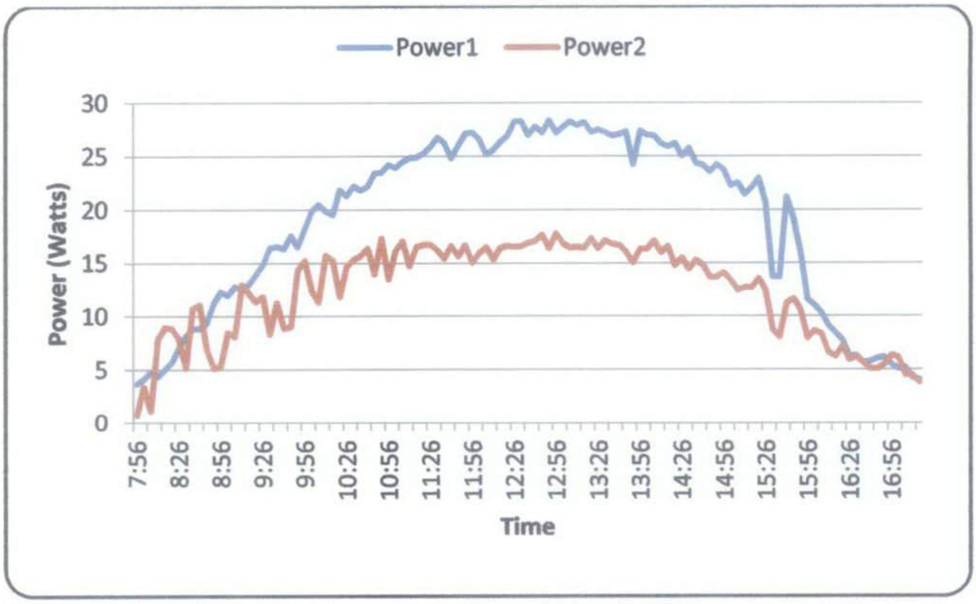

Figure 29 : Measured PV panels output power

Due to the conventional module experiencing a half-covered surface for the debris accumulation, it can be notably seen that there is a low conversion in the panels' efficiency. This is particularly significant during the peak hours of the day. Less power was produced due to the coverage of the conventional module's panel.

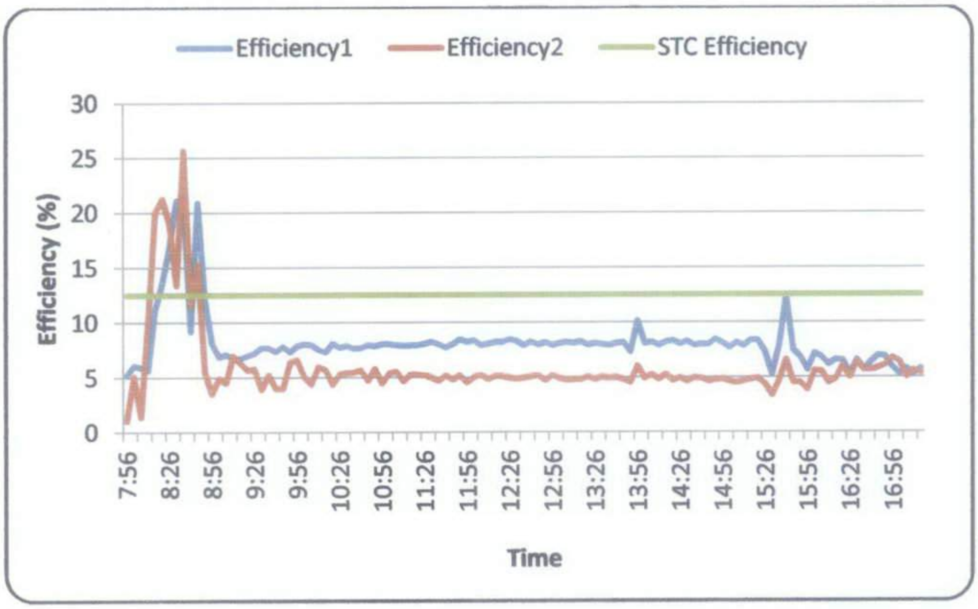

Figure 30 : Comparison of panel efficiency

The overall panel efficiency still shows that the module with surface cooling has a higher efficiency when comparing the two modules. The efficiency of Panel 1 is slightly below than usual if compared to the results obtained from previous experiments. This may be due to the partly cloudy day with the solar irradiation only reaching a highest value of 859 W/m². The values would have definitely been more significant if the solar irradiation had reached above 900 W/m².

During the early hours of the day, it can be seen that the efficiency of both panels are above the calculated STC efficiency. This can be neglected as anomalies occurring due to the equipment set-up. Even though the efficiency is high, the output power from both panels is figuratively low.

The results obtained from the experiments performed are tabulated in the table below.

Table 5 : Tabulated Results of Debris Accumulation Study

Experiment No.	Percentage of coverage (%)	Performance Improvement (%)	Difference in Power (W)	Difference in Efficiency (%)
1	8	52	9.05	2.65
2	8	55	8.53	2.92
3	33	79	12.09	3.45
4	50	81	12.20	3.69

From the results shown above, it can be noticeable seen that the percentage of coverage of the debris simulation directly affects the performance improvement of the system. The difference in power shown in the table represents the difference between the power outputs from Panel 1 (module with water cooling) compared to Panel 2 (conventional module). The overall performance improvement from the comparison between the two panels can be seen to increase with the increment of the debris simulation coverage area. Debris accumulated on the surface of the PV panels can therefore affect the overall efficiency of its performance.

4.5 Infrared Imaging

Figure 31 : Infrared Camera Fluke Ti25

Fluke Ti25 infrared camera was used to capture an infrared thermal image of the PV panels during the day. The captured images act as an additional supported information to the results obtained from the experiments conducted. To obtain a correct measurement of the images, the value of emissivity (ε) was configured to 0.65 for poly-crystalline PV panel (Botsaris,P., 2010). The image was taken on 17th August 2011 at 1p.m.

Figure 32 shows the thermal image of Panel 1 (PV module with surface cooling). From this image, it can be seen that the temperature distribution on the PV panel's surface is spread evenly. While the following Figure 33 shows the thermal image of Panel 2 (conventional PV module without surface cooling). The observed temperature of the panel is higher than Panel 1, and the surface temperature is not evenly distributed along the panel surface. This may be due to partial soiling (dust) accumulated on the PV panel surface.

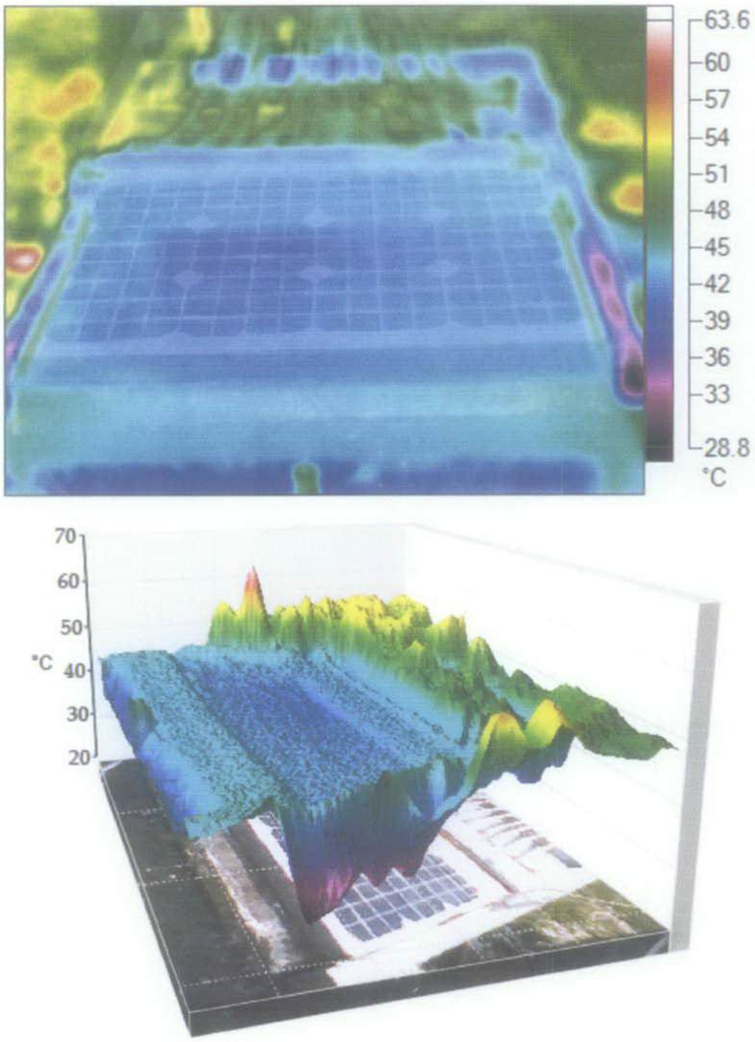

Figure 32: Infrared image of Panel 1 (Module with surface cooling)

Observing the figure above with the temperature scale (28.8 – 63.6°C) and the colour palette (rainbow scale), it can be said that the measured temperature values of the PV module fluctuate within the region of 39 – 41°C. Whereas the ambient temperature is measured to be 36°C during the thermal image was captured. This small declination between the ambient temperature and the temperature of the module can be considered as normal, due to the heating of the surface of the panel due to the solar irradiation.

The water flowing on the surface of the module absorbs the heat generated by the cells during the day. The importance of this system also provides water to help clean the surface from any particles accumulated.

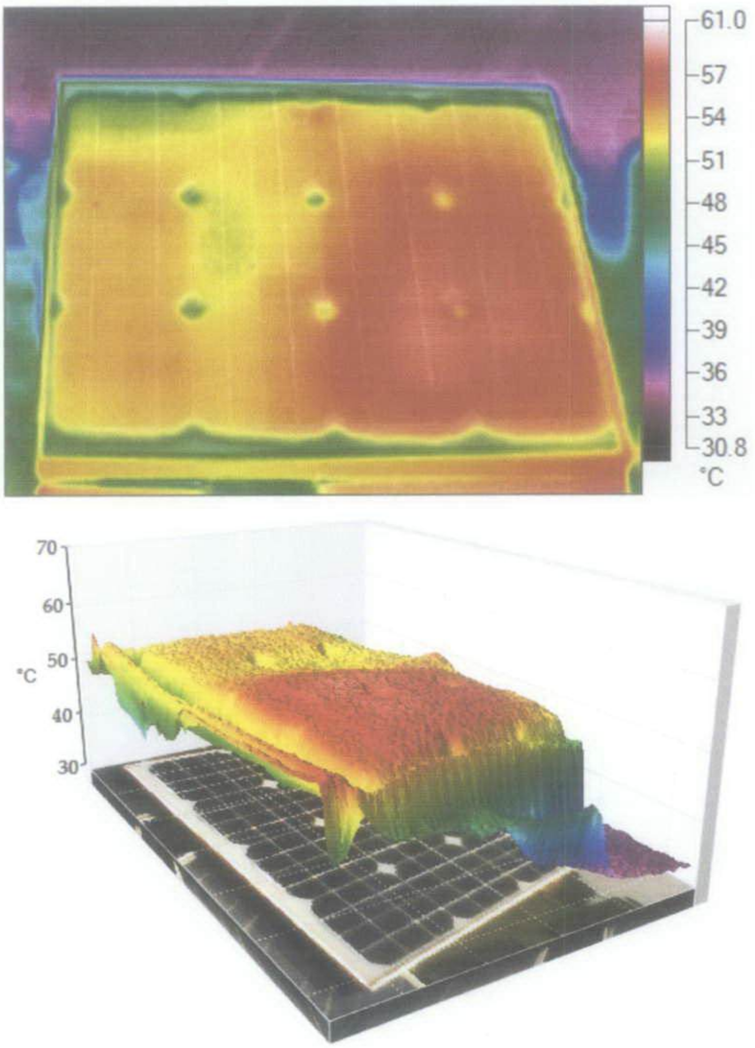

Figure 33: Infrared image of Panel 2 (Conventional module)

Efficiency depends strongly on the temperature of the PV modules and an overheating causes a decrease in the produced power output. Some areas have shown a not uniform distribution of the temperature values on the whole surface of the PV panel. This could be due to the presence on the surface great dust accumulated in comparison to other areas. As a consequence, this area represents a "hot spot" area through the thermal image of the PV module surface, subsequently revealing a deteriorated module performance. It is noticeably that almost half of the right hand side of the module is seen to have an abnormal overheating compared to the other area. Probably this is due to the placement of the module on top of an unused PV module, which limits the occurrence of natural convection from beneath the panel. The measured temperature fluctuates within the region of 53 - 56°C.

CHAPTER 5:
CONCLUSION AND RECOMMENDATION

5.1 Conclusion

Throughout the study, the experiments conducted to prove the objectives of this project have been achieved. Based on the results obtained, the research further confirms that the effect of surface temperature cooling of the PV cells can further increase its overall performance. Most of the light energy from the sun is wasted to heat, therefore, by cooling the cell will results to lowering the operating temperature to near the ambient temperature. This in hand will reduce the amount of efficiency lost as the PV cells work best at low temperatures.

From the PV module with surface temperature cooling, a maximum power output of 45.7 Watts and voltage of 16.2 V was achieved under the operating temperature of 37°C, with low relative humidity of 56% and solar radiation of 843 W/m^2. Current was measured to be 2.82 A producing an efficiency of 14%. Noticeably, from the figures shown taken from the Infrared Camera, it can be seen that from the module with surface cooling the temperature of the panel is much lower if compared to the conventional module. Water can therefore be used as a significant temperature reducer and also prevents dust from accumulating on the surface of the panels.

From the studies conducted, the efficiency of the solar panels has a positive association with solar irradiation and ambient temperature. It is preferable to maintain a low operating temperature as the efficiency of the system and the power output decreases with the increase in operating temperatures. Comparing the temperature of the conventional module, the utilisation of water flowing on the surface of the PV module allows the operation at lower temperatures. The flow of water further reduces the temperature of the module through absorbing the heat generated during the day.

Furthermore, the evaporation of water during its flow on the surface of the module would further decrease the temperature resulting in an increase in voltage output. Throughout the process of conducting the experiment, the water level in the tank further suggests that the evaporation of water was taking place. This can be related to the relative humidity measurements. Additionally during the recording of high amount of RH levels throughout the day (average 70%), it was measured that the water level in the tank decreased by only 3 centimeters. Whereas during fair amounts of RH level measured (average 60%), the decrement in the water level was more significant up to 5 centimeters. Evidently the evaporation rate was higher due to low levels of moisture content in the air. Thus, further cooling of the surface of the PV module had occurred.

The debris accumulation research was performed in stages of covered area. During the smaller coverage of surface area, minimal difference can be seen from the output of power produced and its overall efficiency. Not much of a difference can be seen by covering up one cell. From the research, it can be seen that by covering up more than 30% of the overall surface area, a significant difference in the power output and efficiency can be achieved.

Up to 12 Watts in increase of output power from the module with surface cooling can be seen during the peak hours of the day. The cardboard acts as a second layer of protection towards heat and also solar irradiation to the surface of the panel. Although a high temperature of the panel surface affects the performance of the PV panel, the simulation of the debris accumulated is another cause behind the low conversion efficiency. The cardboard itself does not allow much light to pass through, thus the cells cannot generate current to produce power from the blockage. This research proves that with the debris accumulated on the surface of the panels can contribute to the reduction in the power generated from the PV panel. Hence, a drop in system performance can be noticeably identified due to the debris accumulated on the panels when compared to the module with surface cooling.

5.2 Recommendation

To further continue this research, continuation on the study of how shade can affect the performance of the PV module would be relevant. Simulating the debris and shade by using car tint films can provide a better understanding on how this will further affect the efficiency of the panels. Car tint films have an allowable amount of sunlight to pass through. Therefore it would simulate perfectly the shade percentages and relate it to the overall performance.

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APPENDIX

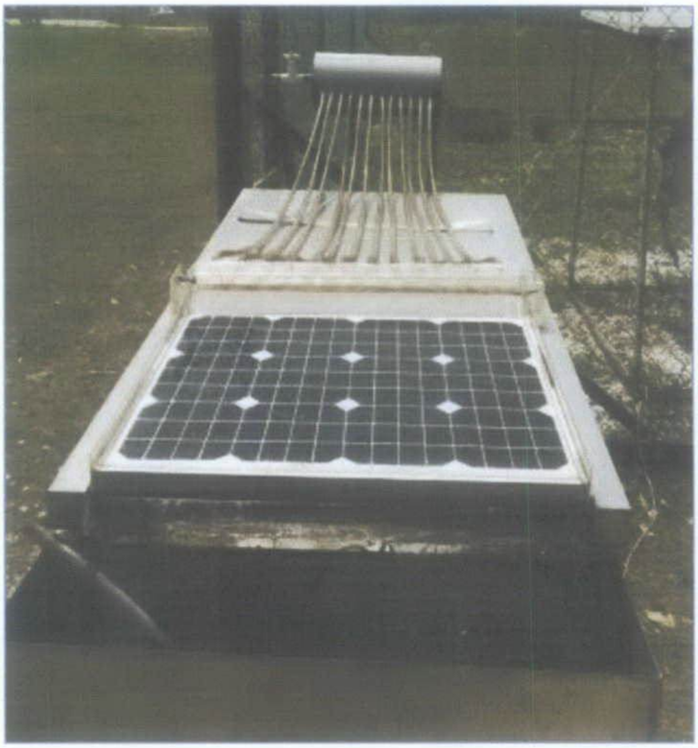

Figure 34 : Top View of Panel with Water Cooling

Figure 35 : Side View of Panel with Water Cooling

Table 6 : Selection of Highest Average Performance Improvement

Date	Average Solar Irradiation (W/m2)	Average RH (%)	Average Performance Improvement (%)
22/6/11	425.55	73.13	27.28
29/6/11	574.85	64.15	20.78
30/6/11	485.93	57.97	27.31
27/7/11	364.25	65.07	25.88
28/7/11	525.56	59.71	26.85
10/8/11	493.64	65.05	29.82
11/8/11	577.61	54.44	20.51
12/8/11	377.62	67.77	28.81
17/8/11	460.36	75.12	31.30
18/8/11	550.41	78.08	22.17

Table 7 : Highest Power Output

e	Time	Tair (oC)	RH (%)	I1 (A)	I2 (A)	Vsupply (V)	Solar Irradiation (W/m2)	Power1 (W)	Power2 (W)	Efficiency1 (%)	Efficiency2 (%)
/11	13:24	36	57	2.63	2.32	14.02	923.78	36.91	32.46	10.00	8.80
/11	13:31	32	59	2.71	2.35	13.38	835.42	36.30	31.44	10.87	9.42
/11	12:56	36	46	2.43	1.88	13.18	771.16	32.04	24.79	10.40	8.04
/11	12:51	34	56	2.75	2.39	12.78	522.14	35.14	30.48	16.85	14.61
/11	13:36	35	49	2.64	2.01	13.41	851.49	35.43	26.95	10.42	7.92
/11	13:19	33	56	2.82	2.46	16.22	843.46	45.73	39.84	13.57	11.82
/11	13:44	35	40	2.91	2.47	13.48	947.88	39.27	33.26	10.37	8.78
/11	11:14	31	66	2.83	2.37	13.02	923.78	38.51	30.91	10.43	8.75
/11	12:00	32	62	2.61	2.20	13.81	795.26	36.02	30.35	11.33	9.55
/11	13:00	34	55	2.66	2.28	13.88	827.39	36.84	31.65	11.14	9.57