IMPROVEMENT OF SOLAR PHOTOVOLTAIC MODULE EFFICIENCIES THROUGH WATER COOLING AND DEBRIS REMOVAL

By

JEIHARISH S.V.SANTHIRASEGARAN

12593

Dissertation submitted in partial fulfilment of

The requirements for the

Bachelor of Engineering (Hons)

(Mechanical Engineering)

JANUARY 2013

University Teknologi PETRONAS

Bandar Seri Iskandar

31750 Tronoh

Perak Darul Ridzuan

CERTIFICATION OF APPROVAL

Improvement of Photovoltaic Solar Module Efficiencies through Water Cooling and Debris Removal

By

Jeiharish S.V.Santhirasegaran

A project dissertation submitted to the

Mechanical Engineering Programme

University Teknologi PETRONAS

in partial fulfilment of the requirement for the

BACHELOR OF ENGINEERING (Hons)

(MECHANICAL ENGINEERING)

Approved by,

…………………………………………......

(Ir.Dr.Mohd Shiraz Aris)

Project Supervisor

UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

AUGUST 2013

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project; 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.

……………………………………………

(JEIHARISH S.V.SANTHIRASEGARAN)

ABSTRACT

Low energy conversion efficiency is one of the major problems that take place in the method of photovoltaic power generation. The factors that cause this problem to occur are mainly due to the extremely high operating surface temperatures of the photovoltaic module and the dust accumulation on the solar module surface. Therefore, the objectives set in this project are to highlight how these factors do affect the module performance and how can they be solved. The first objective of the case study is to study the effects of surface temperature cooling on the photovoltaic modules while the second objective emphasizes on the performance of PV modules with respect to debris accumulation on the module surface. In order to carry out the project, a prototype was first built to implement the method of water cooling on the photovoltaic module. The performance of the module with water cooling is then compared to the conventional module (no modifications). As for the debris accumulation study, the conventional module is covered with opaque sheets of different sizes resembling the dust coverage area on module surfaces and the output power is compared with the module with water cooling (zero dust coverage). Based on the results obtained, it can be analysed that when the water cooling technique is applied on the PV module, the average highest performance improvement comparing to the conventional module, reaches up to a maximum value of 43.24% (5th July 2013). This proves that the addition of water layer helps in improving the amount of power generated for a specific solar irradiation, thus efficiencies increase as well from 11.01% to 17.45%. As for the dust accumulation experiment, the highest average performance improvement achieved is 89.94%; when comparing the module with water cooling to the conventional module set up with 50% dust area coverage. The module with water cooling also has an improved efficiency of 23.92% compared to the efficiency of the conventional module with dust coverage which is only 10.61%, at peak hours. Hence, the project study carried out proves that improvement of the photovoltaic module efficiencies is highly possible with application of the water cooling method. This method does not only reduce the surface temperatures of the module, but also prevent dust settlement on the module surface as well.

ACKNOWLEDGMENTS

I have taken efforts in this Final Year Project research studies. However, it would not have been made possible without the kind help and support from the many individuals around me. I would like to extend my sincerest gratitude and thanks to them.

First and foremost, I would like to express my greatest appreciation to God All Mighty for His wonderful blessings throughout my Final Year Project. I would also like to take this opportunity to express my sincere gratitude towards my project supervisor, Ir. Dr.Shiraz bin Aris, for his continuous guidance right from the beginning to the completion of my Final Year Project. His time and support given was essential towards me successfully carrying out the project.

Besides that, I would also like to thank the lab technicians, Mr. Fahmi and Mr.Mafus, for assisting me on the prototype building of the project. Your kindness in helping me providing the equipment and ideas will always be appreciated.

Furthermore, special thanks to my family members and friends for their great moral support towards my accomplishment of the project. Without your support, I would have faced lots of difficulties throughout the entire project.

Last but not least, many thanks to everyone involved in the completion of my Final Year Project, directly or indirectly. Your support, though how small it is, will always be treasured.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1.0
INTRODUCTION

1.1 Background Study

Energy that comes from resources that are continually replenished such as wind, sunlight, rain, tides, and geothermal heat are known as renewable energy. From Figure 1, it can be clearly seen that from the total world energy consumption, approximately about 17% of the total energy is generated from renewable options.

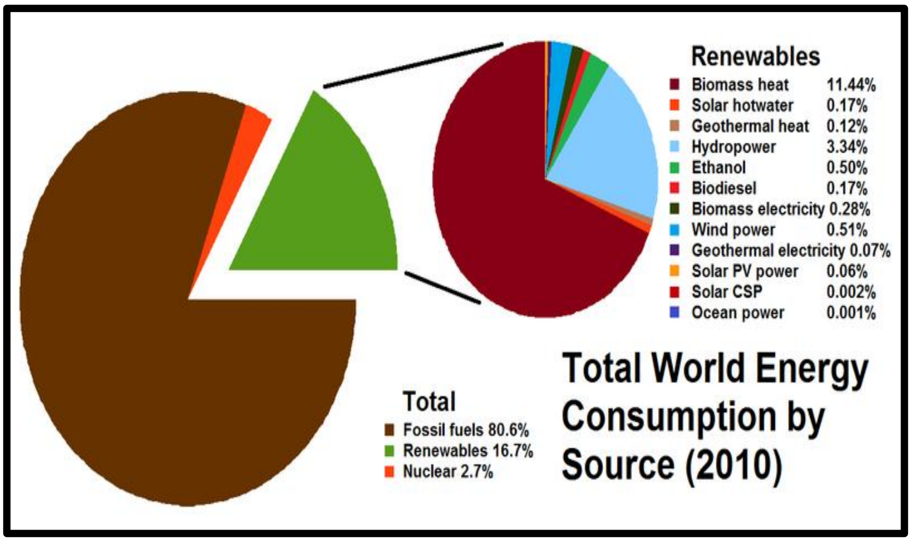

Figure 1: Total World Energy Consumption

Photovoltaic (PV) Power Generation is one of the available options of renewable energy that is being widely applied in our world nowadays. This method of power generation is basically generating electrical power by converting solar irradiation into direct current electricity with the presence of semiconductors on the PV modules that exhibit photovoltaic effect. The term photovoltaic effect refers to creation of voltage or electric current (Direct Current, DC) in a material upon exposure to light. In detail, this phenomenon takes place when there is presence of sunlight or any other light hitting the module surface, causing the electrons present in the valence band of the semiconductors to absorb energy, being excited, jump into the conduction band and become free. The free movements of high energy electrons generate an electromotive force, thus the light energy is converted into electrical energy.

This particular way of power generation is considered attractive as it has many advantages such as:

1) Limited impact on the environment - Reduce CO_2 emissions
2) Reliable and industrially matured – Higher life expectancy
3) Operate autonomous without any noise generation – Do not involve any moving mechanical parts
4) Minimum operating and maintenance costs

With such valuable advantages, it is important to ensure that the performance of the photovoltaic modules is excellent. Photovoltaic modules are packaged connected assembly of solar cells. A single solar cell produces limited amount of power, thus, a packaged array of solar cells are needed to supply sufficient power to the specific demand.

According to several researches related to PV Power Generation, it is said the factors that contribute to the PV module efficiency are the nature factors such as cloud coverage and relative humidity of the surroundings. However, these factors do not play a major role compared to the surface temperature and dust deposition on the PV modules, where the efficiency and performance of the PV Power Generation is affected even more drastically. Due to high demand for renewable energy, solar cells manufacturers have been giving high importance to temperature cooling and debris removal from the surface of the photovoltaic modules, thus ensuring that the efficiency of the power generation is always at its best level.

1.2 Problem Statement

Analysing the amount of output power generated and relating the data with the amount of solar irradiation present together with the area of PV module exposed to sunlight allows us to determine the performance of the photovoltaic modules. One of the serious problems encountered by these existing photovoltaic modules is the low energy conversion efficiency. In an ideal condition, it is expected that maximum electricity is generated from the presence of maximum light energy. However, in the actual situation, only a small portion of the light energy is converted into electricity, while the rest is converted into heat. Cloud coverage and relative humidity do influence the intensity of the solar irradiation present and this indirectly affects the output power generated by the module. Nevertheless, with the solar irradiation for each day being specified and normalized, it is still believed that the energy conversion efficiency is relatively low. The major factors that lead to this problem are as following;

- **Module Surface Temperature**

  Due to the presence of high temperature sunlight hitting the PV module, the exposed surface tends to get heated up. This cause the semiconductors that exhibit photovoltaic effects tend to get equally hot. The semiconductors used in polycrystalline PV cells, lose efficiency as temperature increases. As the temperature of the conducting material increases, phonons get excited and impede the uniform movement of the electrons in the material. This impedance is what decreases the efficiency of the energy level conversion of the photovoltaic module when it gets too hot.

- **Debris Deposition on Module**

  As the modules are set up in open spaces to receive maximum direct sunlight, the dust from the area surroundings tend to fall on the module surface and form a layer on the panel. The longer the time, the thicker the layer of dust becomes. This additional layer formed on the surface module would act as a barrier preventing maximum sunlight from reaching the panel. Thus, energy conversion of the photovoltaic modules would be relatively low. Besides that, the existence of the dust layer would also cause the heat generated on the module surface during the day, to get trapped within this particular layer causing the modules to be constantly heated.

This will reduce the energy level conversion efficiency of the modules, as the modules are operating in high temperatures.

1.3 Project Objectives and Scope of Study

The performance of the photovoltaic module relatively drops when the energy conversion efficiency is low. From the problem statement, it is understood that the major factors that contribute to this problem are basically the module surface temperature and the debris/dust accumulation on the modules. Therefore, the target of this project is to enhance the efficiencies of the photovoltaic modules with relating to the measures of surface temperature cooling and debris removal. The specific objectives that are set to be achieved are as follows:

1) **Investigating the effects of surface temperature cooling on photovoltaic modules.**

2) **To study the performance of the photovoltaic system with respect to dust/debris accumulation and shading of panels.**

This project is targeted on improving the efficiencies of the photovoltaic modules. Water cooling and removing the accumulation of debris on the surface module are the modifications implemented in this project. The project study mainly focuses on analysing the differences in output power generation of the water cooling module and the conventional module (no modifications). The performance improvement of the modules is determined by comparing the differences of power generation and relating it to the changes of surface temperatures of each module. Meanwhile, for the study on debris accumulation, the conventional module is modified with a setup of area coverage, as the module of water cooling is estimated to have zero dust accumulation – continuous water flow prevents dust collection. The output voltage and current of both the modules is taken from time to time and the amount of power generated will then be calculated and compared. The efficiencies of these modules would then be analysed by normalizing the output power generated with the amount of solar radiation present throughout the whole day. The variables taken into account in this project are surface temperatures of the modules, output current, output voltage and the dust concentration on the modules.

With the variables specified taken into account, the project study on the improving the efficiencies through water cooling and debris removal is carried out effectively.

1.4 Relevancy of the Project

The demand for renewable energy is increasing tremendously in the global energy field. Photovoltaic power generation is a sustainable energy source. Its method of converting light energy into electrical energy makes it a constant stable energy supply as there is presence of sunlight every day in our country. Photovoltaic power generation has a lot of advantages compared to the other ways of power generation. Minimum cost and maintenance jobs are needed for this method. This is because there are no moving parts required such in the wind turbines and the panels can operate for many years. Besides that, this PV power generation method is also pollution free. Energy is generated safely without harming the environment. Thus, throughout the entire project study, researches on improving the performances of the photovoltaic modules will be given utmost importance. Modifications such as water cooling and debris coverage will be applied to the modules to study on how the modules perform at different conditions. It is believed that water cools off the surface of the module and ensures no dust accumulates on the module at the same time. Therefore, this study will also show us how does water cooling technique improves the efficiencies of the photovoltaic module and provides a better performance which is essential to the increasing demand of renewable energy in the market.

1.5 Feasibility of the Project

Basically the performance level of the photovoltaic modules relates to the modules' efficiencies. The higher the efficiency, the greater the level of performance of the module will be. Based on previous research studies conducted, surface temperature cooling does show slight positive changes positive change in terms of power generation. The method of surface cooling applied was by attaching the photovoltaic modules with water sprinklers where water droplets provide the cooling effect. The comparisons between the module with the sprinklers and the normal module where does and it is identified that the maximum temperature of the normal module rises up to 65°C while the temperature of module with sprinklers rises up to 50°C. The differences in power generation were also taken into account where the modules with sprinklers produce almost 20% higher output power compared to the normal module. Thus, the idea of implementing continuous water flow on the photovoltaic module was applied in this case study and the results were analysed. For the second part, accumulation of debris prevents maximum sunlight reaching the panel at the same time trapping heat causing the module surface temperature to be always high. The focal point of this project is to improvise the performance of the photovoltaic modules, by studying and understanding the effects of surface temperature cooling and debris removal of the photovoltaic module.

The completion of the project is scheduled to be done within two semesters. Therefore, there will be sufficient time to understand how the PV modules function and perform in relating to surface temperature and deposition of debris. With full commitment given by the respective individual, the prototype will be ensured to be set up properly and obtain the desired results; the project could be accomplished successfully.

CHAPTER 2.0
LITERATURE REVIEW

2.1 Type of Photovoltaic Modules Used

Solar photovoltaic modules are the main component in the photovoltaic power generation method. These modules comprise a group of solar cells that are connected in series and/or parallel and encapsulated in an environmentally protective laminate to generate electricity. There are several categories of photovoltaic modules which are mono crystalline, polycrystalline and thin film. The type selected for this case study is the polycrystalline modules. Polycrystalline modules are also known as multi crystalline or semi crystalline modules. These modules are made from multi crystalline silicon (mc-Si). They are economically cheaper compared to the other photovoltaic modules. It is understood that these modules have more disordered atomic structure means that their efficiency is generally slightly lower, at typically 12% compared to the mono crystalline. However, at average solar irradiation conditions the energy generation ratio of the polycrystalline module is the highest compared to the other types. The life expectancy of these modules are also relatively long that is about 20-25 years compared to the thin-film modules which only last around 15 years maximum (David Tan, 2010). Thus, polycrystalline modules would be the best choice for this case study.

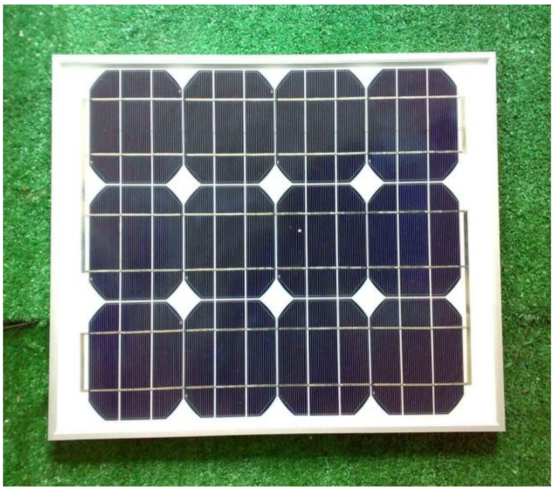

Figure 2: Mono Crystalline Module

Figure 3: Poly Crystalline Module

Figure 4: Thin Film Module

2.2 Effects of Surface Temperature Cooling and Debris Removal on Photovoltaic Modules' Performance

Low energy conversion efficiency is one of the major problems that occur in photovoltaic systems. The open circuit voltage generated varies with different operating temperatures of the solar module. As the module surface temperature rises above the standard operating temperature of 25°C, operation of the panel becomes less efficient and the output voltage decreases. In this scenario, heat can be considered as resistance to the flow of electrons in the solar cells within the module. Effective current will also decrease. At between 60°C to 70°C surface temperature, the solar modules loses 0.5% in efficiency per every degree rise in temperature. This will therefore cause the power to significantly decrease as well (Korzadeh A., 2009).

Hence, it is essential to ensure that the operating temperature of the module must be kept close to optimum level at all times to overcome this problem.

Surface temperature cooling is one of the techniques suggested in reducing this problem. Generally, some techniques, such as the air cooling and water cooling, are utilized to cool the PV module, in order to maintain low operating temperature. However, water cooling is understood to be a better option as water particles has a higher value of heat conductivity that is 0.60 at 20°C compared to value of heat conductivity of air particles that is 0.023 at 20°C. Thus, heat can be transferred away from the panel more effectively with the application of water. With this idea, a layer of water is allowed to flow on the photovoltaic module to produce cooling effects. The heat energy generated by the modules due to high temperature sunlight will be absorbed by the water particles, allowing the temperature of the module not to rise very high (Odeh S., 2009). This provides a tendency for the module to be kept cooled and close to optimum operating temperatures, thus improving the efficiency of the system.

There is a glass layer that covers the solar cells on the photovoltaic module. This glass layer is important as it prevents damages of the cells from taking place during operation and maintenance of the modules. From the above figure, it is shown that the glass layer has a refractive index of 1.5 causing the sunlight reaching the module to be slightly refracted away. The addition of a layer of water, which has a refractive index of 1.3, for cooling purposes, will cause further sunlight to be refracted away from the module. This causes less light energy reaching the module for energy conversion, which indirectly affects the module’s efficiency. However, when comparing the efficiency reduction of the module operating at high temperature and the module with water layer reducing the solar irradiation towards the module, the performance of the module with the water layer on surface top has better efficiency improvement, thus the effects of refraction on sunlight due to existence of water is negligible, as the efficiency decrease due to this reason is relatively small (Dan M. J. Doble, 2009).

Besides that, the addition of water layer would allow cooling process of the existing photovoltaic modules to take place through convection. Convection is the transfer of heat within a fluid by mixing one portion of the fluid with another (McConkey, 2009). Differences in temperature of the module and water layer will cause heat energy to be transferred away from the module; as heat energy particles move from hot to cold regions. This would ensure the photovoltaic module always operates close to optimum temperature.

When two modules are compared; module with water cooling and conventional module, its measured that there is an increase in electrical energy yield over the whole day by 10.3% (Krauter S. 2008). This can be seen from the following figure.

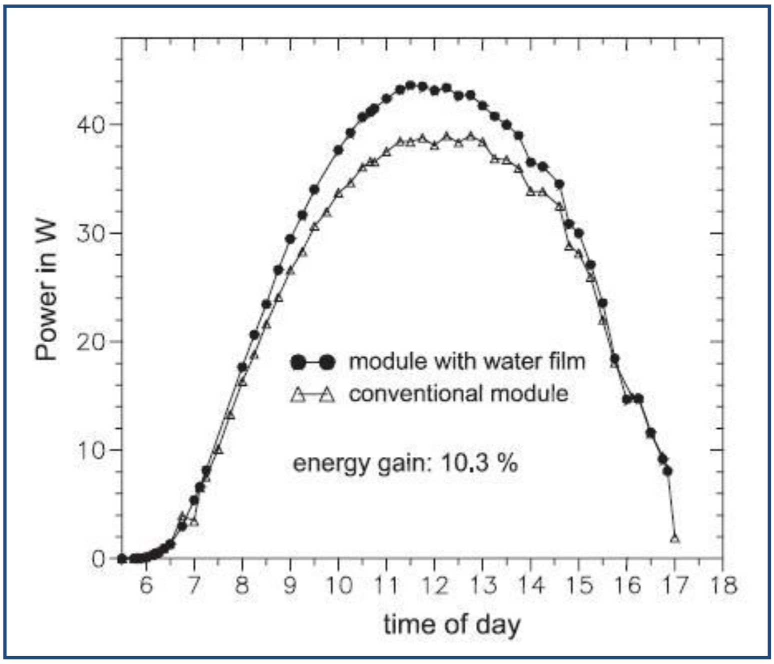

Figure 5: Performance Difference of Module with Water Cooling and Conventional Module (Krauter S. 2008)

From the figure, there is a rise in the performance of the photovoltaic module with water cooling compared to the conventional module. Although there is not much change during the day and towards the evening, on peak hours where there is high radiation of sunlight, the difference in both these modules in terms of energy gained can be seen obviously.

Nevertheless dust accumulations on the surface module also play an important role in photovoltaic modules' low energy conversion efficiency. In general, dust is a term which applies to minute solid particles with less than 500mm. Dust can come from various sources such as wind lifting soil dust and pollution. Highly populated areas with intensive economic development experience high concentration of dust in the surroundings. The factors that cause dust to settle on photovoltaic modules are as follows;

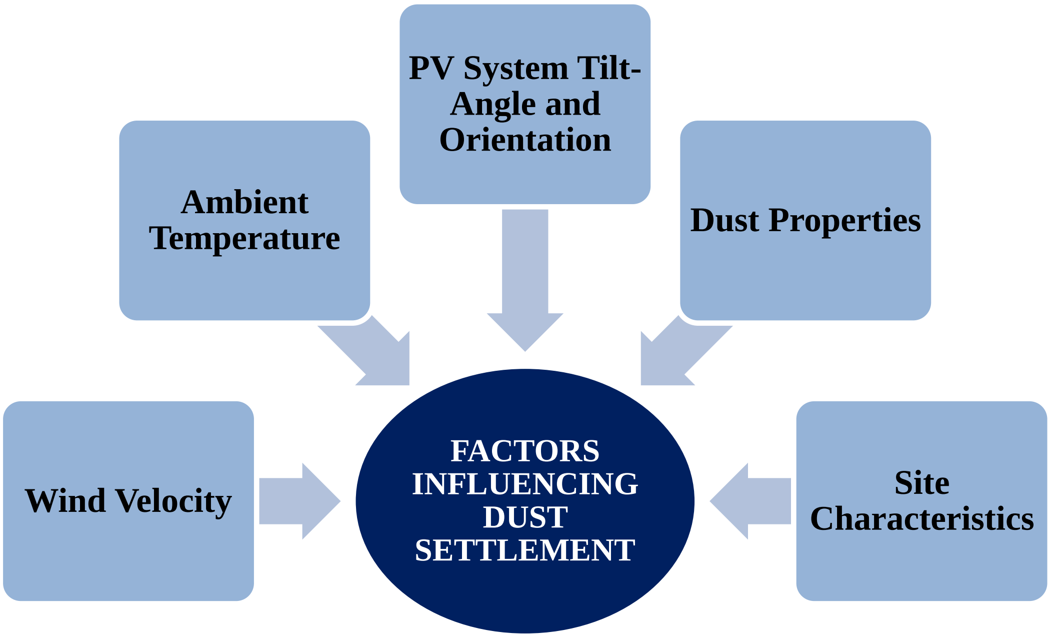

Figure 6: Dust Settlement Factors (Mani M., 2010)

Based on Figure 6, one of the factors that influences dust settlement on the PV modules is the properties of dust. It is important to understand the type of accumulated dust on the panels, right from its kind, size, shape, and weight of the dust. Finer dust particles settle easily on modules from time to time and are harder to remove as they are more compact when accumulated. Besides that, site characteristics also play an important factor in why dust settles on the module. Human activities carried out in specific sites such as open burnings and construction works will cause an increase in dust generation in the surroundings promoting the chances of dust settlement on the photovoltaic modules to be higher (Mani M., 2010).

At hot temperature as well, the air would be very dry and movement of air particles would be limited – less wind velocity causing dust to easily settle on the surface of the modules. In addition, the tilt angle of the PV system is also important as it must be close to the best tilt angle that is 30 degrees. Any lower tilt angle lower than 30 degrees would cause dust to easily settle on the photovoltaic module and any tilt angle over 30 degrees would directly affect the amount of solar radiation hitting the panel (Shariah A. M., 2012).

Furthermore, cement which is used in building works, often present in the atmosphere of urban areas, has proofed to reduce both the short circuit output and the output power of the modules. As understood, this occurs due to the very small diameter of cement particles that deposit on the modules. Combustion processes at industrial areas which generate carbon particulates are among the different dust produced, and has the worst deterioration of performance of the photovoltaic modules (El-Shobokshy M. S., 2008). Once an initial later of dust starts to accumulate on the photovoltaic module surface, it will tend to promote further settlement of dust causing the layer on the module to get thicker and thicker. Hence, not only sunlight would be blocked from hitting the modules, but also the heat generated on the module will get trapped within the dust layer causing the module operating at high temperature affecting the energy conversion efficiencies of the modules.

2.3 Similar Project Studies Related to Surface Temperature Cooling and Debris Removal

Project Title : An active cooling system for photovoltaic modules

Written by : (Rosa-Clot M., R.-C.P. 2010)

The importance of surface cooling was understood by the author where a study on how water can help to cool the PV module was conducted. For water source, the author used water sprinkler to cool of the panels which were placed at the roof top. The technique of water flow used in this experiment was the open loop system where continuous water supply must be available, in order to carry out the experiment.

Figure 7: Water Sprinklers Cooling PV Modules

Upon conducting the experiment, the author plotted graphs to show the performance changes of the module with the modification done. The following is the graph of Power versus Time plotted with the results obtained.

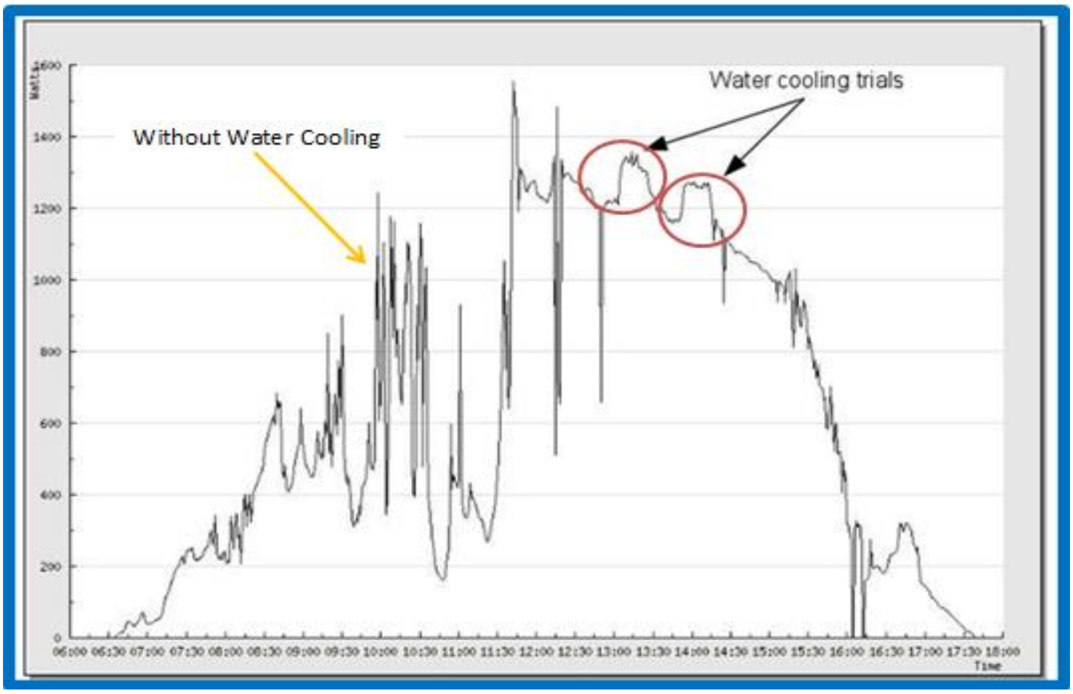

Figure 8: Effects of Water Cooling on Power vs Time Graph (Rosa-Clot M., R.-C.P. 2010)

From the graph in Figure 8, it can be clearly seen when the water cooling technique from the sprinklers was applied to the module, the module generates more constant high output power. The output power also tends to be stabilized at high levels when there is water cooling; limiting fluctuations of the output power value. From the case study, it is proven that 10% increase in stabilized output power of the PV modules is possible with the water cooling method. Water cooling will not just lower the surface operating temperature of the module, but also clear the dust particles on the surface which could increase the level of shade of the module, thus improving the efficiencies of the solar photovoltaic module.

CHAPTER 3.0
METHODOLOGY

3.1 Research Methodology

The project study was carried out with a strategized research methodology that compromises of five main steps. The first stage was the preliminary research collecting relevant details regarding the project. The following step was the development of the project experiment. The project was then continued with the third stage that was mainly conducting the experiment itself. Upon completing the project experiment, results were taken systematically and analysed in detail. Last but not least, the final stage of the project was the documentation of all the study performed and concluding whether the objectives set were achieved or not. The details of each stage are clearly explained as following:

3.1.1 Preliminary Research Work

The target of this stage was to have a better understanding regarding the photovoltaic systems and how the power generation method takes place. With that, literature reviews were conducted to gain more information on the photovoltaic systems and what are the problems encountered in reaching maximum efficiency. Researches were done from existing books and journals from the library and online sources. The information gathered was then related to each other and important points were highlighted based on the project study which is mainly the low energy conversion efficiency of the modules and the factors causing this problem. All gathered information was recorded for referencing in later stages. Nevertheless, additional researches from time to time were carried out, to ensure the best and most feasible method was performed for the case study.

3.1.2 Development of Project Experiment

Upon having a clear understanding on the project, the stage of developing the project experiment was begun. Firstly, the variables set to be taken into account were decided to ensure the objectives of the case study were met at the end of the experiment. The variables were related to the improvement on the performance of the photovoltaic modules; focussing on surface temperature cooling and debris removal. With the idea planned, a working prototype was then designed and developed to study on the modules' performance. The prototype consists of two different photovoltaic modules of the same size and type; module with water cooling and conventional module (no modifications). For the second part of the experiment, dust area coverage of the PV modules was simulated using different sizes of cardboards. The tools used for the experiment development were specified and each development process of the prototype was approved by supervisor and assisted by lab technicians.

3.1.3 Conduct of Experiment

The prototype was completed and placed on the selected project site. The project site selected was based on the level of light intensity at that particular area throughout the whole day – maximum direct sunlight. With everything set in place, the experiments of the project study were conducted. The experiment run was divided into two parts. The first part was the study on surface temperature cooling and the second part was the study on debris accumulation. Both parts of the experiment run were done within the time frame of the project and the results were recorded systematically for interpretation purposes on the following stage. In addition, repair works and slight modifications were done to the prototype from time to time, to prevent leakages and ensure water flow is constantly fluent on the module, to achieve best results.

3.1.4 Analysis of Results and Discussion

The results of the experiments conducted were tabulated and graphs were plotted to compare the differences in performance of the module with water cooling and conventional module. The performance differences were then related to surface temperature cooling and analysed how it improves the module efficiency in terms of temperature reduction and power generation. For the second part of the experiment, the results of the modules with different areas of dust coverage were recorded and the module efficiencies were than calculated. The reliability of the results where then evaluated to determine whether dust coverage does impact the module performances or not. With the improvement in efficiencies observed in both experiments, it was then concluded if the objectives set in the earlier part of the experiment were succeeded or not.

3.1.5 Final Documentation

Upon completely verifying the reliability and relevancy of the results collected, all activities and data were compiled for documentation purposes. The whole research was recorded in detail and the experiment setup and procedures were clearly explained. Literature reviews conducted in the earlier stages were also properly referenced and documented in the final report.

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

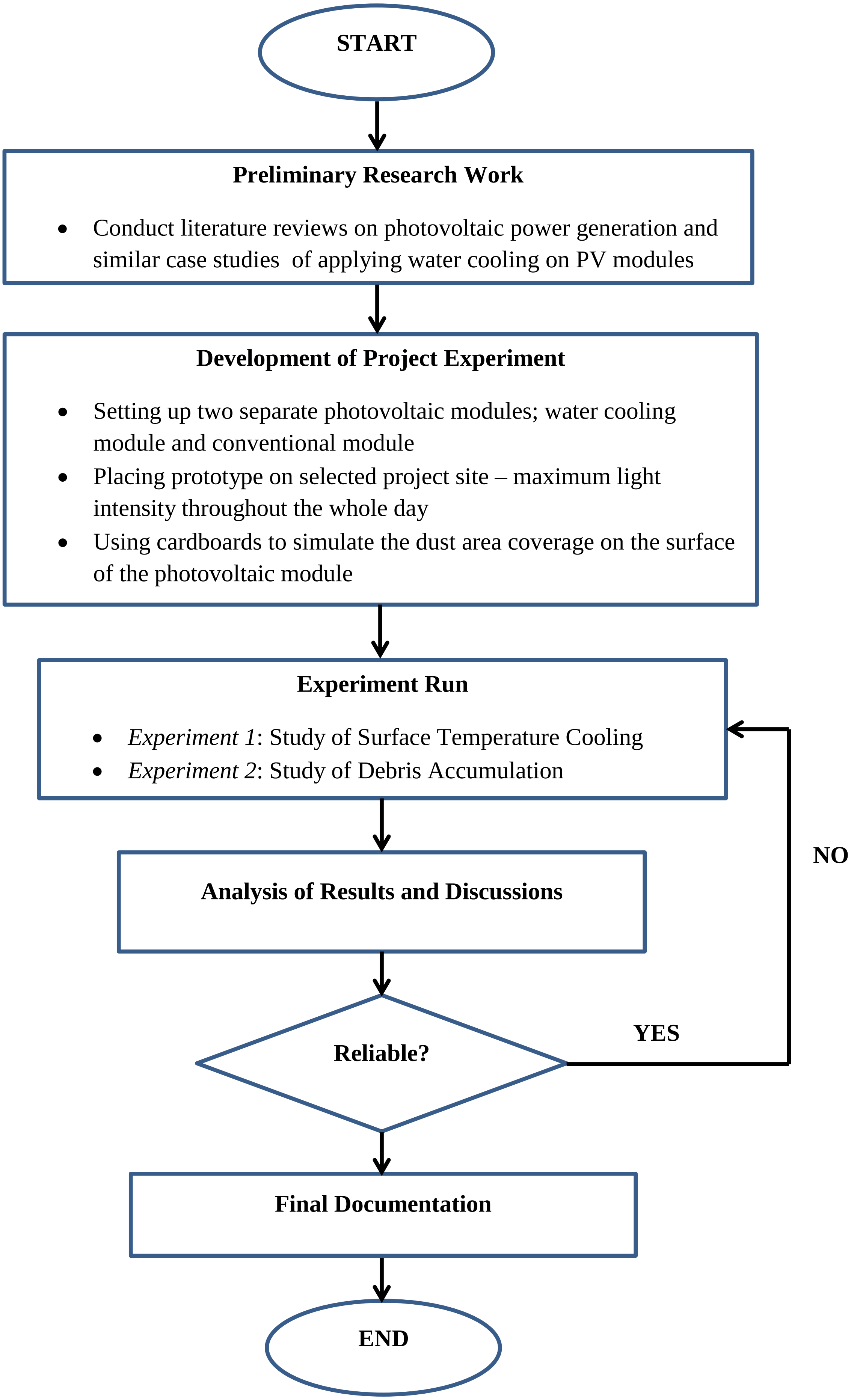

Figure 9 : Project Flow Chart

3.2 Experiment Setup

The experiment was placed at the chosen project site – Block 18. The setup of the experiment was mainly focussed on highlighting the effects of surface temperature cooling and debris accumulation on the efficiencies of the photovoltaic modules. The diagram below displays the experimental setup of the project;

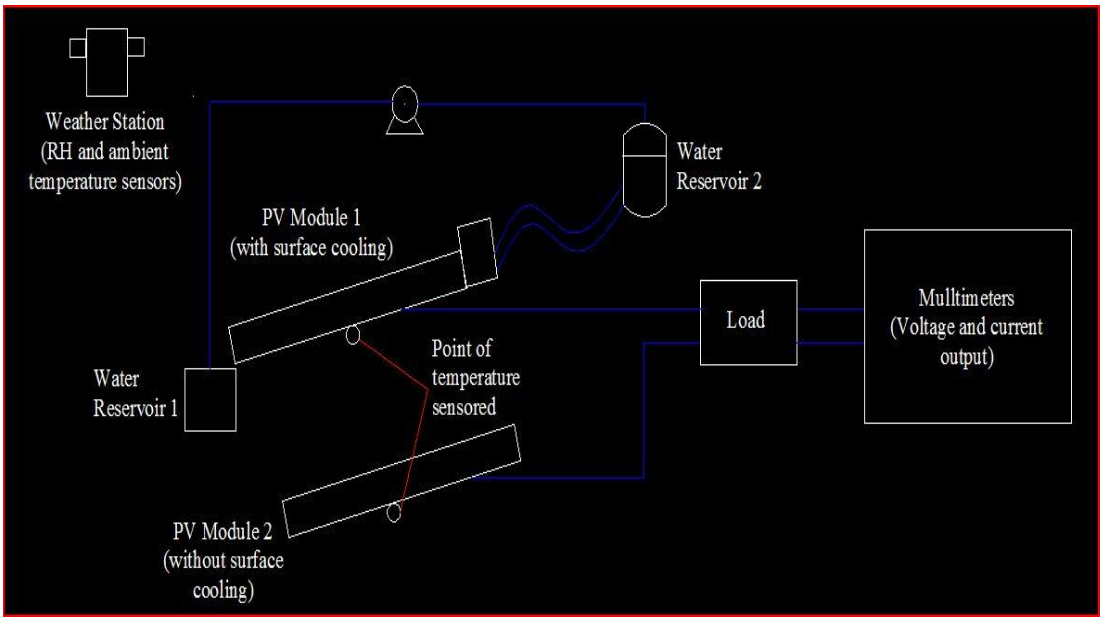

Figure 10: Setup of Project Experiment

From the diagram, it can be seen that there are two photovoltaic modules are used in the experiment. The module 1 is modified with surface cooling (water cooling) and the module 2 is without surface cooling (conventional). The type of modules used is the same which is the poly-crystalline type. Poly – crystalline modules are the most common type of solar technology used in residential areas. As explained in the literature review, although the poly-crystalline type has lower efficiency than mono-crystalline type, the price is cheaper and the overall performance ratio can be better during diffused solar radiation conditions (Carr,A.J, 2009). The following is the specifications of the photovoltaic modules use;

Table 1: Photovoltaic Module Specifications

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

For the surface cooling, a layer of water was allowed to flow on the module and the water flow was assisted by a submersible pump. This pump is powered by AC power source and it ensured the flow of the water was always good. The details of the pump used are as below:

Table 2: Pump Specifications

Description	Characteristic/ Value
Type	Fully Submersible
Power	38 Watts
Flow Max	2700 litres/ hour
Head Max	2.1 metres

For the measuring process, temperature readers were used to detect the surface temperature of the modules. Meanwhile to obtain the voltage and current outputs, multi meters were used. In addition, weather information of the surroundings was also measured using the weather station unit and all data were related on the later part of the experiment.

3.3 Experiment Run

3.3.1 Surface Temperature Cooling

For the first part of the project, the study on effects of surface temperature cooling was conducted. A thin water layer was allowed to flow on one PV module. Water was used in this experiment as it acts as a good cooling factor, absorbing the heat generated by the photovoltaic module throughout the day. The flow of water was made sure to be in a continuous cycle, pumping the water from the bottom to the top reservoir tank, where the water flows down to the surface of the module through levelling tubes. The water is then collected back in the bottom reservoir tank where the cycle repeats itself to allow a constant cooling process.

The experiment run was conducted for 10 days and the variables such as the output current, output voltage and surface temperature of the photovoltaic module were measured at intervals of one hour daily from 8am to 5pm. The obtained data was then tabulated and the day with the best average module performance was chosen for analysis.

3.3.2 Debris/Dust Accumulation

Upon completion of the first part of the project, the second part was begun. This involves the study of how debris accumulation relates to the overall performance of the photovoltaic module. The experiment was conducted by modifying the photovoltaic module 2 (conventional module) by covering it with opaque sheets; cardboards. Different percentage openings were set in this part of the experiment to simulate different levels of dust concentration on the module. The performance of the conventional module with cardboards was then compared to the module with water cooling, where it's assumed that zero dust accumulates on that module as there is a constant water flow on the module surface which prevents dust settlement.

The experiment was run for 4 specific days with four different sizes of cardboard that represents different areas of dust coverage on the module. The percentages of area coverage applied are 10%, 20%, 30% and 50% of the total module surface area. All the data (variables specified in first part) were recorded and compared between both the modules; conventional module with dust coverage and module with water cooling.

3.3 Calculations

For data analysis, firstly, the photovoltaic module efficiency at Standard Test Conditions (STC) was been calculated. The formula applied is as below;

$$\boldsymbol{\eta_{stc} = \frac{P_{STC}}{G_{STC}\, A_{PV}} \times 100} \tag{1}$$

where,

η_{STC} = Module Efficiency at STC (%)

P_{STC} = Output Power of Module at STC (W)

G_{STC} = STC Solar Irradiance (W/m^2)

A_{PV} = Total Surface Area of Module (m^2)

Note: At STC, the solar irradiance is 1000 W/m^2, and the ambient temperature is 25°C.

To calculate the efficiency in actual conditions, the following formula was used;

$$\boldsymbol{\eta_{actual} = \frac{P_{actual}}{G_{actual}\, A_{PV}} \times 100} \tag{2}$$

where,

η_{actual} = Module Efficiency at Actual Conditions (%)

P_{actual} =Actual Output Power of Module (W)

G_{actual} = Actual Radiation Received (W/m^2)

A_{PV} = Total Surface Area of Module (m^2)

From the specifications in Table 1, the efficiency of the module at Standard Temperature Conditions was identified by applying Equation 1. **The efficiency was calculated to be 12.51%.**

3.4 Project Activities

3.4.1 Design and fabrication of project prototype

With having ideas of surface temperature cooling and debris removal to improve photovoltaic module efficiencies, a systematic prototype was planned and designed to carry out the experiment. The first semester was mainly fabricating the prototype that is one module with water cooling and another is the normal conventional module. For the module with water cooling, two separate water reservoir tank; primary and secondary, were built for water collection purposes for the cooling process. The primary tank was situated at the bottom of the module while the secondary water tank was located at top of the module. A submersible pump was added into the primary water tank to assist the flow of water in overcoming the head of 1.4m. Besides that, water connecters were also fixed within the same axis with same tube sizes to ensure an equally balanced water layer constantly flows of the module. Perspex frames were also attached to the sides of the module with PVC glue to prevent water leakages throughout the entire experiment.

As for the conventional module, the angle of inclination was ensured to be equal with the module with water cooling that is 30 degrees. For the second part of the project study, different sizes of cardboards were attached on this module to display dust area coverage of the photovoltaic module – 10%, 20%, 30% and 50% area coverage of the module.

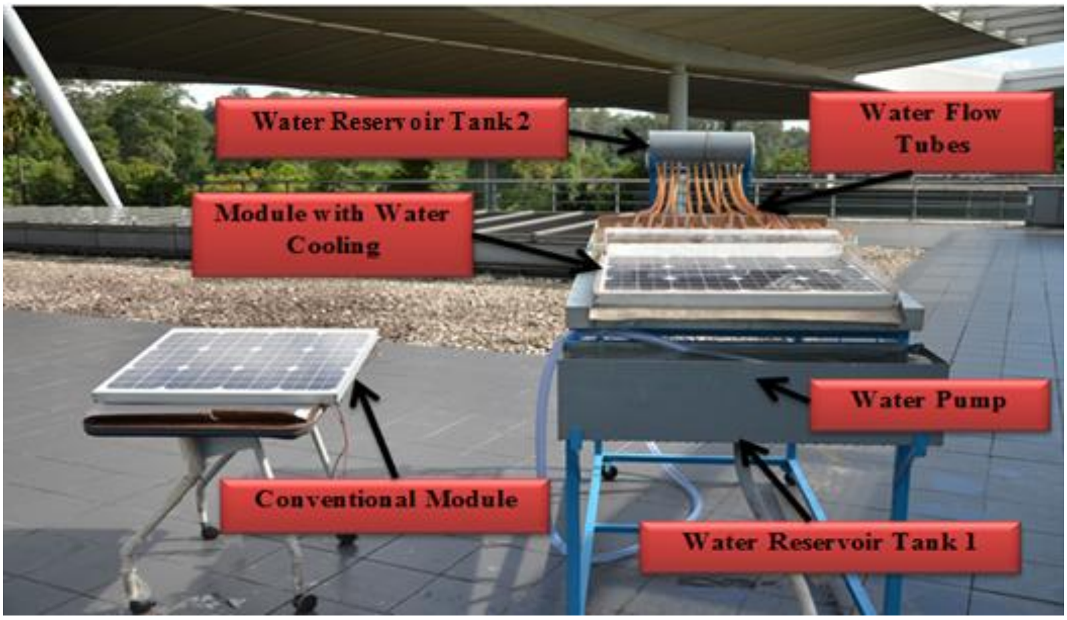

Figure 11: Experiment Prototype

3.4.2 Selection of project site

In process of conducting the experiments of the project study effectively, a proper project site was first been surveyed. The criteria on choosing the best project site was based on the direct sunlight intensity reaching the module with zero sunlight disturbance. It was also taken into account that the sunlight reaching the modules should not come from diffused surfaces or reflected from other surfaces. This is to ensure the efficiency of the photovoltaic modules would be high as expected and not affected due to reduced direct sunlight source.

From the survey conducted, the selected project site was determined at the Foyer of Academic Block 18 as there is complete direct sunlight throughout the whole day.

Figure 12: Selected Project Site - Academic Block 18 Foyer

3.4.3 Setting up Weather Station

An additional weather station was installed to obtain information of the surroundings weather data. This equipment was installed near to the location of the modules and the information was collected via wireless transfer of data from five different sensors to an indoor receiver. The weather station will record the indoor and outdoor temperature, wind speed, wind direction, humidity, barometric pressure, barometric pressure history, rainfall amounts, time and date. All readings were recorded at intervals of every five minutes. This is to ensure the modules and the weather station is working concurrently to avoid any misleading in data collection. A custom stand was also designed to hold the weather station firmly throughout the whole case study.

Thus, the evaporation of water used for surface temperature cooling can be better explained relating to the wind speed and relative humidity of the day. This will ensure that water quantity is topped up from time to time to make sure there is a constantly stable flow of water on the module surface.

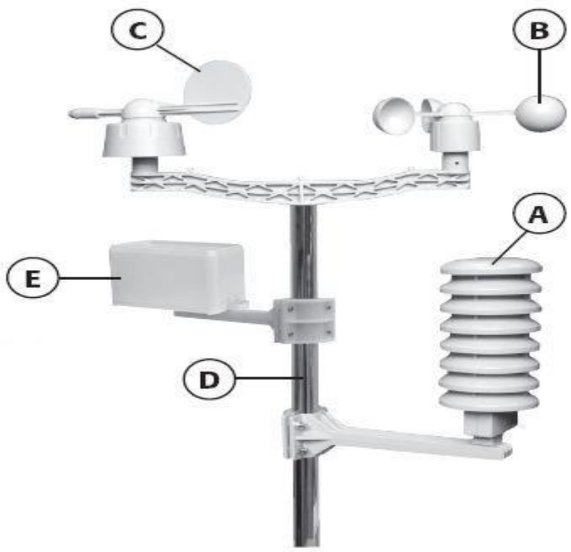

Figure 13: Weather Station Components

A – Transmitter (Thermo – Hygrosensor) including protective cap
B – Wind Speed Sensor
C – Wind Direction Sensor
D – Bracket
E – Rainfall Gauge

Figure 14: Weather Station Set Up at Project Site - Block 18

3.5 Key Milestones

The following were the key milestones of the project study that were set for the two semesters (28 Weeks):

Figure 15: Key Milestones of Project

WEEK	DETAILS
2	Confirmation of project title – Improvement of Solar Photovoltaic Module Efficiencies Through Water Cooling and Debris Removal
4	Study on how PV power generation works and factors lowering its efficiency
7	Submission of extended proposal (Draft & Final)
9	Completing proposal defence
13	Manufacturing needed prototype parts and setting up experiment at site
14	Submission of interim report
16	Checking on the function ability of the set up prototype on the fixed project site
18	Repairing and fixing the weather station
21	Submission of progress report
23	Collecting results and simulating debris accumulation
25	Presentation at Pre-SEDEX
28	Submission of Final Year Project complete report

3.6 Gantt Chart

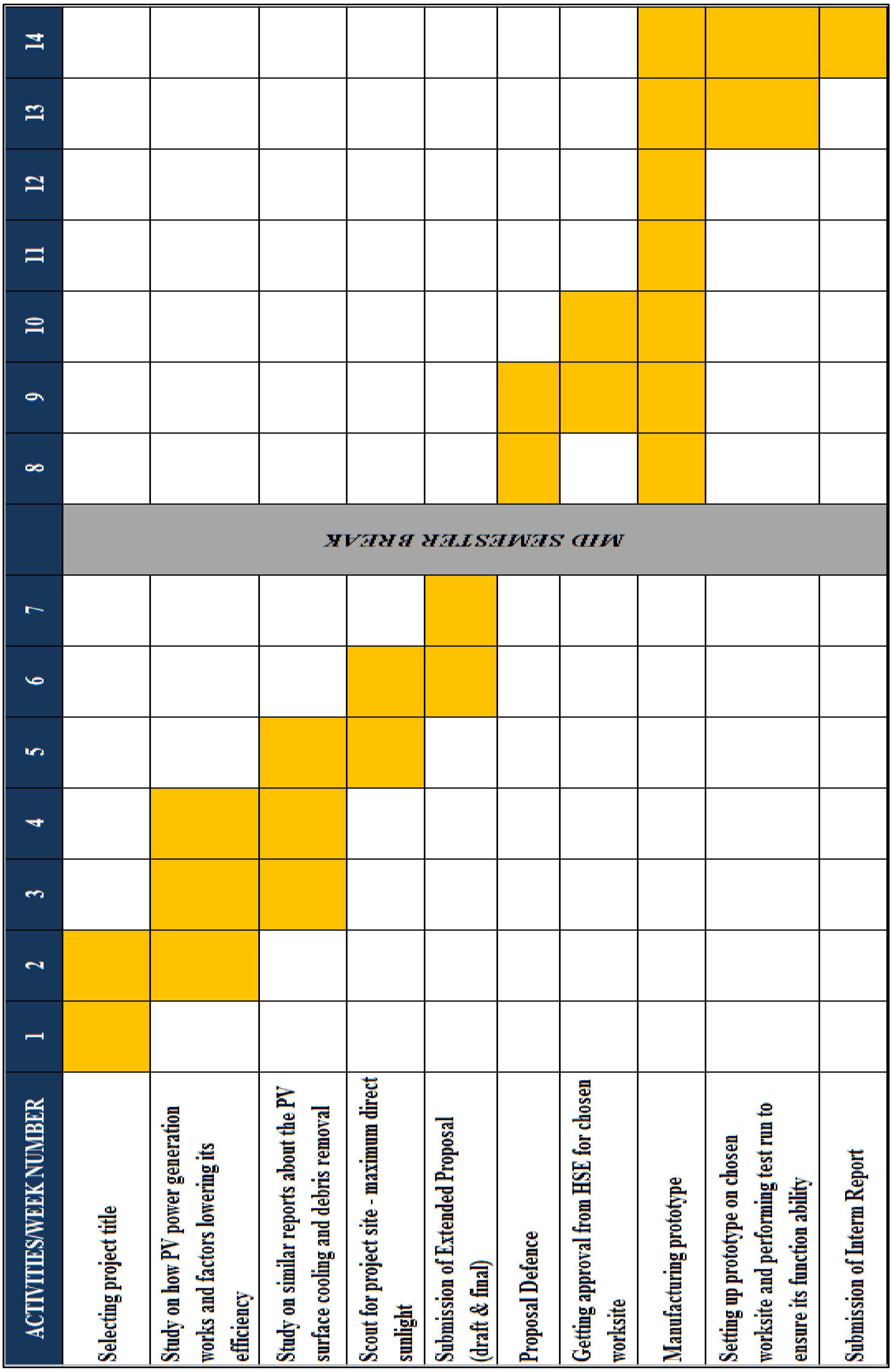

Figure 16: Gantt Chart of Research Work (FYP 1)

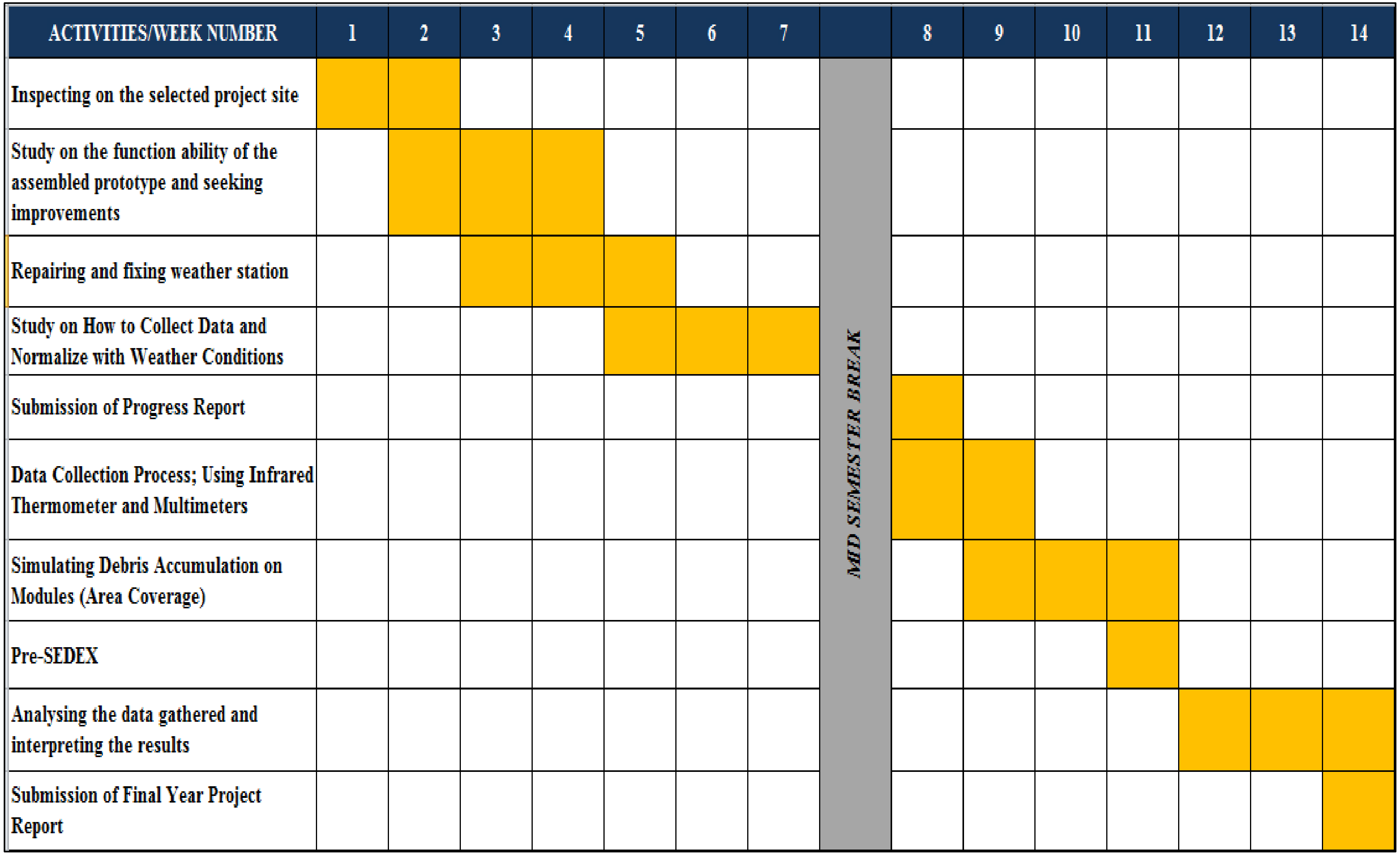

Figure 17: Gantt Chart of Research Work (FYP 2)

3. 7 Tools Used

3.7.1 Tools

- Mechanical Tools

  To manufacture components for the prototype such as water reservoirs and Perspex water flow frames.

- Electrical Tools

  To measure the output current and voltage values of the photovoltaic module. Example: Multi Meters

- Recording Tools

  To measure and record data related to power generation.

  Example: Solar Charge Meter, Weather Station, and Infrared Thermometer.

3.7.2 Software

- Microsoft Excel

  Used for creating tables and graphs to represent the results and discussions

- Microsoft Word

  For documentation purposes such as the extended proposal, interim report, progress report and final report.

CHAPTER 4
RESULTS AND DISCUSSIONS

For ease of data analysis, all the tabulated data were displayed in graphical forms. There were several graphs plotted for both the experiments. The first graph plotted was the Temperature versus Time graph, where the temperatures of the PV module 1; with water cooling (T_{PV} 1) and PV module 2; conventional (T_{PV} 2) were compared with relating to the temperature of the air (T_{air}).This graph was also related to the amount of solar radiation and relative humidity present throughout the day. The next graph plotted was the Power versus Time graph of the module with water cooling (Power 1) and the conventional module (Power 2). The power output was calculated as the product of the voltage and current outputs of the modules. The following graph generated was the graph of Efficiency versus Time. The actual efficiencies of modules were calculated using Equation 2; module with water cooling (Efficiency 1) and conventional module (Efficiency 2).Meanwhile, the efficiency of the module at Standard Test Condition (STC Efficiency) was calculated using Equation 1, and also plotted on the same graph together with the actual module efficiencies for comparisons.

4.1 Study of Surface Temperature Cooling

For best representation set of data, the 10 days of experiment run were compared and the day that has the **Highest Average Performance Improvement** was chosen for analysis. This method was conducted by averaging the total overall performance improvement of the module throughout the day. The tabulated data of average performance improvement for all experiment run days is attached in Appendix (Table 4). From the table, it is identified the day that has the highest average performance improvement was on 5th July 2013 with a percentage value of **43.24%**, thus this set of data was selected for analysis purposes.

The following are the discussions on the graphs plotted relating to the surface temperature cooling experiment.

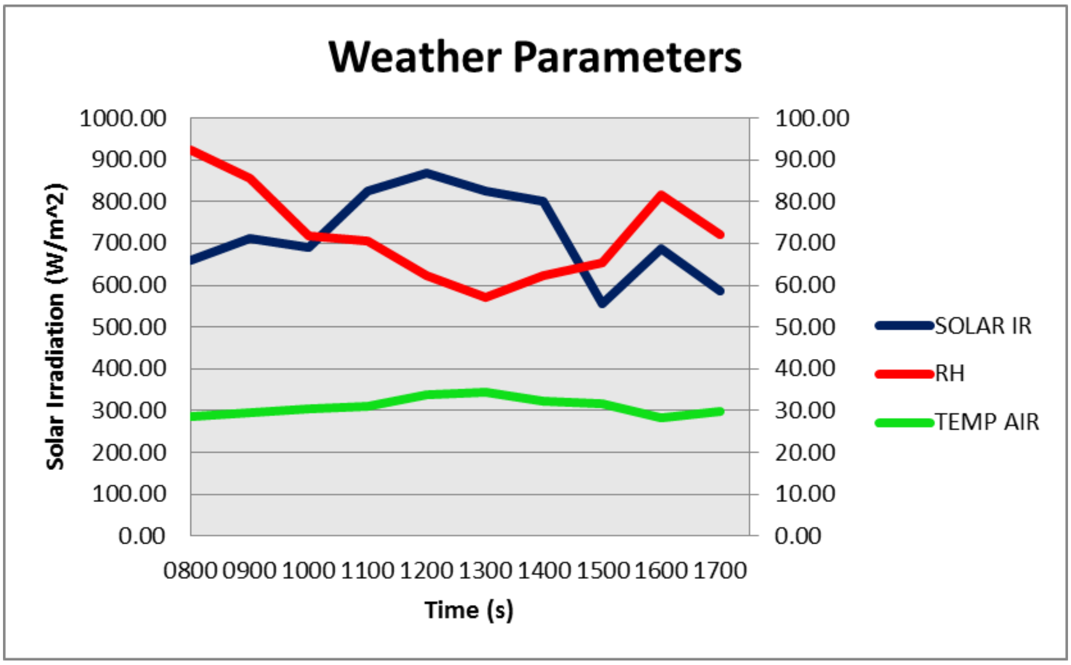

Figure 18: Weather Parameters (5th July 2013)

Based on the weather parameters graph, it can be seen that solar irradiation was low during the earlier hours of the day. As time moves on, the solar radiation increases to a maximum value of 867.43W/m^2 and then decreases. The decrease after peak hours was due to the high presence of dark clouds. Although the temperature throughout the day was high, the relative humidity was above normal level due to light rain conditions in the morning and evening of the day.

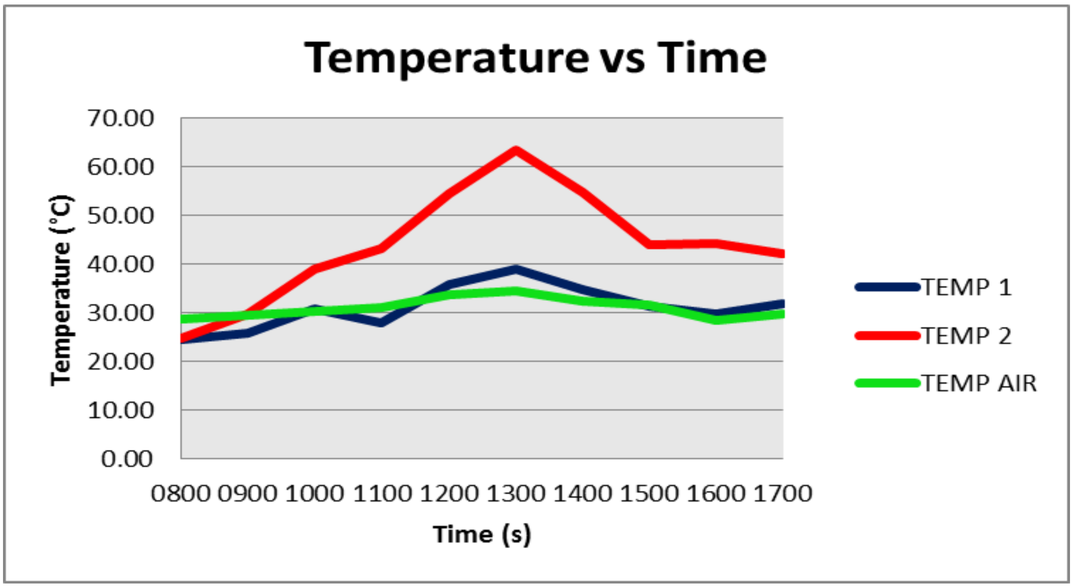

Figure 19: Surface Temperatures of Photovoltaic Modules

The blue line represents the temperature of module with water cooling, while the red line represents the conventional module. The green line shows the temperature of air throughout the day. It can be clearly seen that the temperature of the conventional module rises extremely high to almost 65°C. This is because the heat from sunlight causes the module to get very hot and increase the surface temperature. In the evening, the conventional module temperature drops slightly lower to around 41°C due to strong wind movements in the surroundings. This situation is different in the water cooling module, where the water constantly cools the heated module, thus the temperature of the module remains moderately low in a range of 25 to39°C.

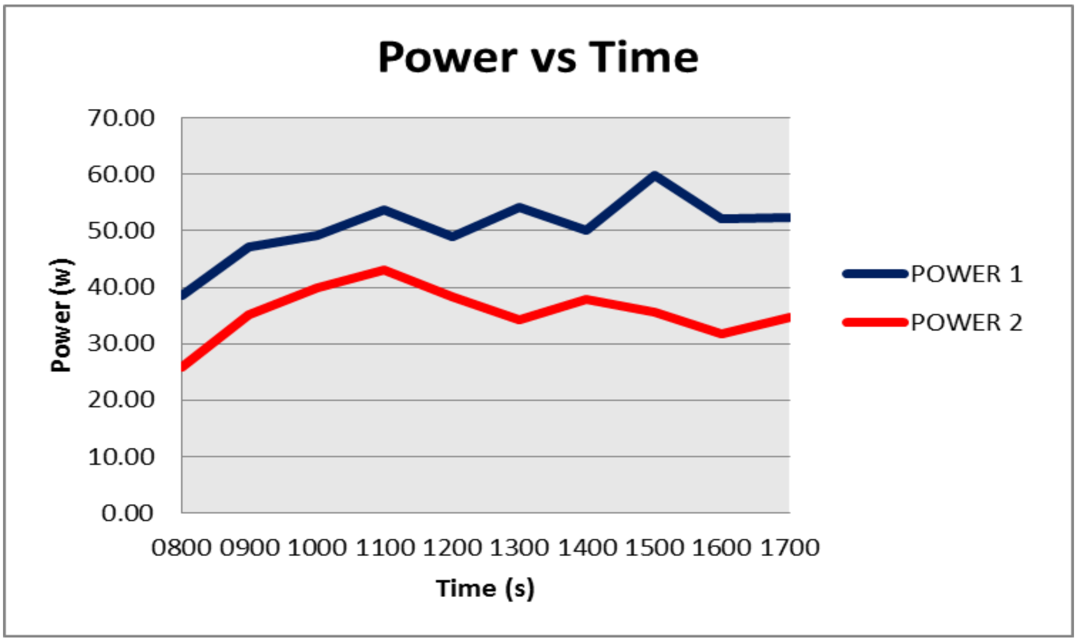

Figure 20: Output Power Generation of Photovoltaic Modules

Figure 20 shows the relationship between the output powers generated by both the modules with time. It can be observed that the module with water cooling (Power 1) has a higher value of output power generated throughout the whole day compared to the conventional module (Power 2). The maximum power of the water cooling module and conventional module is 59.93W and 43.08W respectively. The power output calculated was based on the product of output current and voltage generated by each module.

$$Power_{Output} = Voltage_{Output} \times Current_{Output}$$

The difference in output power generation could be related to the temperature of both the modules. From the previous graph of temperature versus time, it was shown that the conventional module gets hot greater compared to the water cooling module. Even though the voltage outputs generated by both the modules differ by a small amount, the current output value is the one affected more in the conventional module as flow of electrons will be inhibited due to high surface temperature, causing less power generation.

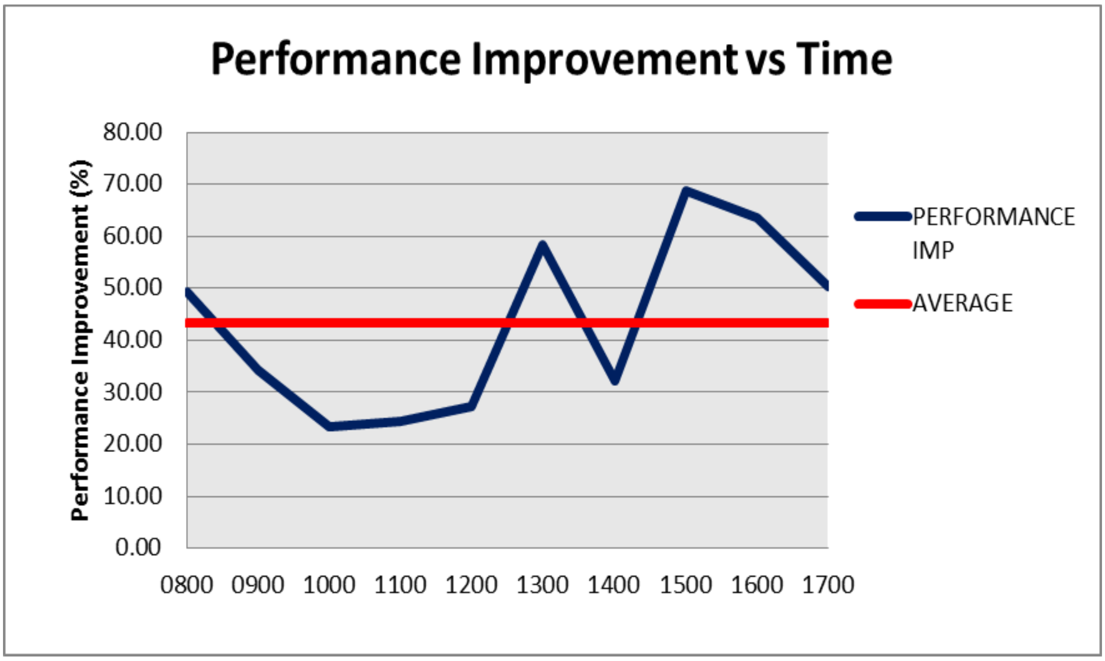

Figure 21: Performance Improvement between Photovoltaic Modules

In order to select the best day for data representation of the experiment, the Average Performance Improvement of all the days were calculated and the day with the highest average value was chosen. The table of Average Performance Improvements was attached in Appendix (Table 4) and the day chosen was on 5th July 2013 (Highest Average Performance Improvement).The formula used to calculate the performance improvement was as following:

$$\boldsymbol{Performance\ Improvement}\ (\%) = \frac{\boldsymbol{Power\ 1 - Power\ 2}}{\boldsymbol{Power\ 2}} \times \mathbf{100}$$

Where, Power 1 is the power generated by the water cooling and Power 2 is the power generated by the conventional module.

Figure 1 shows the performance improvement of the module with water cooling compared to the conventional module on 5th July 2013. It can be seen that there is positive performance improvement throughout the day. The water cooling implementation provides a high average improvement of 43.24% over the conventional module. This proves that surface cooling does assist towards a better performance of the solar module as it prevents the module from getting heated up, thus keeping the operating temperatures low for effective power generation.

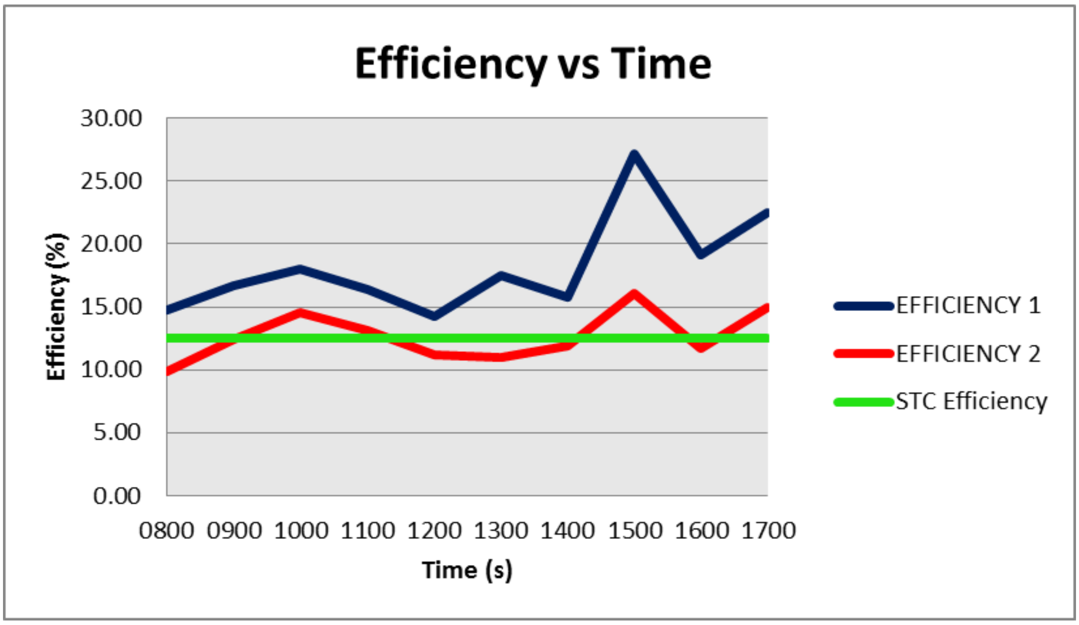

Figure 22: Measured Efficiencies of Photovoltaic Modules

The graph of Efficiency versus Time was mainly plotted to compare the efficiencies of both the modules; with water cooling and conventional, together with the efficiency of the module at Standard Temperature and Conditions, which is 12.51%. Relating to the STC Efficiency line, the efficiency of module with water cooling (Efficiency 1) is always positively above the STC value compared to the efficiency of conventional module, where the value drops lower than 12.51%.During early hours of the day, the efficiency difference between both the modules were not that high. As the module surface temperature increases during peak hours, it can be seen that the conventional module produces a low efficiency value of 11.01%. Meanwhile, with the constant cooling effect provided by the water layer on Module 1, the module efficiency tends to drop slightly due to increase in temperature caused by sunlight, however still produce a high efficiency value of 17.45%. In fact, it is also noticed that in the evening with slightly low surrounding temperatures, the water cooling method promotes the efficiency of the module to the maximum value of the day which is 27.15%.

From the experiment conduct, weather parameters such as ambient temperatures, relative humidity and solar irradiation does relate to the overall performance of the photovoltaic module. However, the main factor that affects the photovoltaic power generation is the operating temperature of the surface module. Most light energy hitting the module surface is wasted as heat energy. The data interpretation of the experiment shows that adding a water layer on the module cools the surface and constantly keeps the surface temperature of the module close to ambient temperature. The efficiency of the water cooling module is relatively high compared to the conventional module. This is because solar cells works best at low temperature. In addition, the thermal degradation of the PV module was measured to be -0.0.74V/°C (Table 1: PV Module Specifications). Thus, increase in operating temperature, will only cause decrease in power output and vice versa.

4.2 Study of Dust/Debris Accumulation

4.2.1 1st Experiment: 10% Area Coverage of Photovoltaic Module

A cardboard with an area of 0.03965m^2 (10% of the total surface area of the PV module) is used to cover a portion of the module surface. The size of the cardboard represents the coverage area of the module caused by debris accumulation.

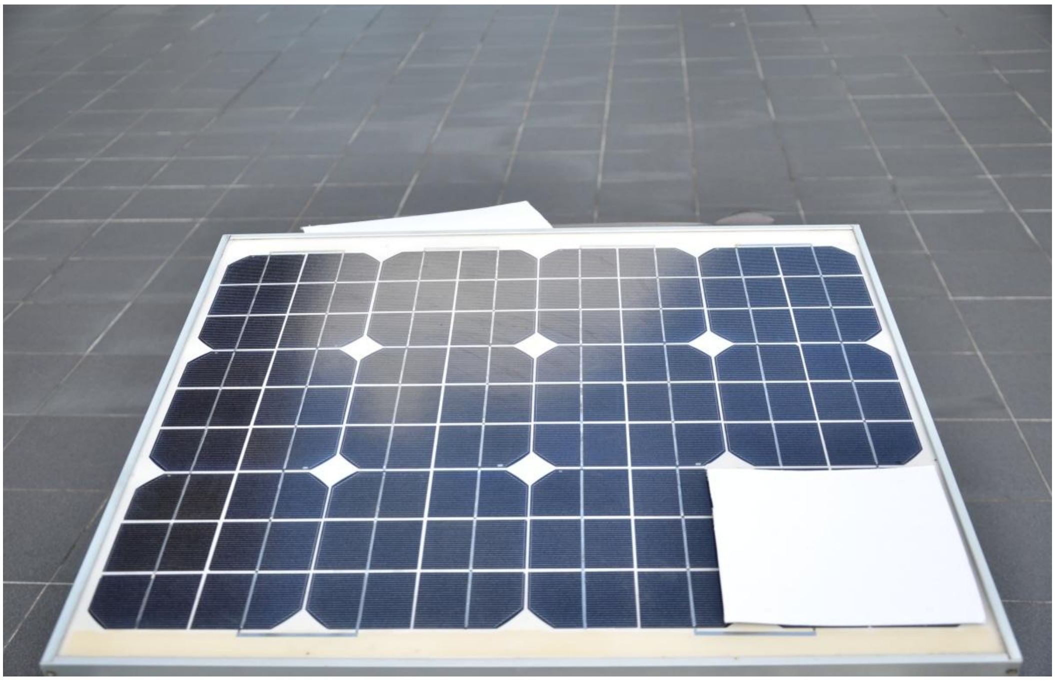

Figure 23: Set Up of Photovoltaic Module with 10% Dust Coverage Area

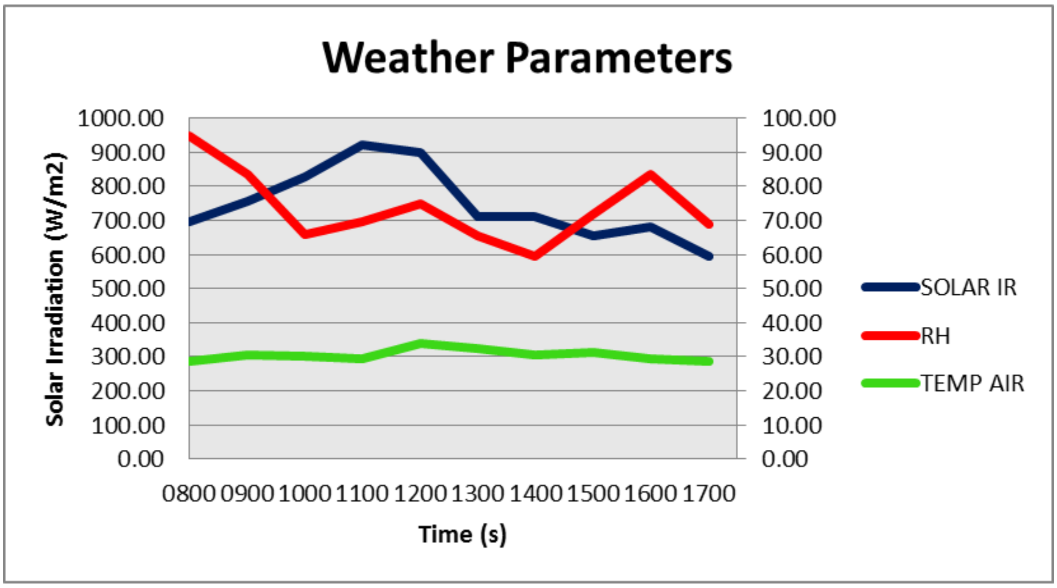

Figure 24: Weather Parameters (22nd July 2013)

Based on Figure 24, the solar irradiation was high during the early part of the day. Upon reaching peak hours, the solar radiation tends to decrease reaching a value of 595.88W/m^2

at end of the day. The relative humidity was high throughout the day and only reaching to a minimum value of 60% due to slight rainy conditions in the morning and evening. Furthermore, the temperature of air did not vary that much on the specific day, maintaining within the range of 28°C to 32°C.

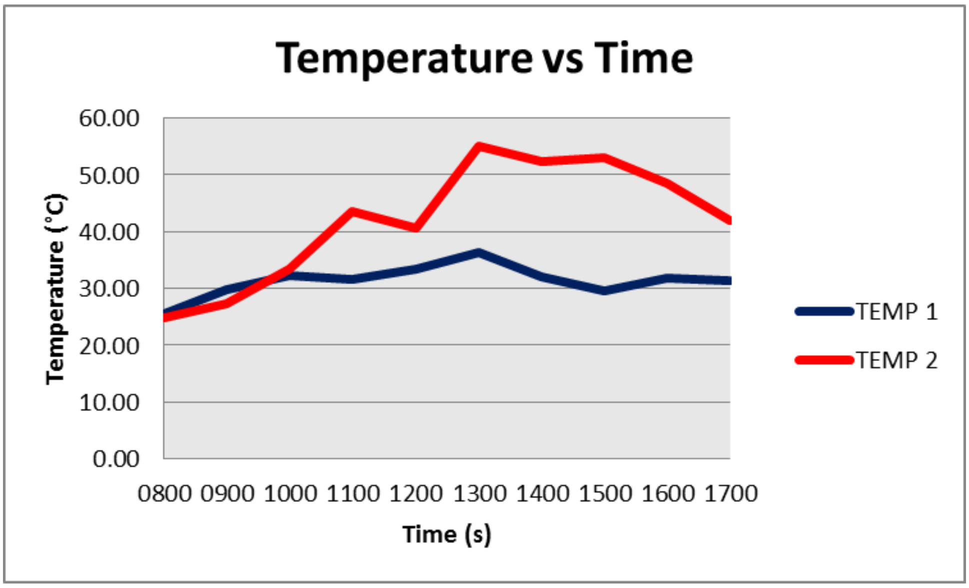

Figure 25 : Surface Temperatures of Photovoltaic Modules

From Figure 25, it can be observed that the temperature of module with the 10% dust coverage (TEMP 2) increases way higher compared to the module with water cooling (TEMP 1). The conventional module heats up normally as sunlight hits the panel. The presence of the extra shaded area of dust (cardboard) on the same module increases the chances of heat being trapped, forcing the surface temperature of module to rise very high. This situation does not take place in the water cooling module as the constant flow of water prevents dust from accumulating on the module surface.

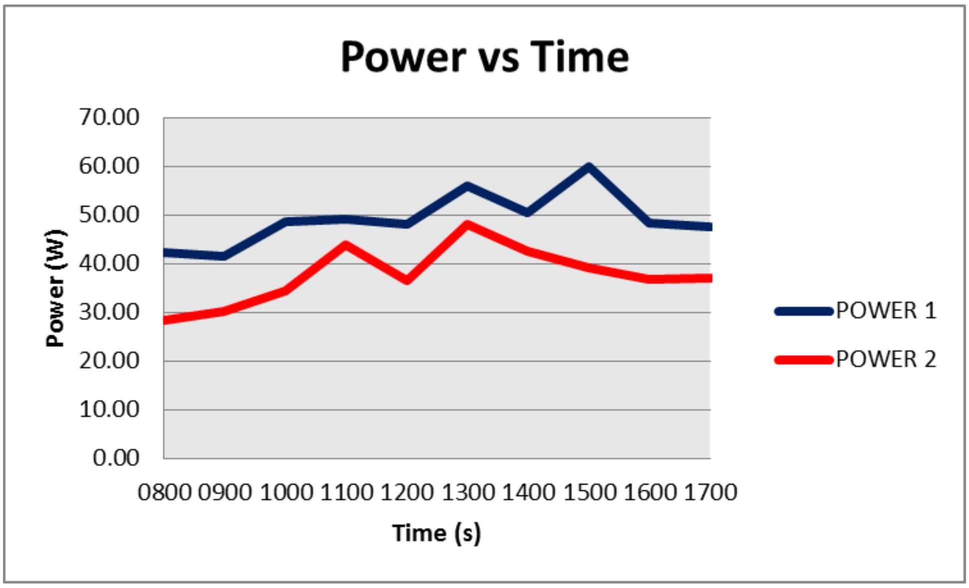

Figure 26: Output Power Generation of Photovoltaic Modules

It is noticed that the power output generated by the module with surface cooling (Power 1) is always higher compared to the conventional module with dust coverage (Power 2). Furthermore, at peak hours, the power generated by both the modules almost differs by almost 10W. This is because at peak hours the module tends to get hot easily as the surrounding temperature is high at this period of the day.

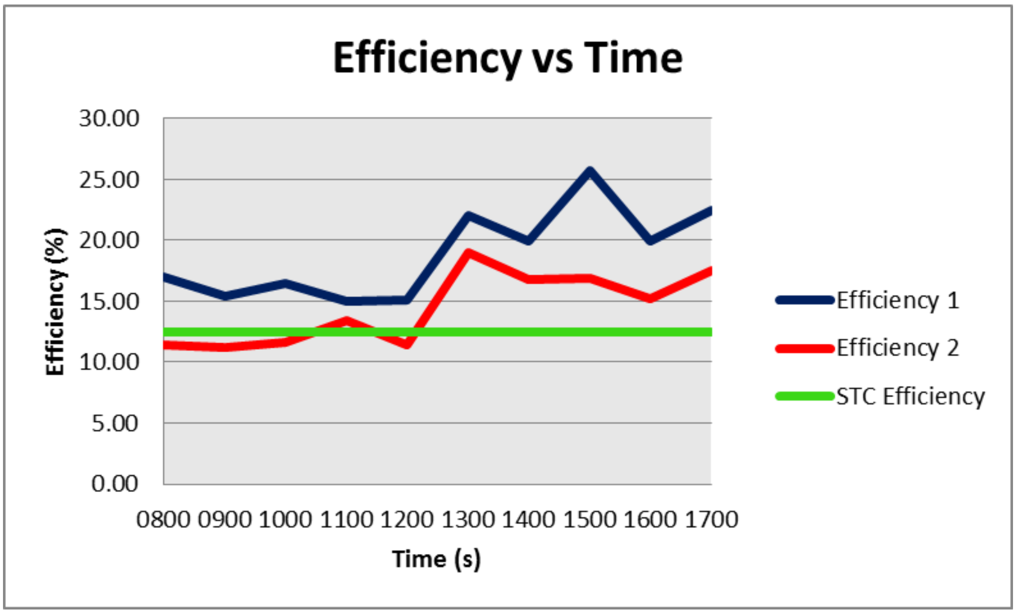

Figure 27: Measured Efficiencies of Photovoltaic Modules

When comparing the efficiencies of both the modules, there is a significant decrease in the conventional module. This is mainly due to the presence of the extra shaded area on the module. Considering the normal sunlight heats up the module, an addition of dust coverage on the module will further decrease the efficiency of the module. The existence of dust coverage on the module will trap heat energy to remain on the module causing the solar cells to operate at high temperatures and at the same time prevents sunlight from completely reaching the module surface. Thus, the level of efficiency of the energy conversion of the PV module will be low.

4.2.2 2nd Experiment: 20% Area Coverage of Photovoltaic Module

For this experiment, a cardboard with an area size of $0.0793m^2$ (20% of total surface area of the module) is use to cover the module surface. The cardboard represents the amount of dust accumulation on the photovoltaic module.

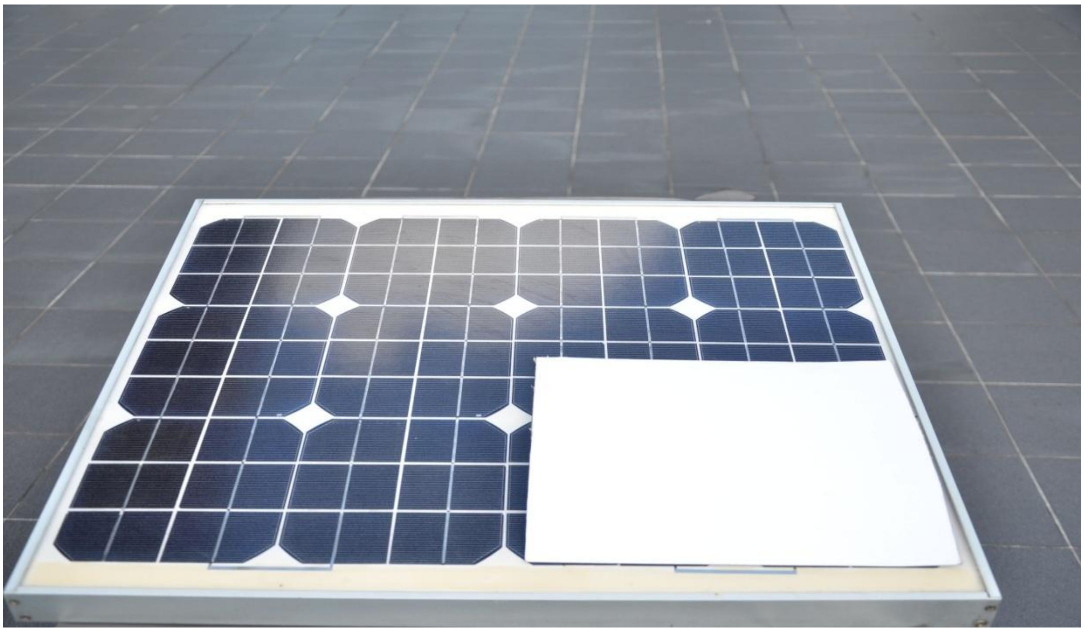

Figure 28: Set Up Of Photovoltaic Module with 20% Dust Coverage Area

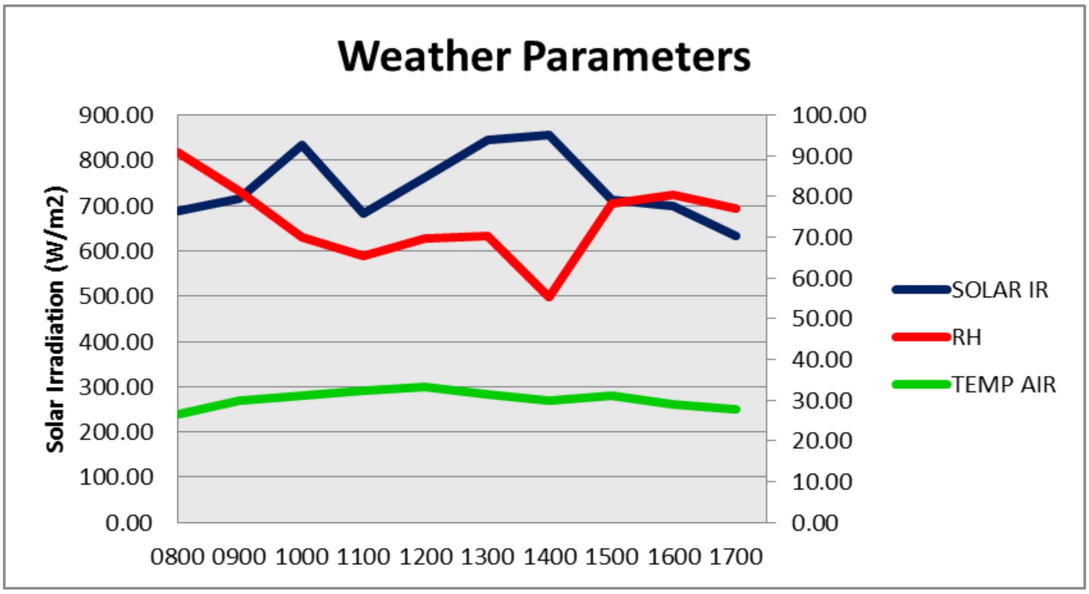

Figure 29: Weather Parameters (23rd July 2013)

From Figure 29, the solar irradiation and the relative humidity were high throughout the day. The solar irradiation is at maximum level from 1200 hours to 1400 hours that is around 860W/m^2. Due to slight wet conditions, the relative humidity did not drop below 60%. On the other hand, the temperature of the day is considerably low as it only exceeds 30°C on at 1200hours and remains below that temperature at other times of the day.

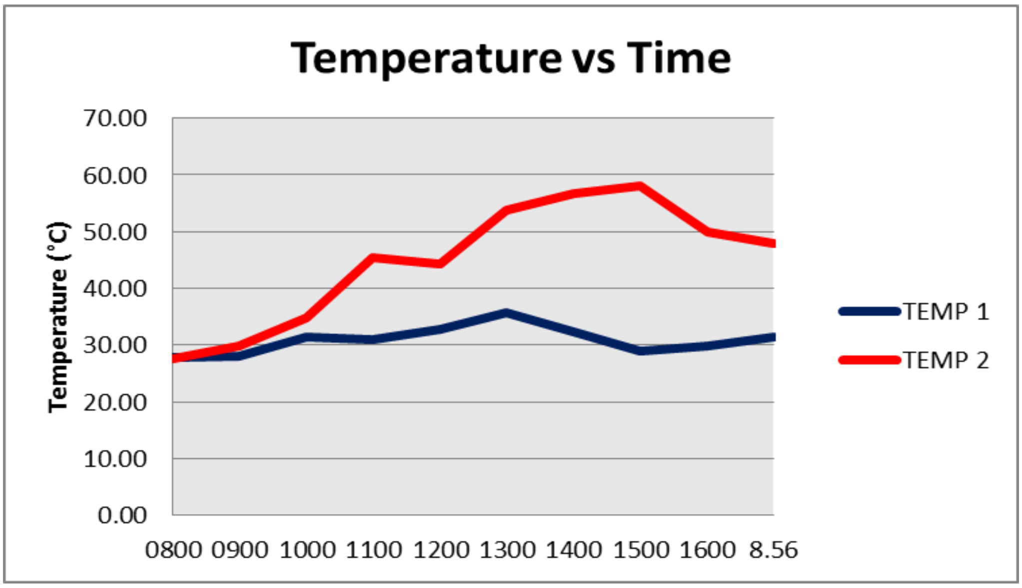

Figure 30: Surface Temperatures of Photovoltaic Modules

Based on the temperature versus time graph, it can be observed that conventional module with opaque sheet covering (TEMP 2) operates at higher temperature compared to the surface cooling module (TEMP 1). Although at the beginning of the day, the two module operating temperature were roughly around the same value of 29.5°C, as more sunlight heat reaches hit the modules, the conventional modules gets easily hotter at a higher rate due to the 20% dust covering on the module. This scenario does not take place in the surface cooling module as the water flow on the module keeps the surface cool within the range of 29°C to 33°C.

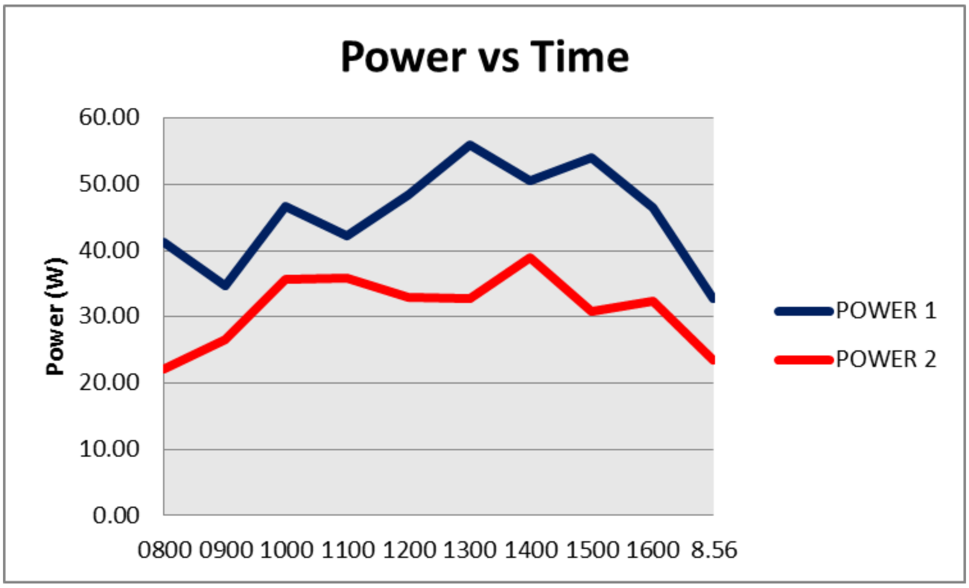

Figure 31: Output Power Generation of Photovoltaic Modules

In this experiment, the power of the module with surface cooling (POWER 1) still shows a higher output value compared to the conventional module (POWER 2). In fact, the difference in power generation is bigger than the 1st experiment as the coverage area of the conventional module is increased to 20%. This is because increased dust coverage causes even less sunlight to hit the module at the same time slow the heat transfer process away from the module surface.

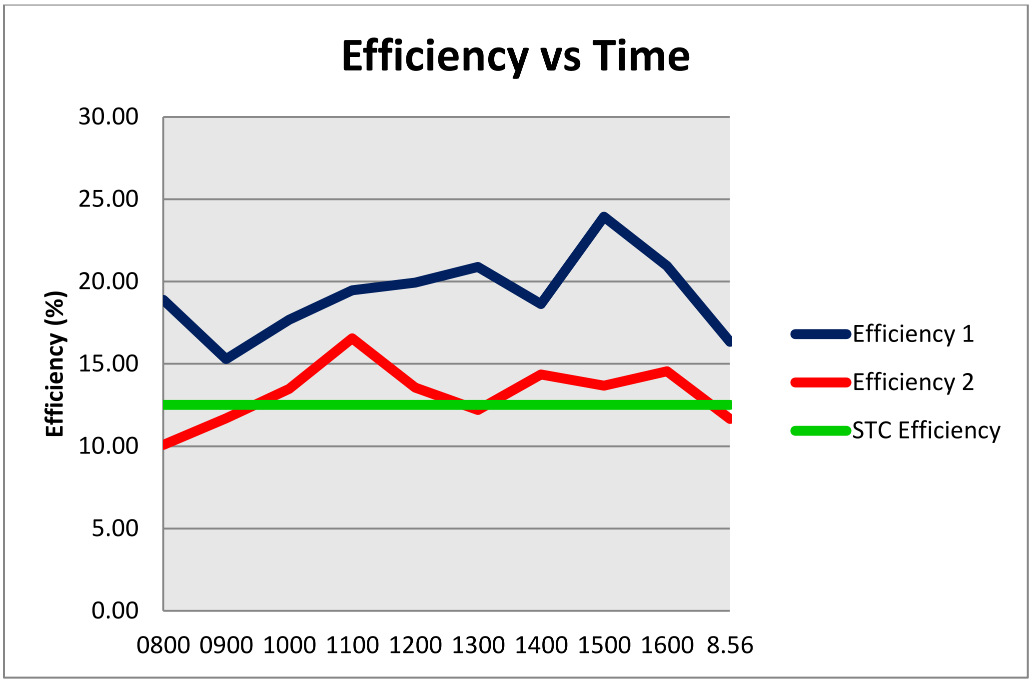

Figure 32: Measured Efficiencies of Photovoltaic Modules

Relating to Figure 32, it can be interpreted that when the output power generated by the module is low, the efficiency of the module would also be low at any value of solar irradiation. Due to increased coverage area, the efficiency of the conventional module (Efficiency 2) drops further as the surface temperature is increases. However, there is an increase in efficiency for the conventional module at the early hours of the day. This is because the temperature of the surrounding air is low throughout the day causing the rate of the module to get hot is relatively low. As for the module with surface cooling (Efficiency 1), the efficiency does not drop below the STC Efficiency line (12.51%) and maximum point is at 1500 hours with a value of 23.94%.

4.2.3 3rd Experiment: 30% Area Coverage of Photovoltaic Module

A cardboard layer with an area of $0.119m^2$ is use to cover the photovoltaic module. The area of the cardboard represents 30% dust coverage of the total surface area of the photovoltaic module. The following figure shows the covering of the module.

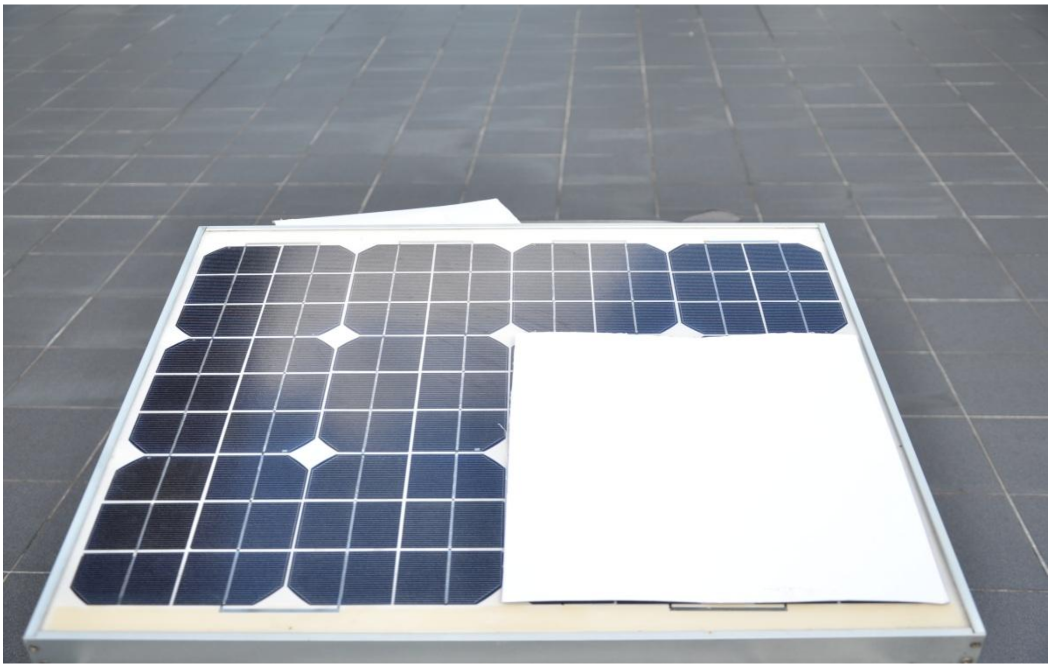

Figure 33: Set Up of Photovoltaic Module with 30% Dust Coverage Area

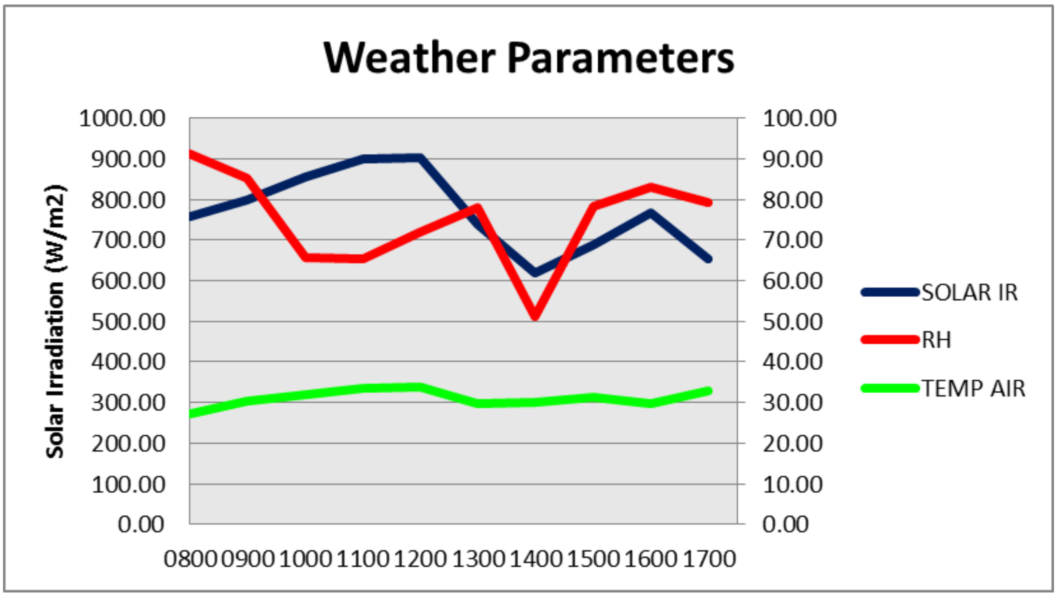

Figure 34: Weather Parameters (24th July 2013)

From Figure 34, the solar irradiation is high during the early part of the day reaching a peak value of 901.34W/m^2. During the evening, the solar irradiation level drops. This is possibly due to the moving dark clouds that block the sunlight. Meanwhile, the relative humidity is at a range of 70% – 90% throughout the day. Only at 1400 hours, the humidity drops to 51.22% due to dry atmosphere. The maximum temperature of air is during peak hours with a value of 31.45°C.

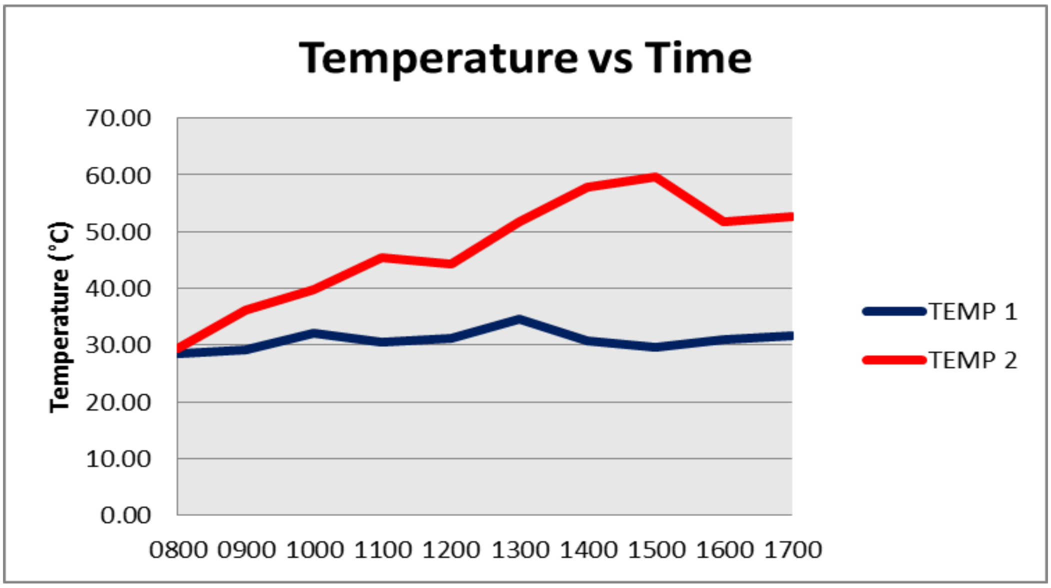

Figure 35: Surface Temperatures of Photovoltaic Modules

As expected, the temperature of the module with water cooling (TEMP 1) is low compared to the conventional module with 30% covering. The surface temperature of the water cooling module remains close to the temperature of the air throughout the day as there is thin water layer absorbing the module heat. The conventional module temperature (TEMP 2) increases tremendously in this experiment to a maximum surface temperature of 59.59°C and eventually drops at the last two hours of the day due to strong wind blow presence. The rise in temperature is due to the increase in dust coverage of the module surface area from 20% to 30% as it prevents more heat escaping the module.

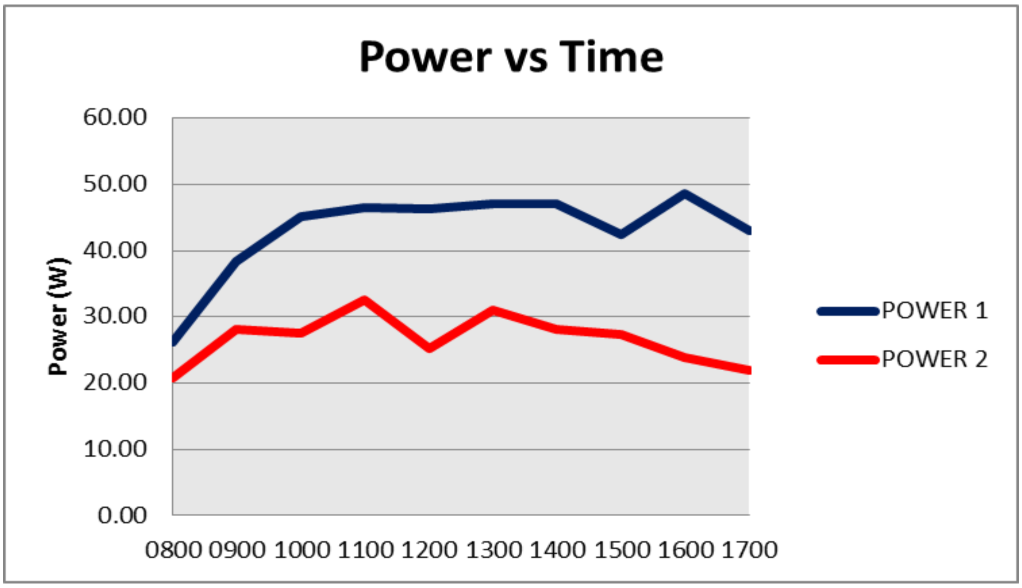

Figure 36: Output Power Generation of Photovoltaic Modules

From Figure 36, it can be seen that the output power generation of the module with surface cooling (POWER 1) is higher compared to the conventional module (POWER 2). However, the module with surface cooling generates low output power for the whole day when compared to the previous experiments as the solar irradiation throughout the day is not very high. Nevertheless, the conventional module with 30% dust coverage provides an even lower power output in this situation reaching a minimum output power value of only 20.69W.

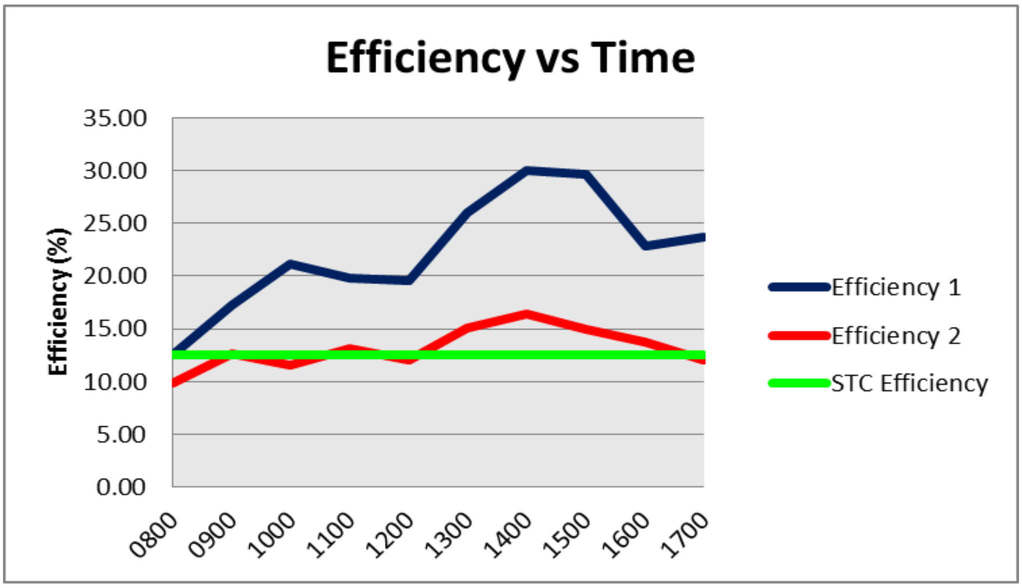

Figure 37: Measured Efficiencies of Photovoltaic Modules

It can be noticed that the efficiency of the conventional module (Efficiency 2) is below the STC Efficiency at the early part of the day. During the evening, the efficiency value is still low only reaching a maximum value of 16.43%. This can be basically related to the high operating temperature of the surface module as mentioned earlier. On the other hand, the module with surface cooling generates high efficiency throughout the day having a peak value 27.38%. The existence of the constant water layer on the module surface cools the solar cells allowing them to operate at low temperatures.

4.2.4 4th Experiment: 50% Area Coverage of Photovoltaic Module

In this experiment, a cardboard sheet with the surface area of 0.198m^2 is used to cover the surface module. The area of the cardboard represents 50% dust coverage of the total surface area of the photovoltaic module.

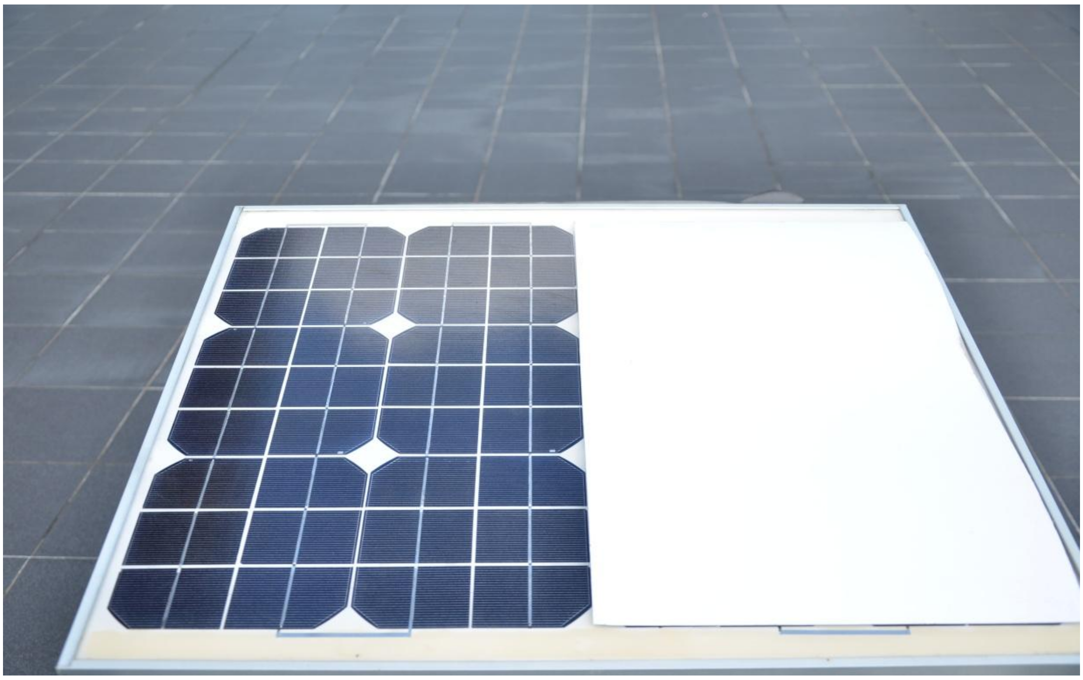

Figure 38 : Set Up of Photovoltaic Module with 50% Dust Coverage Area

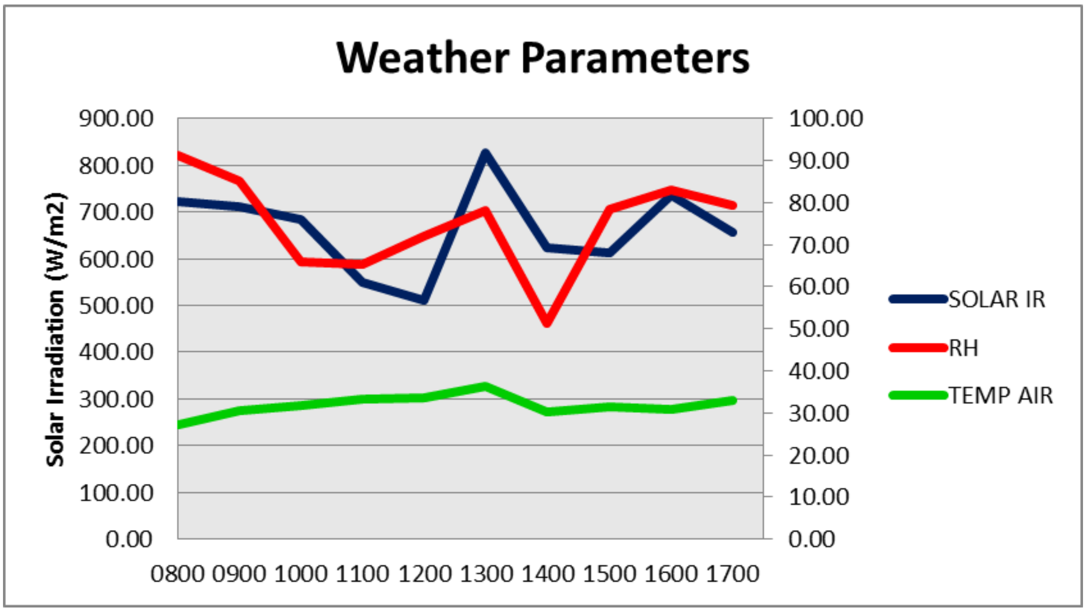

Figure 39: Weather Parameters (25th July 2013)

Based on the weather parameters in Figure 39, it can be seen the maximum value of solar irradiation is 825.12W/m^2 at 1300 hours. The relative humidity throughout the whole day is slightly unbalanced as it high early in the morning, decreases later on and increases again in the evening. The maximum temperature of air is 36.43°C at 1300 hours and the temperature of air is relatively hot considering the value is exceeding 30°C frequently in the day.

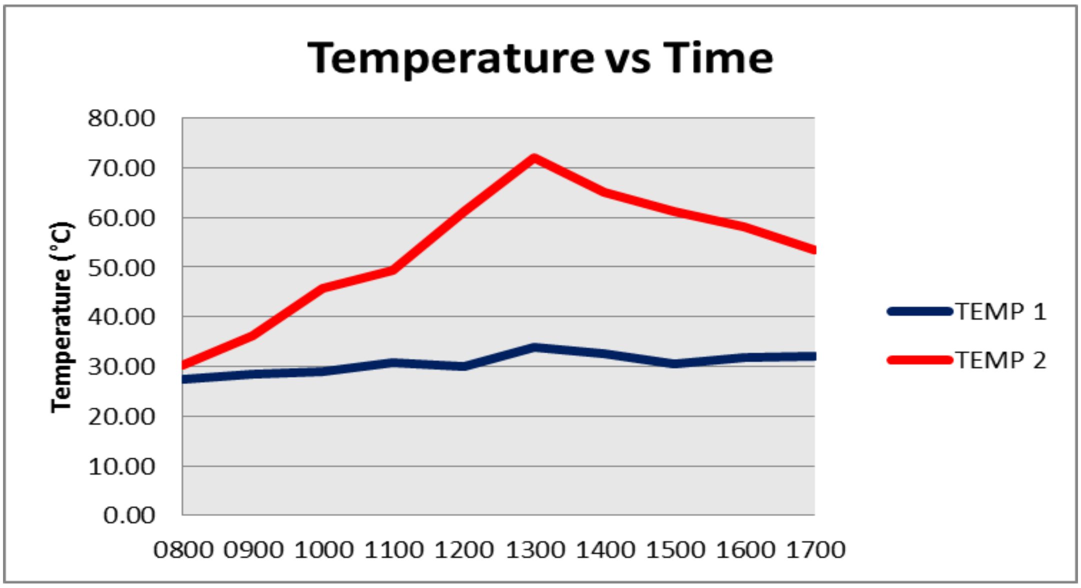

Figure 40: Surface Temperatures of Photovoltaic Modules

Figure 40 shows the relationship between temperature of the modules and the time of day. The temperature of the conventional module (TEMP 2) rises the highest compared to all the other experiments. It reaches a maximum temperature of 71.99°C during peak hours of the day. This directly shows that the 50% dust coverage causes the heat from the sunlight hitting the module to get constantly trapped and stay within the module surface, causing the surface to be extremely hot. However, the temperature of module with water cooling modifications (TEMP 1) remains stable and low for the whole day, which is only around 30°C.

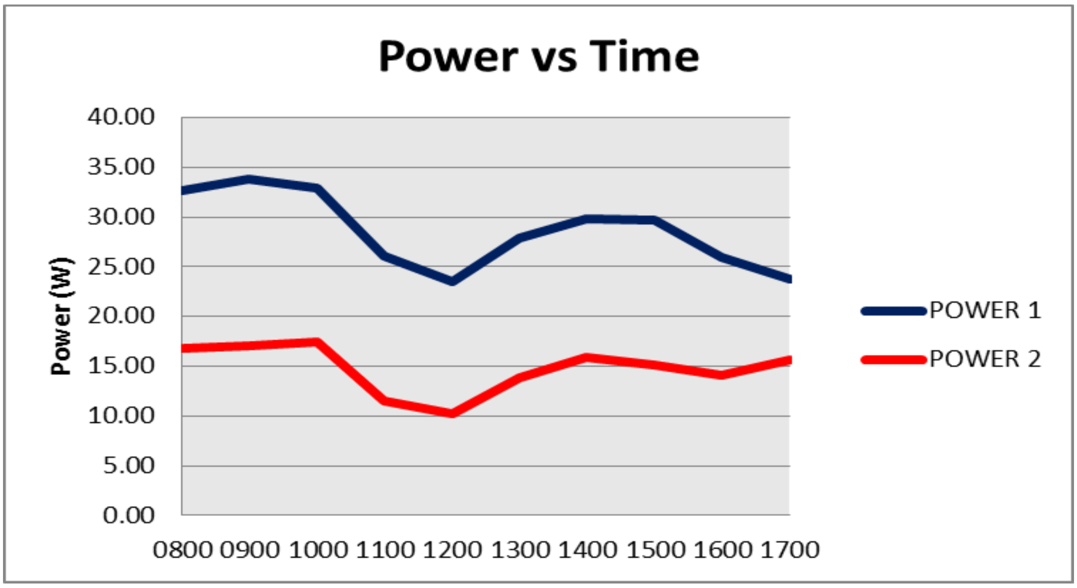

Figure 41: Output Power Generation of Photovoltaic Modules

Based on the Figure 41, the power generation for both the modules is low due to the high air temperature of the surroundings. As for the conventional module, the value of output power generated is lowest during peak hours among all the 4 experiments reaching a minimum value of 11.56W. This is due to the presences of high dust coverage area causing the surface module operating temperature to be high. Meanwhile, it can be understood that the efficiency of module with surface cooling is higher than the conventional module but still faces a drop in power generation on peak hours. This is due to the high air temperature of the surroundings which heats up this module as well.

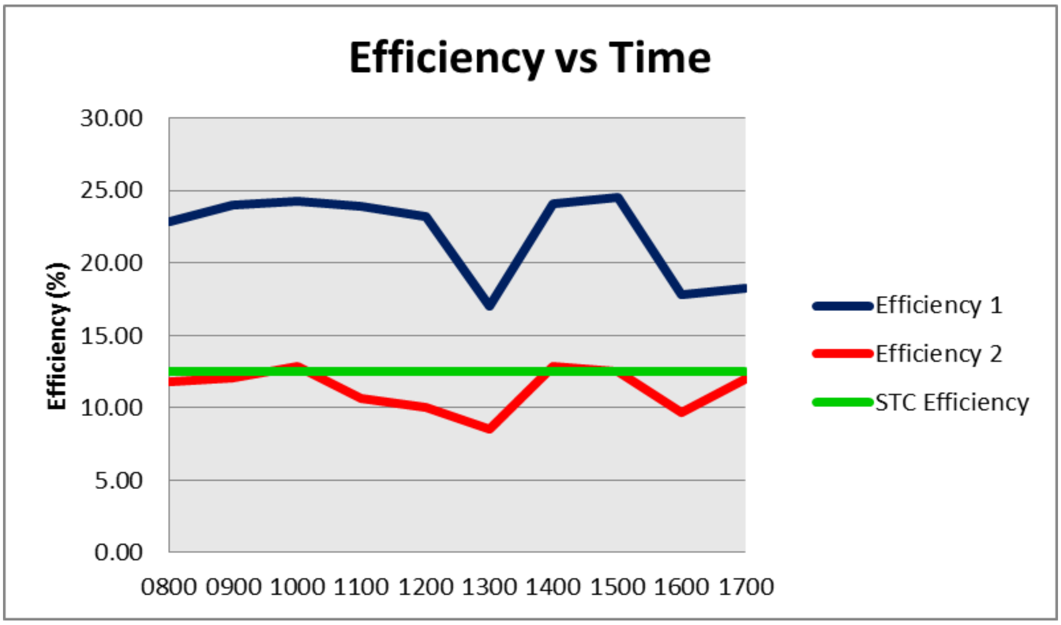

Figure 42: Measured Efficiencies of Photovoltaic Modules

The Figure 42 clearly shows the efficiency of the conventional module (Efficiency 2) drops significantly below STC Efficiency line for most of the time of the day. The maximum efficiency of the module only reaches up to a value of 12.87% while the minimum value drops to 8.49% – the lowest among all the 4 experiments conducted. This is because the dust area coverage of the module is the most among all the experiments conducted in the second part, which is half of the total surface area of the module. The presence of high debris accumulation on the module causes the heat to get trapped easily within the surface of the module and the dust layer. This heat constantly increases the surface temperature of the module causing the efficiency of the module to drop further. It is totally different in the module with surface cooling, where the efficiency reaches a high maximum value of 24.51%. However, there is strange efficiency behaviour of this module during peak hours, where it drops down to the lowest value of the day which is 17.04%. This could be highly related to the temperature of the air surroundings which was high during peak hours causing the module temperature to rise although with water cooling. Nevertheless the efficiency of the surface cooling module is highly better when compared to the efficiency of the conventional module with 50% dust covering.

Table 3: Comparisons between Module with Surface Cooling and Conventional Module with Dust Coverage

EXP NO.	PERCENTAGE OF DUST COVERAGE (%)	POWER DIFFERENCE (W)	PERFORMANCE IMPROVEMENT (%)	EFFICIENCY DIFFERENCE (%)
1	10	5.29	31.70	3.63
2	20	8.11	47.42	6.38
3	30	10.42	62.72	8.44
4	50	13.14	89.84	13.31

Based on Table 3, the power difference between both the modules; module with surface cooling and conventional module increases with increasing dust coverage. The module with water cooling is assumed to be with zero dust coverage as water layer prevents any possibilities for dust settlement on the surface. The difference in power generation causes the performance improvement of the module with water cooling to be greater as more dust is assumed to be covering on the conventional module. This directly causes the efficiency difference to increase as well, when the area of dust coverage on the PV surface module gets bigger.

From all the four experiments carried out, it can be clearly understood that dust coverage does play an important factor in decreasing the energy conversion efficiencies of the photovoltaic module. As the dust coverage area increases from 10%, 20%, 30% to 50%, the output power generated by the conventional module eventually drops even more causing the efficiency of the module to be considerably low. This is mainly due to the increase in the surface temperature of the module with dust accumulation. The dust layer on top of the module surface causes the heat transfer process of photovoltaic module to be inhibited. Therefore, heat gets trapped on the module surface itself causing the operating temperature to be massively high. At high temperatures, the electrons in the semiconductors do not flow properly as they have limited energy causing less power output to be generated. Meanwhile, with the same amount of solar irradiation, the module with water cooling exhibits a better efficiency as the water layer not only cools off the surface temperature of the module, but it also prevents dust from collecting on the module. Thus, heat will not be trapped within the module surface as the constant water flow absorbs the heat and transfers it away from PV module allowing the solar cells to operate at low temperatures.

4.3 Snapshots using Infrared Thermal Camera

To further support the information on the analysed from both the experiments, infrared thermal images of the photovoltaic module were captured. The images display the differences in thermal distribution on both the module surfaces; module with surface cooling and conventional module with 50% dust coverage. The snapshots are taken upon completions of both parts on the experiment which is on 30th July 2013.

The following are the thermal images taken;

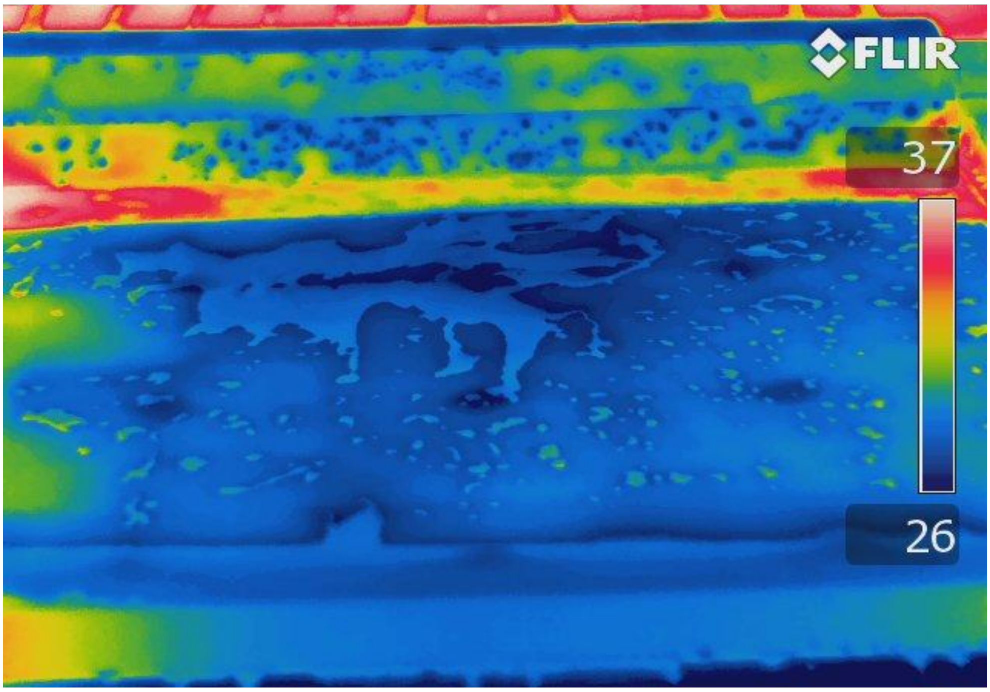

Figure 43: Infrared Thermal Image of Module with Surface Cooling

From Figure 43, it can be seen that the camera sets a range on temperature between 26°C to 37°C for the image taken. This shows the maximum temperature on the module will not exceed 37°C. About 90% of the whole module surface is in blue colour, which means the surface temperature of the module is relatively low, close to 26°C. This explains that the presence of water flow absorbs heat from the module surface providing a constant cooling effect on the solar module throughout the day. As previously explained, with low surface operating temperatures, the energy conversion efficiency of the module will be high.

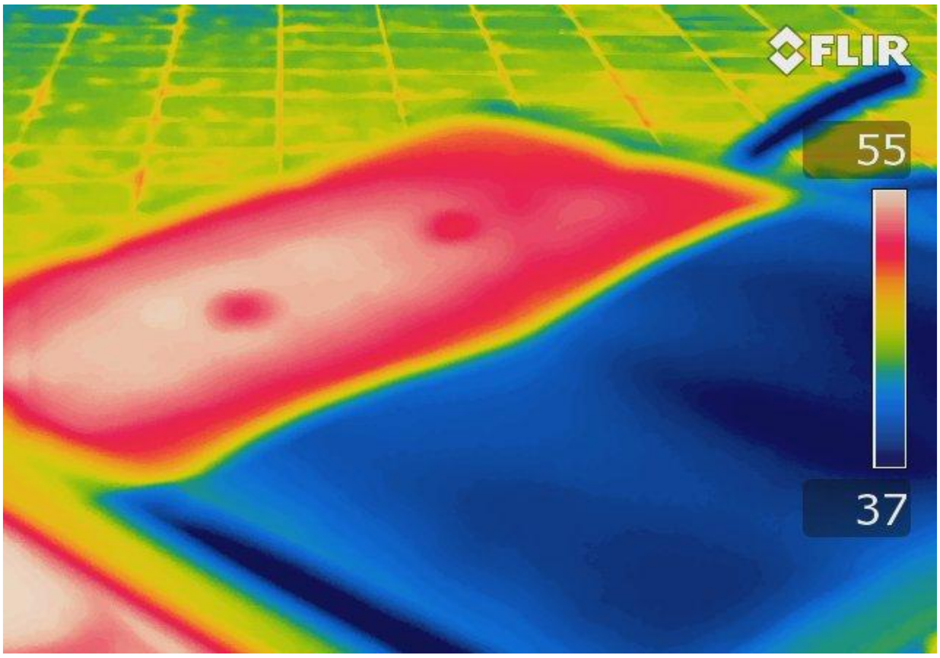

Figure 44: Infrared Thermal Image of Conventional Module (50% Dust Coverage)

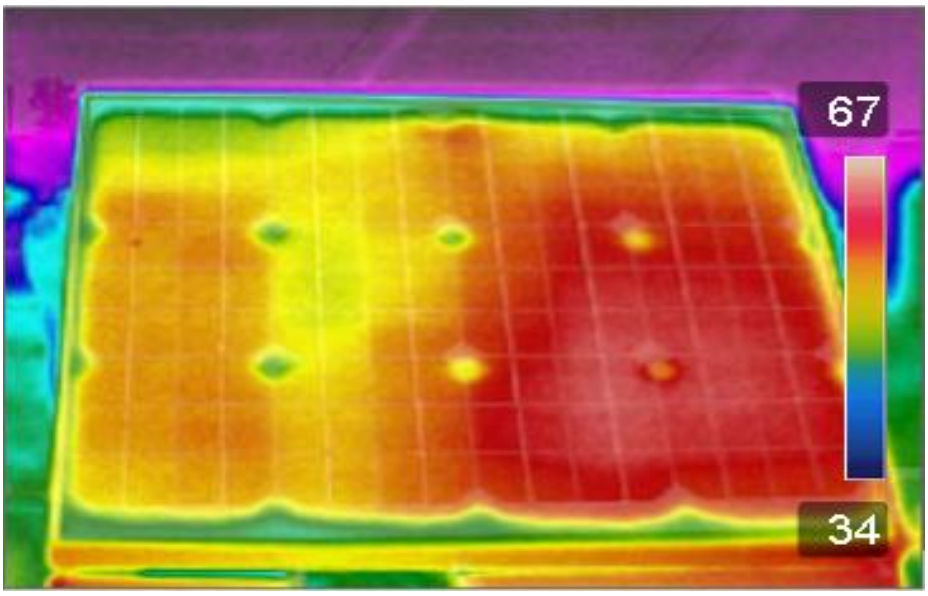

Figure 45: Thermal Infrared Image of Conventional Module (Dust Coverage Removed)

Referring to Figure 44, the image displays a range of temperature from 37°C to 55°C. This range is higher compared to the previous image of module with surface cooling. The maximum value reaches up to 55°C indicating the surface of module is very hot. From the colour distribution of the image, it can be observed that half of the module surface is in bright red colour. This shows the temperature of that particular section is close to 55°C. The PV module gets very hot due to the presence of the 50% dust coverage (using cardboard) as heat gets trapped within the module surface. However, the other half of the module is in light blue colour indicating the temperature is about 39°C. This is because the camera takes the temperature of the dust layer coverage of the module. The dust layer does not conduct heat as much the module surface. It just acts as a layer preventing heat from escaping the photovoltaic module. Nevertheless, referring to Figure 45, when the dust shaded layer is removed from the module surface, the thermal distribution of the section below the dust layer is observed to be in extremely bright red in colour compared to the open half, as it is because of the presence of the dust accumulation; the overall surface of the module appears to be extremely hot especially the section directly below the dust coverage.

CHAPTER 5.0
CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

From both parts of the experiment conducted, it can be directly observed that the performance of the photovoltaic module is determined by the energy conversion efficiency level of the module. Based on the research carried out, low energy conversion efficiency of the module takes place when the surface temperature is relatively high. The increase in surface temperature is due to heat energy generated on the surface when hot sunlight hits the module. This causes only a minimum amount of the light energy is converted into electrical energy, where else most of the energy is basically converted to wasted heat energy.

The objectives set on the beginning of the project basically emphasize on the factors that affect the photovoltaic module performance and how can they be countered. The first objective focuses on studying the effects of surface temperature cooling on the PV module. For this part, the experiment carried out is by implementing the idea of water cooling on the solar module. A continuous thin layer of water is allowed to flow on top of the module surface throughout the day and the performance is compared to the conventional module. From the interpretation of the data obtained, it can be clearly seen during peak hours of the day the module with water cooling generates a higher efficiency value of 17.45% where else the conventional module generates an efficiency of 11.01%. The big difference in efficiency is due to the high rise in surface temperature of the conventional module. As sunlight hits the module, conversion of energy takes place from light energy to electrical energy. However, not all light energy is converted into electrical energy, as most energy is dissipated in the form of wasted heat. The presence of this heat causes the semiconductors on the module to not function efficiently as the flow of electrons in these components will be weak causing low current value. This would affect the amount of power generated causing the efficiency to simultaneously decrease. Meanwhile, water cooling method helps in absorbing the wasted heat energy, keeping the module at low operating temperatures. Thus, efficiency of power generation will be higher as more power is produced for a same amount of solar irradiation. The higher the surface temperature, the lower the module performance will be in terms of energy conversion efficiency.

As for the second objective, the experiment carried out focuses on the performance of the photovoltaic system with respect to the dust accumulation on the module. From the research, it is analysed that the module with dust coverage gives a lower performance compared to the module with water cooling. Overall, the efficiency values of the module with dust coverage are relatively lower than the STC efficiency of 12.51%. The lowest efficiency of the module is identified during the last experiment of the second part of the project, when the module is shaded by 50% dust coverage; it gives an efficiency of 8.49%. This explains when there is dust on the module surface; first of all it decreases the sunlight reaching the module. Less exposed area to light source causes relatively lower energy conversion. In addition, the accumulation of dust also causes the wasted heat generated on the module surface to be trapped. This causes the module to be constantly heated causing the operating temperature to be extremely high. Considering already receiving low sunlight intensity, the increase in surface temperature causes the module power generation to be low affecting its performance badly. This scenario is totally opposite for the water cooling as it efficiency remains high throughout the experiment conduct. This is because water cools the PV module surface and at the same time is prevents any dust settlement on the module, thus power generation will be high guaranteeing the performance of the module to be at its best.

Therefore, it is clear that water cooling and debris removal helps in improving the efficiencies of the solar photovoltaic module. Surface temperature cooling maintains low operating temperatures of the module, boosting the efficiency level up. As for debris accumulation, the more the dust coverage area on the module, the lower the efficiency of the module will be and vice versa. The objectives of the experiment are successfully achieved.

5.2 Recommendations

Although the objectives set in the project are successfully achieved, there is still room for improvement on the case study. In terms of the prototype build, a bigger pump can be used to overcome the head flow, providing a better flow rate of water on the photovoltaic module. Besides that, instead of using the continuous water flow method on the module, the water cooling technique can be implemented by spraying water vapour on the module throughout the day. This would not only lower the operating temperatures of the PV module, at the same time it will minimise the light refracting away from the module due to the thin layer of water. In addition, an artificial light source, such as a spot light could be applied in this experiment to ensure constant high light energy is provided on the modules throughout the day. Thus, the study on improving the module efficiencies can be conducted even better.

As for study of dust accumulation on the module surface, car tints can be used as a replacement for cardboards. Car tints have a specific amount of sunlight allowable through them, thus the shaded level of the tints can be directly related to the dust coverage area of the module. As shaded levels of the module are perfectly set up using car tints, the performance of the module can be further analysed in terms of dust accumulation on the photovoltaic module surface.

REFERENCES

[1] Krauter S. (2008). Increased electrical yield via water flow over the front of photovoltaic panels. Solar Energy Materials & Solar Cells 82, 131-7.

[2] El-Shobokshy M. S., H. F. (2008). Effect of dust with different physical properties on the performance of photovoltaic cells. *Solar Energy 51,* 505-511.

[3] Mani M., P. R. (2010). Impact of dust on solar photovoltaic performance: Research status,challenges and recommendations. *Renewable and Sustainable Energy Reviews 14,* 3124-3131.

[4] Rosa-Clot M., R.-C. P. (2010). Submerged photovoltaic solar panel: SP2. *Renewable Energy 35,* 1862-5.

[5] Kordzadeh A. (2009). The effects of nominal power of array and system head on the operation of photovoltaic water pumping set with array surface covered by a film of water. *Renewable Energy 35, 1098-1102.*

[6] Abdolzadeh M., Ameri M. (2009). *Improving the effectiveness of a photovoltaic water pumping system by spraying water over the front of photovoltaic cells*, Journal of Renewable Energy 34,pp. 91–96.

[7] Shariah A. M., Al-Akhars A., AlOmari I. A. (2012). Optimizing the tilt angle of solar collectors, *Renewable Energy* 26,587−98.

[8] Messenger R. A., Ventre J., (2008*). Photovoltaic Solar Systems Engineering*, 2nd Ed, Florida: CRC Press.

[9] Eastop., McConkey., (2010). *Applied thermodynamics for engineering technologists*, Longman, 5th edition, 1193.

[10] Odeh. S., Behnia. M., (2009). *Improving Photovoltaic Module Efficiency using WaterCooling*, Taylor and Francis Ltd, Heat Transfer Engineering, Volume 30, pp. 499 – 505 (7).

[11] David. T., (2010). *Types of Photovoltaic Modules*, Proceedings of international ISES Conference, 1979, pp. 1865–1869.

[12] Carr A. J., Pryor T. L., (2008) “A comparison of the performance of the different PV module type in temperature climates”, *Solar Energy 76*,pp 285 – 294.

[13] Doble. D. M. J., (2013). *Minimization of Reflected Light in Photovoltaic Module*, Renewable Energy World, Article 03.

[14] Kalogirou. S. A., Tripanagnostopoulos. Y., (2009) *Industrial application of PV/T solar energy systems*, Journal of Energy Conversion and Management 47, pp. 3368–3382.

APPENDIX

Figure 46: Type of Solar Photovoltaic Module Selected - Polycrystalline

Figure 47: Prototype Set Up - Module with Surface Cooling and Conventional Module

Table 4: Average Performance Improvement of Photovoltaic Modules

Date	Average Solar Irradiation (w/m^2)	Average RH (%)	Average Peformance Improvement (%)
18/6/2013	535.83	49.56	23.65
20/6/2013	611.36	62.55	25.21
24/6/2013	853.50	57.61	38.09
25/6/2013	745.51	82.55	32.67
28/6/2013	816.23	56.72	40.06
1/6/2013	489.67	82.20	29.55
3/7/2013	778.32	70.73	35.18
5/7/2013	721.14	72.13	**43.24**
9/7/2013	682.15	81.37	26.73
10/7/2013	503.97	62.45	24.80

Table 5: Sample Tabulation of Weather Parameters (5th July 2013)

TIME	SOLAR IR	RH	TEMP AIR
0800	659.82	92.30	28.70
0900	712.54	85.50	29.50
1000	689.56	71.70	30.30
1100	825.66	70.60	31.10
1200	867.43	62.30	33.70
1300	824.99	57.20	34.50
1400	800.32	62.40	32.30
1500	556.77	65.50	31.60
1600	686.90	81.80	28.40
1700	587.40	72.00	29.80

Table 6: Sample of Tabulation Data - Experiment 1 (5th July 2013)

TIME	VOLTAGE 1	CURRENT 1	POWER 1	TEMP 1	VOLTAGE 2	CURRENT 2	POWER 2	TEMP 2	SOLAR IR	PERFORMANCE IMP	EFFICIENCY 1	EFFICIENCY 2
0800	18.78	2.05	38.50	24.50	16.85	1.53	25.78	24.90	659.82	49.33	14.72	9.85
0900	20.34	2.32	47.19	25.70	18.80	1.87	35.16	29.90	712.54	34.23	16.70	12.44
1000	21.00	2.34	49.14	30.80	18.95	2.10	39.80	39.10	689.56	23.48	17.97	14.56
1100	21.72	2.47	53.65	27.90	17.95	2.40	43.08	43.10	825.66	24.53	16.39	13.16
1200	20.97	2.33	48.86	35.77	17.85	2.15	38.38	54.50	867.43	27.31	14.21	11.16
1300	21.65	2.50	54.13	38.96	17.79	1.92	34.16	63.50	782.11	58.46	17.45	11.01
1400	19.54	2.56	50.02	34.80	18.44	2.05	37.80	54.80	800.32	32.33	15.76	11.91
1500	20.81	2.88	59.93	31.30	17.32	2.05	35.51	43.90	556.77	68.80	27.15	16.08
1600	19.86	2.62	52.03	29.70	18.50	1.72	31.82	44.20	686.90	63.52	19.10	11.68
1700	20.50	2.55	52.28	31.83	17.55	1.98	34.75	42.11	587.40	50.44	22.44	14.92
			50.57				35.62			43.24		