STUDY ON HYBRID PHOTOVOLTAIC AND THERMAL SOLAR POWER

BY

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CERTIFICATION OF APPROVAL

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Approved by,

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CERTIFICATION OF ORIGINALITY

This 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.

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MUHAMMAD NAJMUDDIN BIN RUSLI

ABSTRACT

Solar power is one of the leading fields of renewable energy sources. The establishment of solar power are already quite strong in the world with multiples solar power plants currently competing against fossil-fuels-powered plants in providing electricity while producing clean and sustainable energy. To improve the reliability of solar power, a new field of study is currently being developed known as hybrid of photovoltaic and thermal system. In this report, the research on concentrating photovoltaic/thermal solar system is elaborated in form of Project Background, Literature Review, Research Methodology and finally Result and Discussion. Chapter 1: Project Background includes a brief introduction to the study in hand as well as the problem statement and objectives of study. In the end of the chapter, relevancy and scopes of the research project are elaborated. The Second Chapter: Literature review illustrates the critical analysis on the research according to literatures and past works done by other researchers. The review narrows down the scope of the study and allowing for development of a relevant research project. Chapter 3: Research Methodology demonstrates the current and future plans of the project. It begins with descriptions on the project research methodology followed by the detailed elaboration of the fabrication and experiments to be performed during the project. A study plan in form of Gantt chart is provided with this report as well as the important key milestones. Lastly, Chapter 4: Result and Discussion elaborates the two stages of the research; first is the equipment fabrication stage where details of the fabrication are explained and secondly, the experimentation stage of the research studies. All in all, this dissertation represents the knowledge, plans as well as the progress regarding the research on concentrating hybrid photovoltaic/thermal solar power system.

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CHAPTER 1

INTRODUCTION

1.1 Project Background

In this modern world, human thirst for energy is endless. According to the data from International Energy Association (IEA), energy consumption per human being in the world from 1990 to 2008 elevated by 10% while 27 percent increase is shown per world population ("The Energy Development Index,"). Our dependent on non-renewable energy sources makes the conditions even worse. In order to cope with the demand for energy, reliable renewable energy sources need to be established.

One of the leading alternatives in sustainable energy source is solar energy. Our sun is producing limitless energy every second and only a small fraction of the energy reaches the earth in form of heat and sunlight. If we can harvest most of this abundant energy source, the supply is more than enough to sustain human crave for energy throughout the world. The revelation to gather energy from sunlight begins in 1839 when Becquerel observed that photocurrents were produced on illuminating platinum electrodes coated with silver chloride or silver bromide and immersed in aqueous solution thus marks the discovery of photovoltaism (Archer, 2001).

Photovoltaic technology has immensely advanced throughout the 20th century and commonly used today as additional energy source. Aside from Photovoltaic (PV), another type of energy that utilizes the heat energy from the sun known as thermal solar energy also developed and largely used since long ago. On the late 1970s, a study to incorporate these two separate technologies into single device began thus indicates the birth of hybrid Photovoltaic/Thermal (PVT) solar system. There are two benefits can be gained from PVT system: firstly, the efficiency of PV cells can be improved by reducing its temperature using the solar thermal system. Secondly, by incorporating both systems into single device, the area required to collect the sun's energy also reduced significantly (T. N. Anderson, 2008).

1.2 Problem Statement

The technology for hybrid of photovoltaic and thermal (PV/T) solar system has been around since late 1970s. However, currently in energy industry, the system is still not applied or implemented due to cost and efficiency issues. Combining both photovoltaic and thermal system into a single component will surely amplify the cost making the system unsustainable economically. One of the solutions to reduce cost for PV/T system is to apply concentrator to the solar collector. Applying concentrators in to PV/T system will reduce the total usage of expensive equipments such as photovoltaic components, replaced with economically affordable reflectors. However, by concentrating the sunlight, the intensity of solar radiation that lands on the PV cells are much higher leading to significant increase in surface temperature. Non-uniform temperature distribution along the PV cells and high operating temperature causing the efficiency of common PV cells to decrease (Segal A., 2004). Different designs of concentrators and various arrangements of the components can also affect the efficiency of certain concentrating PV/T system in producing electricity and thermal energy.

1.3 Objectives

The main purpose of this project is to study on the hybrid system of photovoltaic and thermal solar power. The aim is to design a Concentrating Photovoltaic/Thermal (CPV/T) solar power system with maximum efficiency and energy output. During the project, various researches will be conducted to identify the issues that reducing the efficiency and countermeasures will be developed and implemented to rectify the problems while maintaining the thermal output of the system. In this project, a novel concentrating PV/T collector prototype that recently presented in literature and tested in simulation will be constructed to further analyse the prototype by experimental data. The model consists of a parabolic through concentrator and a unique triangular receiver.

1.4 Scope of Study

The scopes of study for this project are as follows:

1. Research on hybrid photovoltaic/thermal system
2. Identifying the issues with CPV/T system
3. Seeking for established solutions for the problems
4. Designs a working CPV/T equipment
5. Constructs a working CPV/T equipment
6. Performs experiments on CPV/T system
7. Implements modifications to improve system

1.5 Relevancy of the study

The establishment of reliable renewable energy sources are essential in today's world due to the limited energy sources that we have been burning are now closing to extinction. Aside from that, the level of pollution are now reaching to a critical height and solutions need to be found to replace the usage of fossil fuels as main energy source. Even though solar power has already quite established in industry, further improvements are required to ensure better performance and output.

CHAPTER 2

LITERATURE REVIEW

Solar energy has always been one of the renewable energy sources that are commercialized to sustain world energy demand. Solar energy is considered to be the dominant renewable energy source because through photovoltaic (PV) technology, clean electricity can be generated without pollutants emission. It was observed that the implementation of PV solar energy in the European countries, United States, Japan and China had increased exponentially in the past decade (Dinçer, 2011). However with PV solar power, the major obstacle is the initial cost of the system mainly due to expensive PV modules. One way to do it is to maximize efficiency of the system is by minimizing the effect of shadows via accurate design, increasing the incident light as well as utilizing maximal power point tracking (Kan & Strijk, 2006) to capture as much sunlight as possible even on cloudy weather (Kelly & Gibson, 2011). Studies on optimizing the efficiency of PV cells are going on around the world and advanced triple junction solar cells is the current leading technology which has the capacity produce electricity with high efficiency as well as durable at extreme operating conditions (Nishioka et al., 2006). However, due to cost effectiveness, silicon cells are still the dominant PV technology (Razykov et al., 2011).

Another measure to enhance the capacity of PV solar system is by concentrating the incident sunlight. This will allows extraction of larger area of sunlight with similar amount of PV modules thus increasing the amount of energy collected. Concentrating photovoltaic (CPV) has been around since 1970's with the study on low concentrating (40x) system with capacity of 1 kWp. The advantage of CPV as compared to normal PV system is the substitution of expensive PV modules with low-cost concentrator optics in order to cover larger ground of sunlight (Viana, Rüther, Martins, & Pereira, 2011). Unfortunately, by implying concentrators, as the amount of solar radiation that hits the surface of PV cells amplifies and temperature increase can be observed. Non-uniform heat distribution across the modules contributes to a measurable change in temperature gradient due to Peltier effect (Ari & Kribus, 2010). This temperature gradient tends to reduce the efficiency solar cells in producing electricity (Royne A., 2005).

Aside from PV solar technology, another popular technology used to extract the energy of the sun is via thermal solar power or better known as concentrating solar power (CSP). The system works by using the concentrated solar radiation to heat up water, either directly or through an intermediate compound, to produce high-temperature steam which then used to power a conventional Rankine cycle for electricity generation (Adinberg, 2011). Even though CSP does not utilize expensive photo-electric components, but it has a much more complicated system and requires more expenses in equipment operations and maintenances as compared to PV solar power system. But, CSP has one benefit over PV solar in term of energy reliability. To provide electricity continuously day and night truly a challenge for solar power plant but CSP has more up its sleeve. The thermal energy collected during the day can be stored and used to run the generator once the sun sets. Many methods were studied to store thermal energy for CSP plant such as heat storage in solid (high temperature concrete or packed bed rocks (Zanganeh, Pedretti, Zavattoni, Barbato, & Steinfeld, 2012)), storage in liquid (molten salt (Zaversky, García-Barberena, Sánchez, & Astrain, 2013), (Rodríguez, Pérez-Segarra, Lehmkuhl, & Oliva)) as well as latent heat storage which uses phase change material (PCM) (Oró, Gil, de Gracia, Boer, & Cabeza, 2012). Nonetheless, CSP still covers a small fraction of world energy supply in today's world due to the hard competition given by fossil fuels.

From there, comes a new kind of solar power technology, a hybrid system that combines both PV and thermal into one, the photovoltaic/thermal (PV/T) solar power system. PV/T system functions by harnessing the solar radiation to produce electricity by using PV cells and at the same time, the heat energy dissipated by the cells is extracted (da Silva & Fernandes, 2010) with dual benefits; to produce thermal energy while maintaining the operating temperature of PV cells at optimum level (Chow, 2010), (Vokas, Christandonis, & Skittides, 2006), (Mishra & Tiwari, 2013). Many studies have been done on PV/T system mostly for domestic applications due to the ability of the system to produce electricity along with moderate thermal energy (Assoa, Menezo, Fraisse, Yezou, & Brau, 2007). PV/T was seen as a good replacement for conventional home solar water heater which can fulfill the heat requirement of a common housing while simultaneously provide energy saving in form of electricity (Chow et al., 2009). However, conventional flat-plate PV/T module can only produce low or at least moderate quality thermal energy due to small area of solar radiation and lack of concentrator as used by CSP system.

Implying concentrator on PV/T system is still a fairly new idea and studies are now been undertaken to test on the theory. Kostic et al. performed a research to investigate the effect of installing reflectors panel on PV/T system. The results shows that even though the energy saving efficiency of concentrating PV/T is lower with 46.7% instead of 60.1% for PV/T system without reflector panels, both the energy collected in form of electricity and thermal for concentrating PV/T system are significantly higher than the conventional PV/T collector (Kostic L. T., 2010) showing a promising future for concentrating photovoltaic/thermal (CPV/T) solar power system. On the other hand, another study by Bernardo shows that even though CPV/T system has the capability to produce high quality thermal energy, but due to the fact that PV cell tends to lose efficiency at high temperature, the thermal output of CPV/T system was limited to low temperature (Bernardo, Perers, Håkansson, & Karlsson, 2011).

Many reviews have been done on conventional PV/T solar power system for the past decade whether on the PV/T technologies (Chow, 2010), (Tyagi, Kaushik, & Tyagi, 2012), on the parameters that affecting PV/T performance (Charalambous, Maidment, Kalogirou, & Yiakoumetti, 2007), even on the practical applications of PV/T technologies (Zhang, Zhao, Smith, Xu, & Yu, 2012), (Fang & Li, 2013) as well as specific reviews that focus on the different kind of PV/T system such as air type (Kumar & Rosen, 2011) and liquid type systems (Daghigh, Ruslan, & Sopian, 2011). This review is different from other works before as it focuses on the development of Concentrating PV/T technology throughout the recent years and compiles the various designs and technologies used for CPV/T system.

2.1 Groundwork of Concentrating Photovoltaic/Thermal (CPV/T) solar

2.1.1 Basic concepts

Concentrating photovoltaic (CPV) system operates at higher temperature due to high intensity of solar radiation on smaller area. The idea to collect the heat from

CPV system leads to concentrating hybrid photovoltaic/thermal (CPV/T) system, providing both electricity and heat energy for various applications. To date, multiple researches are undergone in order to develop the most efficient and reliable CPV/T system that can be applied either for domestic or industrial applications. CPV/T differs from conventional flat-plate photovoltaic/thermal system (PV/T) because CPV/T utilizes less area of photovoltaic cells contributing to more economical value and CPV/T also produces much higher temperature output giving wider range of applications for the heat outlet. Conventional flat-plate PV/T module produces thermal output with quite low temperature around 40 ^{o}C for uncovered collectors while for covered collector, the temperature can be achieved up to 60-90 ^{o}C due to lower heat loss to surrounding. One way to increase the thermal output of the PV/T system while improving the photovoltaic efficiency is to combine PV/T technology with an optical concentrator that focuses the sunlight onto a receiver with relatively smaller surface area (Helmers & Kramer, 2013).

2.1.2 Advantages and disadvantages

Installing concentrators on PV/T system has its own benefits and drawbacks as compared with flat-plate system. For instance, the major problem with photovoltaic cells is the cells efficiency drop with increase in temperature caused by high radiation concentration (Royne & Dey, 2007), (Pathak, Pearce, & Harrison, 2012). While one of the obvious benefits in installing concentrators is smaller amount of photovoltaic cells used which will significantly reduce the cost for the construction per unit area (Whitfield et al., 1999), (Matsushima, Setaka, & Muroyama, 2003). However, additional cost may be implemented on the complex sun tracking system to ensure that the concentrators are receiving maximum sunlight intensity all the time (Segal A., 2004). Aside from that, the thermal system also has its pros and cons with the implementation of sunlight concentrators as explained in **Table 1** (Kalogirou S., 1994).

Table 1 Advantages and disadvantages of installing concentrators on thermal system

Advantages	Disadvantages
▪ The operational fluid can achieve higher temperatures in a concentrator system as compared to a flat-panel system of the same solar energy collecting surface. ▪ With a concentrator system, it is possible to achieve a thermodynamic match between temperature level and task. ▪ The thermal efficiency is greater because of the smaller heat loss area ▪ Reflecting surfaces require less material and are structurally simpler than flat panel system ▪ Due to small area of receiver per unit of collected solar energy, selective surface treatment and vacuum insulation is economically viable.	▪ Concentrator systems collect little diffused radiation depending on the concentration ratio. ▪ Tracking system needs to be designed in order to allow the concentrators to follow the sun. ▪ Solar reflective surfaces may lose their reflectance with time and may require periodic cleaning and refurbishing.

2.2 Development of CPV/T

2.2.1 Concentrator design

After the development of flat-plate PV/T system, many researchers have been investigating with the effect of incorporating concentrators into PV/T system. A recent study by Kribus et al. utilizes a simple on-axis parabolic dish to collect solar irradiance. The concentrating dish was made from a single piece of glass, thermally bent to shape and then back-coated with silver to produce reflective surface. The study focused on experimental analysis of the miniature concentrating photovoltaic/thermal (MCPV) system. In the study, the MCPV system was able to produce both the electrical and thermal energy, which then supplied to a nearby consumer. As compared to conventional flat plate PV/T, the MCPV did not limited to low temperature thermal output (Kribus et al., 2006).

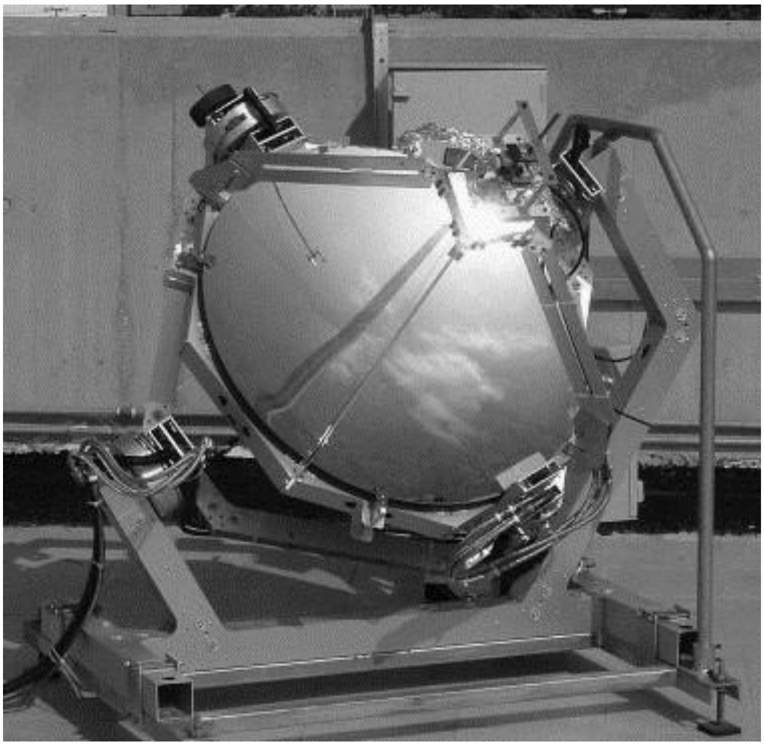


Figure 1 Photograph of the MCPV unit which utilized a simple parabolic dish concentrator (Kribus et al., 2006).

Kerzmann and Schaefer perform a simulation study on linear concentrating photovoltaic system (LCPS) with an active cooling system. In the simulation, linear Fresnel lens are used to concentrates the solar radiation onto an array of high efficiency, triple-junction GaInP/GaAs/Ge solar cells. The conceptual design of this system can be seen at Fig 3.1.2 where the solar radiation is focused onto the multi junction cells and heat produced are removed by using an active cooling system. The output heat is then collected into a storage tank before sent for domestic usage such as bathing water and warming houses. The LCPV is mounted on a two axis tracking system, capable of tracking the sun within one degree on both axes, that moves via an electric motor and is stabilized by a concrete base (Kerzmann T., 2012).

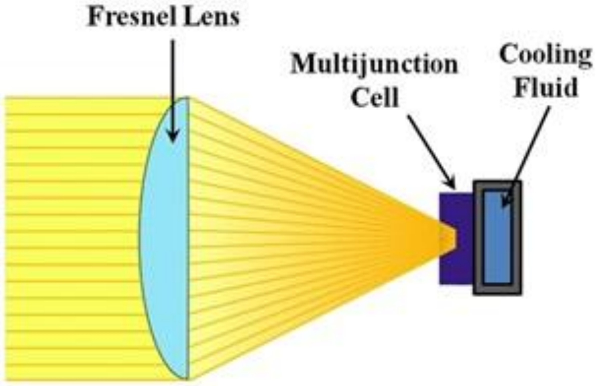


Figure 2 Conceptual design of LCPS (Kerzmann T., 2012).

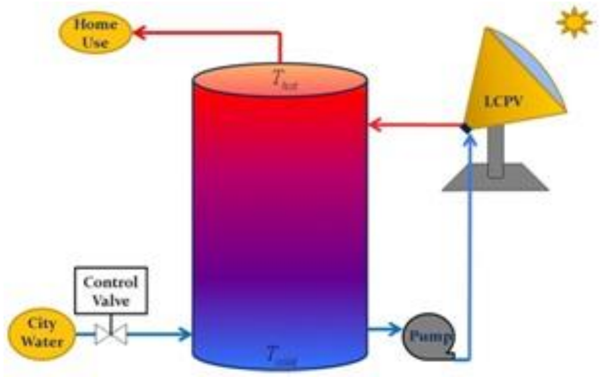


Figure 3 Flow diagram of the whole system (Kerzmann T., 2012).

Chemisana, Ibáňez and Rosell present in their study the characterization of a photovoltaic/thermal module for Fresnel linear concentrator. However, the Fresnel concentrator used in this study is different from what used in Kerzmann and Scaefer. For this experiment, instead of mounting the solar collector mechanism on top of a sun tracking system, Chemisana and his friends design a stationary, wide angle optical concentrator which, whatever the location of the Sun, the input radiation is transmitted into a small moving focal area containing the PV/T module. Fig 3.1.3 explains the conceptual design of the system (Chemisana D., 2011).

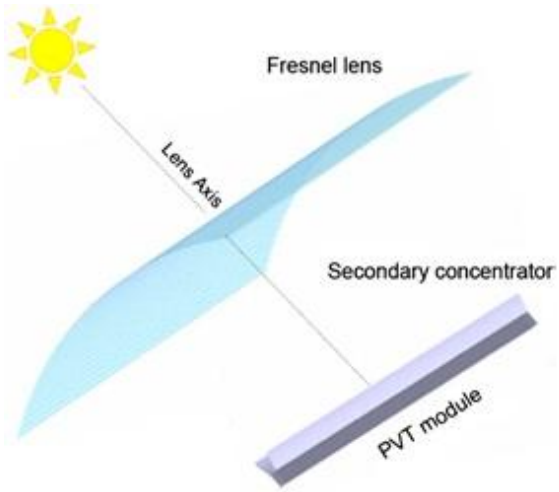


Figure 4 Schematic draw of the wide angle optical concentrator elements (Chemisana D., 2011).

Li et al. conduct a performance analysis of the Through Concentrating Solar Photovoltaic/ Thermal (TCPV/T) system a different types of solar cells. In their experiment, they used two parabolic through modules; one is 2 meter square and the other is 10 meter square. For the 2 meter square module, the geometric concentration ratio achieved is 16.92 with its 1.44 x 1.45 m^2 reflecting mirror. The solar energy collected is converted into electricity via photovoltaic cells while the heat generated is absorbed for thermal energy. The concentrator is required to track the sun in order to get maximum sunlight, thus a simple push rod single-axis tracking mode is applied in the instrument (L. G. L. Li M., Ji X., Yin F., Xu L., 2011).

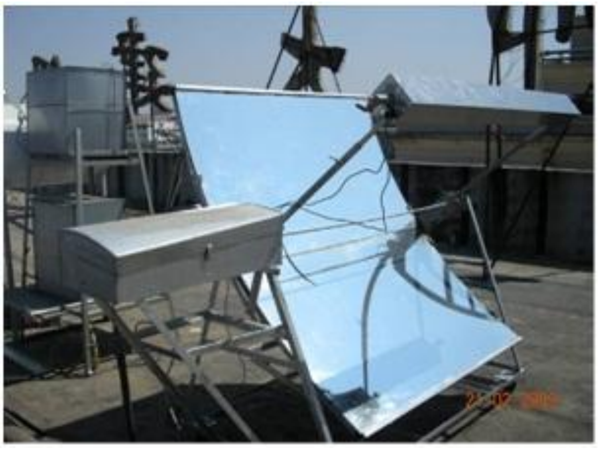


Figure 5 The 2 m^2 TCPV/T system (Li M., 2011).

2.2.2 Efficiency of different PV cells

Over the decades, various types of photovoltaic cells are invented with varying properties and value each with its own advantages and disadvantages. Li et al. investigate in their research the efficiency of using different types of solar cells including; single-crystalline silicon cell, polycrystalline silicon cell, Super cell and GaAs cell on a parabolic through concentrating photovoltaic/thermal (TCPV/T) system.

Figure 6 Four types of solar cell arrays, left top: single-crystalline silicon cell; right top: polycrystalline silicon cell; left bottom: Super cell; and right bottom: GaAs cell (L. G. L. Li M., Ji X., Yin F., Xu L., 2011).

All of the four cells are tested in the TCPV/T system under different sun concentration ratios in order to discover the optimum ratio that produces highest efficiency. The I-V curves for different cells are obtained and compared as below:

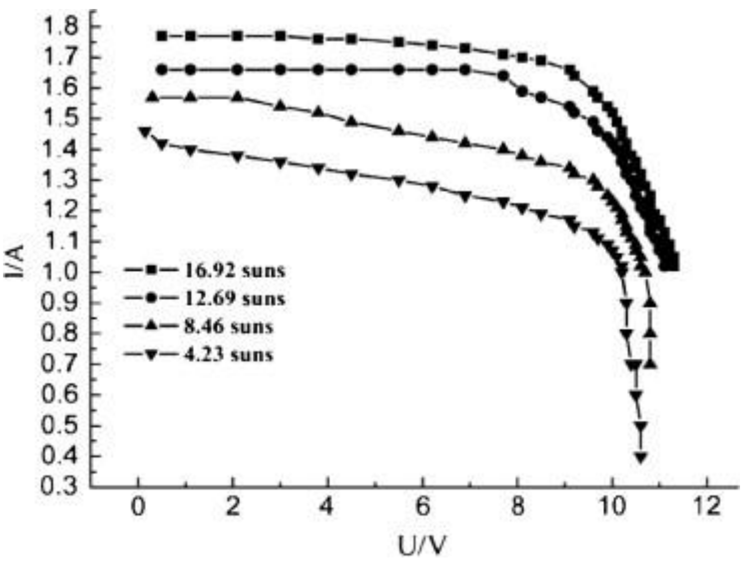


Figure 7 The I-V characteristic of GaAs cells (L. G. L. Li M., Ji X., Yin F., Xu L., 2011).

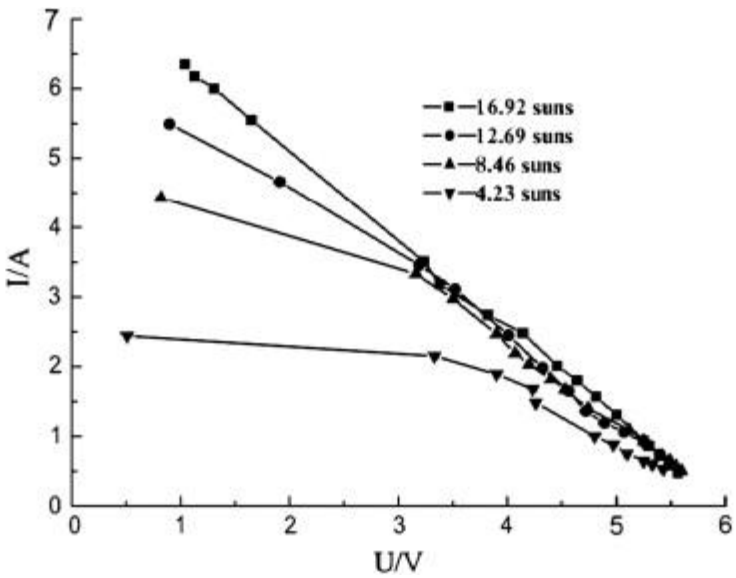


Figure 8 The I-V characteristic of single-crystalline silicon cells (L. G. L. Li M., Ji X., Yin F., Xu L., 2011).

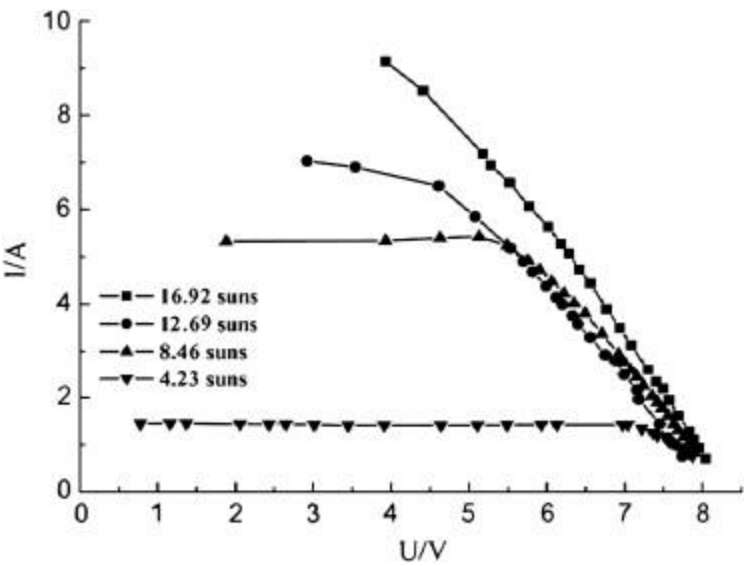


Figure 9 The I-V characteristic of Super cells (L. G. L. Li M., Ji X., Yin F., Xu L., 2011).

Fig 3.22 shows that the I-V curves for GaAs cells for different sun ratios are nearly unchangeable with the increase of radiance intensity. The current and power are increasing as the radiance concentration increases. As shown in Fig 3.2.3, for single-crystalline silicon cells, the optimum concentration ratio is 4.32 where the output performance is highest and efficiency reaches 5.67%. For the Super cells, Fig 3.24 indicates that the preferred concentration ratio is 8.46 as output performance is optimum and maximum efficiency of the Super cells reaches 8.66%.

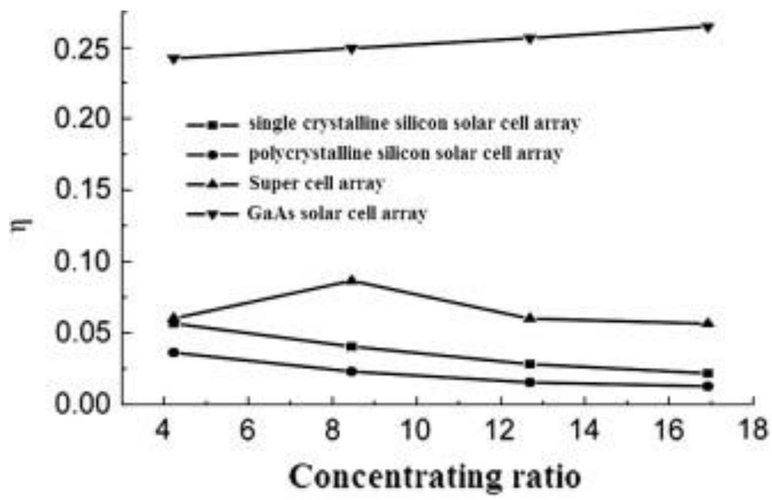


Figure 10 Efficiency, ŋ of solar cells in different concentration ratios (L. G. L. Li M., Ji X., Yin F., Xu L., 2011).

Fig 3.25 illustrates the relationship between concentration ratios and cells efficiency in generating electricity. Of all four cells, only GaAs cells that increase in efficiency with increasing concentration ratios. The efficiency of Super cells rises up until 8 suns concentration ratio and drop from that point further. As for single-crystalline and polycrystalline silicon cells, the efficiency to generates electricity just drop as the sun concentration ratios increases (J. X. Li M., Li G., Wei S., Li Y., Shi F., 2011).

2.3 Literature Analysis

Concentrating Photovoltaic/Thermal (CPV/T) solar power is the future of renewable energy source. Over the past decades, researchers had been experimenting with various designs and technologies of CPV/T system to maximize energy recovery and efficiency as well as minimize cost. The design of concentrator is crucial to the performance of the whole system. Among many concentrator designs such as parabolic dish, parabolic through and Fresnel lens, parabolic through is one of the most common design used due to its high thermal capability. A novel CPV/T prototype by Bernardo utilizes the parabolic through solar reflectors concentrating on a triangular shaped receiver in the middle coated by photovoltaic cells on both of its downward facing surfaces. In this research, Bernardo used monocrystalline silicon cells to convert the solar radiation to electricity. In the research, Bernardo concluded that a CPV/T system cannot maximize both of its electrical and thermal output. Due to the fact that common silicon cells cannot produce high electrical output in high temperature conditions, the thermal system was forced to operate at low temperature thus producing low quality thermal energy. As tested by Li et al., monocrystalline silicon cell and its cousin polycrystalline silicon cell are not suitable to be used under concentrating conditions. This is due to the drop of electrical efficiency of common solar cells under high temperature. In their research, Li et al. discovered that triple junction cells such as triple junction Gallium Arsenide cells perform excellently under high radiation intensity. Triple junction cells are fairly new and mostly used for extraterrestrial purposes due to its extreme durability and high energy output per unit area of cells. Another research conducted by Calise and Vanoli tested the novel CPV/T model by Bernardo with slight modifications to improve the performance of the prototype. In their simulation, Calise and Vanoli applied triple junction GaAs cells onto the triangular receiver. They tested the simulation model under extreme temperatures to analyze its performance. As a result, they concluded that CPV/T system works best with advanced solar cells as it can produce both high electrical and thermal energy output. However, because triple junction cells are still very recent, they are fairly expensive and hard to obtain.

For this project, the simulation model by Calise and Vanoli will be tested with experimental data and analysis. The advanced CPV/T prototype will also be tested under varying weather conditions of equator climate in Malaysia.

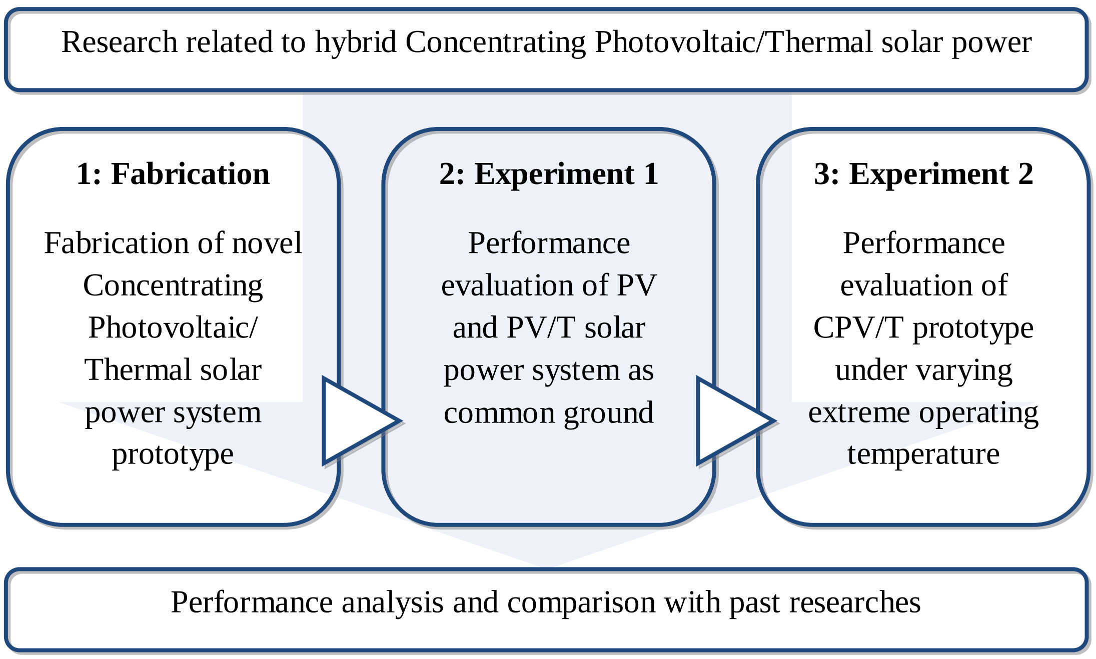
CHAPTER 3

METHODOLOGY

In this section, details regarding the project process flow which includes the fabrication process and related procedures in conducting the experiment are explained. Aside from that, also provided here are the key milestones that need to be met in carrying this project as well as the Gantt chart.

3.1 Research Methodology

The aim of this research is to study on the hybrid photovoltaic and thermal solar power system while focusing on the effect of implementing concentrator. In order to study on the case first hand, first a working prototype of the equipment needs to be fabricated. Once the prototype is ready, experiments will be conducted on the equipment to evaluate its performance and if required, modifications are done in order to further improve output. Basically, the project is divided into two sections; equipment fabrication and experimentation. Given below is the summary of process flow for this project. The flow includes works involved in FYP 1 and FYP 2.



3.2 Prototype Fabrication

The fabrication process begins with research on the literatures for designs and materials needed to fabricate an experimental prototype of a novel Concentrating Photovoltaic/Thermal solar power system. The equipment is separated into two major parts, the thermal system which consists of the reflector and liquid cooling system as well as the electrical system that mainly made up of the photovoltaic cell arrays. Another crucial part of the experimental set up is the data recording. For this experiment, the data will be collected through the whole time via a digital data acquisition system that automatically stores the data inside the designated computer.

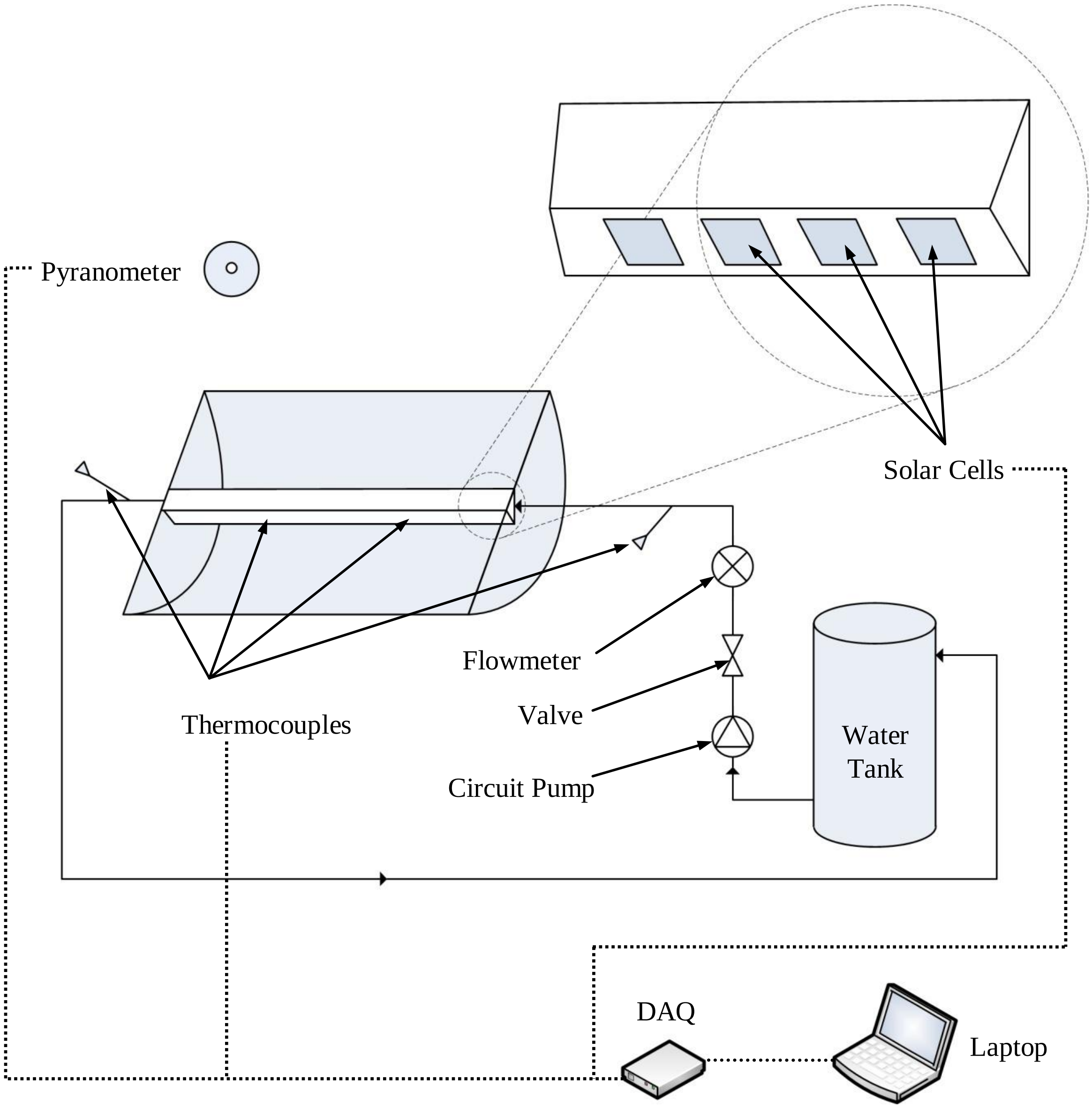


Figure 11 Set-up of equipment for the research experiment

3.3 Experimental Procedures

The experiment to be conducted focused mostly on evaluating the performance of the novel concentrating PV/T prototype. In order to put the advance gallium arsenide cells to the maximum capacity, the prototype will be tested under extreme condition of high operating temperature. The CPV/T model will also undergo performance evaluation in varying weather conditions in equator climate to see whether CPV/T system can be applied in tropical country such as Malaysia. The detailed experimental procedures are as follows.

3.3.1 **Experiment:** Performance Evaluation of CPV/T Prototype under Varying Operating Temperature

For this experiment, the CPV/T prototype will undergo performance evaluation in form of electrical and thermal efficiency under varying operating temperature especially extreme high temperatures. The procedures are as follows:

1. The data acquisition system is turned on and signals from solar cells, thermocouples as well as pyranometer are recorded.
2. Before the reflector panel is directed to sunlight, the water circuit in the thermal system is ensured running. This is to prevent sudden temperature rise which can cause damage to the solar cells.
3. The water flow rate in the circuit is set to maximum.
4. The reflector panel is exposed to sunlight section by section and surface temperatures of the solar cells are observed.
5. Once steady state is achieved, the water flow rate is regulated to produce cells surface temperature of 30^{o}C.
6. The water inlet (T_i) and outlet (T_o) temperature, solar cells Voltage (V) and sun solar radiation (P_{sun}) is kept on recorded every 5 minutes for 9 hours a day begin from 9.00 am until 6.00 pm tabulated as shown in **Table 2**.
7. The data T_i and T_o is then analyzed to calculate the thermal energy obtained from the prototype.
8. Voltage and Current is analyzed to calculate electrical power produced from the solar cells.

9. By using the solar radiation data as reference, the electrical and thermal efficiency is calculated for the designated cells surface temperature.
10. The procedures are repeated for different cells surface temperatures (40, 50, 60, 70, 80 and 90°C) to measure the thermal and electrical efficiency at each operating temperature.

Table 2 Data recording for Experiment 1

Time		Voltage (V)	PV Surface Temp (°C)	Solar Radiation (W/m^2)	Water Inlet Temp (°C)	Water Outlet Temp (°C)	Water Flowrate (m^3/s)
Day 1	1						
	2						
	3						
	…						
	n						
Day 2							
…							
Day n							

3.4 Data Analysis

From the data collected in each of the experiment, analysis will be done in order to find the electrical and thermal efficiency. Thermal efficiency is calculated by using water inlet (T_i) and outlet (T_o) temperature while electrical efficiency is calculated via the voltage (V) and current (I) from the solar cells.

To calculate thermal efficiency, first heat energy that collected by the prototype is first calculated as follows:

$$P_{th} = \rho_w \dot{m} C_p \frac{(T_o - T_i)}{A_{ap}}$$

Where:

ρ_w = density water (kg/m^3)

C_p = specific heat capacity (J/kg·K)

A_{ap} = area of aperture (m^2)

Then, thermal efficiency is calculated by using the following:

$$\eta_{th} = \frac{P_{th}}{x\, A_{ap}\, P_{sun}}$$

Where:

x = concentration ratio

A_{ap} = area of aperture

For the electrical efficiency, first the electrical power produced by the solar cells needs to be calculated by using voltage and current. Current is calculated as follows:

$$I = \frac{V}{R}$$

Where R is the resistance applied onto the voltage. Power is calculated:

$$P_{et} = VI$$

By using the power, electrical efficiency can be calculated:

$$\eta_{et} = \frac{P_{et}}{x\, A_{PV}\, P_{sun}}$$

Where:

x = concentration ratio

A_{PV} = cells area

3.5 Key milestones

To ensure that the research project running smoothly, several key milestone need to be placed and obeyed. Since this project involves the fabrication of the equipments and experimental analysis, the schedule is quite tight and time is the essence. The key milestones for the research project are as follows:

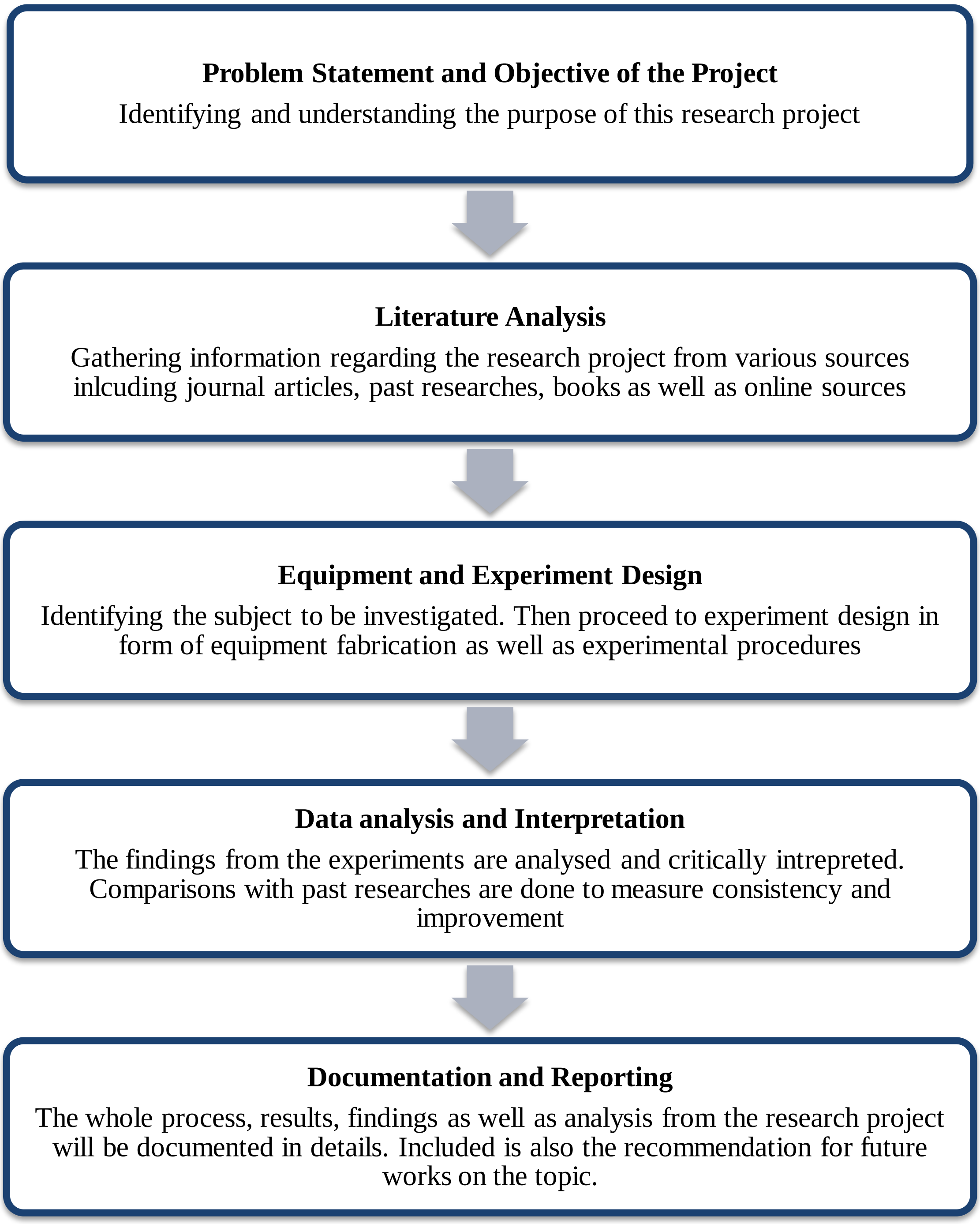


Figure Important milestones during the research project

FYP I Milestones

1. Confirmation of research at Week 2
2. Completion of literature studies at Week 4 or 5
3. Completion and submission of Extended Proposal at Week 6
4. Conformation on the equipment design at Week 6
5. Begin construction of equipment at Week 7
6. Outlining detailed experimental procedures at Week 8
7. Completion of proposal defence presentation at Week 9
8. Finish construction of equipment at Week 13
9. Submission of Interim report at week 14

FYP II Milestones

1. Finalize equipment set-up at Week 2
2. Begin investigation on Experiment 1 at Week 3
3. Begin investigation on Experiment 2 at Week 5
4. Completion of progress report at Week 7
5. Preparation for SEDEX at Week 10
6. Completion of draft report at Week 11
7. Completion of technical paper at Week 12
8. Completion of oral presentation at Week 13
9. Submission of project Dissertation at Week 15

3.6 GANTT CHART

Details\Week	FYP I															FYP II													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14		1	2	3	4	5	6	7	8	9	10	11	12	13	14
Preliminary Stage																													
Project confirmation																													
Review literatures																													
Confirmation of experiment design																													
Submission of Extended Proposal																													
Intermediate Stage																													
Begin fabrication																													
Outlining experimental procedures																													
Proposal defence																													
Submission of Interim Report																													
Finalize equipment set-up															Semester Break														
Experimental works and analysis																													
▪ Varying operating temperatures																													
▪ Different weather condition																													
Completing progress report																													
Submission of progress report																													
Final Stage																													
Result analysis and discussion																													
Submission of Technical Paper																													
Oral Presentation																													
Submission of Project Dissertation																													

3.7 Tools required

For the study, several equipments will need to be obtained. Some of them are as follows:

1. Triple-junction solar cells

Advanced triple-junction Gallium Arsenide cells are to be used in this research.

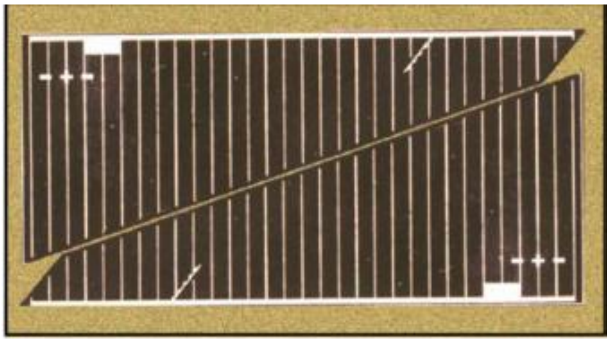


Figure 12 Triple-junction Gallium Arsenide cells.

The cell has a capability to produce 100.0 mW/cm^2 of electrical power in room temperature. Output current and voltage of a single cell are 31 mA and 2.52 V respectively with 27% efficiency. The efficiency reduces as temperature increases with coefficient as low as -6.2 mV/^{o}C. (See details in APPENDIX I).

2. Solar radiation sensor

Figure 13 WE300 Solar radiation sensor.

This sensor is crucial in order to measure the reference radiation of the sun during the data collection by the CPV/T equipment. This sensor has 4-20 mA analog output with operating range from 0 to 1500 W/m^2. The accuracy is very high with tolerance of only ±1% full scale. (See details in APPENDIX I).

3. Parabolic through reflector

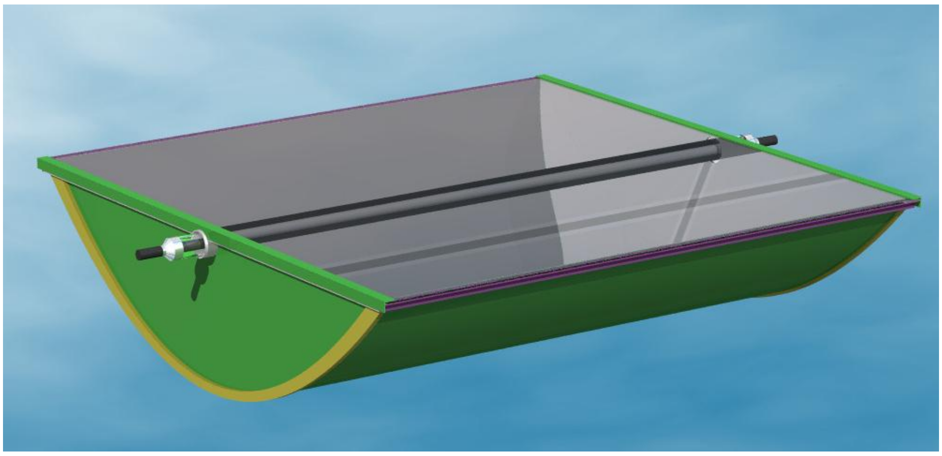


Figure 14 Illustration of a parabolic through reflector.

A single axis parabolic through reflector will needs to be fabricated to collect the solar radiation required.

4. Voltage data acquisition card

Figure 15 USB-1208FS voltage data acquisition card.

This data acquisition cards will allow the recording of real time data from the solar cells as well as from the solar radiation sensor. It has an analog voltage input up to 20 V and more than capable to deliver the task. (See details in APPENDIX I).

5. Temperature data acquisition card

Figure 16 USB-TC thermocouple data acquisition card.

Thermocouple data acquisition card allows the recording of temperatures needed to be analyzed throughout the experiment. This model has 8 analog input and able to accommodate all types of thermocouples. It has its own internal coldpoint and ready to be used. (See details in APPENDIX I).

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Fabrication of equipment

The concentrating photovoltaic/thermal (CPV/T) solar power system was fabricated in based on a novel concentrating PV/T collector simulated by Calise and Vanoli. In the simulation study, a parabolic through concentrator was used to focus the solar radiation onto a unique triangular receiver in the middle. On the receiver housed a series of high performance solar cells known as triple-junction cells which can withstand extreme operating condition and usually used for extra-terrestrial purposes such as on satellites. This unique feature of triple-junction cells making them perfect to be used under high radiation intensity of concentrating PV/T system. The triangular receiver consist of flowing cooling fluid intended to both to maintain the surface temperature of the cells as well as to absorb heat energy to be used. In the simulation, Calise and Vanoli proved that triple-junction solar cells are very suitable to used for a CPV/T system and allowing the system to run a higher temperature as compared to conventional silicon cells which degrades at high operating temperature. Operating at high temperature allows the production high quality heat energy to be used for either domestic or industrial purposes.

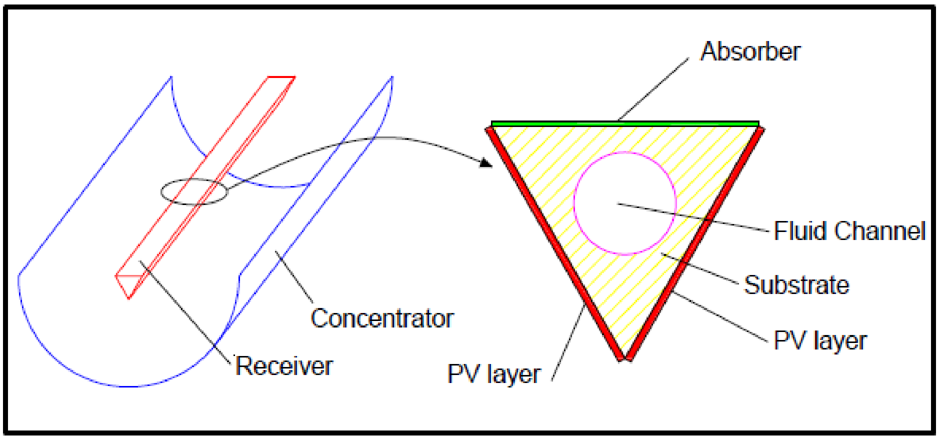


Figure 17 Diagram of simulation model by (Calise & Vanoli, 2012).

4.1.1 Parabolic through concentrator

Similar to the model simulated by Calise and Vanoli as well as many other researches that study on CPV/T system (Jiang, Hu, Mo, & Chen, 2010; J. X. Li M., Li G., Wei S., Li Y., Shi F., 2011; Ong, Escher, Paredes, Khalil, & Michel, 2012; Xu, Zhang, & Deng, 2011), for this study a parabolic through concentrator will be utilized to focus the solar radiation onto the photovoltaic cells and thermal receiver. One of the most crucial factors in a parabolic reflector is the focal point. The focal point of the reflector needs to be identified and the receiver must be precisely placed at the focal point where all of the reflected solar beams fall. The design processes begin with a very raw design which then perfected stage by stage. It began with a simple parabolic through concentrator to be fabricated using only aluminium L bar and aluminium sheet as shown in figure:

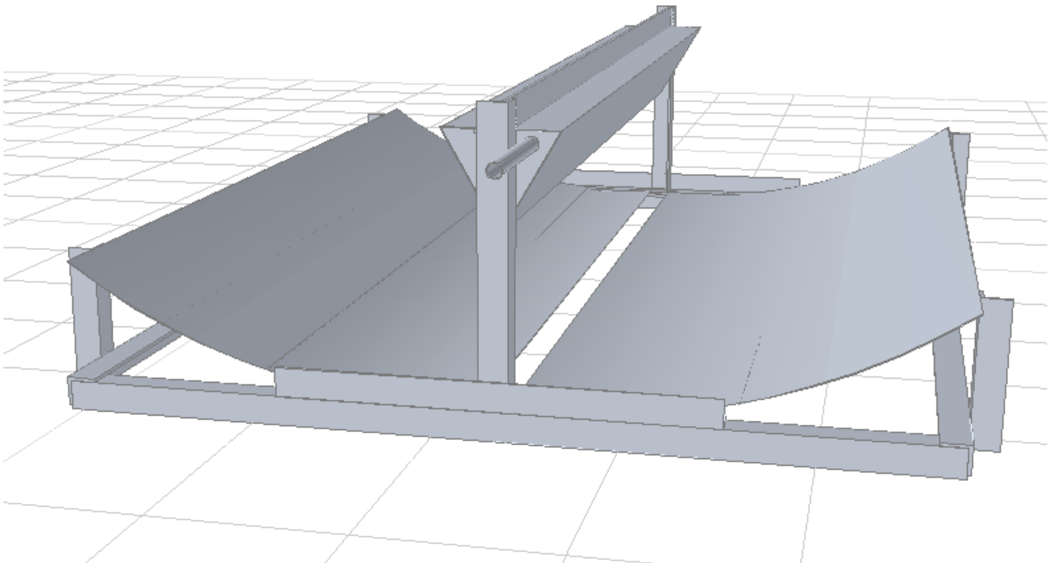


Figure 18 Initial design of the parabolic through reflector.

However, the structure was too complicated and would take unnecessary extra hours to be constructed. Then, a further research had provided with a manual that contained a step-by-step procedure of making a parabolic through concentrator by Gang Xiao from University of Nice, France (Xiao, 2007). By referring to the manual, a new design was produced as shown below:

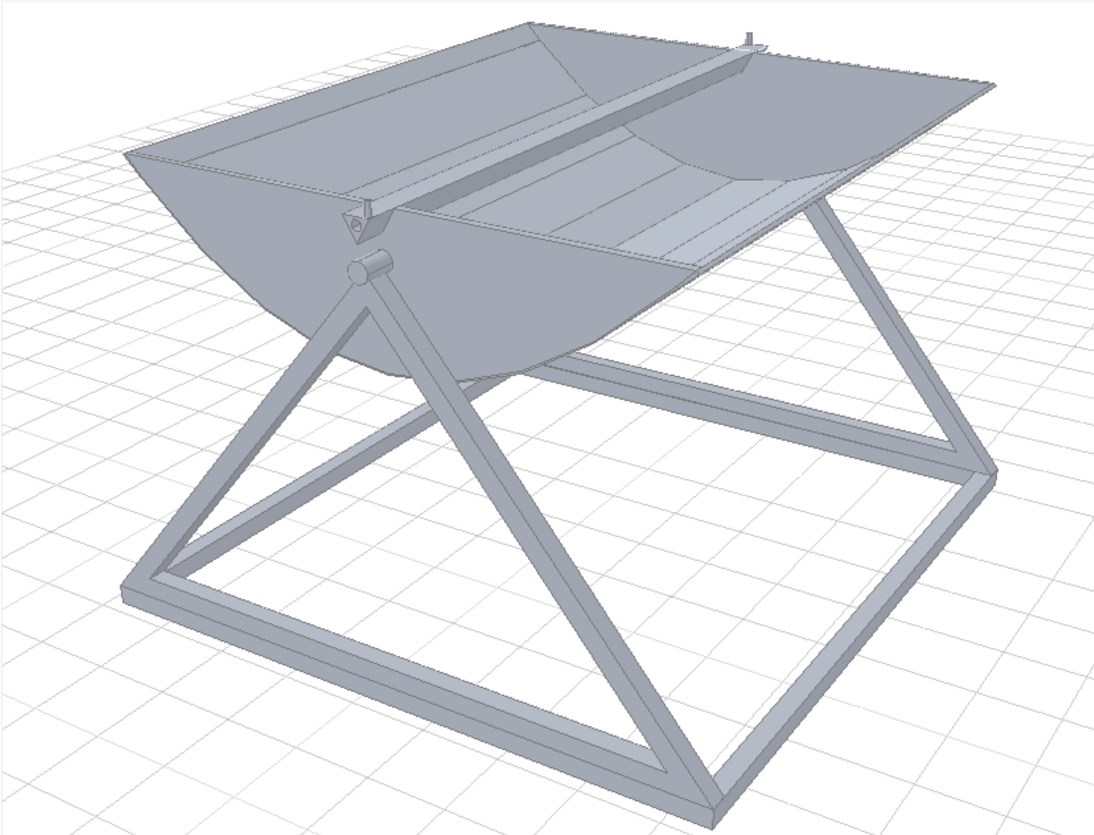


Figure 19 Second design of parabolic through reflector

The new design was easier to build with more flexibility and functions. Unfortunately, the design never had the chance come to life. Just before the fabrication works started, an old but still functioning, abandoned parabolic through concentrator built for a research on thermal concentrating solar power (CSP) system was discovered in the corner of a storeroom. The structure just needed a few repairs and modifications to be converted into a concentrating photovoltaic/thermal (CPV/T) solar power system.

Figure 20 Photograph of the parabolic through concentrator

The reflector was built using 2 by 4 woods to ensure structural integrity with overall dimension of 1.78 meter width and 1.64 meter length. For the reflector, an array of 0.10 by 1.52 meter flat mirrors was arranged on a curved structure to form the parabolic shape. Because the concentrator was very old, several structural repairs were undertaken and wheels were installed for mobility as the structure was very heavy.

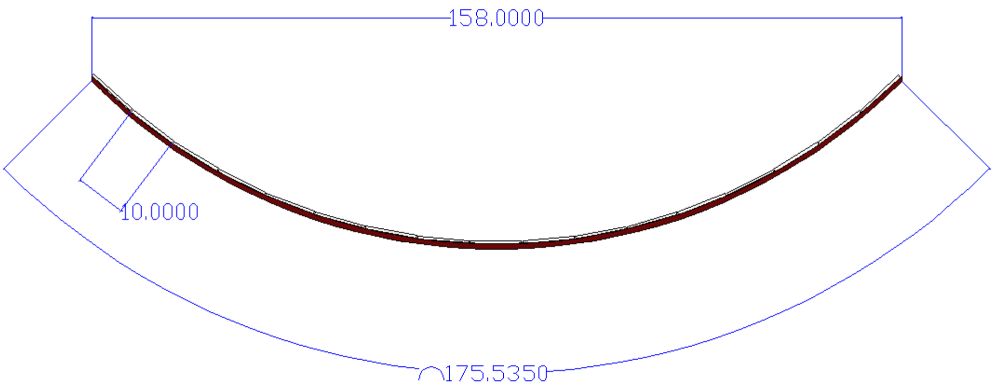


Figure Dimensions of the parabolic through. 17 mirrors were arranged on the curve.

The concentration ratio of the concentrator was calculated as below:

$$concentration\,ratio = \frac{area\ of\ reflected\ sunlight, A_r}{area\ of\ shaded\ sunlight, A_o}$$

$$= \frac{\frac{1}{2}(0.035 \times 1.52)(17)}{0.035 \times 1.52}$$

$$= 8.5\ concentration\,ratio$$

4.1.2 Photovoltaic/thermal receiver

Normally for a thermal concentrating solar power (CSP) system a simple round tube is used as the receiver and sometimes a vacuum tube is utilized to reduce the possibility of heat loss to surrounding. However, in a CPV/T system, in order to equip the thermal receiver with solar cells, a more rigid shape is needed. That is where the idea for a triangular shaped receiver was born. Theoretically, the receiver will be made of conductive metal and the pointy side of the triangle was directed downward into the curvature of the parabolic reflector. Both of the downside surfaces are to be covered with solar cells and the top side is left blank and painted black for efficient heat absorbance.

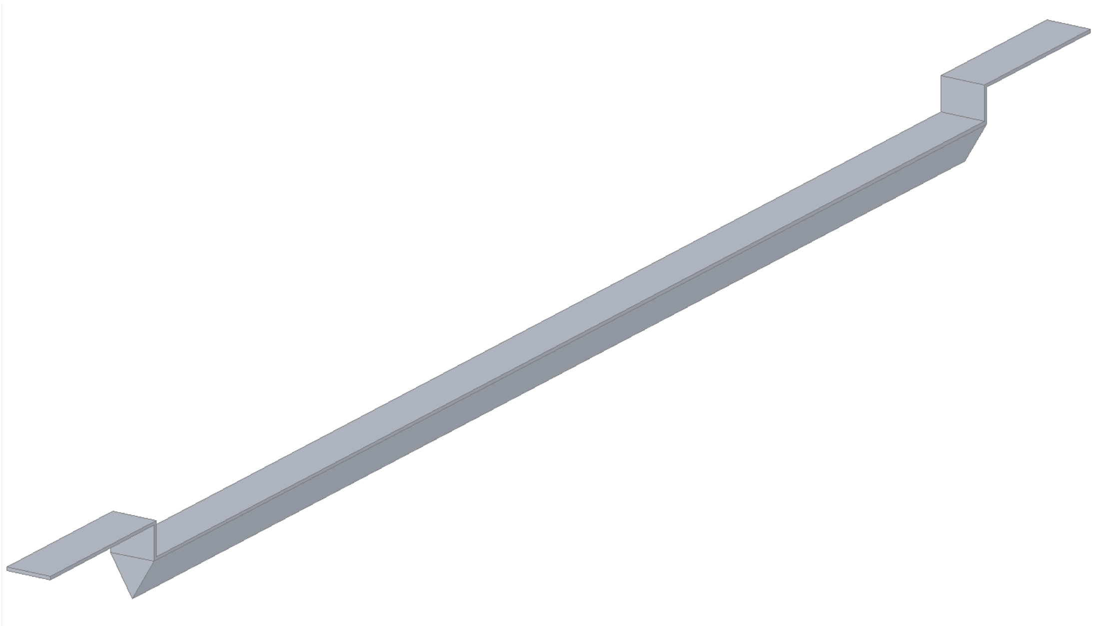


Figure 21 Drawing of the triangular photovoltaic/thermal receiver.

During the fabrication process, a minor adjustment needed to be done to the initial design. Even though aluminium sheet is a very flexible and malleable material, it does have a certain limit to its flexibility. According to the original design, the aluminium sheet needed to be bended to form a 60 degree angle. Unfortunately, the aluminium cannot withstand such reform that it failed and ruptured during the process. Thus, a simple solution was taken where a square-shaped tube was used to replace the triangular design and welded with round pipes at both ends to fit into the parabolic through concentrator structure.

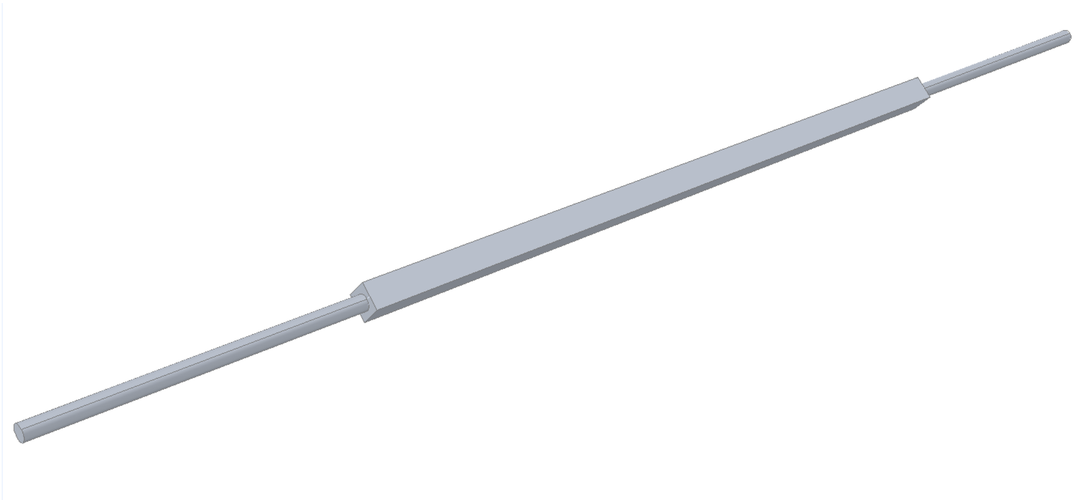


Figure 22 Drawing of the modified receiver.

The whole receiver was painted with matte black to enhance heat absorbance from solar radiation.

Figure 23 Photograph of the painted photovoltaic/thermal receiver.

Originally, triple-junction Gallium Arsenide cells were intended to be used in comparison with conventional silicon cells to test the CPV/T under extreme conditions. However, there had been some slight issue with the availability. Triple-junction cells are very advanced and only a few manufacturers in the world produce them. One of the manufacturers is Spectrolab, Boeing's sub-company that specializes in aerospace technology, which is also the supplier of high performance cells to NASA. Unfortunately, after the deal was done, the supplier had to refuse the transaction because the items were regulated by U.S Department of Commerce and export to Malaysia was restricted. The research was left with no choice but to proceed with conventional silicon cells that can be easily obtained. The result will then be compared with Bernardo's study and analyzed. The mono-crystalline silicon solar cells were mounted onto both of the downward facing surfaces by using silicon thermal compound to maximize heat transfer from the solar cells to the cooling fluid flowing inside the receiver. Electrical wiring was protected from the weather by sealing any exposed wiring with silicon glue.

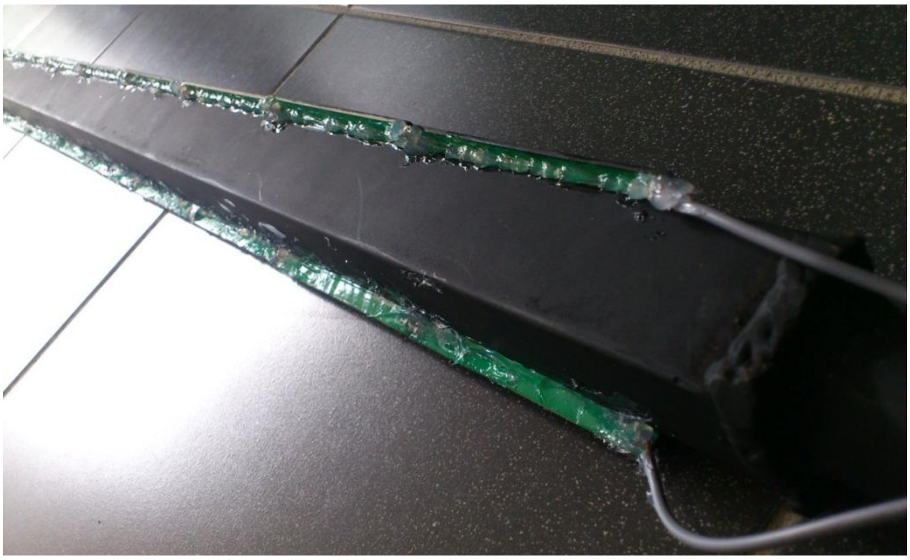


Figure 24 Solar cells were mounted and electrical wiring sealed with silicon glue.

4.1.3 Piping and pumping system

Water is used as the cooling fluid to maintain surface temperature of the solar cells as well as to extract heat in the system. The reservoir was able to contain up to 15 litres of water and the water was circulated inside the system by using a submerged water pump. Reinforced rubber tubing used to connect the water reservoir, flowmeter and the thermal receiver as normal rubber tubing unable to withstand high temperature fluid for a prolonged period.

Figure 25 Close-up at the reinforced rubber tube. At the exit of the receiver, the tube was intentionally pointed upward to ensure that water fills up the receiver cavity.

4.1.4 Test run and finding optimum resistance

The partially finish equipment was brought under the sun for test run. The water pumping system was tested and instantly, problem surfaced. The submerged water pump failed to pump the water from the reservoir into the receiver due to insufficient power. The water pump was then replaced with a powerful pump capable to displace up to 2000 litres of water per hour under the range of 2 meter height and the problem was solved. The piping connections and receiver was observed closely to monitor for any leakage. The leakages found were fixed by using silicon compound.

In order to obtain maximum power from the solar cells, an optimum resistance needed to be determined. In order to do so, several power resistors ranging from 2 ohm up to 100 000 ohm were used. It was crucial to used power resistor as solar cells tend to produce high power, thus if using normal resistor for a prolonged period, the resistor might get overheat and fried ("Measuring The Power Of A Solar Panel," 2007).

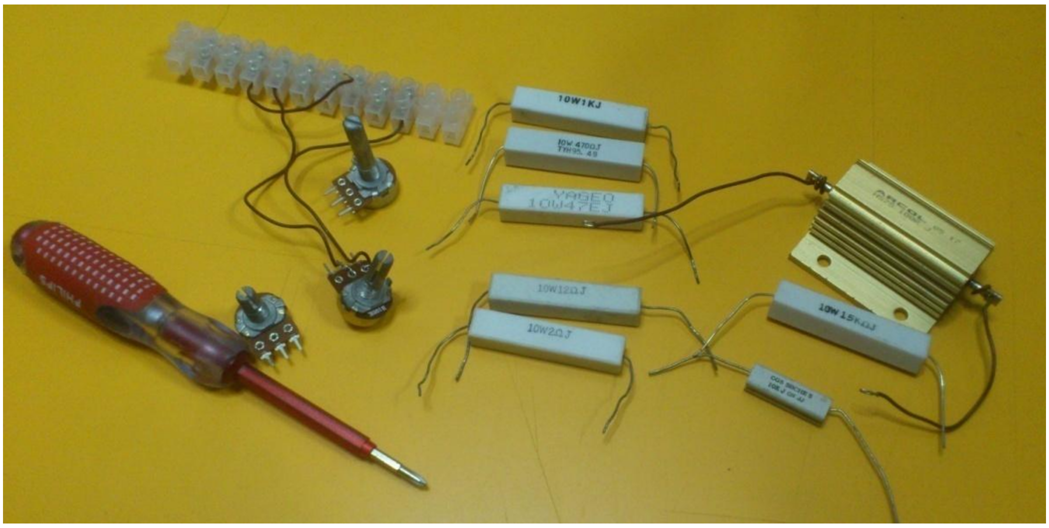


Figure 26 Various fixed and variable power resistors used to find the optimum resistance.

The solar cells were connected in series and a resistor was installed to the circuit. Voltage was measured by using multimeter for different values of resistance as shown on the figure below. From the voltage, current can be calculated and thus power. Below is the measured voltages from resistance valued from 2 ohm up to 100000 ohm plotted in an I-V curve.

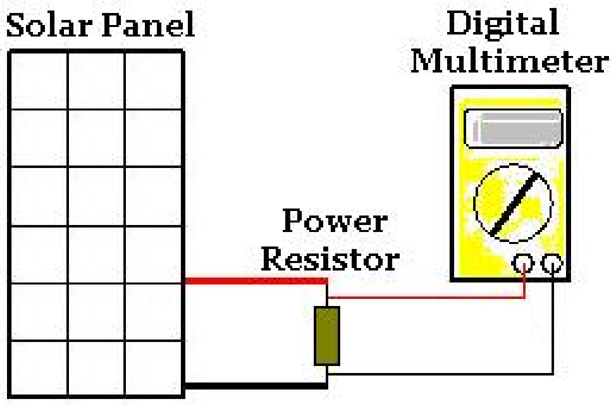


Figure 27 Diagram of circuit to measure the power of solar cells ("Measuring The Power Of A Solar Panel," 2007).

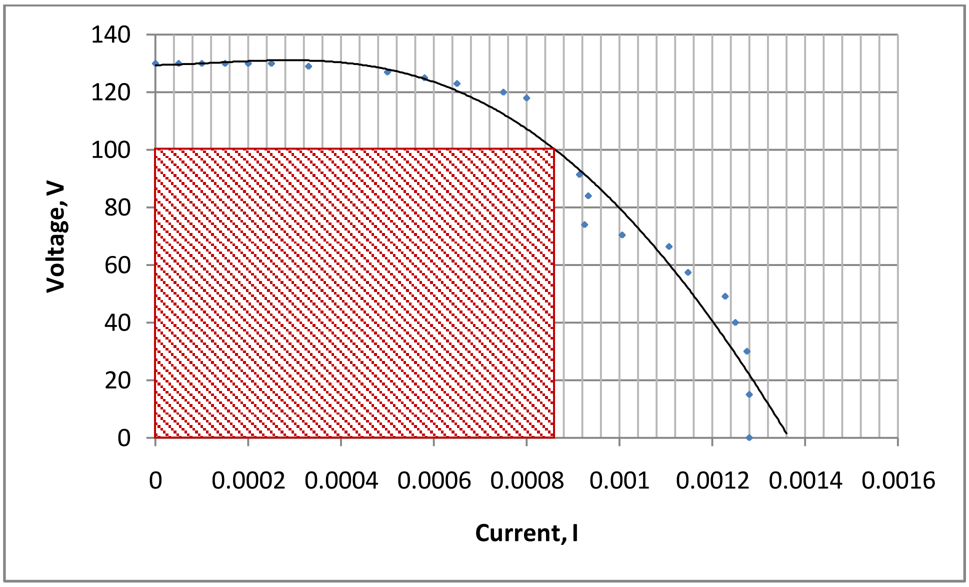


Figure 28 I-V curve of the solar cells.

From the plot, in order to find the optimum resistance to produce maximum power, a point between voltage and current where maximum power produced was chosen. To do that, a rectangle was drawn under the graph and the point where maximum rectangle area produced was selected. As shown in the plot above, the optimum power is at voltage 100 volt and current 0.00088 amps.

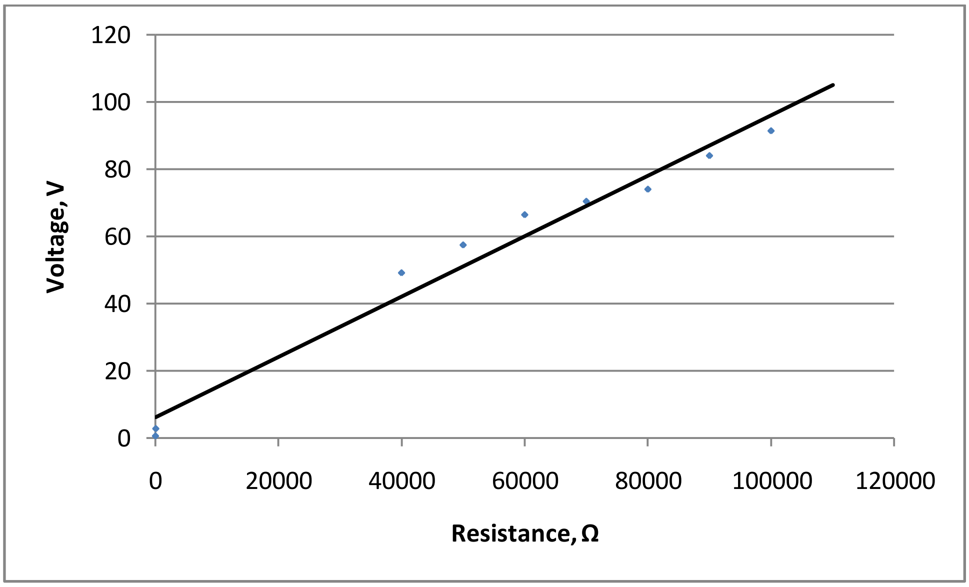


Figure 29 Voltage vs. resistance of the solar cells.

By inserting the voltage value of 100 Volts into the voltage vs. resistance plot above, we got the resistance value of 105 000 ohms. This is the optimum resistance to be used in the system for the entire experiment.

4.1.5 Modification: Installation of cooling tower

Through out the test run under the sun, multiple times efficiency of the solar cells degrades due to high surface temperature. The cells overheated because the cooling fluid failed to absorb the heat from the solar cells surface. After an hour of troubleshooting, it was discovered that the heat inside the circulating water and the reservoir was not dissipated to surrounding as fast as expected. A quick check with thermometer showed that the water inside the reservoir that was fed into the receiver was maintained at more than 40 degree Celsius. Low temperature gradient between the cooling fluid and the cells surface had caused the heat transfer to be slow and inefficient. A simple solution was to install a cooling tower to cool down the outlet water from the receiver before it entered the reservoir.

By studying on the design of cooling tower provided by industry, a simple miniature cooling tower was proposed. The cooling tower consist of three parts; packing material to encourage contact between water an air, sprinkler to disperse the hot water uniformly over the packing material and a fan to drive cool air through the hot water. The cooling tower utilized a counter current concept between the hot water and cool air.

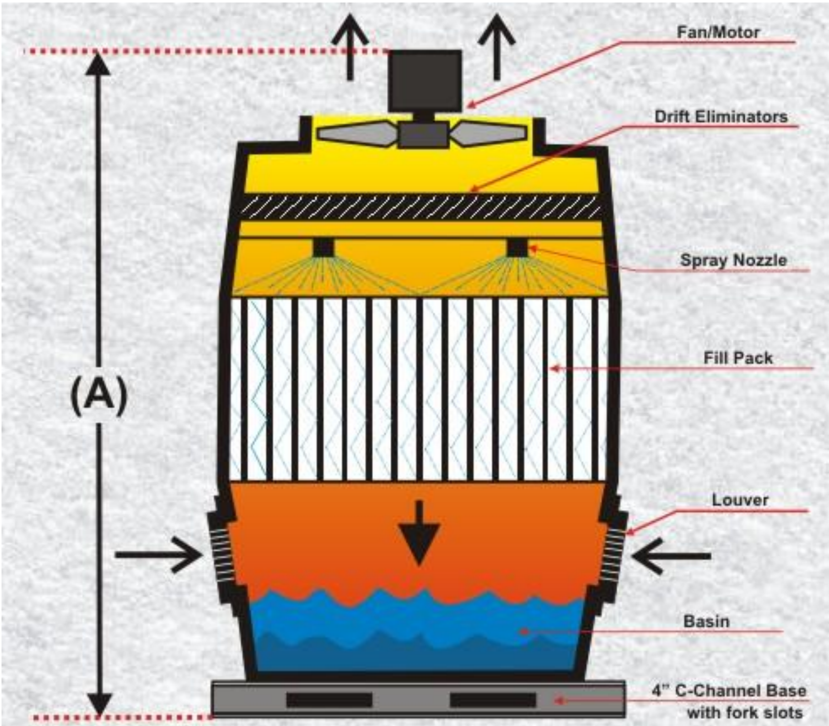


Figure 30 Cross section design of a industrial standard cooling tower.

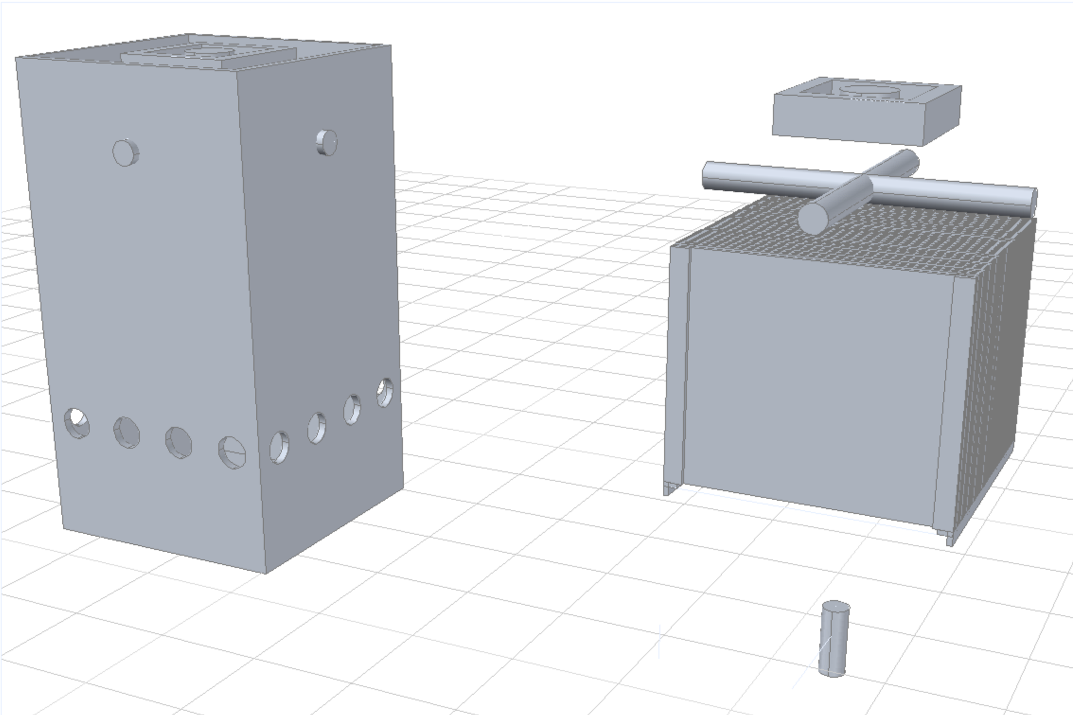


Figure 31 Designed simple cooling tower for the CPV/T system.

The body of the cooling water was constructed by using plastic sheet and for the packing material; plywood was cut into small rectangular shapes and stacked in cross manner. Gap is left between the plywoods to allow for water to flow down and air to flow upward.

Figure 32 Stack of plywoods as packing material.

Figure 33 Left: The completed cooling tower placed on top of the water reservoir; Right: Cooling tower in action.

Test run of the cooling tower under shade (not exposed to sunlight) showed that the cooling tower was very efficient in lowering the water temperature down to 26 degree Celsius at outdoor environment. By including cooling tower into the CPV/T system, overheating of solar cells could be avoided.

4.1.6 Data acquisition for voltage and thermocouples

To analyse performance of the system, data such as voltage, temperatures and solar radiation level needed to be measured. As for voltage produced from the solar cells, a data acquisition card specialized to measure voltage was used. The data acquisition card received the analog output from the solar cells and converted it into digital signal to be read and recorded by laptop. For this study, USB-1208FS-Plus voltage data acquisition card will be utilized. However, the analog voltage input to the card was ranges only between -20 Volts up to 20 Volts DC while the solar cells were capable to produce up to maximum 140 Volts DC. To solve this problem, a simple circuit known as voltage divider was installed into the system. A simple two resistors divider can be used for this problem. The circuit works by dividing the voltage into two outputs by using two different resistors. To control the scale of voltage on each output, the resistance values of both of the resistors are manipulated (Wyss, 2007).

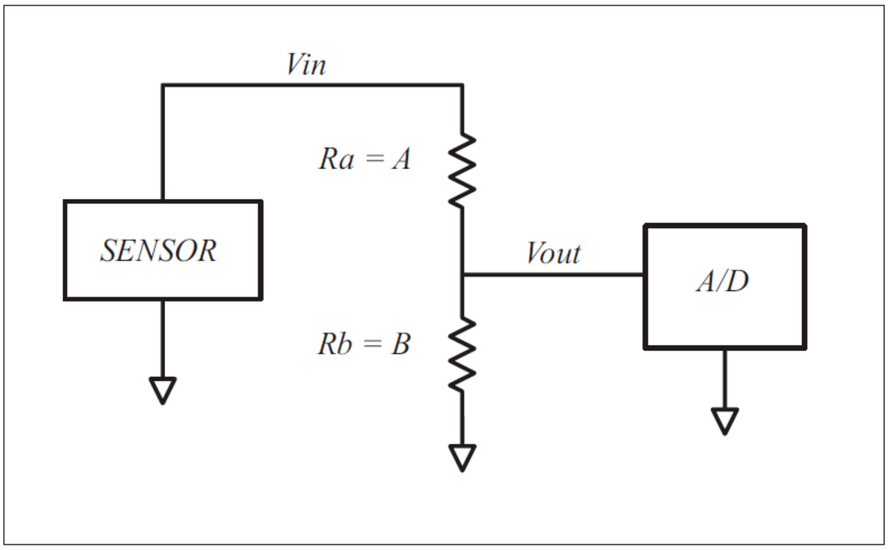


Figure 34 Basic two resistors scaling divider.

By using Kirchoff's and Ohm's laws, and assuming that there is no loading on V_{out}, the output voltage of this circuit is:

$$V_{out} = \left(\frac{R_b}{R_a - R_b}\right) \cdot V_{in}$$

The voltage divided through resistor R_b will then dissipate to earth while the value of V_{out} will be a scaled value of V_{in}.

For this case, the maximum value of V_{in} can be up to 110 Volts, but to be safe value of 140 Volts will be selected. To reduce V_{out} to 20 Volts, the calculation is as follows:

$$Lets\ insert\ the\ value\ of\ R_a\ and\ R_b\ as, \qquad R_a = 100k\ ohm,\ \ R_b = 1k\ ohm$$

$$V_{out} = \left(\frac{10k}{100k - 10k}\right) \cdot 140$$

$$V_{out} = 15.56$$

$$\frac{V_{in}}{V_{out}} = \frac{140}{15.56} = \frac{9}{1}$$

The value of output voltage is lower than the data acquisition card input range, so the resistance values are acceptable. According to the calculation, the ratio V_{in}:V_{out} is 9:1. But after testing the circuit with multimeter, it was observed that the actual V_{in}:V_{out} ratio is 11:1. So for the data recording, the actual ratio will be used.

With the values of resistance required were obtained, the circuit divider was assembled and installed to the solar cells output before entering the data acquisition card. Correction value was then inserted to the output of the data acquisition card in the laptop.

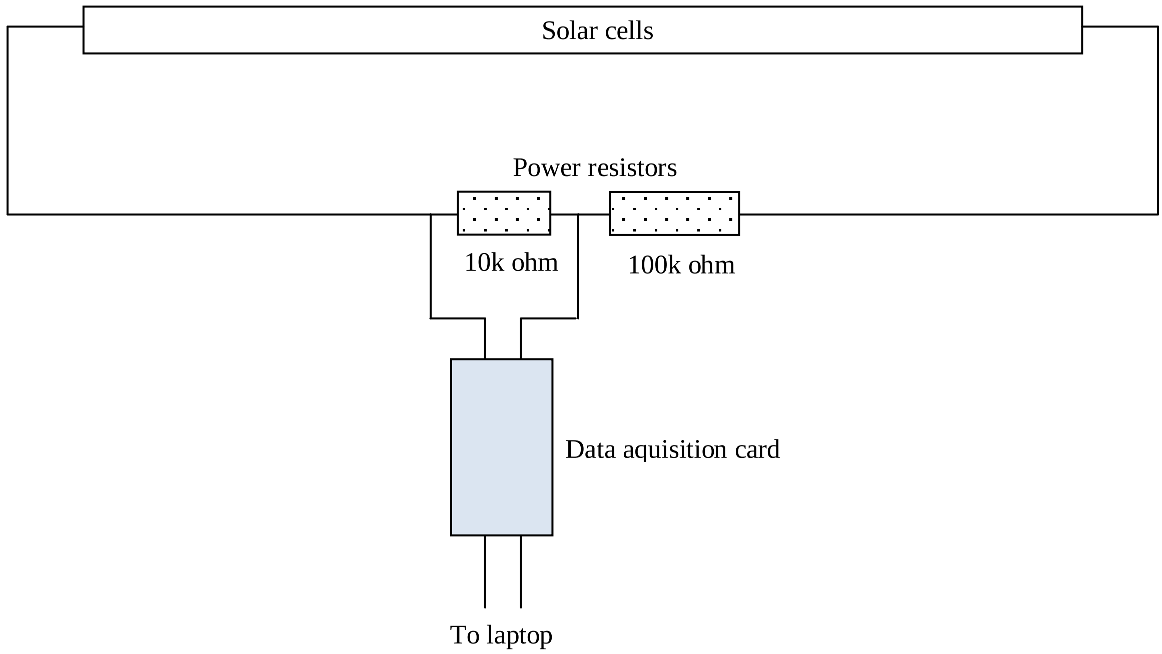


Figure Layout of the whole electrical circuit.

For thermocouples, the analog signal will be transmitted to another data acquisition card that specialized for thermocouple. Temperatures from inlet and outlet of the photovoltaic/thermal receiver, solar cells surface as well as temperature of the water reservoir were recorded in order to analyse the performance of this CPV/T solar system. Common K-type thermocouples were used for this study.

Figure 35 Thermocouple attached to inlet/outlet of the receiver by using silicon thermal compound and silicon glue.

4.2 Performance analysis of CPV/T solar power system

After fabrication of equipment (see APPENDIX II for photograph), the study moved on to experimentation stage. In this stage, theoretically the CPV/T system will be tested to run under various operating conditions focused mostly on operating temperature. The performance of the system in term of electrical and thermal will be recorded and analysed. Aside from that, another experiment will also be conducted simultaneously where the performance are observed with correlation to a variety of weather conditions in equator climate. This is to investigate the suitability of implementing concentrating photovoltaic/thermal solar power system in countries along the equator like Malaysia.

Recall back the basics, this study was aimed to investigate a new and innovative solar power system that incorporates both photovoltaic and thermal solar into a single system. Initially, the concept to integrate solar thermal into photovoltaic system was to provide a heat removal mechanism due to the tendency of photovoltaic cells to degrade in performance under high temperature. The concept of hybrid photovoltaic/thermal (PV/T) solar power system was born. Even though PV/T system was reliable in removing heat from PV cells, the quality of thermal energy produced was quite low. In order to produce both high quality electrical and thermal energy, the notion of concentrating photovoltaic/thermal (CPV/T) solar power system was introduced. In this study, the performance of all PV, PV/T as well as CPV/T systems were investigated and analysed.

4.2.1 PV and PV/T system

Performance analysis of PV and PV/T system were conducted in order to provide a common ground as reference for the CPV/T study. To test on the performance of PV system, all of the features such as concentrator, coolant circulation, and cooling tower were disabled except only for voltage and surface temperature monitoring. As for PV/T system, the coolant system is set to maximum to remove as much heat as possible from the solar cells to provide maximum output. The results were as followed:

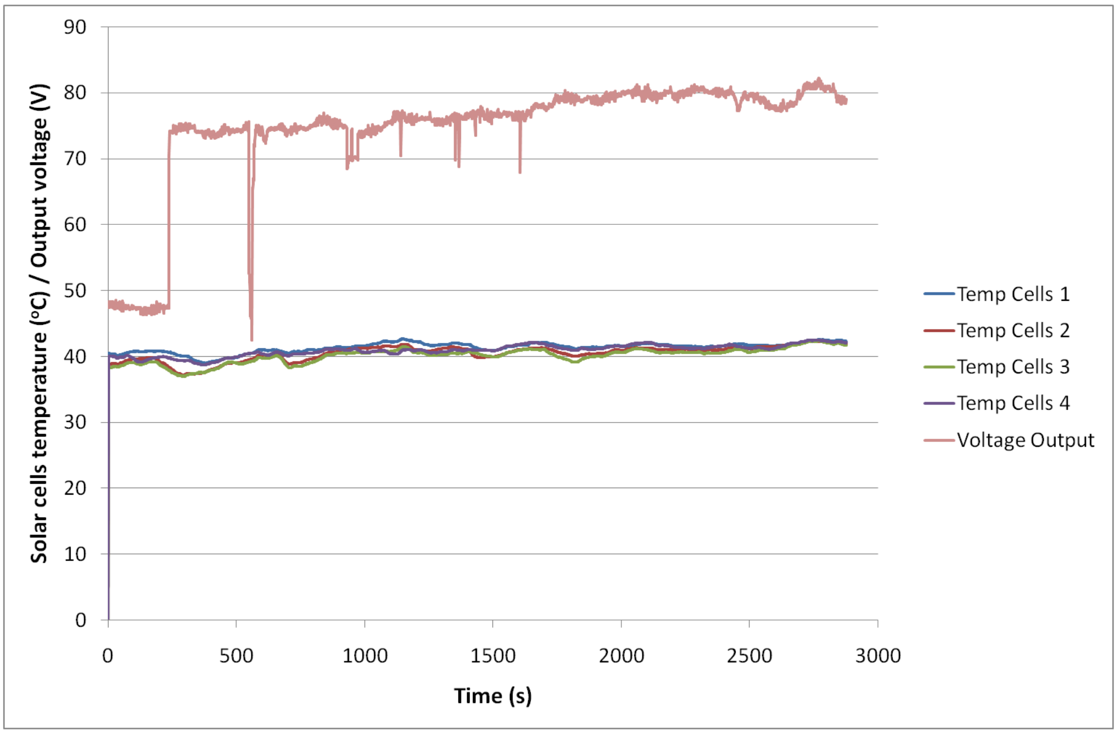


Figure 36 Voltage output for PV system with corresponding to cells temperature

Table 3 Data recording and analysis for PV system

Time (s)	Temp cells (°C)				Scaled Voltage (V)	Actual Voltage (V)	Current (A)	Power (W)
	Ch0	Ch1	Ch2	Ch3				
1	40.4327	38.7112	38.2313	40.0436	4.2637	47.374444	0.000429	0.020308
2	40.4483	38.7223	38.2469	40.0473	4.3516	48.351111	0.000438	0.021154
3	40.4502	38.7797	38.2679	40.0702	4.3028	47.808889	0.000433	0.020682
4	40.432	38.7706	38.2916	40.0692	4.3419	48.243333	0.000437	0.021060
...								
2874	40.4294	38.7789	38.2799	40.0739	4.2637	47.374444	0.000429	0.020308
							AVERAGE POWER	0.053746

From the data, the baseline for electrical power produced by the solar cells without concentrator and coolant circuit averaged at 0.053746 Watt. As shown in the plot above, the solar cells surface temperature remains around 40 °C while producing electricity ranging between 70 to 80 Volts. The test is then continued with performance analysis of PV/T system and the results were as followed:

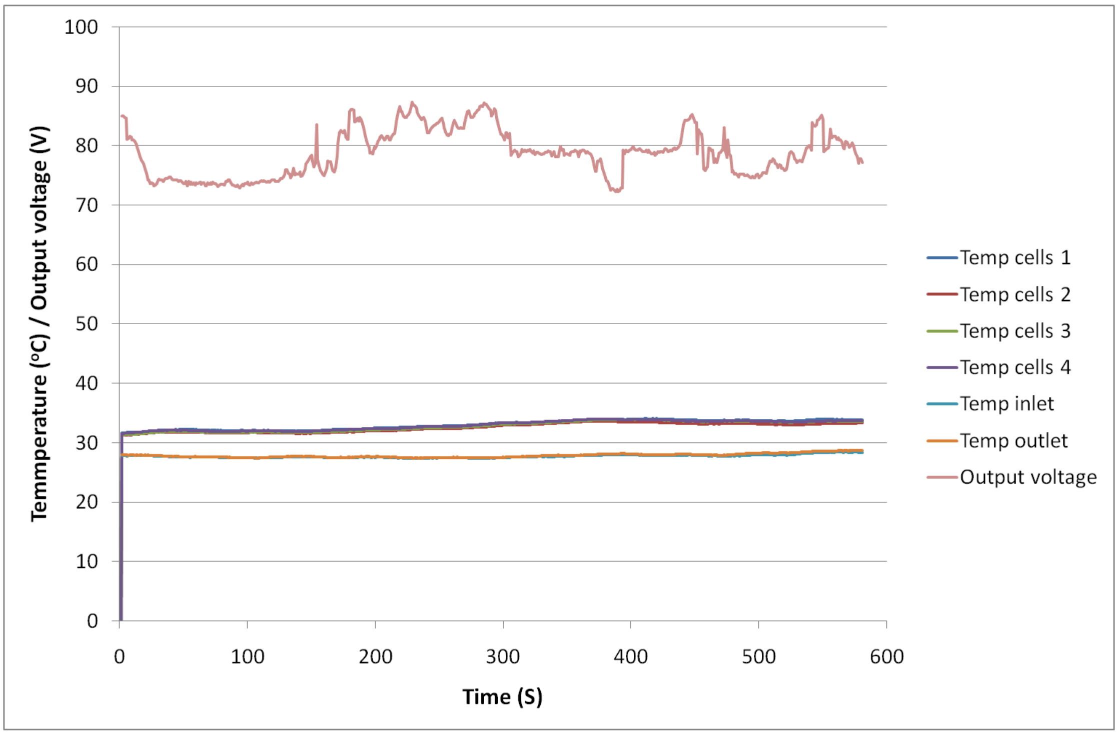


Figure 37 Voltage output of PV/T system with corresponding to cells temperature and coolant inlet/outlet temperature

Table 4 Data recording and analysis for PV/T system (Electrical)

Time (s)	Temp cells (°C)				Scaled voltage (V)	Actual voltage (V)	Current (A)	Electrical Power (W)
	Ch0	Ch	Ch2	Ch3				
1	31.6552	31.2317	31.3142	31.5535	7.6532	85.035556	0.000769	0.0654310
2	31.6589	31.2381	31.317	31.5663	7.6532	85.035556	0.000769	0.0654310
3	31.6919	31.2555	31.3536	31.5892	7.6337	84.818889	0.000767	0.0650980
4	31.6818	31.2858	31.36	31.6039	7.6142	84.602222	0.000766	0.0647658
...								
580	31.7011	31.3161	31.3875	31.6268	7.3016	81.128889	0.000734	0.0654310
							AVERAGE POWER	0.0561877

Table 5 Data recording and analysis for PV/T system (Thermal)

Time (s)	Water flowrate (m^3/s)	Temp Inlet (°C)	Temp Outlet (°C)	Thermal Power (kW)
1	0.0002	27.8374	27.9524	0.0963700
2	0.0002	27.8402	27.9644	0.1040796
3	0.0002	27.8642	27.9636	0.0832972
4	0.0002	27.8182	27.958	0.1171524
...				
580	0.0002	27.7768	27.9332	0.1310632
			AVERAGE POWER	0.0807514

From the plot, it was shown that with the capability to remove heat from the solar cells, PV/T system managed to reduce the cells temperature to around 32 ^{o}C while producing higher electricity with voltage ranging between 75 and 90 Volts. Aside from enhancing photo-electricity, PV/T system also produces thermal energy. The electrical power produced by the system was slightly higher than PV system averaged at 0.0562 W while producing thermal power of 0.0808 kW.

4.2.2 Performance of CPV/T system with maximum cooling

Theoretically, by implementing concentrator onto PV/T system, the amount of solar radiation that lands on the receiver will multiplies, thus causing higher electrical and thermal output. However, a new concern arises with the improvement. As the radiation intensity increases, the temperature of the cells will also increase causing the efficiency of solar cells to drop. The CPV/T system was tested with various operating conditions to study its performance.

First of all, the CPV/T solar power system was tested with maximum cooling water flow rate to simulate the condition at lowest possible temperature. The results were as followed:

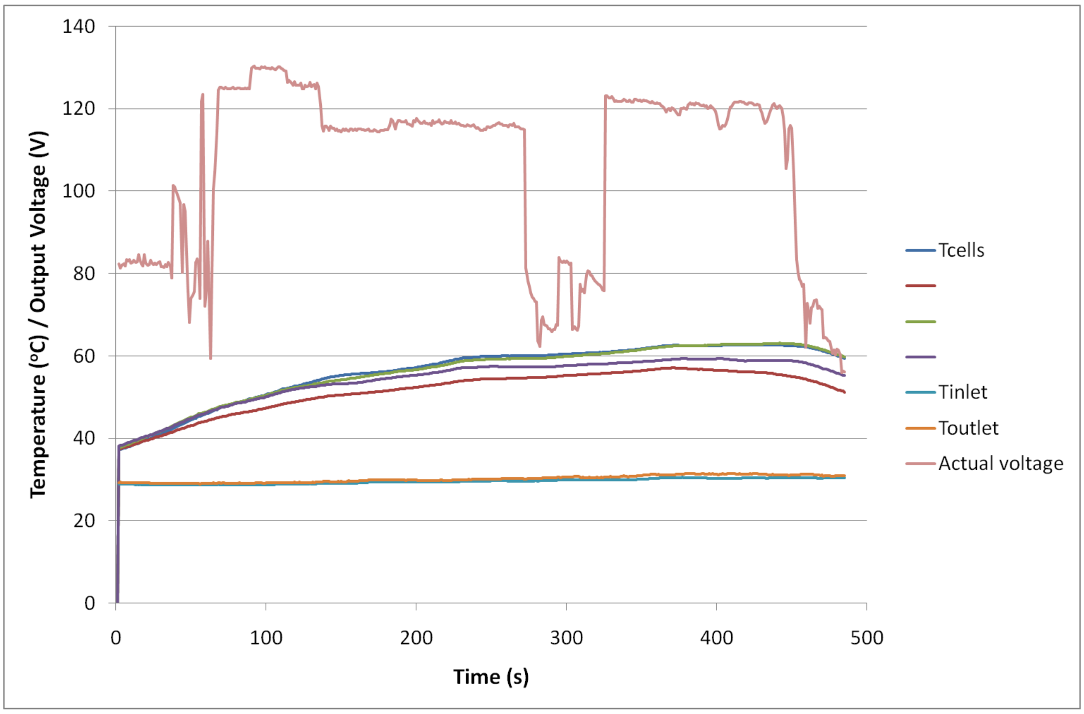


Figure 38 Voltage output and temperatures of CPV/T system with maximum cooling water flow rate.

Table 6 Data recording and analysis for CPV/T with maximum cooling (Electrical)

Time (s)	Temp cells (^oC)				Scaled voltage (V)	Actual voltage (V)	Current (A)	Electrical Power (W)
	Ch0	Ch1	Ch2	Ch3				
1	37.1828	37.3168	37.6897	38.1407	7.409	82.322222	0.000745	0.0613221
2	37.2732	37.4218	37.7828	38.2529	7.3211	81.345556	0.000736	0.0598757
3	37.3507	37.5613	37.955	38.3531	7.3797	81.996667	0.000742	0.060838
4	37.535	37.7191	38.1601	38.5208	7.409	82.322222	0.000745	0.0613221
...								
484	37.6872	37.8002	38.2394	38.692	7.37	81.888889	0.000741	0.0606782
AVERAGE POWER								0.1306935

Table 7 Data recording and analysis for CPV/T with maximum cooling (Thermal)

Time (s)	Water flowrate (m^3/s)	Temp inlet (^oC)	Temp outlet (^oC)	Thermal Power (W)
1	0.0002	28.8328	29.2932	0.3858152
2	0.0002	28.8449	29.2979	0.379614
3	0.0002	28.8726	29.2613	0.3257306
4	0.0002	28.8763	29.2365	0.3018476
...				
484	0.0002	28.8735	29.2181	0.2887748
AVERAGE POWER				0.7432113

Figure 38 showed a significant increase in output voltage of the solar cells as compared with PV and PV/T system with implementation of concentrator. The plot illustrated the effect of sudden increase in radiation to solar cells. Before the cells were exposed to intensified solar radiation, the voltage output maintained around 80 Volts, but once the concentrator was set in position, the sudden exposure causing instability in the cells output. The output is then stabilized and peaks at 130 Volts before dropped significantly in the middle of the test possibly due to non-uniform temperature distribution across the cells. Temperature of the solar cells in CPV/T system peaks around 60 ^oC extensively higher than non-concentrated systems. CPV/T system showed a slight increase in temperature difference between inlet and outlet of cooling water.

4.2.3 Performance of CPV/T system with low cooling rate

In order to obtain high temperature conditions, the rate of cooling water is reduced to minimum. It was expected that with reduced cooling system, the thermal output will be lower. Electrical output will also be affected as with low cooling, temperature of the system will be higher and thus reducing solar cells efficiency. The result for the test is shown below:

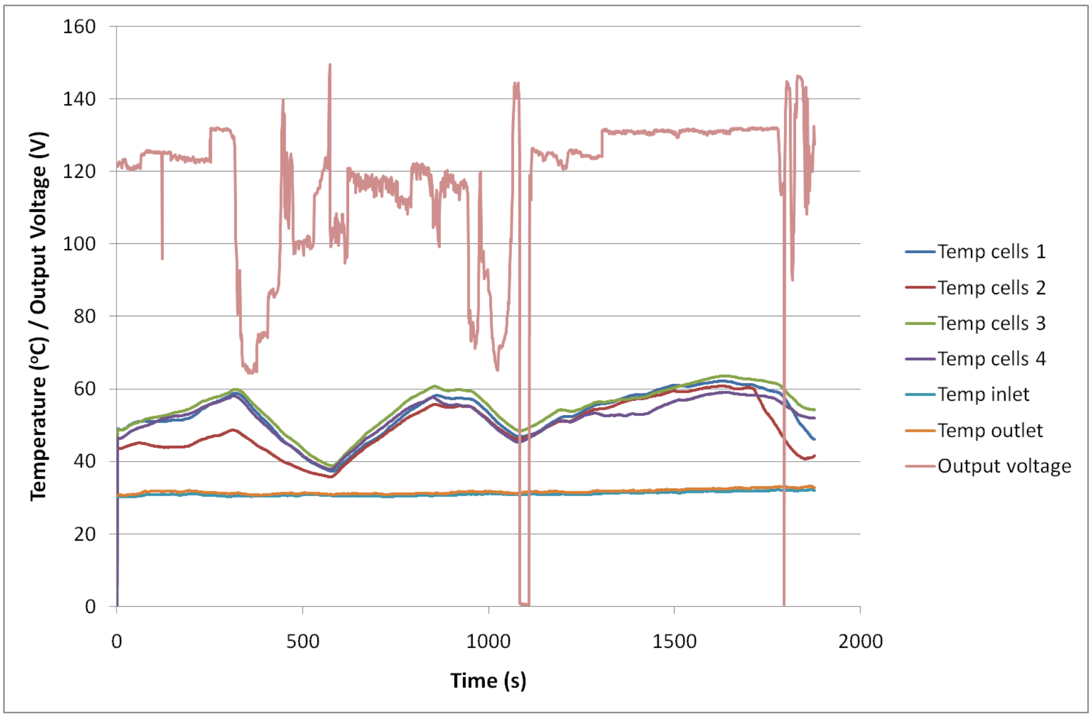


Figure 39 Voltage output and temperature of CPV/T system with low cooling rate

Table 8 Data recording and analysis for CPV/T with low cooling rate (Electrical)

Time (s)	Temp cells (°C)				Scaled voltage (V)	Actual voltage (V)	Current (A)	Electrical Power (W)
	Ch0	Ch1	Ch2	Ch3				
1	49.1627	43.7649	48.9163	46.34	10.9255	121.39444	0.001098	0.1333461
2	49.1012	43.7113	48.8602	46.2946	10.9646	121.82889	0.001102	0.1343022
3	49.0126	43.6694	48.7797	46.2257	11.0037	122.26333	0.001106	0.1352618
4	48.9239	43.6122	48.7055	46.1912	11.0232	122.48	0.001108	0.1357416
...								
1883	48.9077	43.5659	48.6476	46.1704	11.0427	122.69667	0.00111	0.1362223
							AVERAGE POWER	0.1266227

Table 9 Data recording and analysis for CPV/T with low cooling rate (Thermal)

Time (s)	Water Flow rate (m^3/s)	Temp inlet (^oC)	Temp outlet (^oC)	Thermal Power (W)
1	0.000115	30.2524	30.6626	0.1976549
2	0.000115	30.2524	30.6525	0.1927882
3	0.000115	30.2386	30.7369	0.2401059
4	0.000115	30.2268	30.7517	0.2529231
...				
1883	0.000115	30.225	30.8104	0.282075
			AVERAGE POWER	0.3469961

By lowering the cooling water flow rate to minimum 0.000115 m^3/s, the CPV/T system was tested at low temperature conditions. As seen in figure 39, due to low cooling capacity, the solar cells surface temperature fluctuated more than usual. These random fluctuations indicated a non-uniform temperature distribution across the solar cells which causing instability on electrical output. The voltage output fluctuated radically with every change in cells temperature as observed in the plot which then affected the overall electrical output of the CPV/T system. Average electrical and thermal power of the set-up was calculated to be compared with other results.

4.2.4 Performances comparison

By using the data obtained from each individual analysis of PV, PV/T and CPV/T solar power system, a comparison can be done in order to identify the improvement achieved by implementing hybrid CPV/T system. The comparison will be done in term of average electrical and thermal power produced by each set-up.

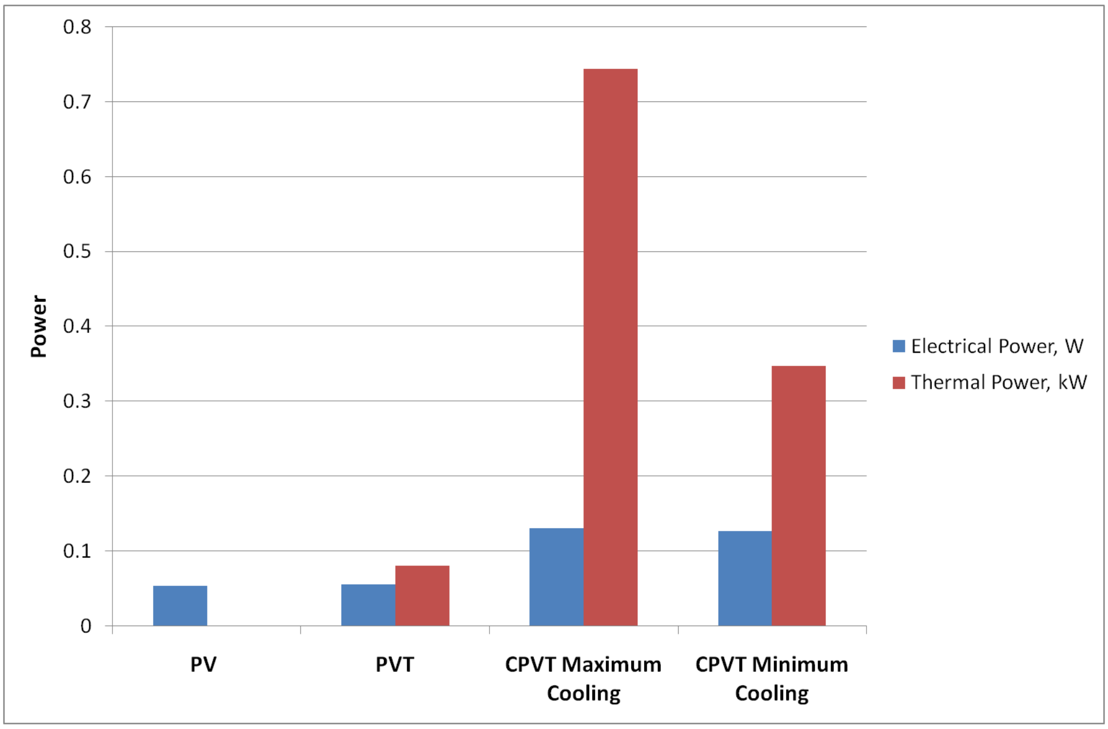


Figure 40 Comparison of electrical and thermal power produced by PV, PV/T and CPV/T solar power system

By closely inspecting the bar chart in Figure 40, we can observe that there was a slight improvement on electrical output of PV/T system as compared to PV due to the usage of cooling water to remove heat absorbed by the solar cells. Aside from that, the PV/T system was also producing a quite amount of thermal energy which could be used for various applications. This proves the benefits and reliability that can provided by hybrid photovoltaic-thermal system.

By implementing concentrator on CPV/T system, a very significant increment on thermal output can be observed. A major increase in electrical power output can also be seen even though all of the readings on CPV/T, PV/T and PV were taken by using the same equipment with the same type and amount of solar cells. This indicated that CPV/T system was able to fully utilize the capability of monocrystalline silicon solar cells to produce electricity. With both high electrical and thermal power output, the CPV/T solar power system was proven to be one of the solutions to renewable energy source.

However, by manipulating the flow rate of cooling water, the equipment was able to simulate high temperature conditions in order to test the capability of CPV/T system at maximum setting. By doing so, the thermal power output was observed to drop down to half of its maximum level. With increase in solar cells surface temperature and non-uniform temperature distribution, electrical power output of the CPV/T system seemed to be slightly reduced. The only benefit of this set-up was that with lower cooling water flow rate, the output water temperature obtained was higher thus allowing for wider range of applications.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

The study on concentrating photovoltaic/thermal solar power system is initially aimed to study on the matter, fabricate the equipment and conduct experimental analysis on the equipment related to CPV/T solar power system. The main purpose is to construct a hybrid system with maximum electrical and thermal efficiency in order to generate as much energy as possible. Studies on the theory and practicality of CPV/T system had been done during the beginning of the research which had led to various designs and options for the fabrication processes. Then the CPV/T system was fabricated as to plan and modifications were made throughout the process such as replacement of solar cells from advanced triple-junction cells to mono-crystalline silicon cells, changes on the shape of the receiver from triangular to square-shaped as well as the installation of cooling tower to the water circulation as good measures. In the end, the whole equipment was completed in time allowing the time for experimental analysis. Performance analyses of the CPV/T system begin with layout of common ground by investigating the maximum output of conventional PV and PV/T system. Once the basis is laid out, the CPV/T system is tested at two condition; maximum cooling and minimum cooling to simulate low and high operating temperature conditions. The results show that implementation of CPV/T enhances the electrical and thermal output of hybrid photovoltaic-thermal system significantly. However, working at high temperature can cause the power output of the system to degrade. The fabricated CPV/T solar power system has proven to be able to produce satisfying results in producing maximum electrical and thermal energy output. In conclusion, the study on hybrid photovoltaic and thermal solar power system had achieved its laid objectives as well as successfully enhances our knowledge on solar power system.

5.2 Recommendations

Since this study is one of the first in UTP, a lot of improvement can still be included for further research such as:

1. Application of high performance solar cells such as triple junction Gallium Arsenide cells instead of conventional monocrystalline silicon cells. By using triple-junction cells, the full capacity of CPV/T system can be achieved in term of electrical and thermal output.
2. Usage of highly conductive metal as thermal receiver. The current iron receiver still has unsatisfying heat conductivity. The gap between coolant temperature and surface temperature is quite large. Plus, the iron receiver is also badly stained. Usage of stainless metal such as aluminium is highly recommended.
3. Scaled up the experiment for domestic application. The current scale is too small and insufficient to produce quality thermal and electrical energy even for domestic usage. With bigger scale, it will provide larger insight as well as taking the new technology to the next level.

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APPENDIX I

1. Triangular Advanced Solar Cells (TASC)

Spectrolab
Photovoltaic Products www.spectrolab.com

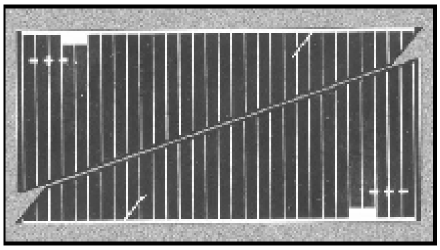
Triangular Advanced Solar Cells (TASC)

Product Description & Applications

- Designed for high power terrestrial applications, where space is at a premium.
- Two solar cells can be arranged within an approximate rectangular area of 0.611 x 1.254 inches (1.55 x 3.18 cm) with a cell gap of 0.018 inches (0.46 mm). See picture.
- Each solar cell is ideally matched to charge a single 1.2 V battery cell (eg. Ni-MH, NiCad, etc.). Cells can be wired in parallel for increased current. Two solar cells in series can charge one 3.6V Li-ion battery cell.
- A major advantage using these solar cells compared to silicon cells is that they deliver greater than 4 times higher voltage. Therefore, only one of Spectrolab's multi-junction solar cells is required to generate the same voltage as 5 Si solar cells connected in series
- Compared to typical silicon cells, these solar cells are ***over twice as efficient*** and thus will deliver more than twice the power for the same area.
- Uses and applications: A variety of power-consuming electronic equipment can benefit from these cells, especially if the area available is small or the time required for charging is limited. For example, these cells help power devices used during business trips, emergency situations or for the outdoor activities.

Product Description

Cell Type	Improved triple-junction gallium arsenide
Method of Cell Growth	Metal Organic Vapor Phase Epitaxy
Polarity	n/p
Thickness	190 μm (0.0075 in.)
Area	2.277 cm² (0.353 sq. in.)
Mass	0.234 g
Assembly Methods	Soldering, welding, metallized epoxy
Device Design	Monolithic, two terminal triple junction. n/p $GaInP_2$, GaAs, and Ge solar cells interconnected with two tunnel junctions.
Antireflective Coating	Multi-layer providing low reflectance over wavelength range 0.3 to 1.8μm.



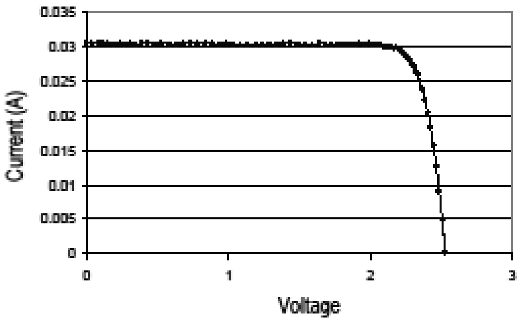
Not Actual Size

Typical Cell Electrical Parameters

1 Sun, AM1.5G (100.0 mW/cm²) 25°C

I_{sc}= 31 mA	I_{mp}= 28 mA
V_{oc}= 2.52 V	V_{mp}= 2.19 V
P_{mp}= 0.027 W/cm²	Cff= 80 %
Efficiency= 27 ± 3% Absolute	Temp. Coeff. V_{mp} = -6.2 mV/°C

Typical Cell I-V Curve (AM 1.5G)



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SPECTROLAB

The information contained on this sheet is for reference only. Actual specifications for delivered products may vary. 4/10/02

Spectrolab Inc. 12500 Gladstone Avenue, Sylmar, California 91342 USA • Phone: 818.365.4611 • Fax: 818.361.5102

2. WE300 Solar Radiation Sensor

WE300 Solar Radiation Sensor

Rugged Solar Radiation Transmitter

Features

- Accurate 4-20 mA output
- Marine grade cable with strain relief
- Precision mounting equipment included

Description

Global Water's WE300 Solar Radiation Sensor is a precision pyranometer that uses a high stability silicon photovoltaic detector (blue enhanced) to obtain accurate readings. The WE300 includes a bubble level, leveling screws, and mounting hardware for a quality installation. The sensor is attached to electronics by 10' of cable, and the electronics are attached to 25' of marine grade cable, with lengths up to 500' available. To ensure moisture protection, you can enclose the sensor and electronics in a protective housing. The sensor's output is 4-20 mA with a two wire configuration.

Specifications

Detector	High-stability silicon photovoltaic detector (blue enhanced)
Output	4-20 mA
Range	0 to 1500W/m²
Spectral Response	400 to 1100 nm
Accuracy	± 1% full scale
Operating Voltage	10 to 36 VDC
Current Draw	Same as sensor output
Warm-up Time	3 seconds minimum
Operating Temperature	-40° to +55°C
Sensor Size	3" dia. x 1½" long (7.6 cm dia. x 3.8 cm long)
Weight	0.25 lb (114 g)

Ordering & Options

Order No.	Description
WE300	Solar Radiation Sensor (includes 25' cable)
WQEXC	Extra Sensor Cable, per foot (up to 500')

Global Water
a xylem brand

In the U.S. call toll free
at 1-800-876-1172
International: 1-979-830-5580
Fax: 1-979-830-3440
Email: globalw@globalw.com

Visit our online catalog at:
www.globalw.com
Our Address:
11390 Amalgam Way
Gold River, CA 95670

3. USB-1208FS

USB-1208FS/LS/1408FS Series

12-bit and 14-bit Multifunction Devices with 8 Analog Inputs, 2 Analog Outputs

MEASUREMENT COMPUTING.

Features

- Low cost, multifunction USB devices with 4 differential or 8 single-ended analog inputs (software-selectable)
- Provides 12-bit or 14-bit analog input resolution
- Maximum sampling rates ranging from 1.2 kS/s to 50 kS/s
- 2 analog outputs
- 16 digital I/O lines
- One 32-bit counter input channel
- No external power required

Software

- TracerDAQ® software included for acquiring and displaying data and generating analog signals
- Universal Library includes support for Visual Studio® and Visual Studio® .NET, including examples for Visual C++®, Visual C#®, Visual Basic®, and Visual Basic® .NET
- InstaCal software utility for installing, calibrating, and testing
- ULx for NI LabVIEW™
- DAQFlex open-source software framework – includes support for Linux®, and Mac® platforms (USB-1208FS-Plus/1408FS-Plus only)
- Comprehensive drivers for DASYLab®
- USB-1208LS/1208FS/1408FS supported by MATLAB® Data Acquisition Toolbox™
- Supported Operating Systems: Windows® 8/7/Vista®/XP SP2, 32-bit or 64-bit

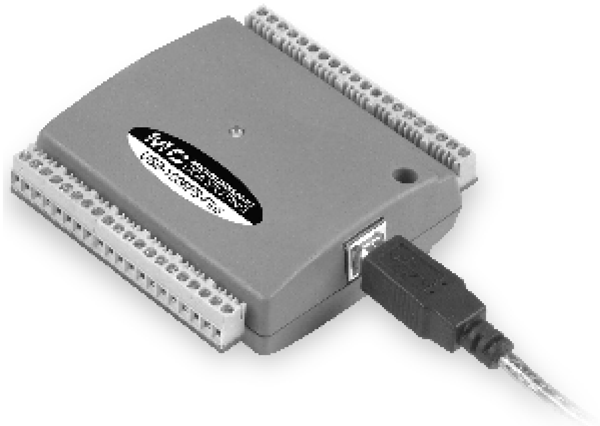
Overview

This product series consists of the following low-cost, analog and digital I/O devices:

- USB-1208LS
- USB-1208FS and USB-1208FS-Plus
- USB-1408FS and USB-1408FS-Plus

All of these devices offer four differential (DIFF) or eight single-ended (SE) analog inputs, two analog outputs, 16 digital I/O channels, and one counter input.

Everything you need to begin acquiring, viewing, and storing data is included with these devices, including comprehensive software support.



All devices in this series offer eight singled-ended or four differential analog inputs, two analog outputs, 16 digital I/O, and one counter input. The USB-1208FS-Plus/1408FS-Plus also include eight high-current (24 mA) digital I/O connections and DAQFlex support.

USB-1208FS/LS/1408FS Series Selection Chart

Model	Analog Inputs	Sampling Rate	Analog Outputs	Digital I/O	Event Counters	DAQFlex Support
USB-1208LS	8 SE 4 DIFF	1.2 kS/s max	2	16	1	–
USB-1208FS	8 SE 4 DIFF	50 kS/s max	2	16	1	–
USB-1208FS-Plus	8 SE 4 DIFF	50 kS/s max	2	16*	1	✔
USB-1408FS	8 SE 4 DIFF	48 kS/s max	2	16	1	–
USB-1408FS-Plus	8 SE 4 DIFF	48 kS/s max	2	16*	1	✔

* Port B is a high-current drive.

Analog Input

USB-1208LS/1208FS/1208FS-Plus: These devices provide eight, 11-bit SE analog inputs or four, 12-bit DIFF analog inputs.

USB-1408FS/1408FS-Plus: These devices provide eight, 13-bit SE analog inputs or four, 14-bit DIFF analog inputs.

All of these devices support software-selectable ranges that provide inputs from ±1 V to ±20 V in a DIFF configuration, and ±10 V in a SE configuration.

Sampling Rate

USB-1208LS: When scanning continuously to computer memory (hardware-paced mode), the USB-1208LS can sample at a maximum of 1.2 kS/s. Burst mode into the 4 kS FIFO is also available at rates up to 8 kS/s.

USB-1208FS/1208FS-Plus and USB-USB-1408FS/1408FS-Plus: When scanning continuously to computer memory (hardware-paced mode), the USB-1208FS/1208FS-Plus can sample at a maximum of 50 kS/s, and the USB-1408FS/1408FS-Plus can sample at a maximum of 48 kS/s.

4. USB-TC

USB-TEMP and TC Series

USB-Based Temperature Measurement Devices

Features

- Temperature and voltage measurement USB devices
- Thermocouple, RTD, thermistor, or semiconductor sensor measurements
- Eight analog inputs
- Up to ±10 V inputs*
- 24-bit resolution
- Eight digital I/O
- One counter input*

Software

- TracerDAQ® software included for acquiring and displaying data and generating signals
- Universal Library includes support for Visual Studio® and Visual Studio® .NET, including examples for Visual C++®, Visual C#®, Visual Basic®, and Visual Basic® .NET
- Comprehensive drivers for DASYLab® and NI LabVIEW™
- InstaCal software utility for installing, calibrating, and testing
- Supported Operating Systems: Windows® 7/Vista/XP SP2, 32-bit or 64-bit

Overview

The USB-TEMP and TC Series are USB-based temperature measurement devices that support all of the common temperature sensor types. There are four models available. Each device is designed for accurate, PC-based temperature measurements. The USB-TEMP and USB-TC each include 8 thermocouple inputs. The USB-TEMP also supports RTD, thermistor, and semiconductor sensor measurements.

The USB-TEMP-AI and USB-TC-AI feature four thermocouple inputs plus four voltage inputs with ranges up to ±10 V. The USB-TEMP-AI also supports RTD, thermistor, and semiconductor sensor measurements. In addition to the analog inputs mentioned, each device also includes eight digital I/O channels which can be user-configured for alarming or triggering.

Each device is self-powered through the USB port for convenient, portable operation without the need for additional wiring or power supplies.

The USB-TEMP Series provides temperature measurement flexibility as each channel can monitor any of the supported input types

USB-TEMP and USB-TC Series Selection Chart

Model	Channels	Thermocouple Inputs	RTD, Thermistor, Semiconductor Temp Sensor Inputs	Voltage Inputs
USB-TC	8	√	—	—
USB-TEMP	8	√	√	—
USB-TC-AI	8	√	—	√
USB-TEMP-AI	8	√	√	√

Analog Input

The USB-TEMP and USB-TC each include 8 thermocouple inputs. The USB-TEMP also supports RTD, thermistor, and semiconductor sensor measurements.

The USB-TEMP-AI and USB-TC-AI feature four thermocouple inputs plus four voltage inputs with ranges up to ±10 V. The USB-TEMP-AI also supports RTD, thermistor, and semiconductor sensor measurements. The USB-TEMP-AI and USB-TC-AI also offer four voltage input channels with ranges from ±1.25 V to ±10 V.

All devices also include open thermocouple detection to identify improperly working thermocouples.

TracerDAQ is an easy-to-use software application which provides four virtual instrument applications used to graphically display and store input data, and generate output signals within minutes

* USB-TEMP-AI and USB-TC-AI only

APPENDIX II

Photograph of the finished CPV/T system