PERFORMANCE OPTIMIZATION OF SOLAR WINDOW

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A project report submitted in partial fulfilment of the requirements for the award of Bachelor of Science (Hons.) Physics

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DECLARATION

I hereby declare that this project report is based on my original work except for citations and quotations which have been duly acknowledged. I also declare that it has not been previously and concurrently submitted for any other degree or award at UTAR or other institutions.

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APPROVAL FOR SUBMISSION

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ABSTRACT

Building integrated photovoltaic (BIPV) has been developed over the years as an application for photovoltaic (PV) systems. The problem with current BIPV solar technology is the sun path in Malaysia is unlikely to favour the use of conventional BIPV solar window which is placed in vertical position. The commercial BIPV solar window available in the market now has low collecting angle as the position of Sun in Malaysia are high in altitude most of the time. Therefore this phenomenon causes large sunray incident to the vertical placed solar cells. This loss is known as cosine loss. Besides, the commercial BIPV solar windows also have the issues of poor daylighting effect and poor aesthetic effect. In this project, double layered glass building window integrated with angle adjustable solar cells are proposed as new BIPV solar window. Non-transparent monocrystalline solar cells with gaps in between are sandwiched in two layers of glass windows. It allows sunlight to pass through during day time to cut down the electricity used, also at the same time it provides better aesthetic effect. The tilted solar panels is proposed so that it can receive more sunlight than vertically placed solar panels. For research purpose, louver windows are used in this project as it provides mechanism to tilt the angle of the monocrystalline solar cells attached to it. This can reduce the cosine loss and yield maximum power output without deteriorating the daylighting and aesthetic effect. The innovative system is particularly suitable for equatorial countries, including Malaysia. In this project, performance study has been carried out to identify the optimized tilting angle for maximum energy yield.

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LIST OF SYMBOLS / ABBREVIATIONS

V	voltage, V
I	current, A
V_{OC}	open circuit voltage, V
I_{SC}	short circuit current, A
V_{rated}	rated voltage, V
I_{rated}	reated current, A
mm	millimetre
cm	centimeter
θ_e	sun elevation angle, ^{o}
θ_t	solar cells tilted angle, ^{o}
h	non-shading distance
BIPV	Building Integrated Photovoltaic
PV	Photovoltaic
FF	fill factor

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CHAPTER 1

INTRODUCTION

1.1 Background Studies

On Earth, the summation of number of beings living is now greater than seven billion (Roser, 2016). This statistic show that the world population has been increasing dramatically during the 20th century alone. As the consequence of rapid population growth, the energy demand also increased, along with social and economic development.

According to World Energy Resource (2013), the main contribution of energy source is fossil, which included oil, natural gas, and coal. Figure 1.1 shows the statistics of the total primary energy supply by resource in year 1993, 2011 and 2013. There comes a question that is in how many years will the fossil fuel be drained out? At current consumption rates, proven world coal lasts well over a thousand years, oil for 40 years, and natural gas for around 50 years (Kathryn, 2016). Hence, the importance of renewable energy, which is energy that naturally replenished, comes in.

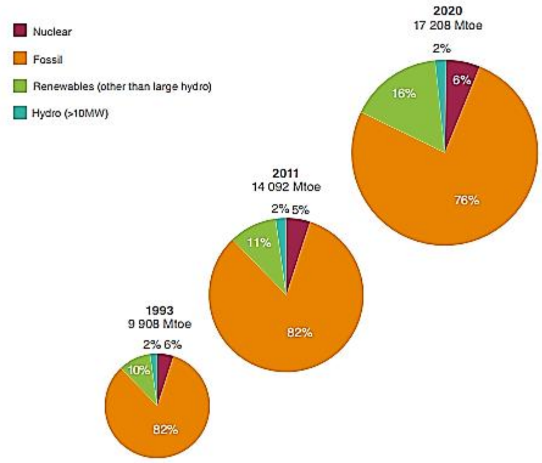


Figure 1.1: Statistics of the Total Primary Energy Supply by Resource

Renewable energy that commonly used included wind energy, geothermal energy, tidal power, hydroelectricity, bioenergy, solar photovoltaic, solar thermal energy and other. These renewable energies are clean and do not cause environment pollution. Nowadays, one of the rapid growth of renewable energy is photovoltaic cells, as it is now widely used in a wide range of applications, from calculators, buildings, and power stations. The segment of building-integrated photovoltaics (BIPV), or 'solar window' is also emerging as the advancement of technology.

Building integrated photovoltaic (BIPV) has been developed over the years as an application for photovoltaic (PV) systems. The problem with current BIPV solar technology is the sun path in Malaysia is unlikely to favour the use of conventional BIPV solar window which is in vertical position. The commercial BIPV solar window available in the market now has low collecting angle as the position of Sun in Malaysia are high in altitude most of the time. Therefore this phenomenon causes large sunray incident angle to the vertical placed solar cells, also known as cosine effect. Apart from that, the cons of the conventional BIPV solar window are poor aesthetic and daylighting effect if using high efficient monocrystalline solar cells. These problems can be solved by using semi-transparent thin films solar cells, however, it paid off for the low efficient of solar cells. Therefore, this project is aimed at designing a BIPV solar windows using high-efficiency monocrystalline solar cells while does not affect its aesthetic and daylighting effect. The built-in tilted angle solar cells also enable to reduce the cosine effect.

1.2 Project Objectives

The objectives of this project are listed as follow:

- To construct four sets of prototypes of angle adjustable BIPV solar windows.
- To compare the performance of solar window facing different directions.
- To optimize the tilting angle for maximum electricity yield.

1.3 Scope of project

In this project, angle adjustable BIPV solar windows are built by using high efficient monocrystalline solar cell attached with louver windows, as shown in Figure 1.2. This project will be done in Malaysia, and thus the performance of the angle adjustable BIPV solar windows is studied based on Malaysia climate. Besides, the data collection of this project will be done at the rooftop of UTAR, Sungai Long campus. The data collection period for this project is 2 months due to time constraint by time allocated. All data are collected in the month of July and August.

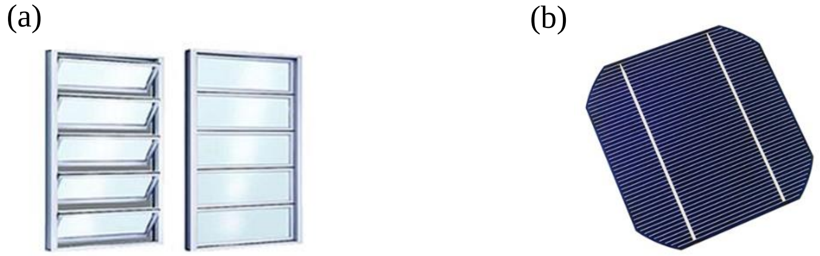


Figure 1.2: Angle Adjustable Solar Window Prototype which Consists of (a) Louver Windows and (b) Monocrystalline Solar Cell

CHAPTER 2

LITERATURE REVIEW

2.1 Photovoltaic (PV) Systems and Building Integrated Photovoltaic (BIPV)

Sunlight is the most abundant energy that can be found on the planet. PV modules are devices that can directly convert sunlight into electricity without producing noises and pollutant into the environment.

A PV cell comprises of two or more thin layers of semiconducting material, most commonly silicon. Generally, electrical charges are generated when the PV cell is exposed to sunlight. Multiple PV cells are connected to form module, or panel because a single cell can only generate small electrical output. The PV panel is the main building block of a photovoltaic system, and a desired electrical output can be done by connecting any number of panels together (Kalogirou, 2014).

As PV systems have no moving parts, thus they will last long. Besides, it can be used on one's own or together with other electrical power sources. Applications of PV systems are now widely used around the world. One of it is BIPV installation for home systems.

One of the feasible technologies that been identify to improve building energy performance is BIPV system. Besides, it can also reduce environmental effects by the on-site electricity generation with solar energy. In the system, solar photovoltaic electricity technologies are combined with typical building fabrics such as roof, sky lights, or facades. In particular, the BIPV windows have become increasingly attractive due to the optical and thermal properties of a window system. The solar cells incorporated in a typical window system can generate electricity. It can also, therefore, reduces electricity demand for supplying to the building, and yet allow daylight which enhances occupants' visual comfort (Chae, Kim, Park, and Shin, 2014). Examples of the types of commercial BIPV windows that available in the market now are amorphous crystalline silicon thin film solar photovoltaics modules, double glasses solar panels with square cells inside, and luminescent solar concentrator.

Recent years, Malaysia is one of the countries that has fastest growing building industries, and this corresponding increases the demanding of energy in coming years. Malaysia government also concern and promote about green buildings for a sustainable built environment for every Malaysians (MGBC, 2016). BIPV technology will be one of the solutions to become substitute part of the conventional fossil fuel electricity generator, at the same time it provides unique aesthetic effect to that particular building. BIPV windows are also suitable to be installed in the high-rise building as the rooftop will not have sufficient space for installation of PV panels. In author's opinion, BIPV technology is reliable and will bring lots of benefits even though it is costly for installation but it is definitely worth it.

2.2 Basic Principles of PV

2.2.1 P-N Junction

As mentioned in the previous subsection, a PV cell is normally made from two or more layers of silicon. Silicon (Si) is belonging to group four in the periodic table. An n-type semiconductor is formed, when Si is doped with group five elements, for example, arsenic (As) or antinomy (Sb). These elements have more electrons in the valence gap compared with Si. The n-type semiconductor is electronically neutral but has excess electrons that available for conduction. The atoms will become positive charges when these extra electrons are removed. The other way round, when Si has doped with group three elements, such as gallium (Ga) or indium (In), which has fewer electrons than Si, and thus forming a p-type semiconductor. It has positive holes or missing electrons in its structure but it is electronically neutral. Therefore, it can accommodate excess electrons. When there comes an additional electron and fill the holes, the impurity atoms would fit more uniformly in the structure and become negatively charged. Both p-type and n-type semiconductors allow electrons and holes to move easily in semiconductors. The schematic diagrams of n- and p-type semiconductors are shown in Figure 2.1.

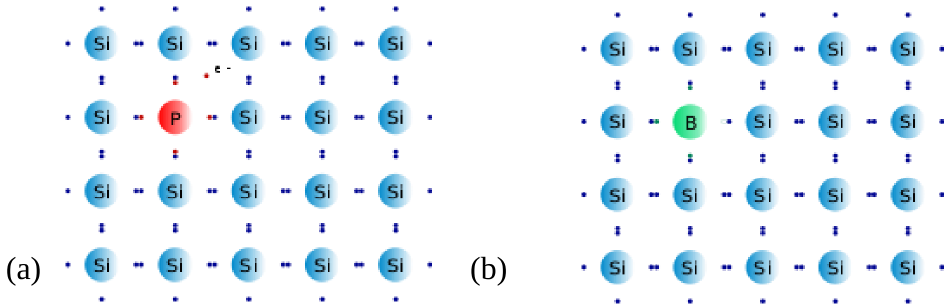


Figure 2.1: Schematic Diagram of (a) n-type Semiconductor and (b) p-type Semiconductor

By joining these two different semiconductors together, a p-n junction will be formed. An electric field in the region of the junction will be induced when electrons in the n-type jump to fill the holes in the p-types and vice versa. This induced positively charged on n-side and negatively charged on p-side. The movements of extra electrons from n-side is restricted by the negative charges on p-side; however, positive charges at the junction of n-side ease the movement of additional electrons from p-side. Hence, the p-n junction acts as a diode, as shown in Figure 2.2.

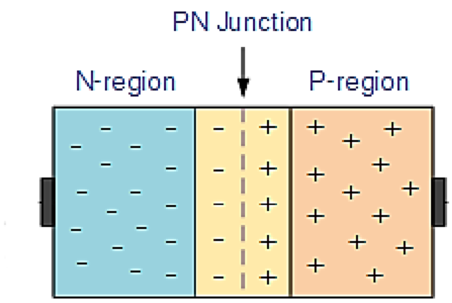


Figure 2.2: Schematic Diagram of a p-n Junction

2.2.2 Photovoltaic Effect

Light has duality properties, which comprises of tiny particles of energy, known as photons and also behave as wave. The electric current will be generated inside the depletion zone of the PN junction. When the electrons from the n-side have diffused and filled the holes of the p-type, a depletion region is formed. When a photon hits the surface and been absorbed by atoms in n-side, an electron will be released and become free electron, while a hole will be left behind in the n-side. The free electron and hole will have sufficient energy to jump out of the depletion zone. As a result, electrons will flow through a wire if the wire is connected from the cathode (n-type silicon) to the anode (p-type silicon). Thus, a current flow is created. The hole left behind is attracted to the negative charge of n-type material and migrates to the back electrical contact. The electron combines with the hole restoring the electrical neutrality when it enters the p-type silicon from the back contact (Images, n.d.). This process is known as photovoltaic effect and it is as shown in Figure 2.3.

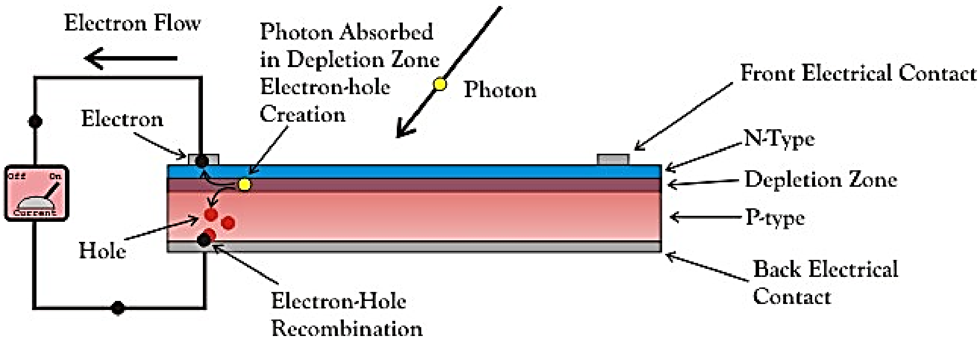


Figure 2.3: Schematic Diagram of Photovoltaic Effect (Images, n.d.)

2.2.3 Band Gap

The quantity of energy possessed by any given electron in a material will lie within one of several levels or ‘bands’ according to the quantum theory. Those electrons that normally hold the atoms of a material together are occupying a lower-state energy known as valence band. In addition, the conduction band is referring to the higher-energy state that some electrons may acquire enough energy to move into in certain circumstances. The difference between these two bands is called energy gap, or band gap, as shown in Figure 2.4.

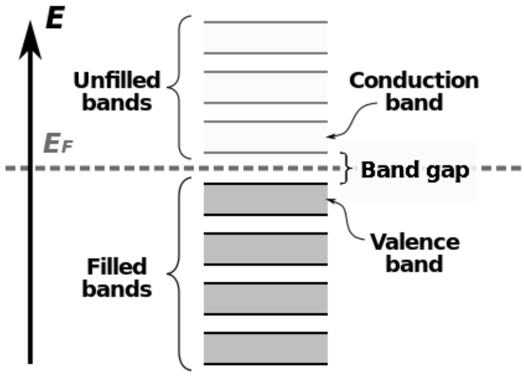


Figure 2.4: Schematic Diagram of Band Gap

For an electron to excite and transfer energy from valence band to conduction band, the photon that hits the PV cell surface must have an energy at least equal to the band gap. As the photons successfully promote an electron to the conduction band, it dissipated heat as excess energy. This is the reason why PV cells are not fully efficient in converting solar radiation into electricity. Another reason is that not all the photons incident on PV cell are absorbed, some are reflected at the PV cell surface (Boyle, 2004).

It is essential to know all the physics theory behind the working principle of PV cells. By knowing this basic characteristics and principle of PV cells, we can have a better understanding of how it is going to function.

2.3 Solar Irradiance in Malaysia

Irradiance is a measure of the amount of sunlight falling on a given surface. The higher the irradiance on a PV panel, the more energy the panel will generate. Malaysia is located at the equatorial region and the tropical environment has been characterized by rich sunshine and solar irradiation, constantly high temperature, heavy rainfall, and relative humidity (Solar, n.d.).

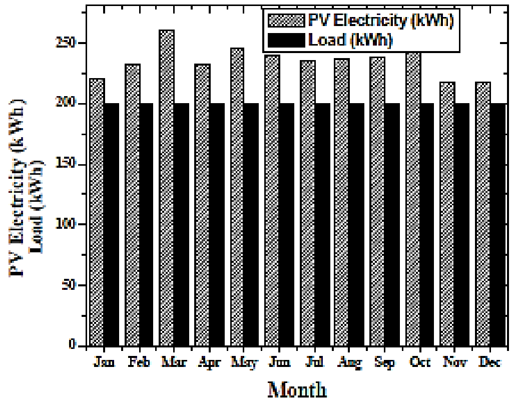


Figure 2.5: Average PV Electricity Generated in Kuala Lumpur (Muhida et al., 2009)

From a research, a BIPV system has been installed in the urban area, which is Putra Jaya and the electricity generated is recorded for one year. From Figure 2.5, the average PV electricity generated by the BIPV system is 235 kWh, which is a great amount of electricity (Muhida et al., 2009). With this data, the author sees the potential of having BIPV system in Malaysia.

2.4 Sun Path Diagram

Sun path diagram is a convenient way of representing the annual changes in the path of the Sun through the sky on a 2D diagram. It indicates the position of Sun for all daylight hours, from sunrise to sunset for the same day of all months of the year when the azimuth is within -120 º to 120 º and the altitude is 90 º or less. Figure 2.6 shows the sun path diagram generated for latitude of 3 º, which is the location of Kajang, city where UTAR, Sungai Long campus located. From Figure 2.6, it shows that the solar altitude, α increases very fast, especially during the month of March and September. Figure 2.7 shows a 3D sun path trajectory of Kajang city throughout the year. The simulation for the sun path on 16th August 2016 is shown with a yellow line. The azimuth and elevation angle is shown in the top left corner of the figure.

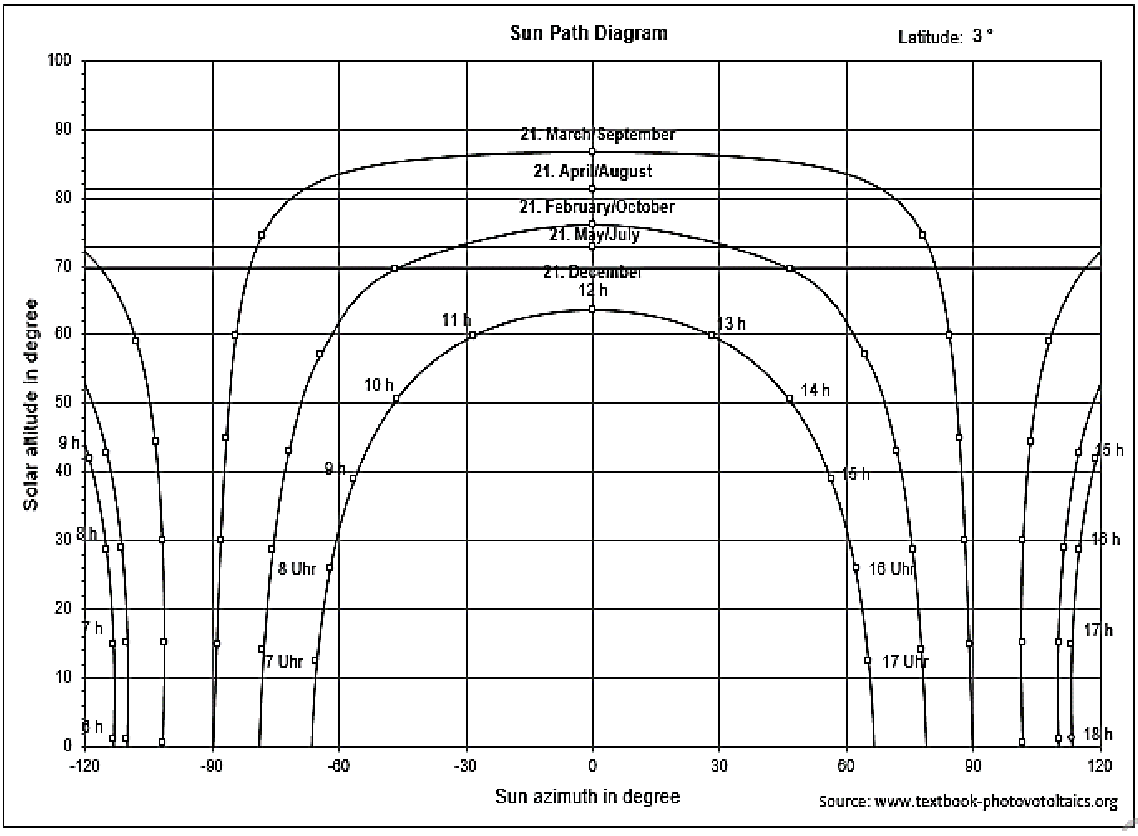


Figure 2.6: Sun Path Diagram of Kajang City (Photovoltaics, 2016)

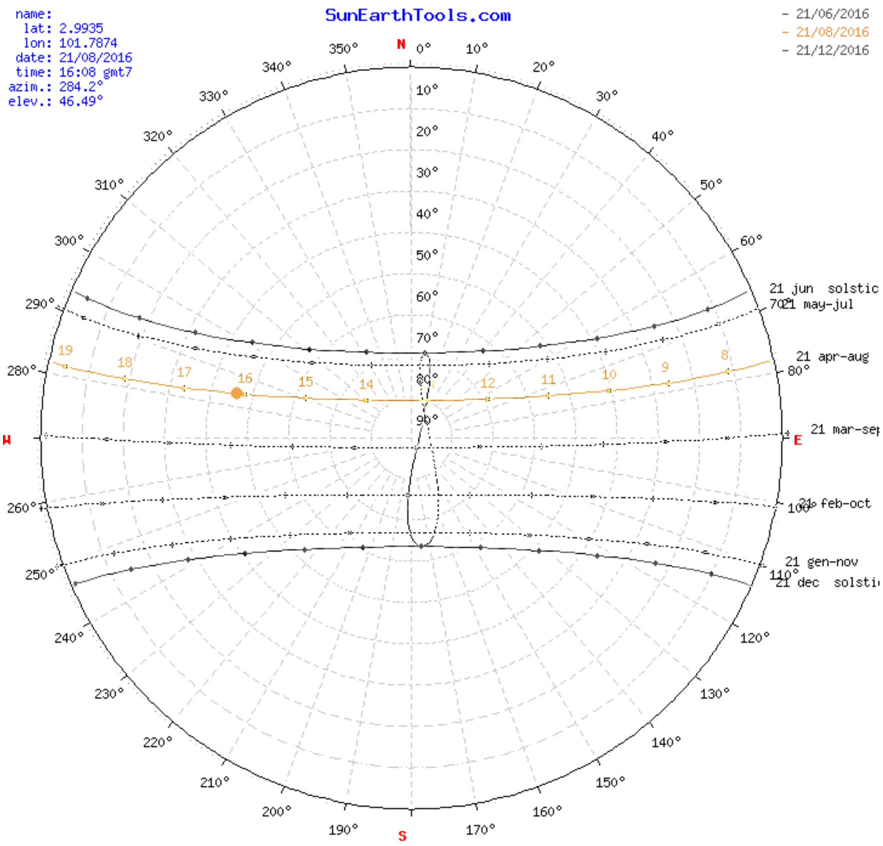


Figure 2.7: 3D Sun Path Trajectory of Kajang City (SunEarthTools, 2016)

2.5 Sun Altitude and Cosine Effect

As stated in section 2.4, the sun altitude, α in Malaysia is much higher than in western countries, such as the United Kingdom. Figure 2.8 and 2.9 shows the 3D sun path generated for Malaysia and United Kingdom respectively. From both figures, it clearly shows that sun altitude angle is much greater than in the western country. The technology of BIPV windows used in Malaysia are adopted from western countries and thus it is all in vertical direction. However, the high altitude of the sun in Malaysia creates a big impact on cosine effect. Cosine effect is the reduction of radiation by the cosine of the angle between the solar radiation and a surface normal. The vertically placed solar cells on the windows will receive less radiation, and thus decrease in the power output.

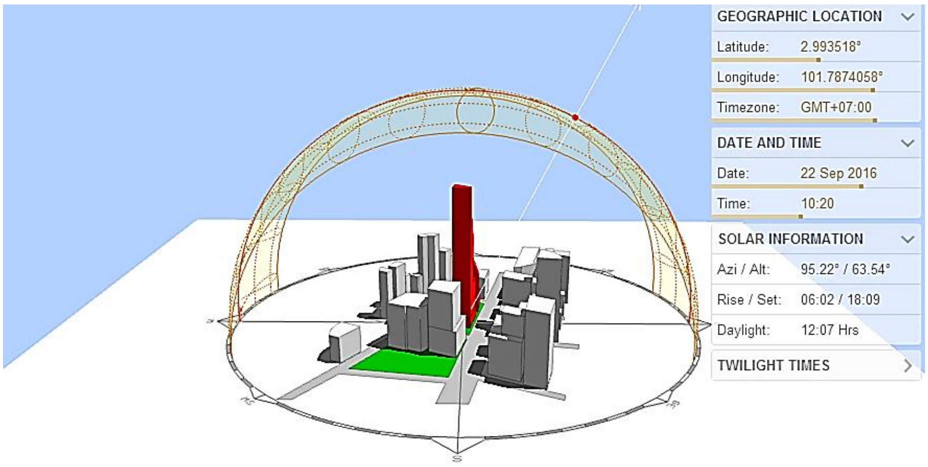


Figure 2.8: Sun Altitude of Kajang City (Andrewmarsh, 2016)

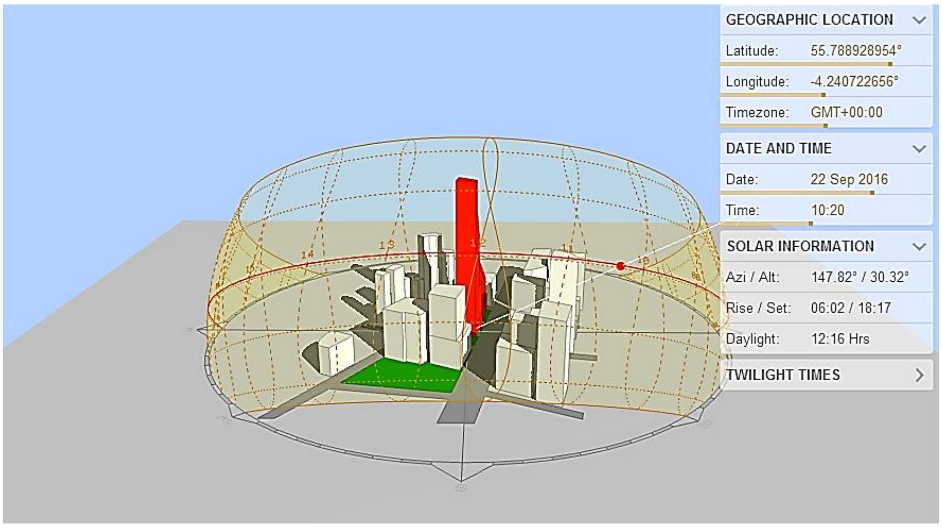


Figure 2.9: Sun Altitude of United Kingdom (Andrewmarsh, 2016)

2.6 Factors Affecting PV Panel Performance

2.6.1 Irradiance

Irradiance varies throughout the day. There are many factors that can affect irradiance level, such as the angle of the sun, passing clouds, hazy weather, and air pollution (SunPower, n.d.). The higher the irradiance received by PV panel, the higher the output electricity produced. Figure 2.10 shows the relationship between the solar irradiance and expected PV output.

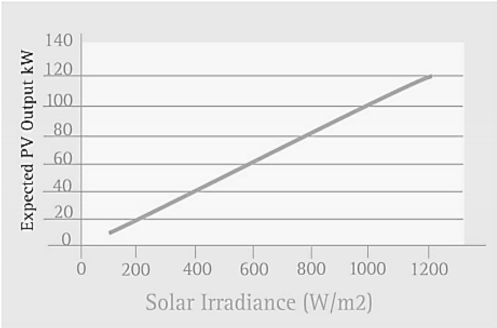


Figure 2.10: Relationship between Solar Irradiance and Expected PV Output (SunPower, n.d.)

2.6.2 Temperature

The warmer the PV cells get, the less efficient they are. The hotter the cell material is, the more resistance there is and the slower the electrons can move through it. Thus, the production goes down due to not as many electrons can get through the circuitry in the same amount of time as before. High-quality panels are designed to maintain performance levels in extreme heat. Figure 2.11 shows the relationship between solar panel temperature and expected PV output.

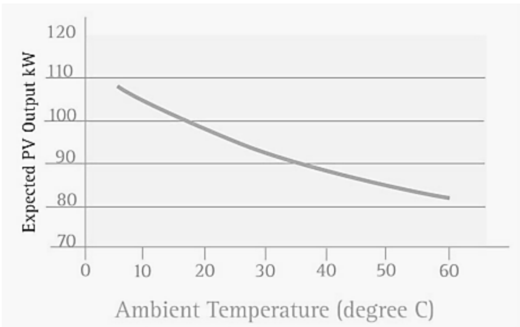


Figure 2.11: Relationship between Ambient Temperature and Expected PV Output (SunPower, n.d.)

2.6.3 Shading

Shaded PV panels produce less electricity. The shading may cause reduction in the power output of the PV cell because the photoelectric effect is reduced by shading. When the PV cell is fully shaded, the power production in the cell is zero and dissipates power from other cells in the series string which may cause the hot-spot phenomenon. A hot-spot is a localized region in a PV cell whose operating temperature is very high when compared to the surroundings. It occurs when the PV cell generates less current and the rest of cells connected in series as a result of partial shading, cell damage, mismatch or interconnection failure. The defected cell operates in a reverse bias mode and dissipates power in form of heat. (Ariho, 2013) Under some circumstances, it is not possible to avoid all shading, so the solar systems must be properly designed to minimize or eliminate shading. This is a critical and important parameter for this project, as the shading of the window panel on the top may affect the performance of PV module. Therefore, the shading effect is taking into account seriously in this project.

Figure 2.12 shows the effect of shadow on the different PV module technologies done by Denis Ariho in the year of 2013. The maximum power of the PV module technologies was converted to standard test conditions (STC) for easier comparison. The unshaded modules were taken as the reference and the variation of the maximum power at STC of the different PV module technologies under shading from the reference was analyse. The results show that the shading effect has greatly affected the power output of every type of PV module technologies.

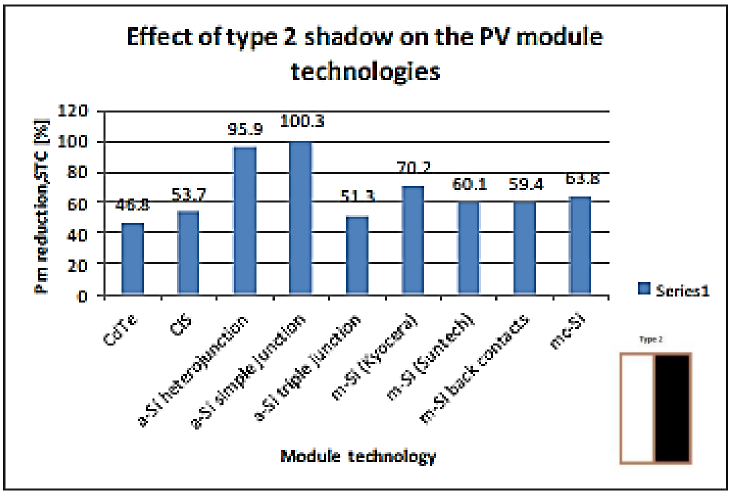


Figure 2.12: Effect of Shadow on Different Type of PV Module Technologies (Ariho, 2013)

2.6.4 Soiling

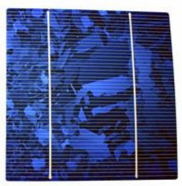
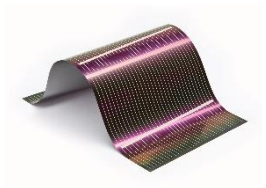
The dirtier the surface of PV panel, the lesser the electricity it produces. Soiling refers to dust and dirt that settling on the surface of PV panels. As a result, it blocks sunlight from reaching the PV cells and reduces its performance. Therefore, the BIPV should always be cleaned in order to maintain high performance.

The author is considering all the factors that will affect the efficiency of PV panels while designing the prototype and during data collection. High-quality PV panels are chosen for better heat resistance.

2.7 Type and Efficiency of PV Cells

There are several different types of solar cells can be found in the marketplace. The main different in the solar panel is the purity or alignment of silicon. Its ability and performance to convert sunlight to electricity depend on how perfect the alignment of molecules of silicon align in solar cells. Several types of PV cells, its efficiency, and its pros and cons is summarized as shown in Table 2.1.

Table 2.1: Types of PV Cells

Types	Pros	Cons	Efficiency
Monocrystalline 	• High efficiency • Last longer • Perform better in low light	• Expensive • Can be affected by dirt or shade	15%
Polycrystalline 	• High efficiency with respect to price	• Expensive • Suffer more at high heat and reduce lifespan	13%
Thin Film 	• Low price • Save space • Work well in low light, even moonlight	• Low efficiency • Degrade quicker	7%

Even though thin film solar cell can allow partial sunlight into the building for better daylighting, but it has much lower efficiency than monocrystalline solar cell. Hence, monocrystalline solar cell is chosen to be used in this project.

2.8 Present Applications of BIPV Solar Window

There are several types of conventional BIPV solar windows found in the markets recently. Crystalline silicon (c-Si) solar cells, as shown in Figure 2.13, are the most common that attached in between double layered glass windows. Although the c-Si solar cells have the highest efficiency with maturity in technology and also commercially inexpensive, it paid the price of poor aesthetics effects, and also poor daylighting effect, as the non-transparent solar cells block the sunlight from entering the building. And this causes the users have to use built in lights even during day times and thus cost electricity usage.

Figure 2.13: c-Si Solar Cells Windows

Another typical type of BIPV windows that available is built with semi-transparent thin films, as shown in Figure 2.14. Its advantage of semi-transparent do improve the daylighting effect and also aesthetic effect. However, thin film solar cells have the lowest efficient compared with others type of solar cells and also low transmittance in the visible. Apart from that, thin film solar cells are also immature in technology.

Figure 2.14: Semi-transparent Thin Films Solar Windows

Luminescent Solar Concentrator (LSC), as shown in Figure2.15, is another types of BIPV windows that developed recently. It’s bright and fluorescent coloration do provides colourful effect to environment and also it is flexible in design, where it has variety shape, size, and colour, depends on users' need. Even though it improve the aesthetics effect but yet it does sometimes create poor visual comfort effect to the users due to the coloration of the windows. (Vossen, M., Aarts, M. P. J., Debije, M. G., 2015).

Figure 2.15: Luminescent Solar Concentrator

As conclusion, the common problems with the existing technology are low power output and low efficiency if good daylighting and aesthetic issue are to be maintained. Besides, the vertically placed solar cells will have low collecting angle as the sun altitude in Malaysia is high and due to cosine effect, the sunlight received by the solar cells will reduce. Therefore, this project aimed to introduce an angle adjustable BIPV solar windows with non-transparent solar cells sandwich in between double layered windows. For research purpose, louver windows are used in this project, that the angle of attached monocrystalline solar cells can be titled to study the power output by different tilted angle. Besides, the gaps in between each window panels will serve to allow daylight entering the building, and reduces the payoff of electricity generation. Even though non-transparent high-efficiency solar cells are used, but it will not affect daylighting performance or create aesthetic issue.

CHAPTER 3

METHODOLOGY

3.1 Introduction

In this project, building window with angle adjustable solar cells is proposed, as shown in Figure 3.1. They can produce higher output without deteriorating the daylighting and aesthetic effect. This innovative system is particularly suitable for Malaysia due to the limitation of large cosine effect. Besides, they can also allow more sunlight to go through for better daylighting effect and with better aesthetic effect.

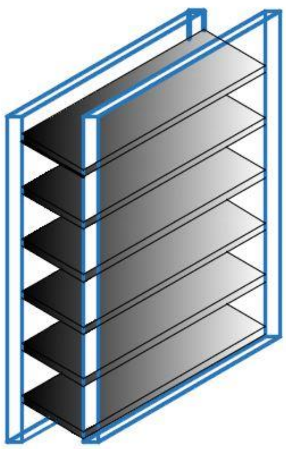


Figure 3.1: Double Layered Glass with Tilted Solar Cells Sandwich In Between

For research purpose, the prototypes are constructed by using louver windows, where the solar cells can be tilted. There are different task to be done for data collection that are comparison the performance of solar window in different direction, and identify the optimized tilted angle of solar cells for maximum electricity yield. In this chapter, the procedure and planning to accomplish the project are also discussed.

3.2 Project Planning

Project planning shows the outlines of all schedules and activity that needed to be carried out to complete this project. A project timeline has been proposed, as shown in Table 3.1.

Table 3.1: Project Timeline

		FYP 1					FYP 2			
Phase	Task	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept
Phase I	i. Research through reading journal and article.									
	ii. Prototype designing									
	iii. Materials purchasing									
	iv. Prototype constructing									
	v. Progressive report									
Phase II	i. Photovoltaic cells testing									
	ii. Circuitry Implementation									
	iii. Assembly									
Phase III	i. Identify optimized tilted angle									
	ii. Compare prototype facing four different directions									
Phase IV	i. Data analysis									
	ii. Final report									

3.3 Prototype design

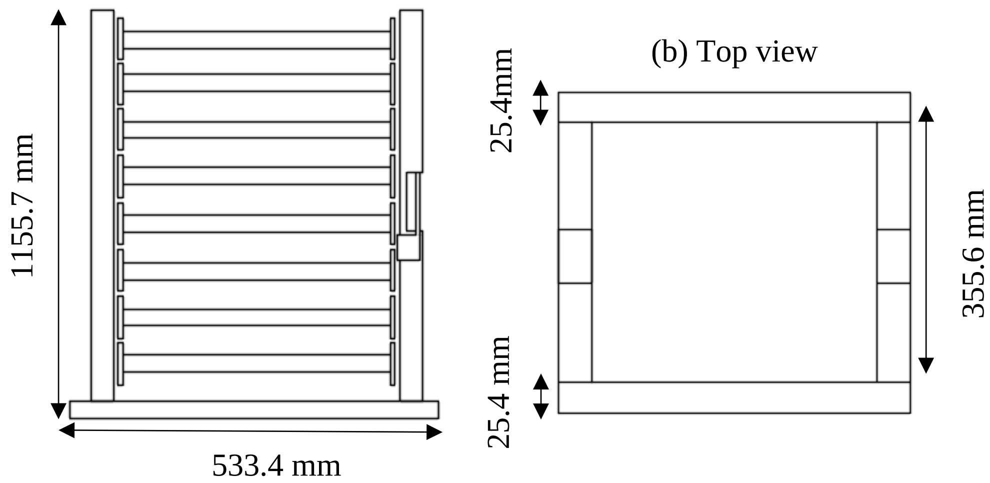


Figure 3.2: (a) Front View and (b) Top View of the Prototype

The design of prototype is as shown in Figure 3.2. It is drawn using AutoCAD software. Initially, the material that was used for building the base of the prototype was aluminium, as shown in Figure 3.3 (a). However, the author has encountered several problems while using aluminium as base. That is the aluminium is too light, and it cannot support the weight of window. Not only that, it is costly and it will increase the investment cost of the final product. Therefore, the author has changed the material to wood, which is cheaper and stronger.

(a)

(b)

Figure 3.3: (a) Aluminium Base and (b) Wooden Base

The side of the prototype is shown in Figure 3.4, the window (grey shaded) is supported with a piece of plywood (brown shaded). This is because the window has high centre of gravity and it is heavy, and it will not be stable if it is just supported by two screws attached to the wooden base. Therefore, the plywood is used to increases the number of supporting points (screw) attached to the wooden base to stabilize the prototype. Initially, the design is as shown in Figure 3.4 (a), but the author found out there’s probability for the sun to been block out by the plywood, especially the front part. Hence, the design is changed, as shown in Figure 3.4 (b). Now, the front part is not being covered, so the sun will not be blocked, and the back part will serve to have more supporting points attached to the wooden base.

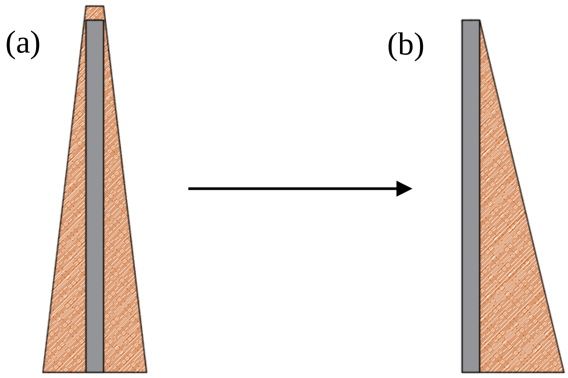


Figure 3.4: Side of the Prototype with (a) Initial Design and (b) Finalize Design

There are different sizes of solar cell that available in the market. The solar cell that the author used has a dimension of 107 mm x 24 mm, as shown in Figure 3.5. It has smaller width so that it can introduce more daylight to enter the building. Besides, it can also help to reduce shading effect. Figure 3.6 shows the window glass and solar cell with dimension measurement.

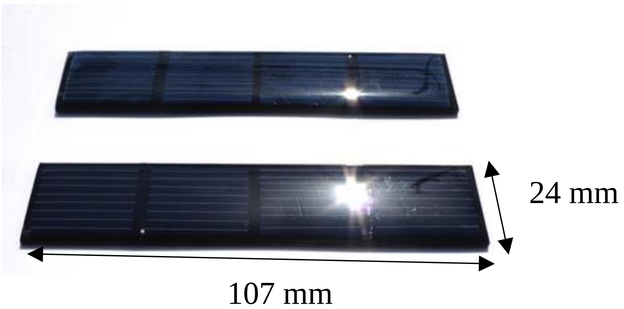


Figure 3.5: Dimensions of Solar Cell

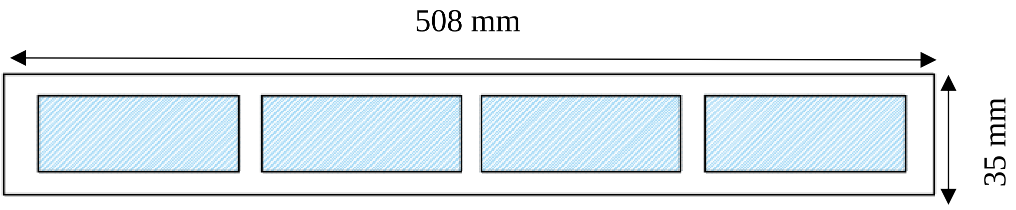


Figure 3.6: Window Glass and Solar Cell with Dimension Measurement

3.4 Circuitry design

It is costly to build a complete BIPV solar windows, hence the proposed prototype is being under designed in terms of the number of row of the solar cell in a present window. In this prototype, only 4 in series and 8 in parallel will be used to construct the angle adjustable solar window. The designed circuitry for the angle adjustable BIPV solar windows is shown in Figure 3.7. Table 3.2 shows the specification of the solar cell that the author bought.

Table 3.2: Specification of Solar Cell

Power	0.165W
Vmp	5.5V
Imp	30mA

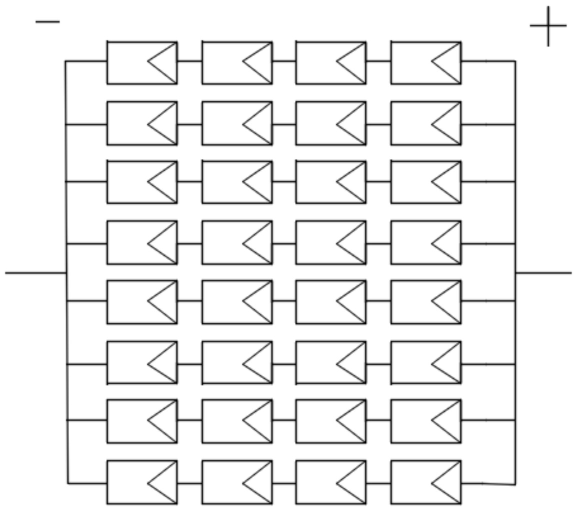


Figure 3.7: Designed Circuit for BIPV Solar Window

Figure 3.7 shows the circuitry for the solar cells that is installed on the window. This module made up of 32 units of solar cells. The solar cells are connected in series-parallel way to increase both voltage and current simultaneously. The open circuit voltage and short circuit current are calculated using Equation 3.1 and 3.2 respectively.

$$
\begin{aligned}
Voltage &= 4 \times V_{rated} \\
&= 4 \times 5.5\ V \\
&= 16.5\ V
\end{aligned}
\tag{3.1}
$$

$$
\begin{aligned}
Current &= 8 \times I_{rated} \\
&= 8 \times\ 0.03\ A \\
&= 0.24\ A
\end{aligned}
\tag{3.2}
$$

3.5 Material Purchasing

The sources of the where the material used is bought is important as high quality and cheaper price are assured. China is famous for solar cell manufacturing. Therefore, around 140 units of solar cell used in the prototype design are purchased via Taobao, a China-based company that is famous for online shopping. The solar cells are not bought from local manufacturer or online because China has variety of dimensions of solar cells compared with local one. Besides, the prices of solar cells bought from Taobao is also cheaper. The wood and plywood that used to build the prototype were bought from a hardware store near UTAR Sungai Long Campus.

3.6 Shading calculation

The performance of solar cells will greatly affect when shading occurred. Thus, a geometrical side view of the module is drawn to model the shading calculation. Figure 3.8 shows a simple geometrical drawing of the module from the side view. This is intended to make the calculation for shading to be easier. θ_e represents the sun elevation angle while θ_t represents the tilted angle of solar cells. The result from the calculation indicates the distance, h between two rows of solar panels so that shading effect will be reduced. Distance calculated can be observed from the side view of the module. The derivation for can be found in Appendix A. The results of the distance between two solar panels are calculated in Equation 3.4.

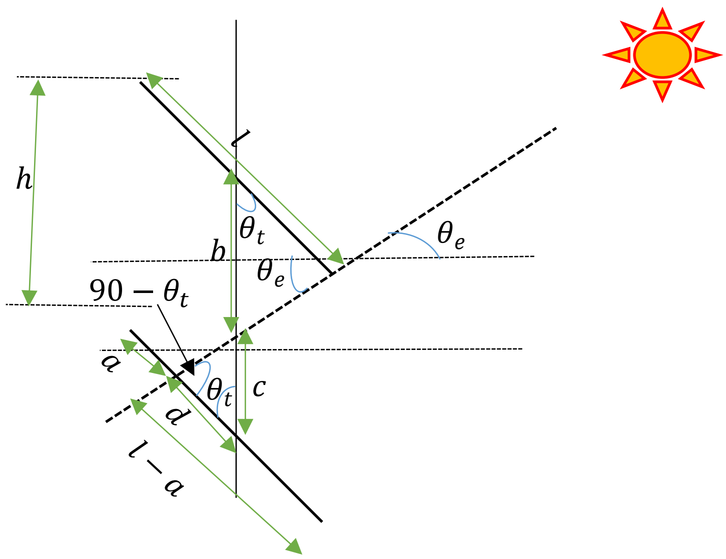


Figure 3.8: Side View of Solar Panels for Calculate Shading

$$h = (l-a)\frac{\sin(90°-\theta_t+\theta_e)}{\sin(90°-\theta_e)} \tag{3.3}$$

From Figure 3.6, the (l-a) value is set as 3.6cm, it is to assume shading will not occur. For the worst case, θ_t is set as 75º and θ_e is set as 86º. This value elevation angle of the sun is getting from the website of SunEarthTools.

$$h \ = (3.6cm)\frac{\sin(90°-85º+86º)}{\sin(90°-86º)} \tag{3.4}$$

$$h \ = 50.66cm$$

From the calculation above, the distance between two rows of solar panels should be 50.66cm to avoid the occurrence of shading. However, this value is unrealistic for this case, as the distance will be too big, and there will be less solar panels being installed and it will affect the final electricity produced by the solar window as well.

In this project, the distance between two rows of solar panels is set as 14cm and it is proved that there will be no shading occur for θ_e =75º for tilted angle of 85º. This distance is chosen as there will be also guarantee of the power output. The calculation is proved in Equation 3.5, for the worst case of $\theta_t = 85$º.

$$h \ = (3.6cm)\frac{\sin(90°-85º+75º)}{\sin(90°-75º)} \tag{3.5}$$

$$h \ = 13.90cm$$

3.7 Data collection

3.7.1 Comparing the Performance of BIPV Solar Windows Facing East with Different Tilting Angle

In this sub-subsection, the purpose is to find out the optimized titled angle, θ for BIPV solar windows. The titled angle, θ is defined as shown in Figure 3.9. The data will be collected by varying the angle with 15º, from 15º to 90º, as tabulated in Table 3.3. Four models of solar windows will be facing at same direction, in this project, East is chosen, but with four different tilted angle for the whole day. The experiment is then repeated with another four sets of tilted angles, until the tilted angle reaches 90º.

The data that will be collected for each module are power output and irradiance. A graph of power output against time for different titled angle will be plotted, and the area under the graph will indicate the energy generated by each module. Therefore, by comparing the calculated energy produced, the author can find out the optimized tilted angle.

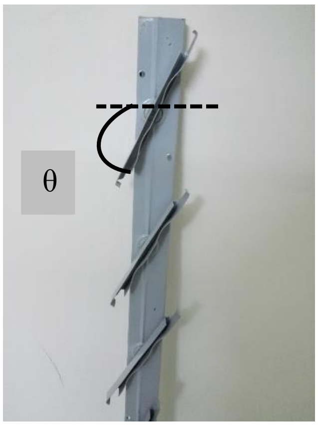


Figure 3.9: Tilted Angle, θ

Table 3.3: Template for Result of Different Tilted Angle

	Energy Generated, E (J)
15	
30	
45	
60	
75	
90	

3.7.2 Comparing the Performance of BIPV Solar Windows Facing Different Directions with Certain Tilted Angle

In this sub-subsection, four tilted angles will be chosen from previous sub-subsection to study the performance of modules facing different direction. The directions that the author chooses to be studied are North, South, and West. Similarly, the open circuit voltage, V_{OC} and short circuit current, I_{SC} are obtained with 5 minutes interval. The fill factor, FF cells is assumed to be constant and therefore power output at instantaneous time is calculated by multiplying V_{OC} with I_{SC}. A graph of power versus time will be plotted for each direction set comparison.

Table 3.4: Template for Result of Four Tilted Angle Facing Different Directions (North, West, and South)

Time	Irradiance, W/m^2	w^o		………		z^o	
		V_{OC}, V	I_{SC}, mA			V_{OC}, V	I_{SC}, mA
8.00 am							
8.05 am							
⋮							
5.00 pm							

3.7.3 Calibration

Figure 3.10 shows the module is being calibrated using mobile application and placed in such a way that the module is directly facing north. The mobile application used in the calibration is called Compass 360 Pro, which is easily available in the play store for android user or app store for iOS users.

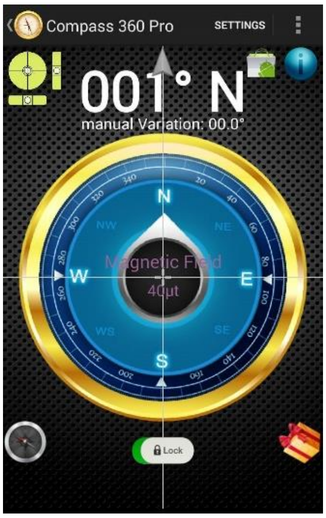


Figure 3.10: Virtual Compass by Compass 360 Pro

The next important calibration is the angle adjustment. Figure 3.11 shows the 30º angle tilted is measured using smart tool application. It is important to ensure each row of the solar cells is having the same tilted angle. Thus, each row of tilting angle has to be measured and adjusted respectively to make sure the desired angle is tilted.

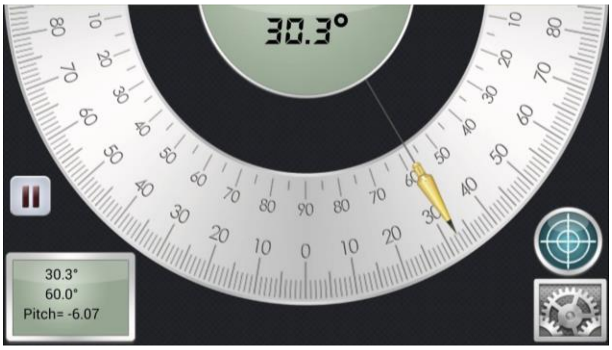


Figure 3.11: Virtual Protractor by Smart Tool

3.7.4 Measuring Tools

The open circuit voltage and short circuit current are taken with a multimeter, model Instek GDM-394, as shown in Figure3.12. Irradiance is measured by using a pyranometer, as shown in Figure 3.13. When the pyranometer is placed in the sun, its surface attains a temperature proportional to the amount of radiant energy falling on it.

The temperature is measured and converted through accurate calibration into a readout of the global solar irradiance falling on the absorbing surface. Global horizontal irradiance is took by placing the pyranometer in horizontal orientation, while global tilted irradiance is took by tilted the angle of pyranometer to the desired angle.

Figure 3.12: Instek GDM-394 Model Multimeter

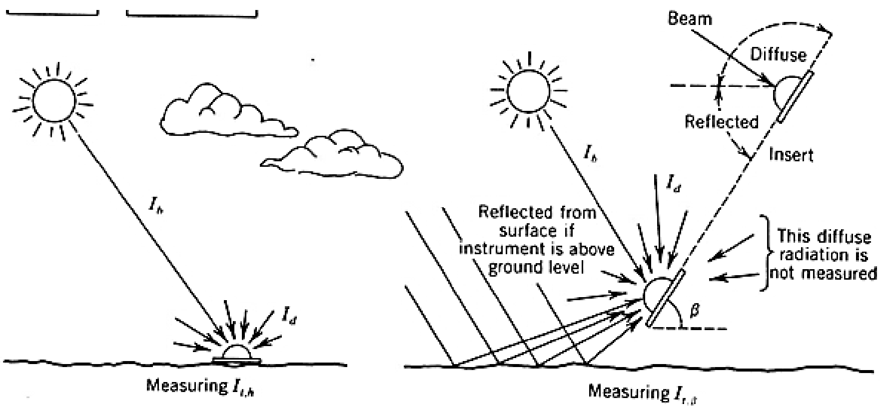


Figure 3.13: Pyranometer Used for Measure Solar Irradiance

3.8 Solar Cells Test

Functionality of solar cells ais tested using a multimeter and xenon lamp. The xenon lamp is switched on to shine the light onto the solar cell and the open circuit voltage and short circuit current were recorded immediately. Figure 3.14 shows the configuration for the test carried out. This test is main for find out whether the solar cell is functioning and determine the output of the solar cell. Through this test, the same output of solar cells has been categorized together in different group.

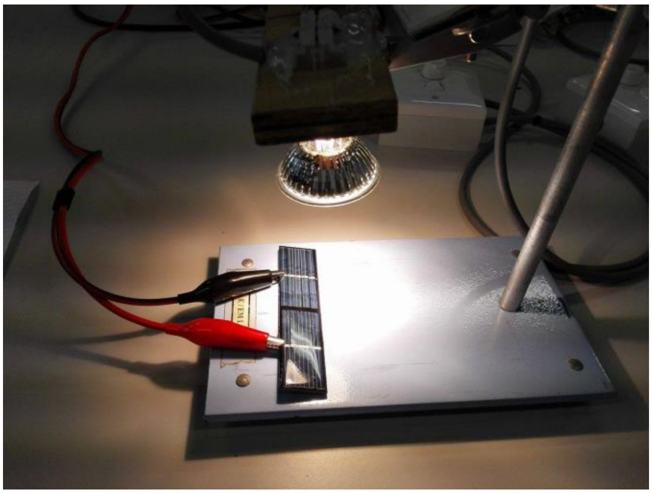


Figure 3.14: Solar Cell Testing

3.9 Calibration of modules

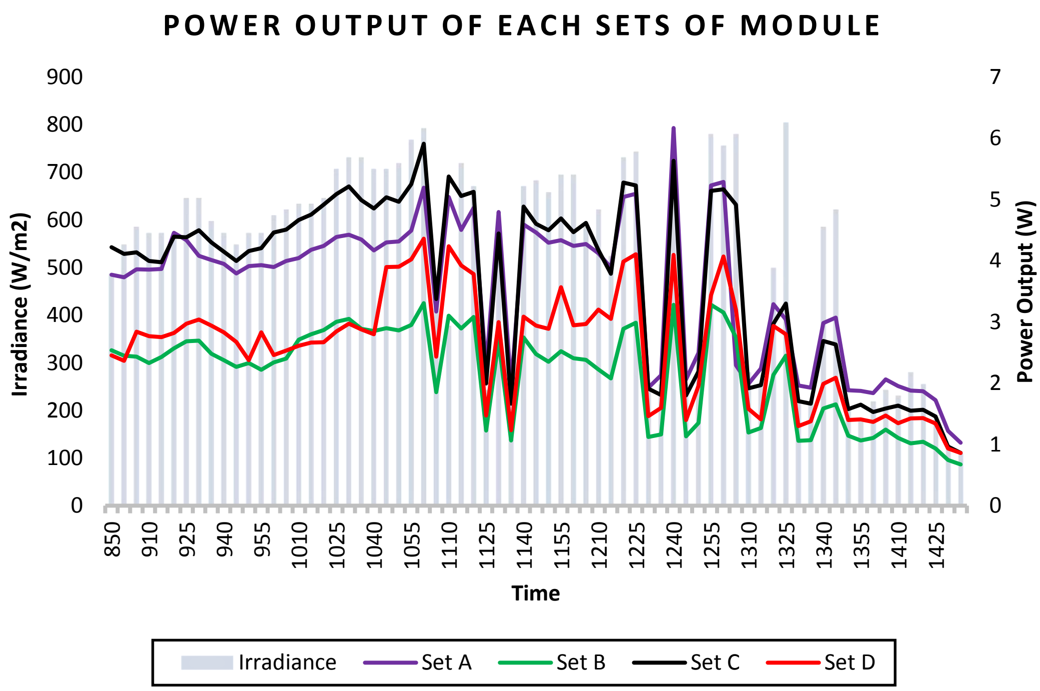


Figure 3.15: Graph of Power Output of Each Set of Module Facing East

There are four sets of solar window prototypes built and therefore calibration must be done to ensure the accuracy of the results. To do the calibration, all sets of prototypes are placed facing same direction, which is East and also with the same tilted angle, 60^o. The irradiance on the graph is the irradiance that received by the tilted pyranometer with 60^o. From Figure 3.15, it shows that Set C leads the others sets. Set B and Set D have relatively low power output compared to Set A and Set C. The possible reason for this is the mismatch of parallel connection of solar cells of different power during early stage. The solar cells that connect in parallel may have different voltage, and the solar cells with lower voltage would act as a load, and begin to absorb current. Thus, it degrades the overall power output of the module set B and set D.

Set A has been chosen to be a reference among all. The differences between each set with set A is calculated and these differences will be multiply into results that produced by each set for coming measurement for normalizing purpose. Besides, the power calculation by multiplying V_{OC} with I_{SC} is just to get the relative performance not the absolute value, because the fill factor within all solar panels are assumed to be same. Figure 3.16 show the total electricity generated for each module, normalize to full irradiance, which is 1000W/m^2, from 8.00am to 2.30pm.

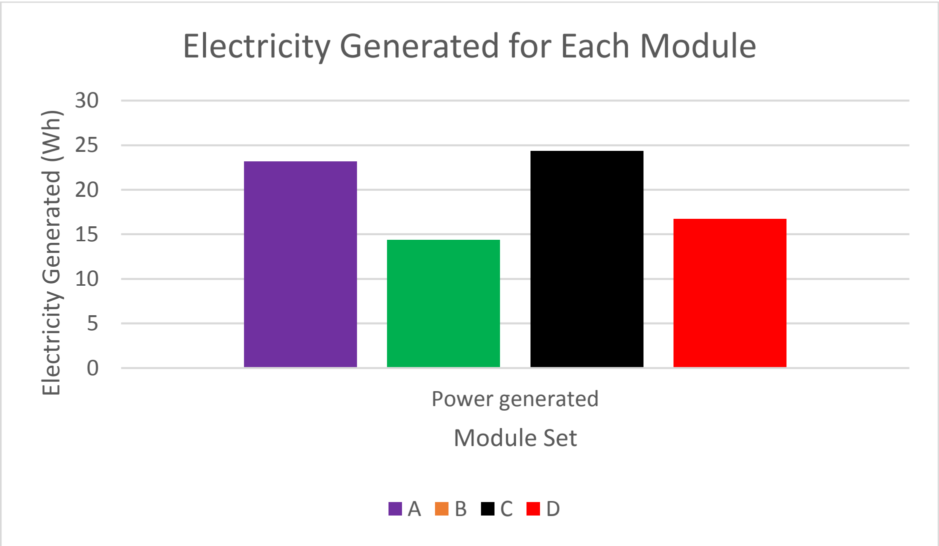


Figure 3.16: Total Power Output for Each Module

From Figure 3.16, it shows that the electricity generated for each module are 23.15Wh, 14.35Wh, 24.35Wh and 16.75Wh respectively. The percentage differences (PD) for set B, C, and D in respect to set A are calculated, and it can be found in Appendix B.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

The method used for data collection in this project is by doing experiment. Figure 4.1 shows how the four sets of solar windows been placed and with different tilted angle during the experiment. The data collection is done from the period of 13rd July to 23rd August 2016.

Figure 4.1: Four Sets of Prototype with Different Tilted Angle

In this chapter, the results of data collection are plotted in a presentable way and analysed quantitatively.

4.2 Various tilted angle of module facing East

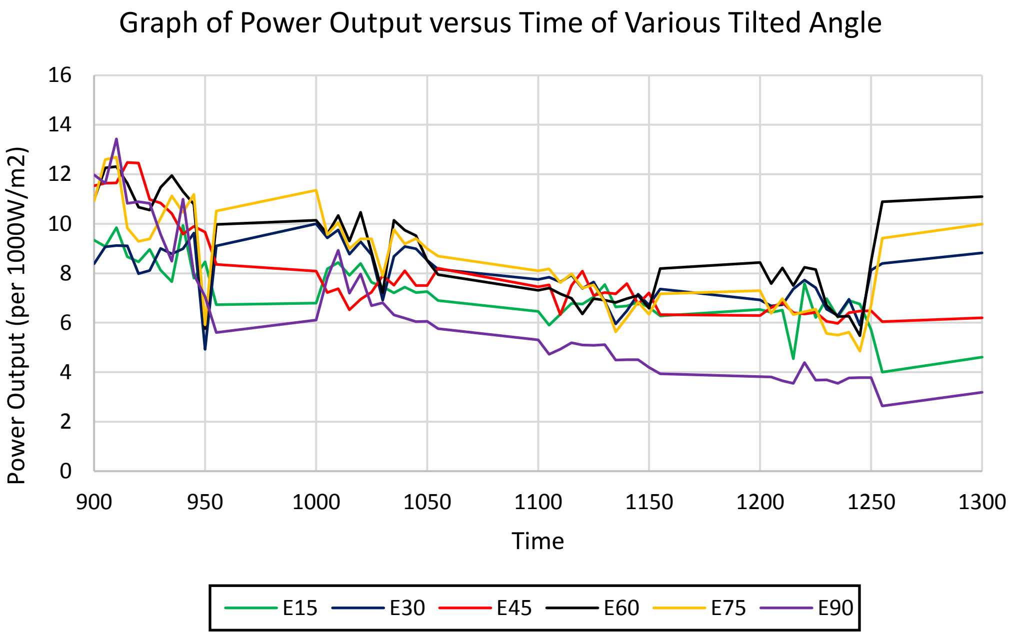


Figure 4.2: Graph of Power Output against Time of Different Tilted Angle

Figure 4.2 shows the power output of various tilted angle throughout the day. These data were taken in different days, and thus the power output is normalized to full irradiance, which is 1000W/m^2. The data were taken until 1.00pm because the modules are facing East and the sunlight will be blocked after solar noon. The results will be insignificant when it comes after solar noon as the power output will be low. This can be proved by Figure 3.15 in the previous chapter. Therefore, the modules do not receive much sunlight in the afternoon compared to the sunlight received in the morning.

Besides, the area under the graph indicates the electricity generated, in Watt-hour (Wh), by the module. From Figure 4.2, the solar window tilted with 60º leads the others, followed by 75º, 30º and 45º. To double confirm this results, a bar chart of electricity generated by each module with different tilted angle is plotted, as shown in Figure 4.3.

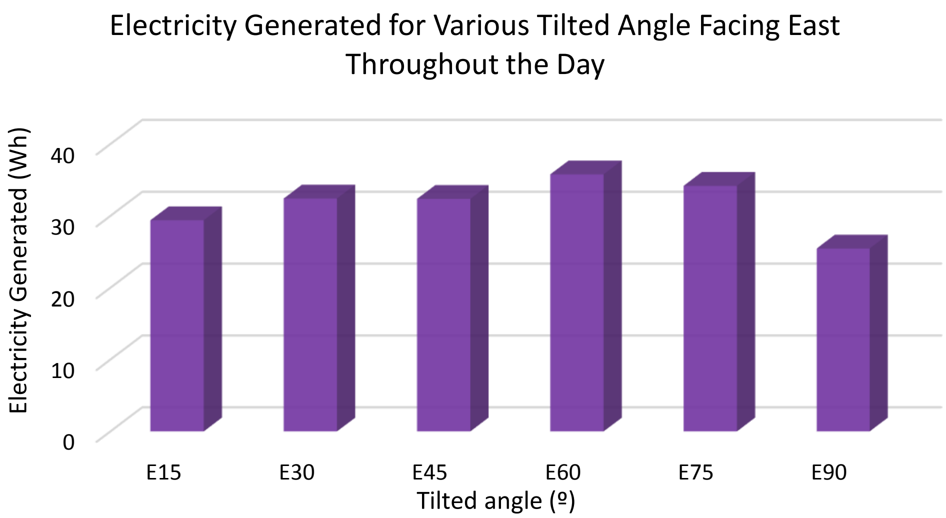


Figure 4.3: Bar Chart of Normalized Electricity Generated of Various Tilted Angle Facing East

Figure 4.3 shows that the module facing east with 60º tilted solar cells have the highest electricity generated than the others. The results also show that vertically placed solar cells have the lowest outcome. The percentage difference (PD) between performance of module facing East with 60º and 90º is calculated as followed:

$$PD = \frac{Electricity\ generated_{60°} - \ Electricity\ generated_{90°}}{Electricity\ generated_{60°}} \times 100\% \qquad (4.1)$$

$$= \frac{35.79\ Wh - 25.46\ Wh}{35.79\ Wh} \times 100\%$$

$$= 28.86\%$$

In a nutshell, the performance of solar window facing East with 60º tilted solar cells is the highest among others tilted angle and also with 28.56% greater than the commercial BIPV solar window with vertically placed solar cells.

4.3 Performance of module with certain tilted angle facing different directions

4.3.1 Performance of module facing North

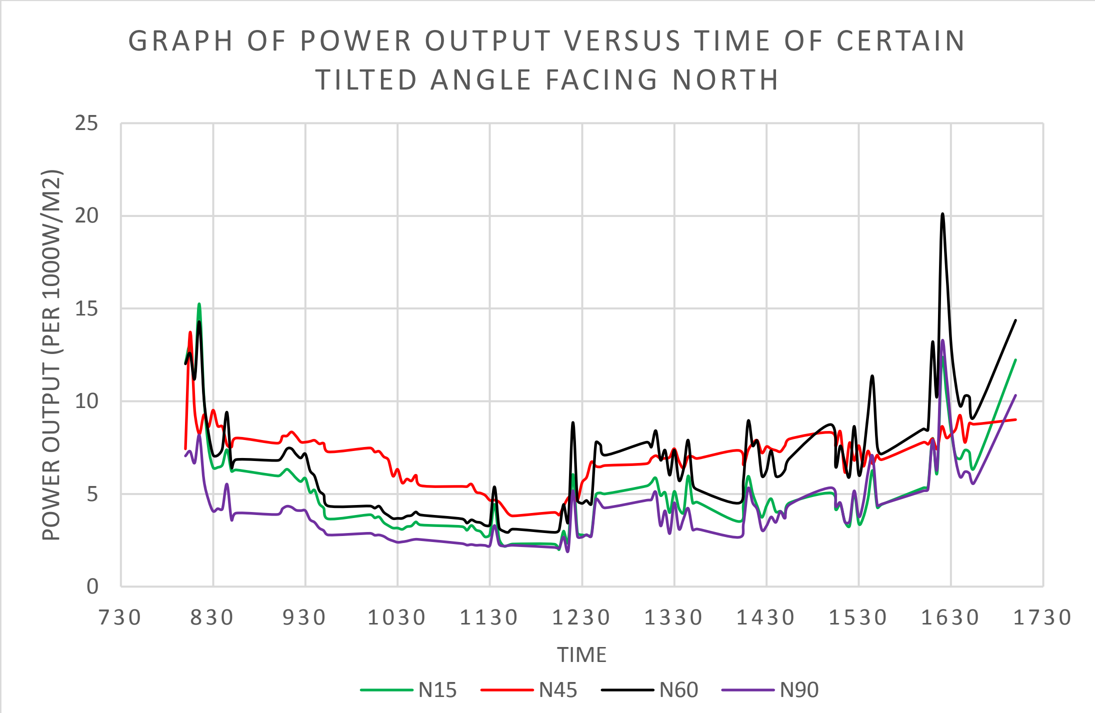


Figure 4.4: Graph of Power Output versus Time of Certain Tilted Angle Facing North

The results from Figure 4.4 shows that solar cells tilted with 45º lead the rest of tilted angle at most of the time. At the afternoon, 60º tilted solar cells takes over the 45º and leads. By average out the power output generated throughout the day, the 45º tilted has the highest power output among others. Besides, the results also show that the power output of vertical placed solar cells, 90º is the lowest during the day and increases slightly in the afternoon. The percentage differences (PD) of the performance of 60º tilted and 90º are compared by calculating the energy produced. Not only that, the performance of 45 º tilted and vertically placed solar cells also compared.

$$PD = \frac{Electricity\ generated_{60^\circ} - Electricity\ generated_{90^\circ}}{Electricity\ generated_{60^\circ}} \times 100\% \quad (4.2)$$

$$= \frac{62.64\,Wh - 37.94\,Wh}{62.64\,Wh} \times 100\%$$

$$= 39.43\%$$

$$PD = \frac{Electricity\ generated_{45^\circ} - Electricity\ generated_{90^\circ}}{Electricity\ generated_{45^\circ}} \times 100\% \quad (4.3)$$

$$= \frac{63.88\,Wh - 37.94\,Wh}{63.88\,Wh} \times 100\%$$

$$= 40.61\%$$

In short, the calculation above again proves that the energy produced by the module facing North with 60º tilted is 39.43% better than vertically placed solar window. In a meanwhile, module with 45º tilted is also 40.61% better than commercial BIPV solar window. This indicates that module with tilted angle solar cells will perform better as it experiences less cosine effect than vertically placed solar window.

4.3.2 Performance of module facing West

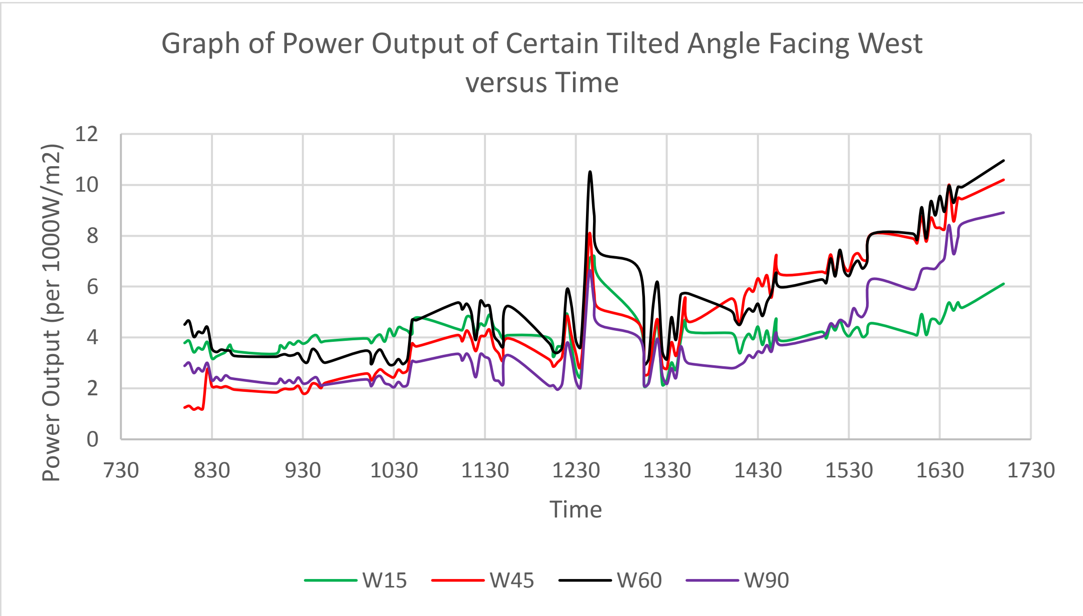


Figure 4.5: Graph of Power Output versus Time of Certain Tilted Angle Facing West

From Figure 4.5, the results show that the module facing West with solar cells tilted 60º leads the others most of the time. The power output for every module is lower in the morning as the modules are facing the opposite direction with the Sun. This is also the drawback of BIPV solar window as if it is installed to face either East or West, its performance is not that satisfying in the evening or morning respectively. However, it does perform well when it faces the same direction with the Sun. In addition, with the tilted angle of solar cells, the power output do increase compared to the commercial solar window. The percentage differences (PD) of the performance of 60º tilted and 90º are compared by calculating the energy produced.

$$PD = \frac{Electricity\ generated_{60^\circ} - Electricity\ generated_{90^\circ}}{Electricity\ generated_{60^\circ}} \times 100\% \tag{4.4}$$

$$= \frac{47.66\ Wh - 32.41\ Wh}{47.66\ Wh} \times 100\%$$

$$= 31.99\%$$

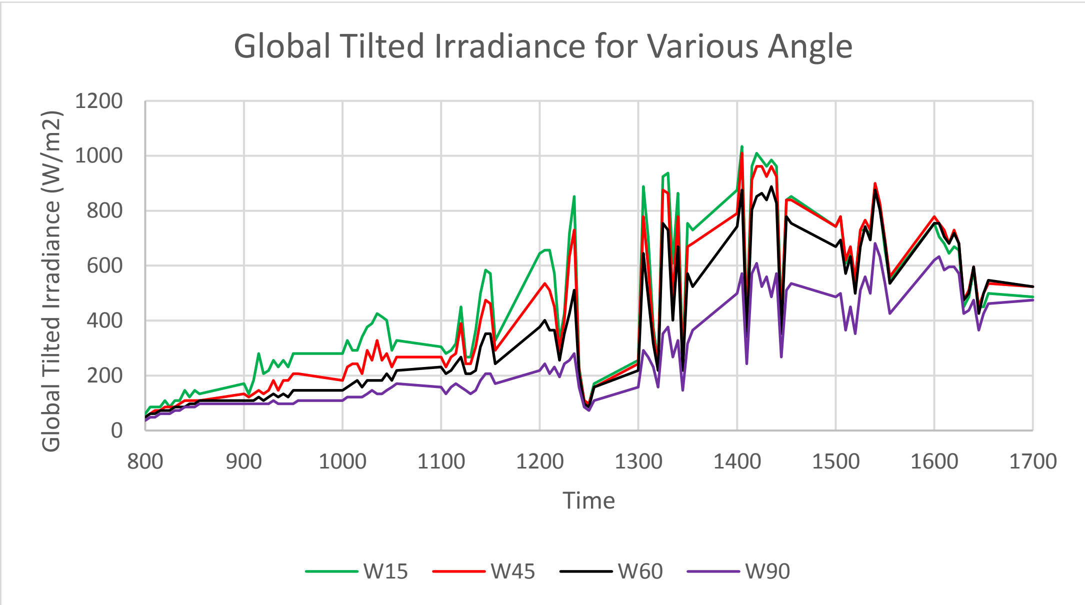


Figure 4.6: Graph of Global Tilted Irradiance for Different Tilted Angle

Figure 4.6 shows the graph of global tilted irradiance measured by pyranometer with different tilted angle on the same day. It shows that 15º tilted has the highest among all in the morning as the sun elevation angle is lower. The irradiance received by each tilted angle is quite consistent with the power output that shown in Figure 4.5.

However, it does shows some different especially for solar cells tilted with 15°, as it can received more sun irradiance but produced lesser power output than 45° and 60°. This can be explained as shading effect occurred for module with 15° tilted solar cells and this generally reduced the power outcome. Besides, it also shows that the sun irradiance received by vertically placed BIPV solar window is the lowest.

4.3.3 Performance of module facing South

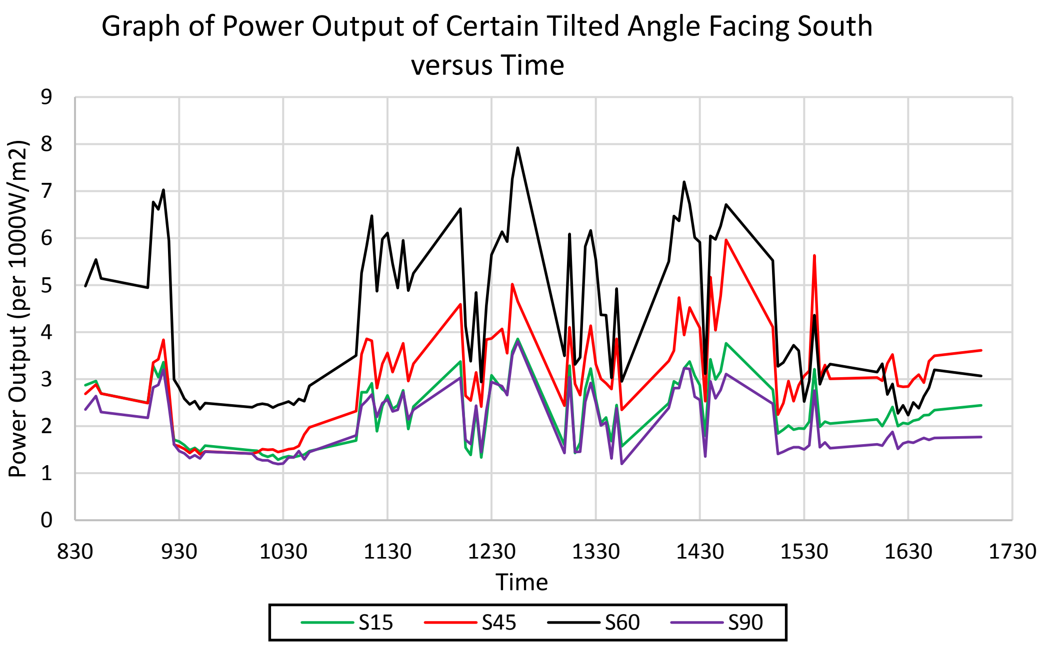


Figure 4.7: Graph of Power Output versus Time of Certain Tilted Angle Facing South

The results from Figure 4.7 shows that 60° tilted still leads the others tilted angle most of the time, followed by 45°, 15° and then 90°. This also indicates that the shading will first occur on 90°, then followed by 15° and 45°. The percentage differences (PD) of the performance of 60° tilted and 90° are compared by calculating the energy produced.

$$PD = \frac{Electricity\ generated_{60^\circ} - Electricity\ generated_{90^\circ}}{Electricity\ generated_{60^\circ}} \times 100\% \qquad (4.5)$$

$$= \frac{39.11\ Wh - 18.73\ Wh}{39.11\ Wh} \times 100\%$$

$$= 52.11\%$$

The calculation above has shown that the 60º tilted is 52.11% better than the vertically placed solar cells. This is mainly because of the large cosine effect by 90º due to the high sun altitude in Malaysia.

4.3.4 Comparison of Performance for Four Different Directions

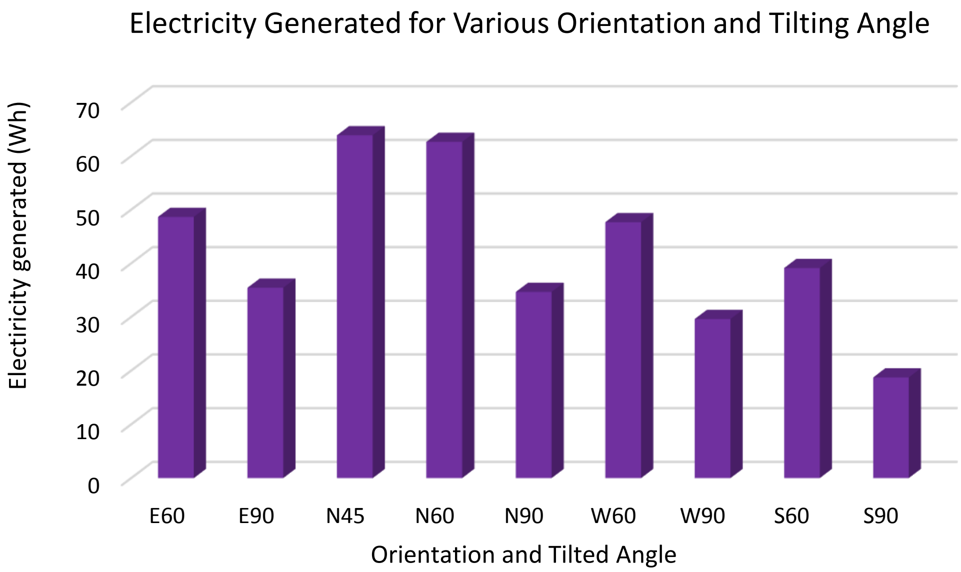


Figure 4.8: Bar Chart of Electricity Generated for Various Orientation and Tilting Angle

Figure 4.8 shows the electricity produced, in Watt-hour (Wh) per day for different orientation and tilted angle. It also shows commercial BIPV solar windows which with vertically placed solar cells have relatively low performance than the tilted angle in each of every direction that have studied. Even though BIPV solar windows that facing East and West have its drawback as discussed in previous sub-subsection, but it still generates higher electricity. The electricity generated by module facing South is lower compared to other three directions as the sun trajectory before September equinox is at the northern region. In general, it can be concluded that the BIPV solar window with tilted angle solar cells is more suitable to be installed especially in equatorial countries which have higher sun altitude, such as Malaysia.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

In a nutshell, the technology of commercial BIPV solar window that available in Malaysia is adopted from the western countries. However, it is less suitable for equatorial countries such as Malaysia as the sun altitude is generally high throughout the year. The high sun altitude in Malaysia greatly increase the cosine effect and this gradually weakens the electricity generated by vertically placed solar cells on windows. Therefore, BIPV solar window with angle adjustable solar cells is introduced in this project.

From Chapter 4, it clearly shows that the tilted solar cells can perform well far better than the vertically placed solar cells. In short, 60º tilted has the greatest electricity generation for module facing East, West, and South. Whereas for module facing North, 45º tilted solar cells has the highest output.

These BIPV solar windows are targeted for the high-rise building as the rooftop may has lesser space to install solar panels. Double layered glass have be used as it provide protection to the building as well as heat insulator. This innovation also makes used of the advantage of number of windows that has been installed in the high-rise building. It can provide better aesthetic effect at the same time allows sunlight pass through and provide better daylighting effect.

5.2 Recommendations

To provide a better end product to the project, there are some points that the author had in mind. Deeper understanding of the project would be a benefit and would be helpful in producing better end results.

The prototype constructed is not perfect. One limitation of the prototype is the power output generated by each set of modules are differ even though they are facing same direction with same tilted angle. Thus, the circuitry of each module has to reconnect. Parallel connected only for solar cells that having same voltage.

Besides that, the effective angle is found to be 60°. In actual practical, this effective angle can be further narrow down to the most accurate result. Another comparison is needed to refine the search for the effective angle. The author suggests that module with 60° to be compared with module ± 5° can further narrow the search for the effective angle. The period of data collection should also be extended as the sun azimuth is different and this also make the results more convincing.

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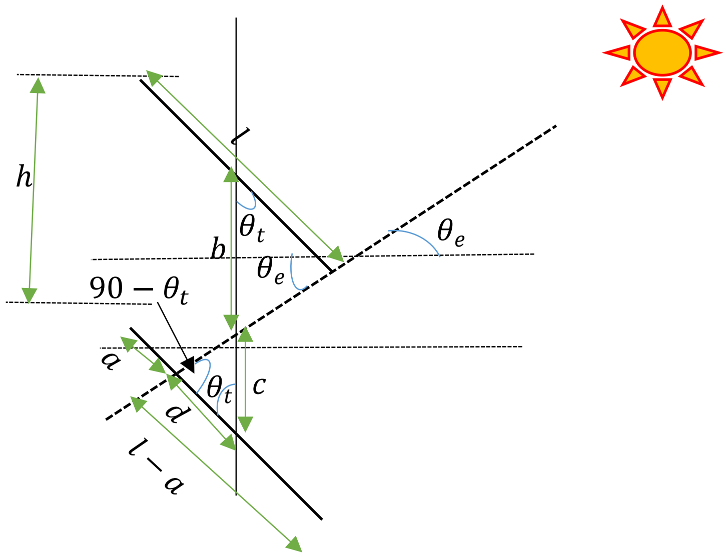
APPENDICES

APPENDIX A: Formula for Shading Calculation



By using sine rule,

$$\frac{b}{\sin(90°-\theta_t+\theta_e)} = \frac{(\frac{l}{2})}{\sin(90°-\theta_e)}$$

Rearrange,

$$b = \left(\frac{l}{2}\right) \times \frac{\sin(90°-\theta_t+\theta_e)}{\sin(90°-\theta_e)}$$

$$c = h - b, \quad \text{(Substitute b)}$$

$$= h - \left[\left(\frac{l}{2}\right) \times \frac{\sin(90°-\theta_t+\theta_e)}{\sin(90°-\theta_e)}\right]$$

By using sine rule again,

$$\frac{c}{\sin(90°-\theta_t+\theta_e)} = \frac{d}{\sin(90°-\theta_e)}$$

Rearrange,

$$d = c\,\frac{\sin(90°-\theta_e)}{\sin(90°-\theta_t+\theta_e)} \quad \text{(Substitute c)}$$

$$= h - \left[\left(\frac{l}{2}\right) \times \frac{\sin(90°-\theta_t+\theta_e)}{\sin(90°-\theta_e)}\right]\left[\frac{\sin(90°-\theta_e)}{\sin(90°-\theta_t+\theta_e)}\right]$$

$$= h\,\frac{\sin(90°-\theta_e)}{\sin(90°-\theta_t+\theta_e)} - \frac{l}{2}$$

$$a = \frac{l}{2} - d, \quad \text{(Substitute d)}$$

$$= \frac{l}{2} - \left[h\,\frac{\sin(90°-\theta_e)}{\sin(90°-\theta_t+\theta_e)} - \frac{l}{2}\right]$$

$$= l - h\,\frac{\sin(90°-\theta_e)}{\sin(90°-\theta_t+\theta_e)}$$

$$l - a = l - \left[l - h\,\frac{\sin(90°-\theta_e)}{\sin(90°-\theta_t+\theta_e)}\right] \quad \text{, (Substitute a)}$$

$$= h\,\frac{\sin(90°-\theta_e)}{\sin(90°-\theta_t+\theta_e)}$$

Therefore,

$$h = (l-a)\frac{\sin(90° - \theta_t + \theta_e)}{\sin(90° - \theta_e)}$$

APPENDIX B: Calculation of Percentage Differences of Modules

Table B.1: Electricity Generated for Each Module Facing East at 60º Tilted (from 8.00am to 2.30pm)

Set	Electricity Generated (Wh)
A	23.15
B	14.35
C	24.35
D	16.75

For Set B,

$$PD = \frac{|\,23.15 - 14.35|Wh}{14.35\ Wh}$$
$$= 0.6132$$

Thus, the results from Set B will be multiply by 1.6132.

For Set C,

$$PD = 1 - [\frac{|23.15 - 24.35|Wh}{24.35\ Wh}]$$
$$= 1 - 0.0493$$
$$= 0.9507$$

Thus, the results from Set C will be multiply by 0.9507.

For Set D ,

$$PD = \frac{(\,23.15 - 16.75)Wh}{16.75\,Wh}$$

$$= 0.3821$$

Thus, the results from Set B will be multiply by 1.3821.