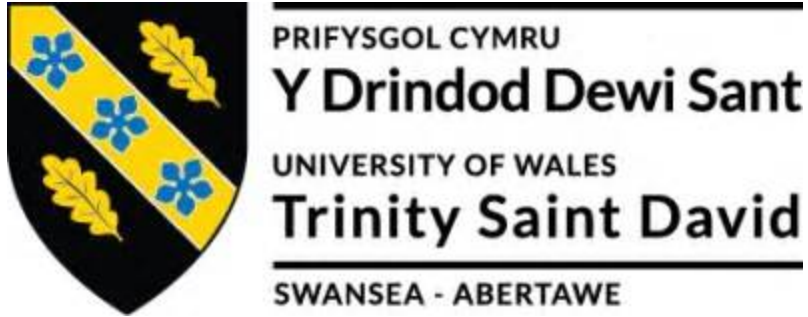




University Of Wales Trinity Saint David – Swansea

BEng Mechanical and Manufacturing Engineering

**Enhance the performance of PV Solar Panels by using
optimal tilt angle**

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Abstract

Electricity produced from renewable energy sources is in greater demand today as it alleviates the need to burn polluting fuels like oil and coal to generate electricity. The production of electricity from PV solar panels has great advantages towards dropping the cost and keeping the environment friendly. In order to maintain an efficient operation of the PV solar panel and having the maximum output power produced, the direction of the PV solar panels should be facing in a southerly direction of the sun. This will ensure the maximum sunlight radiation which has a direct impact on the amount of electrical power produced. The tilt angle is the main parameter that should be considered when PV solar panels are installed. Depending upon the geographical area, the tilt angle should be designed in order to gain the maximum output power. The work conducted in this project was to investigate the most suitable optimum tilt angle which was 30° for the indoor test, as well as the most suitable optimum tilt angle for a location outskirts of Riyadh in KSA was 35°. The measurements made on the site were validated with the theoretical calculations made on different days and for different temperature. Moreover, the theoretical calculations for the output power of a PV solar panel were compared between different locations in the world in order to find out which optimum tilt angle need to be used. A suitable mounting system made of Aluminium was suggested to be used to mount the PV solar panel on it. Finally, a tracking system was suggested in order to reposition the PV solar system that it produces the maximum power.

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Chapter 1

Introduction

1.1 Reasons why the Project is Viable

The electricity produced from PV solar panels became more desirable today because many countries are trying to reduce the dependency upon the fuel based electricity generation in order to reduce the cost and keep the emission low and the environment clean. However, the electrical energy produced using solar technologies is a green renewable energy because it does produce pollution (Boyle, 2011).

There are different factors which has influence on the efficiency of producing electricity from PV solar panels. These factors are tilting angle, the location of the solar panels with respect to the sun light direction and how much irradiation incurred on that specific location (Brook & Dunlop, 2012). Furthermore there are other factors which have impact on the operating efficiency of the PV solar panels such as the operating temperature, the amount of dirtiness because of the weather on the surface of the PV panels, the different losses produced due to the cables connected between the panels and the invertors and the shadow produced when an array of panels are installed. (<http://photovoltaic-software.com/PV-solar-energy-calculation.php>).

Since the tilt angle is the main factor which it has a direct influence on the operating efficiency of the PV solar, there are certain requirement which need to be considered before installing PV solar panels. This requirement is to record the amount of irradiance using a Pyranometer (Hanif et al., 2012) for different tilt angles. This will help to calculate the annual amount of electricity produced as described in the following equation (*Best Practice Guide PV solar*) which is used to determine whether installing PV solar panels is feasible or not:

$$P_{out}(kWh) = 0.8 \times kW_P \times S \times ZPV \quad 1-1$$

Where KW_P is the installed peak power which depends upon the type of PV solar panel, S is the annual solar radiation depending upon the tilt angle and the location of the solar panels towards the direction of the sun light (example; South, South West, South East, North,...etc).

Table 1 is shown the estimating available solar radiation in Ireland:

Tilt of Collector	Orientation of Collector				
	S	SE/SW	E/W	NE/NW	N
Horizontal	963	963	963	963	963
15°	1036	1005	929	848	813
30°	1074	1021	886	736	676
45°	1072	1005	837	644	556
60°	1027	956	778	574	463
75°	942	879	708	515	416
Vertical	822	773	628	461	380

Table 1: Annual Solar Radiation (kWh/m²). (Best Practice Guide PV solar).

Z_{PV} is the shadow factor which it has a value ≤ 1 , which has an impact on the performance factor of the PV solar panel.

Example:

For an array of 5 monocrystalline silicon panels (approx. 0.6 m² per panel) each with a peak power of 185 W_P, mounted on the roof with 45° pitch facing directly south with no over-shading, the total installed capacity would be:

$$0.185 \times 5 = 0.925 \text{ KWp.}$$

The annual output would be:

$$0.8 \times 0.925 \times 1072 \times 1 = 793.28 \text{ kWh.}$$

An optimal tilt angle is used when a solar collection device is designed. According to Ibrahim (1995), it is essential to choose an optimal tilt angle that guarantees the highest solar radiation reaches the surface of the solar collection device. However, the facing south is the best position for the solar collection device in order to ensure the highest solar radiation at a given tilt angle between 0 and 90 degree. Li and Lam (2007) showed that the optimum tilt angle and the optimum orientation are essential to determine the feasibility of using PV solar panels. In many locations there is a possibility that efficient data about solar radiation is difficult to collect, therefore a certain numerical method can be used to calculate the highest solar radiation, and the angle of the solar panels that yield the highest solar radiation is the tilt angle. Kumar et al (2014) showed that mounting PV solar panel at different tilt angles results different output power and operating

efficiency. He conducted an experiment in India and the outcome results were the highest output power achieved when the tilt angle was between 5-10 degrees during the month June in 2013. Furthermore, different types of PV solar panels were used and they came back with same results. Other associated angles, namely the declination and latitude angles (Tamimi&Sowayan, 2012) and Chandrakar& Tiwari, 2013) are used to calculate the solar radiation incident on a PV solar panel in kW/m².

In this project the performance of a PV solar panel was researched in terms of the tile angle. Two types of measurement such as outdoor in Kingdom of Saudi Arabia and an indoor measurement in the Lab's building at the University of Wales Trinity Saint David were conducted in order to study the optimal tilt angle.

The report is divided into 6 chapters; the first chapter is an introduction about the project and how valuable it is to industry as well as the private sector. It contains the aim and objectives of the report. The second chapter is intensive literature review about the subject; it contains many works done in the past about how to determine the optimum tilt angle and which parameters have an influence on the output power of a PV solar panel. The third chapter includes the methodology which contains the outdoor and indoor measurements scenarios conducted during the project time. The fourth chapter is the results and analysis of the data taken from the measurements and from the theoretical calculations. The chapter 5 is a discussion of the results and analysis and link them to the literature conducted earlier. At the end chapter an efficient conclusion and recommendation is added to the report.

1.2 Aims of the Project

The aim of the project is to investigate how the performance of PV solar panels can be enhanced by adjusting the tilt angle.

1.3 Objectives

In order to achieve the aim, the initial objectives are listed below:

- Design and build a suitable base using SolidWorks in order to mount the PV solar panel
- Adjust the PV solar panel at different tilt angles for an outdoor such as (0, 35, 40, 60 and 90)° and an indoor such as (15, 30, 45, 55 and 65)° measurements such to calculate the output power for different tilt angles.
- To analyse findings and draw conclusions from the research done and make viable recommendations.

1.4 Time Scales and Provisional Work Plan

A time frame work should be designed in order to show all activities need to be done during the project phase. These will be considered as a road map of the project and should give a close estimation for the time required to finish each part of the project. For this project a provisional time scale is shown in the next page;

Time	Task
Week 3	Research for information from literature.
Week 5	Determining the suitable PV solar panels which will be used during the test.
Week 6	Design and build a base using SolidWork.
Week10	Starting to make indoor and outdoor tests at different tilt angles.
Week14	Compare the operating efficiency between what will be calculated and measured.
Week 16	Documenting and writing up the final report.

Table 2: work plan.

1.5 Project summary

The project has two major parts namely the research among vast of literatures and the practical part which includes conducting indoor and outdoor measurements. The data achieved will be analysed in order to observe the optimum tilt angle. The data is compared to theoretical data calculated for the same location to find out which tilt angle comes out with the highest output power. Other parameters associated with the tilt angle will be investigated in order to show how they influence the output power. A suitable base will be designed using SolidWorks and suitable material such as aluminium will be used to build the mounting system.

1.6 Project plan and Gantt chart

Activity	Week No.s from 11/10/2016 to 01/05/2017																														
	w1	w2	w3	w4	w5	w6	w7	w8	w9	w10	w11	w12	w13	w14	w15	w16	w17	w18	w19	w20	w21	w22	w23	w24	w25	w26	w27	w28	w29	w30	w31
Literature review (the impact of tilt and elevation angle .material for the base.etc)																															
develop experiments specifications																															
prepare the first poster																															
develop mounting system																															
prepare the first intirm viva																															
Christmas and new year holidays																															
design and fabricate the mounting system																															
Carrying out experiments on different scenarios																															
prepare the second presentation																															
start writing up and Easter holiday																															
submit the first draft																															
submit the final draft																															
Presentation of the project																															
Finish																															

Chapter 2

Literature review

2.1 Introduction

The output power produced by a PV solar panel is directly proportional factors such as the amount of irradiation, the size of the panel and the performance factors as shown in the equation below. (<http://photovoltaic-software.com/PV-solar-energy-calculation.php>):

$$E = A \times r \times H \times PR \quad 2-1$$

Where:

E is the Energy (kWh).

A is the area of all PV solar panels used (m²)

r is the solar panel yield, which is the ratio of the peak solar power to the area of a solar panel

H is the annual average solar radiation on the panels mounted on certain tilt angle and no shading effect. However, the annular irradiation for the given azimuth and altitude of the panels are used to calculate this parameter.

PR is the performance ratio in degree.

The last factor is used to measure the performance of the PV solar disregards the impacts of the roofing inclination angle and the localization of the PV solar panels.

The tilt angle has a crucial effect on the output power of the PV solar panels and the mounting system should be well designed before PV solar panels are installed.

2.2 Types of PV solar panels

There are different types of PV solar panels which are used to produce electricity from converting the sunlight. The most popular PV solar panels are the mono-crystalline silicon, multi-crystalline silicon, amorphous silicon cells (Bouzoukas, 2008) and Gallium Arsenide GaAs solar panels (Hughes, 2012). Each type of them has specifications, advantages and disadvantages according to the usage. The following table 3 shows the main types of PV solar panels with advantages and disadvantages (Alanzi, 2016).

PV Solar type	Advantages	Disadvantages
Mono-crystalline Silicon Cells	• high operating efficiency • Low installation cost • Can last for long time up to 50 years (http://www.solar-facts-and-advice.com/monocrystalline.html)	• Complex manufacturing. • High sensitivity towards infrared and radiation of an electromagnetic
Multi-crystalline Silicon Cells	• Low manufacturing technologies • Less amount of silicon waste during the manufacturing (http://energyinformative.org/best-solar-panel-monocrystalline-polycrystalline-thin-film/) • Slightly lower heat tolerance	• Low quality • Low operating efficiency (12%) due to the internal resistance at the boundaries of the silicon crystals
Amorphous Silicon cells	• thin and flexible silicon solar PV • suitable for the manufacturing of the curved surface solar	• Subject to internal energy losses • Perform low (6% operating)

Cadmium Telluride Cell (thin film)	• Average manufacturing technologies • Operating efficiency is high	• low power • Has restrictions when they are used only with low voltage devices
Gallium Arsenide GaAs	• High performance • Could reach up to 40% of the rate conversion the sunlight into electricity.	• Expensive to produce • Has high poisonous material which has severe environment impact if it is polluted • Too expensive for mass markets • Has a limited applications for space-borne and military

Table 3: advantages and disadvantages of different types of PV solar panels (Alanzi, 2016).

2.3 Principle of operations

The principle of operation is defined by many authors and is based on a semiconductor device which is sensitive to sunlight when exposed to it, it causes electrons to move between the conducting layers which results in electric current flows from the negative side of the semiconductor device to the positive side through a closed circuit (Boyle, 2011).

The output power produced by one PV solar panels is relatively small and cannot be used to fulfil a high usage, consequently a multiple of PV solar panels are used in order to produce enough energy for a given application (Notton, et al, 2005).

The PV solar cells have multi layers which consist of different materials such as cover glass, transparent adhesive, anti-reflective adhesive, front contact, N-type semiconductor, P-type semiconductor, and back contact according to (Notton et al, 2005).

The principle of operation is based on sunlight hitting solar panels. The semiconducting material such as the silicon that exists in the PV solar panels absorbs the photons. The electrons in the semiconductor will be excited and move into the electrode through channels inside the cell which cause potential difference at the positive and negative ages of the cell which is responsible to generate electricity. When a load is connected to the cell an electric current flows through the load circuit from the negative side into the positive side. The amount of electricity produced will be influenced by the temperature in such a way if the temperature is high the operating efficiency will be reduced.

According to Boyle (2011) there is a p-n junction in the semiconductor in which the photons will fall with it when sunlight is directed on the surface of the PV solar panel. The electrons will gain energy which makes them move freely through the p-n junction and create the electric current. Holes will be left behind and electrons will move in the opposite direction of the electrons as seen in the figure (1). The electron will be attracted by the 'p' side while the holes will be attracted by the 'n' side.

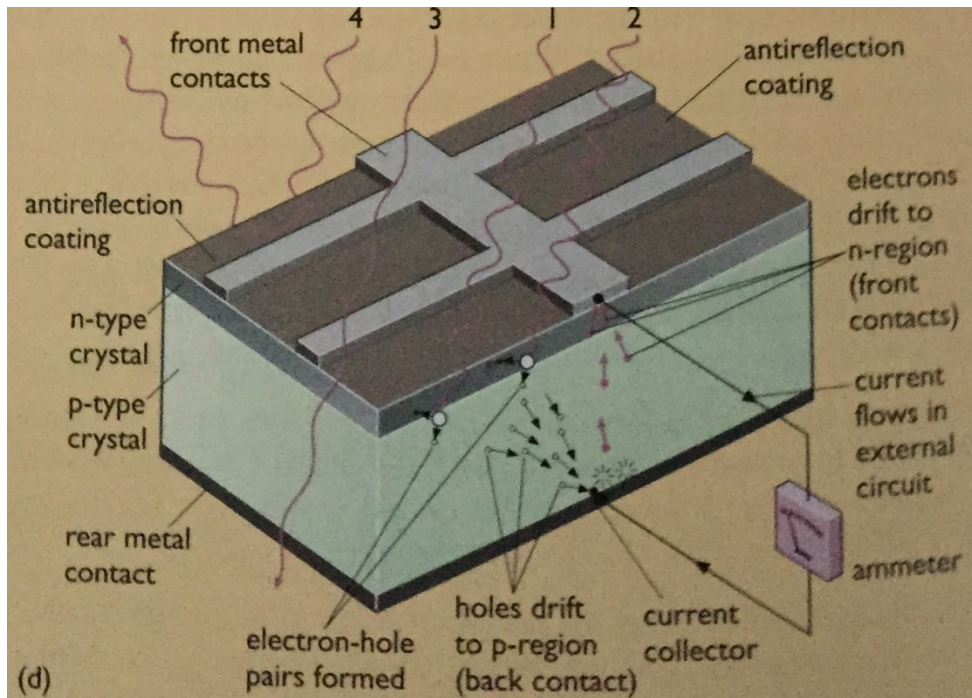


Figure 1: shows the p-n semiconductor and the structure (Bolye, 2011, p, 82).

At a final stage on the junction layer, positive charges will be near to the n-side and negative charges will be near to the p-side. Consequently a depletion region is created around the junction. If there is an external circuit connected to the PV solar, an electric current will flow through the circuit.

2.4 Operating efficiency

The operating efficiency of a PV solar panel is determined by following different scenarios. Most of these scenarios are made in conjunction with suitable measurement's environment and it should be a real one in order to get realistic output power. One of the interested researches was conducted on a large tanker ship in order to measure the electrical energy storage required for the ship at an optimal tilt angle of the PV solar array of panels (Lan et al, 2015). The research considered the impact of a little shadow when the output electrical power was measured at the mentioned optimal tilt angle. Other research was conducted by Bazyari et al (2014) in order to investigate the necessity of a tracking system of single or double axes to change the tilt angle of PV solar array that it utilises the radiation of the sunlight efficiently so that the maximum output

power can be generated. Abdul-Wahid and Mehdi (2010) showed the impact of the tilt angle being changed during a year.

This is because of the sunlight intensity varies during a year. However, the high intensity of the sunlight is between May and August or beginning of September in the Middle East, see figures (2 and 3) which show the highest current produced from the PV solar was achieved between 10:00 AM and 1:00 PM.

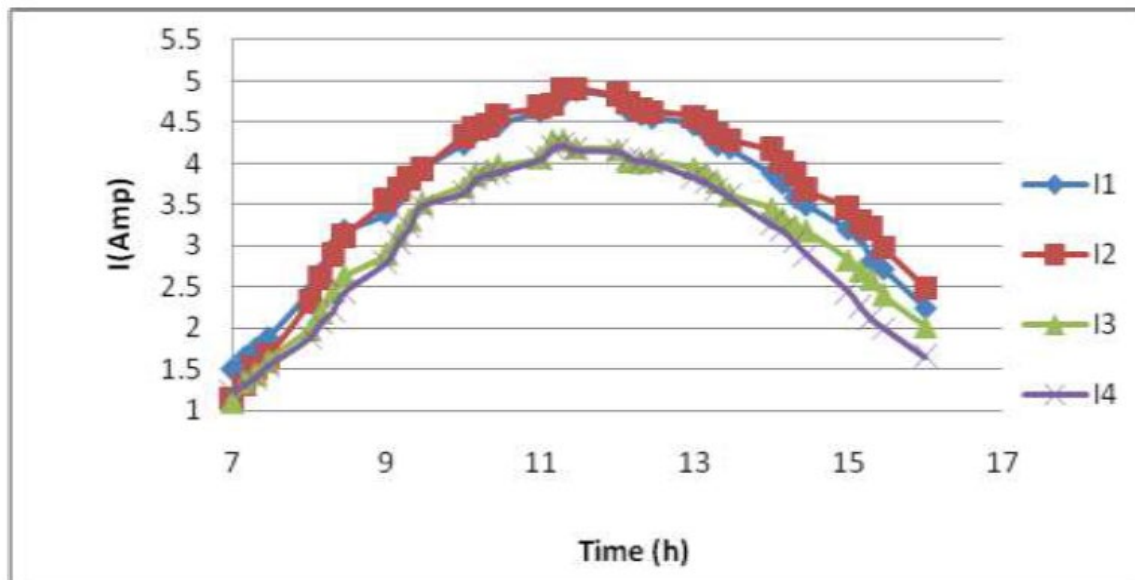


Figure 2: shows the variation of the output current from the PV solar panel during one day in August 2009 (Abdul-Wahid & Mehdi, 2010).

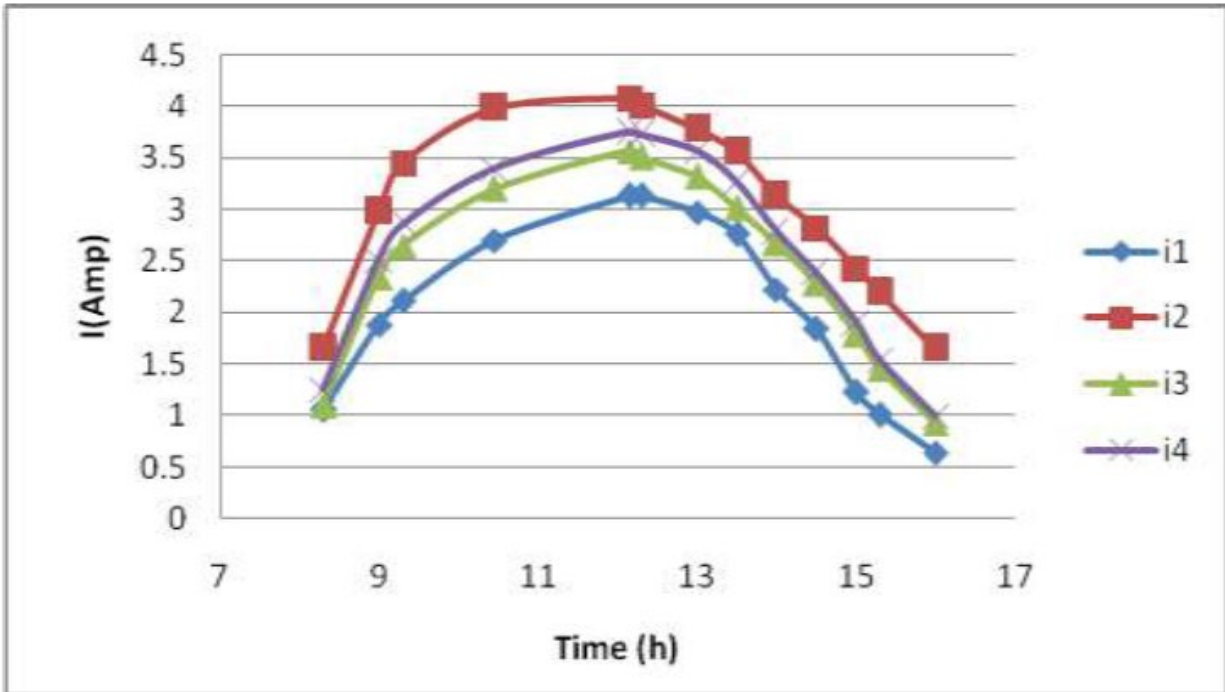


Figure 3: shows the variation of the output current from the PV solar panel during one day in January 2010 (Abdul-Wahid & Mehdi, 2010).

2.5 Characteristics of PV module

It is determined by the curve shown in figure (4) below. This curve shows how the power to voltage or current to voltage changes when the solar irradiation and cell temperature change.

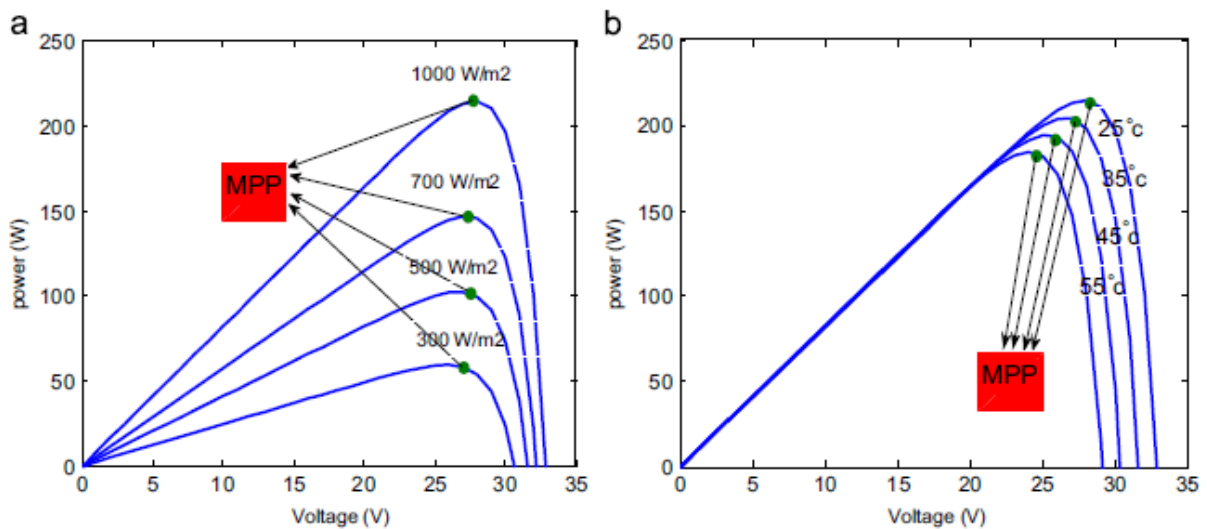


Figure 4: shows the relationship between the voltage and output power of a PV solar panels at a: different irradiation b: different cell temperatures (Maghami, et al, 2016).

According to the figure (4), low output power is produced when the irradiation is low while it becomes high at higher irradiances. This explains why the system operates efficiently in hot and sunny regions. However, the cell temperature is inversely proportion to the output power of the PV solar panels in such a way when its temperature is increasing during the operation. Furthermore, the performance efficiency is decreasing when the cell temperature is increased because of the physical structure of the semiconductor which absorbs some of the heat radiation during the operation. Consequently a suitable cooling or cleaning methods are necessary in order to maintain a good operating performance (Imnesi, 2012).

2.6 Losses produced during the operation

There are different losses generated by different stages during the operation of the PV solar system. These can be described in the table below.

Type of losses	Percentage %
Inverter	4 - 15
Temperature	5 - 18
Cables DC	1 - 3
Cables AC	1 - 3
Shading	0 - 80
Radiation	3 - 7
Dust or any obstacles from dirtiness	2

Table 4: type of losses and the percentage (Alanzi, 2016).

The losses are used to determine the performance factor PR as seen in section 2.1, moreover, before PV solar panels would be installed, it is essential to study the performance factor which is based on the factors above to indicate which one has higher impact on the performance and further on the amount of electricity produced from the system. Maghami, et al. (2016) showed how the output power relays on the amount of irradiance. It is obvious that the environment contributes directly towards changing the performance of the PV solar system. The shading due to accumulating dirtiness on the surface of the PV solar panels causes power loss and reducing the operating performance. This type of soiling is known as hard shading unlike the soft shading which is caused by air pollution according to Maghami et al. (2016). However

deploying a suitable cleaning method is essential to reduce the loss and increase the operating performance.

2.7 Optimum tilt angle

The optimum tilt's angle can be determined in conjunction with the availability of data about the weather condition. According to Elminir, et al (2001), a turbid weather as in city Helwan in Egypt causes reduction in the amount of solar irradiation hence reduces the operating of the PV solar panels. The optimal tilt angle was calculated for a PV solar panel faced to the south direction after estimating the average solar radiation on surfaces located at different positions. The effect of the azimuth angle on the total energy was calculated in different intervals such as days, months or in a year as a requirement to determine the optimal tilt angle (Elminir et al, 2001).

$$\beta_{opt.} = (6 - 4.8K_T + 0.86K_T^{0.27}\varphi + 0.0021\varphi^2) + (31K_T^{0.37} + 0.094K_T^{0.46}\varphi + 0.000634K_T^{-0.17}\varphi^2) \times \cos\left[\frac{360}{365}(N + 11.6)\right] \quad 2-2$$

Where K_T is the average clearness index in a month, φ is the latitude and N is the Number of the day on the year.

The clearness index can be determined using the weather data when limited information about the radiation is available at any location (Santos et al, 2003). Moreover, the global radiation can be estimated using the clearness index in such a way a mathematical model should be used by exploiting the latitude of the examined location and the amount of total perceptible water content in the vertical column at that desired location (Kumar & Umanand, 2005). The value of the clearness index is varies from month to month, hence, any analysis carried out should consider the clearness index at a given with full details about the day, month and year (Okogbue, 2009).

However, in one season the optimal angle is determined by using one plate collector. Consequently and for the specific season, the following equation can be used to determine the optimal angle (Elminir et al, 2001):

$$\beta_{opt.} = \frac{\sum_{K=1}^j \beta_{opt,K} \cdot G_{H,K}}{\sum_{K=1}^j G_{H,K}}, \quad 2-3$$

Where G_H is the global radiation incident on a horizontal surface measured in hour.

Figure (5) shows how different radiations for different tilt angle during a month in a year. Figure (6) shows the optical tilt angle at different clearness index, day number in a year and for a different ground Albedo (Calabrò & Magazù, 2016).

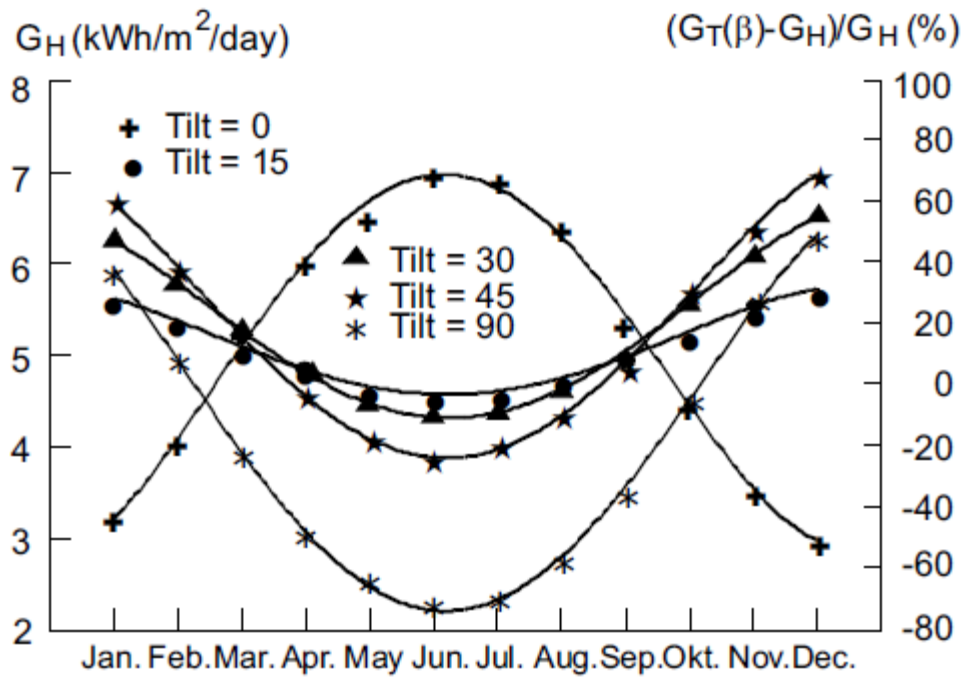


Figure 5: shows the different radiation at different tilt angles during the months in a year (Elminiretal, 2001).

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
K_T	0.23	0.26	0.29	0.28	0.31	0.40	0.35	0.37	0.31	0.32	0.29	0.25
N	15	47	74	105	135	166	196	227	258	288	319	349
ρ	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
$\beta_{Opt.}$	43°	36°	27°	16°	7°	2°	4°	12°	24°	35°	43°	45°

Figure 6: optimum tilt angle (Elminir, et al, 2001).

Agarwal et al, (2012) showed that nearly optimal energy can be collected if the angle of tilt is varied seasonally, four times a year. Annual optimum tilt angle is found to be approximately equal to latitude of the location. This study determined that PV module oriented towards the South gives the greatest value of electrical energy, see figure (7).

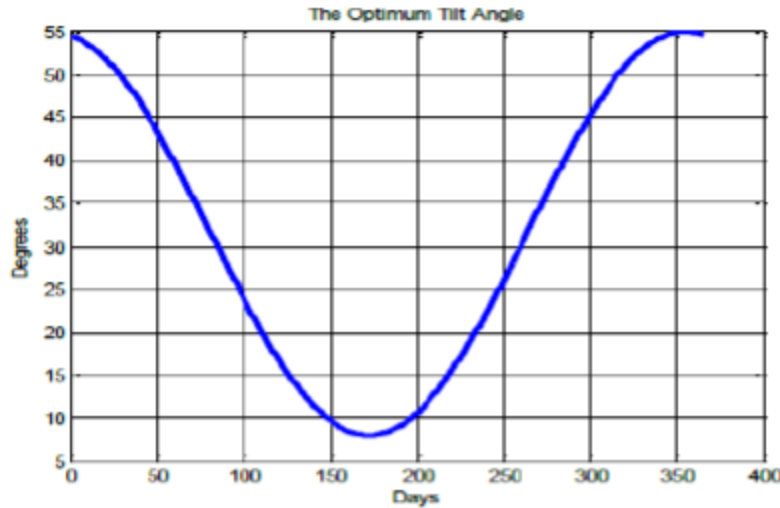


Figure 7: the variation of tilt angle with respect to day's number in a year (Agarwal et al (2012)).

Kemery et al (2012) showed that the optimal orientation of PV solar panels in 10 cities in Canada. The optimal orientation is corresponding to the highest energy could be produced when the solar panel is mounted at that orientation. However, it is always showing that the best tilt angle is less than the latitude of the investigated area by a 9.6° . When the measurement was conducted, the average azimuth angle was 1.9° in the direction of west of due south. A further experiment was conducted by Kemery et al in order to search the best orientation of mounting PV solar stand-alone panel or an array of panels and it is repeated in 16 locations across Ontario.

2.8 The relationship between soiling and tilt angle

When a PV solar is planned to be installed, the environmental impact should be studied in order to minimize the environmental impact of the installation, operation and disposal. The impact of the environment should be studied in order to maintain the performance of PV solar panels. According to Cano (2011), the soiling accumulated because of the pollution has a direct impact on the output power of the PV solar panels. Moreover, the tilt angle has influence on the amount of soiling on the PV solar which leads to reduce the operating performance. A study was conducted in order to show when the effect of the tilt angle becomes high or low. It is already discovered that the average power losses due to the soiling reduced from 2.02 % at zero tilt angle to 1.05 % at 23° tilt angle. This is because short circuit current which measures the irradiance reduces when there is dust or dirtiness. By comparing that module with a module subjected to no soiling, it is obvious shown that the tilt angle has effect only on the output power because of

the intensity of the solar irradiance which is depending upon the direction of the PV solar panels towards the direction of the sunlight, see figure (8).

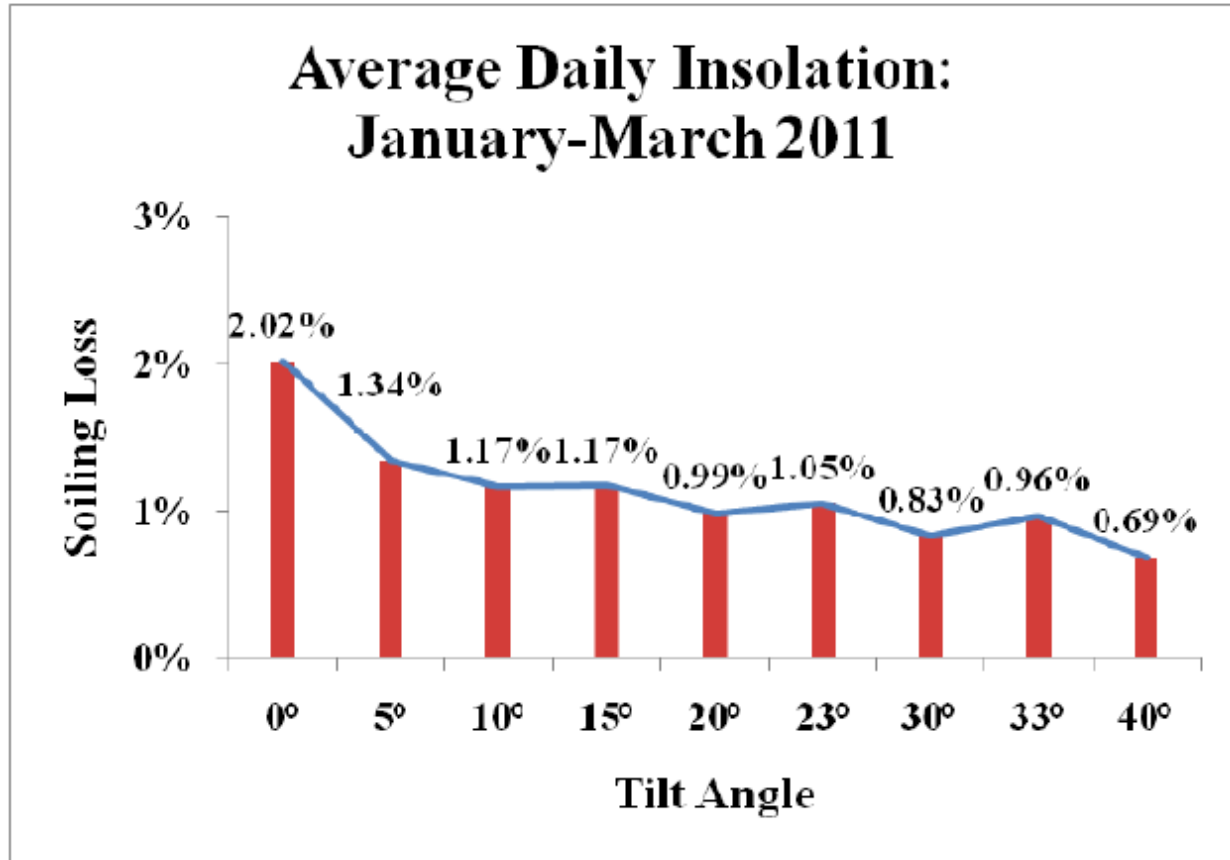


Figure 8: The relationship between the amount of soiling lost and the tilt angle (Cano, 2011).

2.9 Relationship between output power and cell temperature

When a PV solar system is installed, it is expected to maintain constant supplying of power to the consumer with different environment. The irradiation has a strong impact on the output energy from the PV solar panels. Brihmat and Makhtoub (2014) conducted a research to investigate the variation of the temperature during the day time and how it influences output power. The research revealed that PV solar panel's temperature increases because of the ambient temperature and this is highly influenced by the wind speed, but not influenced very much by the wind direction. Moreover, the cell temperature is less influenced by the atmosphere temperature but it was strongly impacted by solar radiation flux according to the same authors.

2.10 PV solar tracking system

Since the sunlight intensity varies during the days, months and years, the performance of PV solar system changes or degrades if PV solar system is mounted on one position with a fixed tilt angle. In many countries where there is a high demand on PV solar systems installed for domestic or commercial customers, a tracking system is added into the whole PV solar system so that the tilt angle changes when the sunlight intensity changes during the day time (Bazyari et al, 2013). The performance is also discussed by the same authors to study the output power without adding a tracking system. Single and double tracking system were investigated for a single PV panel and arrays of panels correspondingly. The purpose of the test was to find out which method produces the highest energy. According to the table below, the highest average output power was when there is double tracking system adding into the module.

Type	Fixed panel	With single axis tracker	With double axis tracker
Average daily received energy	4205 wh/m ²	5694 wh/m ²	5926 wh/m ²
Maximum daily received energy	6040 wh/m ²	8387 wh/m ²	8637 wh/m ²
Average received density	175 w/m ²	237 w/m ²	247 w/m ²
Maximum received density	1098 w/m ²	1120 w/m ²	1140 w/m ²

Table 5: The average daily received energy for fixed panels, single axis tracker and double axis tracker (Bazyari et al, 2013).

2.11 Effect of humidity on PV solar panels

Humidity in the weather is created as a result of the ratio of the actual water vapour pressure contained in the air to the saturated water pressure for the sunlight temperature. It decreases or increases when there is an air with constant water vapour content with temperature increasing or decreasing correspondingly (Elminir et al, 2001). It causes corrosion on the surface of the panel especially on the silicon surface which becomes worse when temperature of the surface is increased during the operation. Moreover, high humidity causes more fungus to grow on the surface which reduces the operating efficiency of the PV solar panel. The sticky layer created on the surface of the PV solar panels catches dust and dirtiness from the weather which reduces the performance of the PV solar panels.

2.12 Mounting system

The mounting system needs to be designed and manufactured appropriately in order to keep the rigidity of the PV solar system and maintain the good performance of PV solar panels. There are different types of mounting system each is suitable to the type of surface fitted above (*20 years mounting system*), see appendix A. Most of the materials used in the mounting system are made of aluminium. The aluminium is rigid, does not rust and light in weight that will not add extra high load on the roof. Moreover, the design of the mounting system should be made in such a way that it resists high wind speed and the drag force produces when winds attack the surface of the panel. According to Shademan and Hangan (2009), to get a minimum drag coefficient on sets of panels, the distance between the panels should be small. The sheltering effect has a direct influence on the drag force from the wind, therefore the maximum sheltering should be determine in order to study the wind loading on the surface of PV panels. Moreover, the maximum drag force is produced when the azimuthally angle is either 90° or 60° . For an azimuthally angle of 90° , there is a monotonic decrease in force from the bottom to the top row of the PV solar panels. For an azimuthally angle of 60° , the right side panels in each row produces local maximum force values. The sheltering effect appears when there is PV solar arrays. Figure (9) shows the location of stand-alone panels or array of panels that are used to minimize the drag coefficients on the panels. The mounting system should be designed to be as simple as possible and panels can be assembled above the mounting without a great deal of efforts, see appendix B.

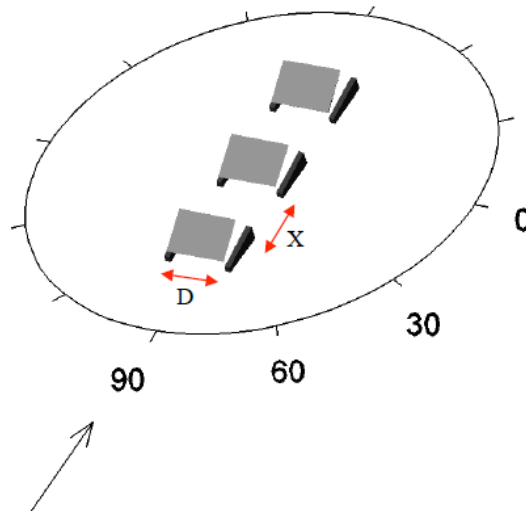


Figure 9: mounting panels to avoid sheltering effect (Shademan and Hangan, 2009).

Chapter 3

Methodology

3.1 Experiments conducted

3.1.1 Experiment specifications for indoor measurement

There are two experiments which were done during the project. The first one is an indoor one which was done in the university lab. It has the following specifications:

- 1- A light chosen from the stock available at the university lab which will be considered as sunlight and it needs to change the position during the day time. The position of the light was changed when the data was taken during the day. The positions of the light should be at the following elevation angles: 20, 40, 60, 90, 120 and 140 degrees. Position of each hole on the arc was made using the geometry. The arc had a radius of 0.85 meter and the elevation angles have been located on the arc using the geometry equation below:

$$x = r\cos(\theta) \quad 3-1$$

$$x = r\sin(\theta) \quad 3-2$$

Hence the exact location for the hole can be made manually on the wooden arc as shown in the figure (10 and 11).

The design of the arc and the mounting system used for the light is shown in the draw in figure 11. The designed was made manually and was fabricated using wood.

- 2- 1 x PV solar panel model Mono-crystalline with specification shown in figure (12) and table (6).
- 3- A multi-meter to measure the output voltages from the PV solar panels, see figure (13).
- 4- A simple wooden mounted base for the PV solar panel, which is adjusted at different tilt angles 15, 30, 45, 55 and 65°, see figure (11) by using a digital protector see figure (14) .
- 5- Light with specifications which is model CL6FS, 230V~ 50Hz, 6W and 500 Lumens showed in figure (15).
- 6- Maintained room temperature between 20-22 °C. This will assume that the environment temperature is stable and does not need to consider thermal loss due to the high environment's temperature.

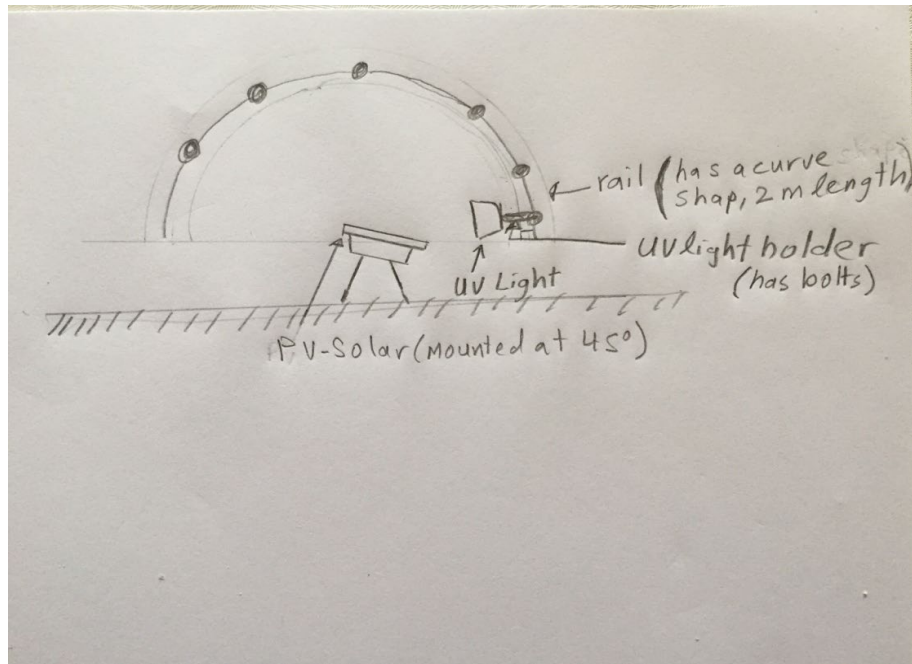


Figure 10: shows a hand drawing of the arc used to mount the UV for the indoor experiment.

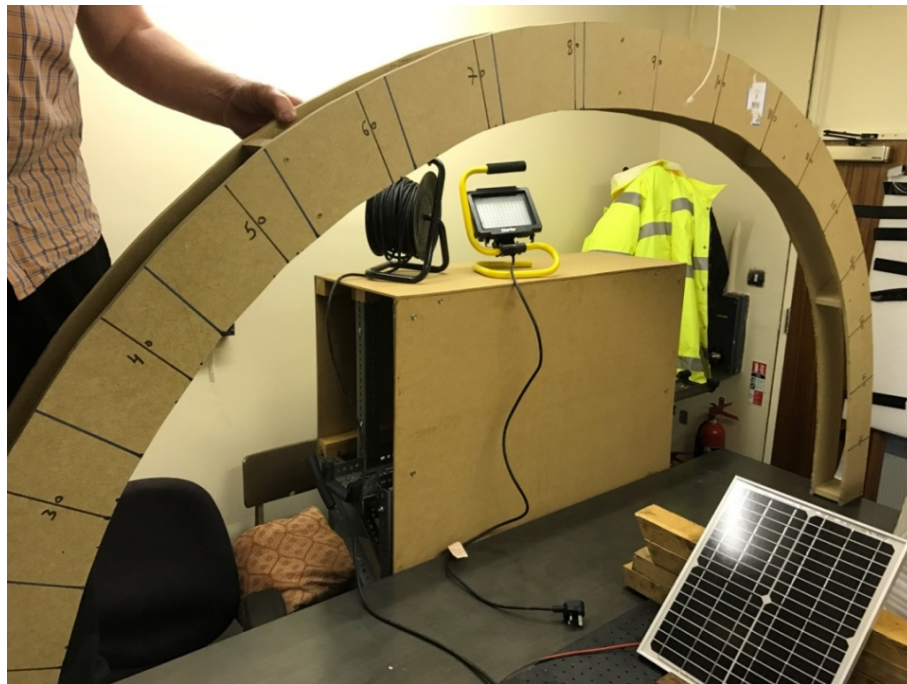


Figure 11: shows the arc used to mount the light at different elevation angles while tilt angle was fixed at 15, 30, 45, 55, 65°.

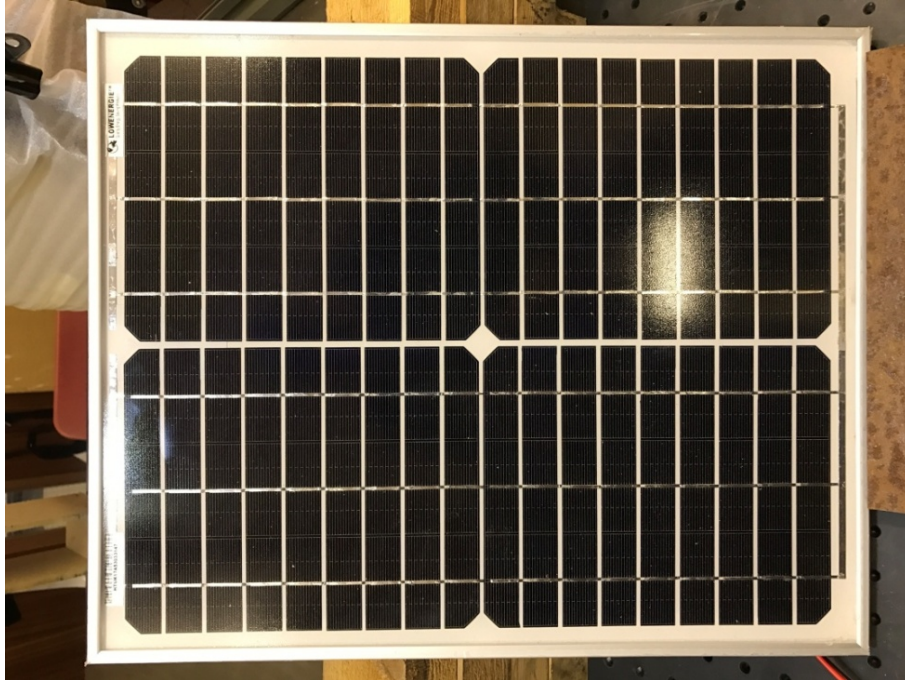


Figure 12: shows PV solar panel used in the indoor measurements.

max power	20 W
max voltage	17.6 v
max current	1.14 A
weight	1.5kg
size	430*350*20 mm
power tolerance	±3%

Table 6: PV solar panel specifications.

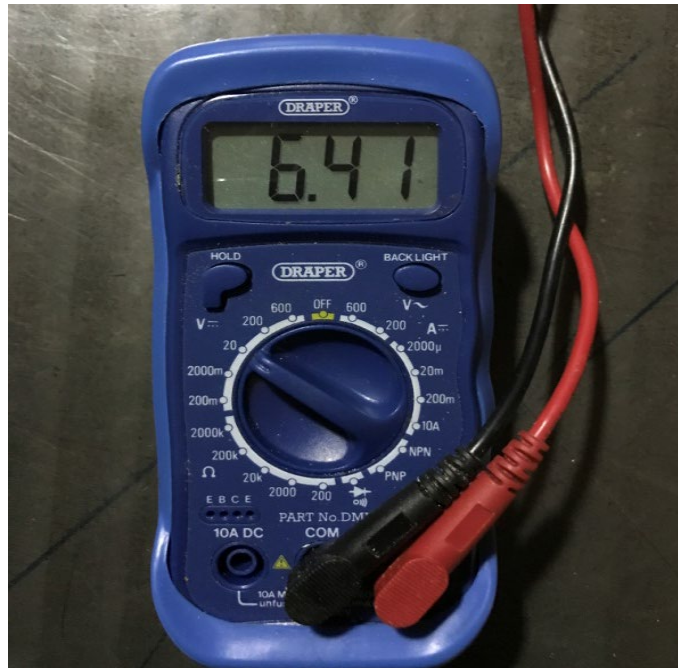


Figure 13: shows the multi-meter used for indoor measurements.



Figure 14: digital protector used for indoor measurements to determine the tilt angle.



Figure 16: Figure 15: light used in indoor measurements.

3.1.2 Experiment specifications for outdoor measurement

The second one is an outdoor measurement which will be carried out in KSA. It will have the following specifications:

- 1- 1 x PV solar panel mono-crystalline which is 185 Wp, see figure (16).
The mounting system is shown in the drawing in figure (17). It should be adjusted at different tilt angles such as (0, 15, 35, 40, 50 and 60) degrees. The mounting system is made of aluminium to reduce the cost, weight and because it has good resistance to the weather conditions. Furthermore the majority of the current mounting systems utilize aluminium because of the last mentioned reasons.
- 2- Measurements can be taken within 8 hours (day time) and in an interval of 2 hours each time.
- 3- The output voltage should be measured by a multi-meter which is shown in figure (18).
- 4- This scenario can be done for the PV solar panel and at the same time / to see the performance of the PV solar panel.



Figure 16: live photo for the tested PV-solar panel.

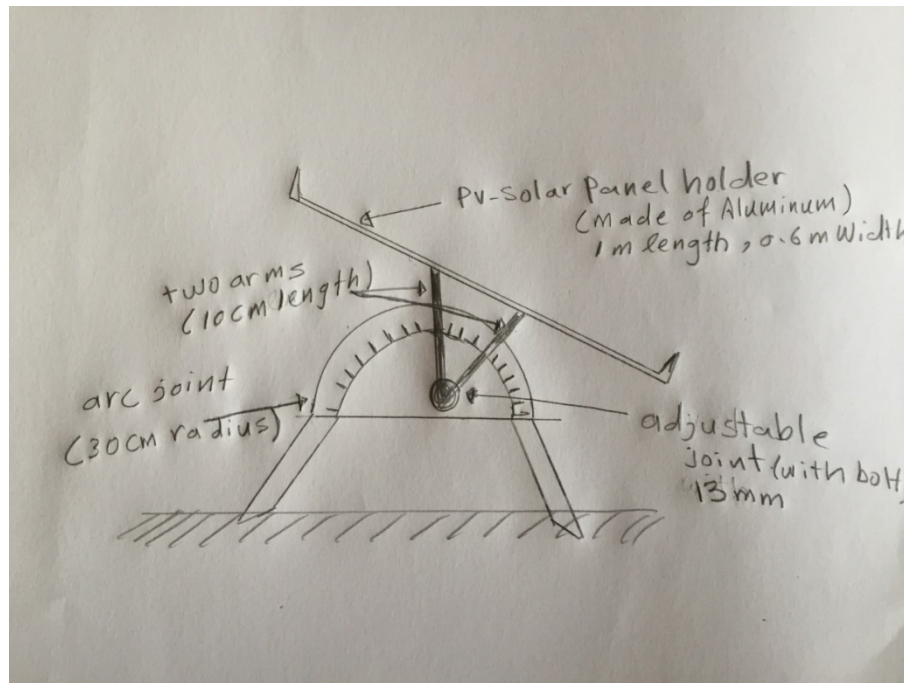


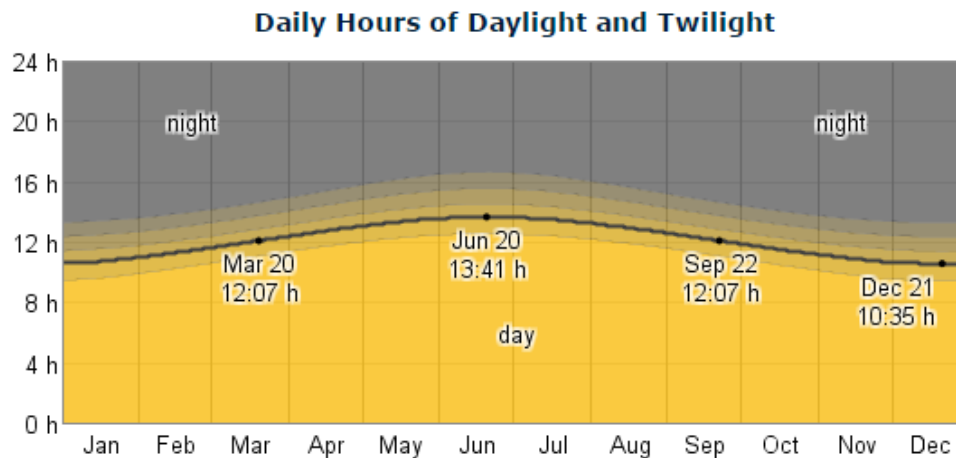
Figure 17: shows the design of the base using Aluminum material.



Figure 18: one meter reading during the outdoor measurement.

3.2 The chosen location

The chosen location for the outdoor measurement was in Riyadh in KSA. The site has an altitude of 24.713552° . It has a rich sunlight and the PV solar panel is expected to work efficiently. The location has an average daily sunlight for 12 hours during a year, see figure (19). This information is useful to calculate the amount of power in kWh/day needed to fulfil the demand. Moreover, it will help to determine the number of hours without sunlight which is taken into consideration to determine the battery size used as a back during the night time.



The number of hours during which the Sun is visible (black line), with various degrees of daylight, twilight, and night, indicated by the color bands. From bottom (most yellow) to top (most gray): full daylight, solar twilight (Sun is visible but less than 6° from the horizon), civil twilight (Sun is not visible but is less than 6° below the horizon), nautical twilight (Sun is between 6° and 12° below the horizon), astronomical twilight (Sun is between 12° and 18° below the horizon), and full night.

Figure 19: daily hours for daylight during a year.
(<https://weatherspark.com/averages/32777/Riyadh-Saudi-Arabia>).

The PV solar panel was mounted in a clear area outskirts of Riyadh city. It was faced the south direction and had the following solar irradiance data shown in figure (20). The panel was used without load, as there was no need to measure the demand in kWh which is expressed by the load. The weather was clear and sunny during the days where measurements were taken, but it was considered as a cold weather where the temperature was varying between 10° to 25°. According to figure (18), the solar irradiation is varied according the tilt angle. Different tilt angles give back different solar irradiation which can be used to calculate the output power of a PV solar panel mounted and installed on that chosen geographical area.

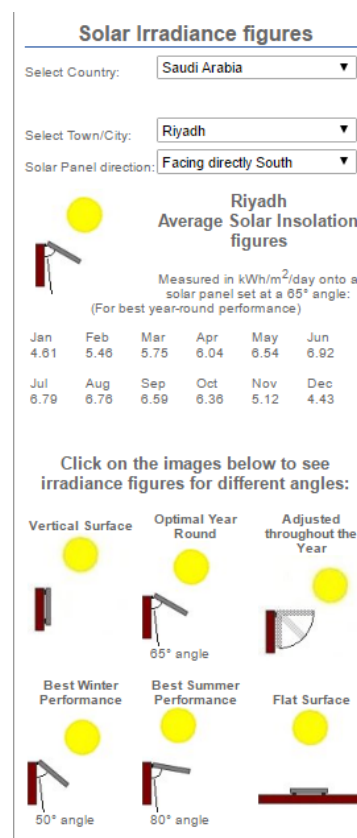


Figure 20: solar irradiance in Riyadh KSA (<http://solarelectricityhandbook.com/solar-irradiance.html>).

The purpose of conducting outdoor measurements is to investigate a real scenario where the tilt angle can be adjusted at different ones and measure the output voltage and current produced from the PV solar panel.

3.3 Determine the optimal tilt angle

The purpose of conducting this research is to find the optimum tilt's angle that improves the performance of a PV solar panel by producing the highest output power when the PV solar panel is mounted and faced to the South direction. It is possible to make the panel facing the South East or South West, but it is strongly suggested to use the tool available in (<http://solarelectricityhandbook.com/solar-irradiance.html>), as this tool is attractive and show different solar irradiation when the panel faces different positions towards the sunlight.

3.4 Measuring the output power

Before the output of the PV solar is calculated by measuring the currents and voltages by using the following equation, the temperature of the PV solar panel should be calculate.

$$P = IV \text{ in Watt.}$$

3-3

This is usually done by using a thermometer installed on the gazing of each panel used (Hanif et al, 2012). The next figure (21) shows the variation of the output power with respect to the PV solar temperature.

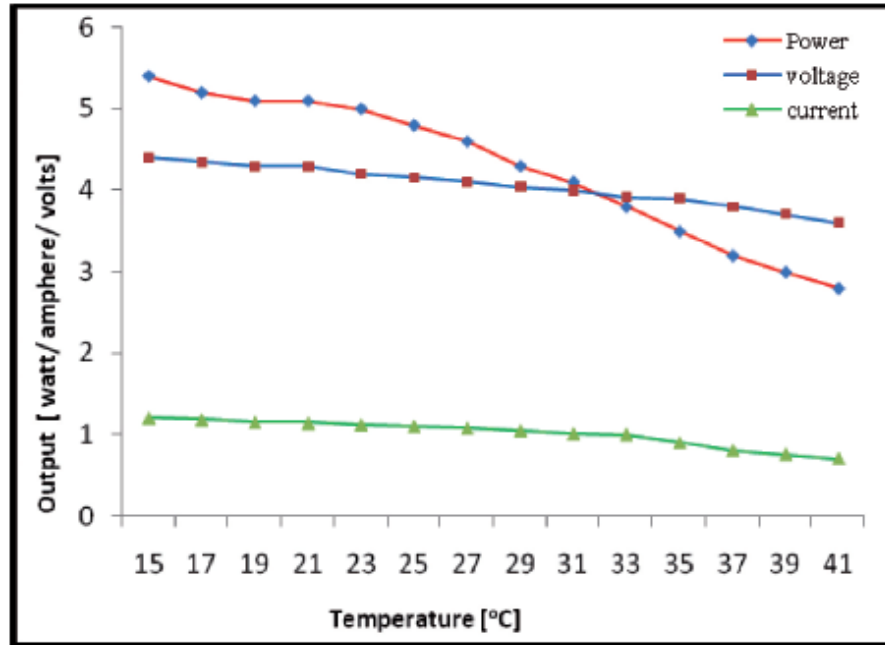


Figure 21: variation of output power with the PV solar temperature (Hanif et al, 2012).

3.5 Design a mounting system using SolidWork

In order to make the research more viable another design for the mounting system was made using the SolidWork. The material considered in the design of the mounting system by using CES software (CES Edupack, 2015) The Aluminium material was used in the design and different environment issues were consider during the design analysis using the FEA analysis. The environment issue considered during the design was the drag force applied on the surface of the PV solar panel because of the high wind speed. The drag force should be taken into consideration in order to maintain a mounting system that should be rigid and solid (Bernard, 2009).

$$F_D = \frac{1}{2} \times \rho \times V^2 \times AC_D \quad 3-4$$

Where A is the area of the PV solar panel, ρ is the density of the air, V is the speed of the wind and C_D is the drag coefficient respectively. The drag coefficient depends upon the surface which is attacked by the wind which it has no units. The drag coefficient produced from attacking the wind on the surface of the PV solar panel and the mounting system respectively has a value equal to 1.17 for a circular plat shape (Bernard, 2009).

When the wind speed is 15.2 m/s, A is 0.6 m², C_D is 1.17 and $\rho = 1.25 \text{ Kg/m}^3$, then the drag force should be equal to 97.31 N.

Moreover, there is no tolerance to a vibration or changing position of the mounting system during the installation and the operation because of the high wind speed, as this will reduce the output power of the PV solar panel because of changing the optimal angle which leads to change in the solar radiation reaches the surface of the PV solar panel. This issue was taken into consideration as the site location is a flat landscape and it is subjected in many occasions to high wind speed and wind storm during the spring, summer and autumn seasons in a year.

Chapter 4

Results and Analysis

4.1 Measurement scenario

In order to achieve the aim of the project different measurements were conducted as described in the previous chapter in order to investigate the optimum tilt angle used for mounting the PV solar panel in order to produce the highest output power. There are two scenarios conducted, one is the outdoor and one is the indoor and the results are analysed as follows

4.1.1 Results from the outdoor measurements

The measurements were conducted in 5 different days, namely, days 31, 33, 41, 45 and 48 in 2017. Table (7) shows all data collected from the PV solar panel during the mentioned days and the output power has calculated by the equation below.

$$P = V \times A \quad 4-1$$

Where:

P is the measured output power in W.

V is the calculated output voltage in V.

A is the calculated output current in Amp.

Outdoor Measurement Experiments

Latitude angle: 24.713°

calculated output current	calculated output voltage	measured output power in Watt	Time	outside temperature
Day 1, Tilt angle 0°				
1.86	20	37.2	10:00	11
1.89	20	37.8	12:00	13
1.9	20	38	14:00	15
1.89	17.46	32.99	17:00	12
Day 2, Tilt angle 35°				
1.68	19.2	32.26	10:00	10
1.7	19.3	32.81	12:00	12
1.65	19.89	32.82	14:00	13
1.58	19.1	30.18	17:00	10
Day 3, Tilt angle 40°				
1.6	16.8	26.88	10:00	10
1.59	17	27.03	12:00	11.5
1.58	17	26.86	14:00	13
1.54	16.8	25.87	17:00	11
Day 4, Tilt angle 50°				
1.61	16	25.76	10:00	15
1.59	16.28	25.89	12:00	18
1.63	16.2	26.41	14:00	19
1.58	16.01	25.30	17:00	14
Day 5, Tilt angle 60°				
1.55	16.03	24.85	10:00	18
1.55	16.15	25.03	12:00	23
1.59	16.1	25.60	14:00	25
1.54	15.9	24.47	17:00	17

Table 7: shows the data collected from the outdoor measurements.

According to table (7), the following figure can be deduced to show the relationship between the output power from the PV solar and the time during different tilt angles.

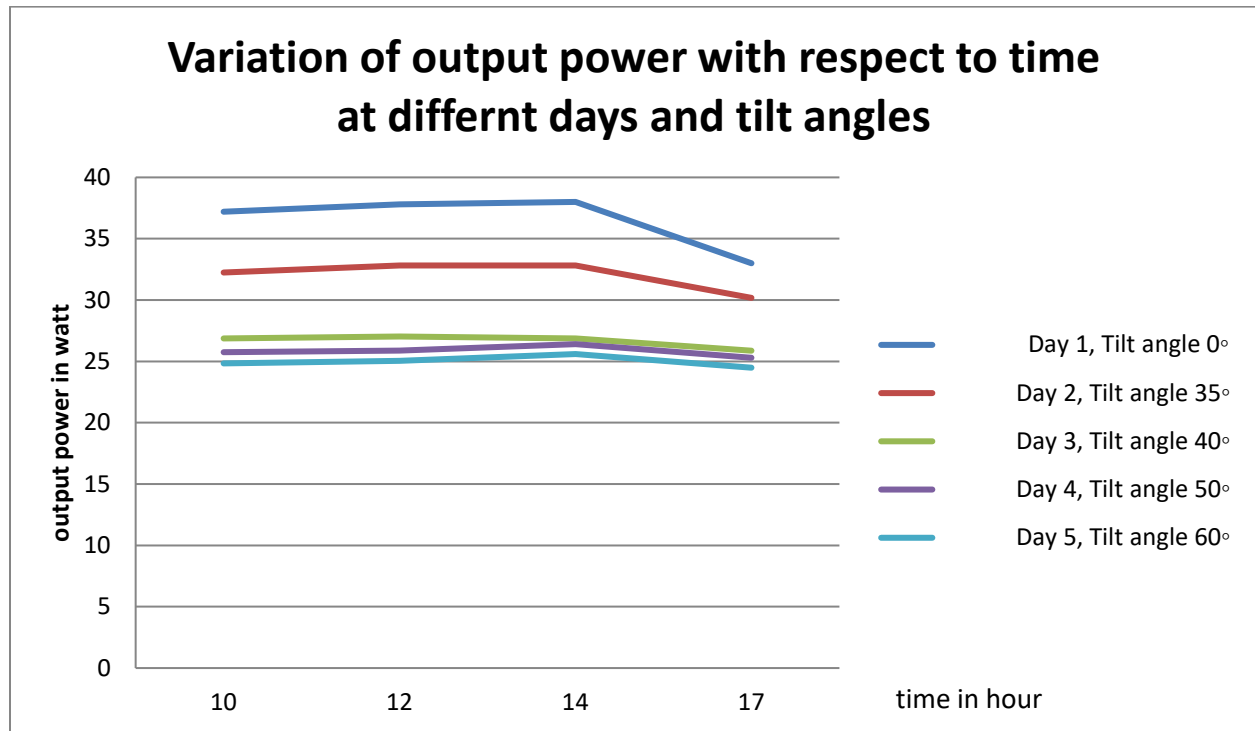


Figure 22: shows the output power at different tilt angles and different time during the days chosen in this year 2017.

According to figure (22), the maximum output power is at tilt angles 0° and 35° degrees. Since the measurements were conducted in Riyadh Saud Arabia, the 0° tilt angle is not taken into consideration because this is not a common position of a PV solar panel, as this accumulate dirtiness and dust easily which reduce the operating performance of the PV solar panel quickly. Moreover, the above figure explained too how the output power changes during the day time and at which time it reaches the highest power as shown by (Abdul-Wahid & Medi, 2010).

In order to observe the relationship between the output power of the PV solar panels and the outside temperature, figure (23) is used to explain this relationship.

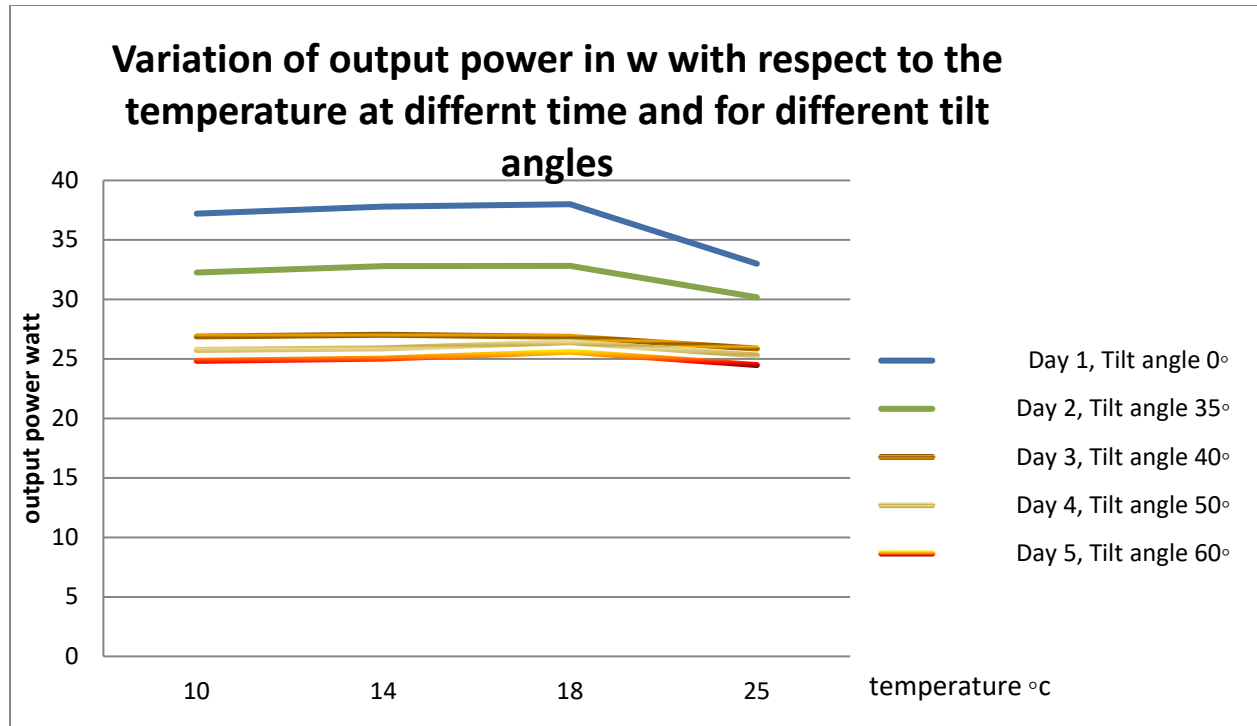


Figure 23: shows the relationship between the output power and the ambient temperature.

According to figure (23) above, the maximum output power from the PV solar panel is achieved when the tilt angle was either 0° or 35°. Moreover, the PV solar panel was producing a steady output power when the output temperature was between 10° till around 20°. Thereafter the power started decreasing. This is because the high temperature reduces the performance of the PV solar panel and reduces the output power. According to Chandrakar and Tiwari (2013), the output power of a PV solar panel can be determined using the following equation:

$$P_{PV} = P_{PVcell} \times f_{PV} \left(\frac{S_T}{S_{T,STC}} \right) [1 + T_{cert}(T_C - T_{C,STC})] \quad 4-2$$

Where S_T is the solar radiation incident on the PV array in the current time step [kw/m²]

$S_{T,STC}$ incident radiation at standard test condition [1kw/m²]

P_{PVcell} is a rated capacity of the PV array under standard condition

f_{PV} derating factor for PV

T_{cert} temperature certification power [%/°C]

T_C is a PV cell temperature in the current time step [°C]

$T_{C,STC}$ is a PV cell temperature under standard condition [°C]

According to equation 4-2, the temperature T_C is inversely related to the output power in such a way when the temperature is further increased the output power will be further reduced.

4.1.2 Results from the indoor measurements

The other objective for the project was to conduct an indoor measurement on a PV solar panel in such a way that the impact of the elevation angle is investigated at different tilt angles. The scenario followed was building a simple arc made of wood and used with a light to be acted as a sunlight changes during the daytime. A light was mounted on the arc and the output power was calculated from measuring the output voltages and currents, see figure (24).

The results achieved from the measurements are shown in table (8) where two different tests were conducted in order to observe the output power of the PV solar panel. The average output power from both tests was used to investigate the variation of the output power with respect to the elevation angles when the PV solar is mounted at different tilt angles, see figure (25). According to the last mentioned figure, the maximum output power was achieved when the tilt angle was 30° and when the elevation angle was 60°, which means the light was directed perpendicularly on the surface of the PV solar panel. This is explaining why the maximum output power is produced when the sunlight hits the panel directly, as the solar irradiation reaches the surface of the PV solar panel is the highest value.

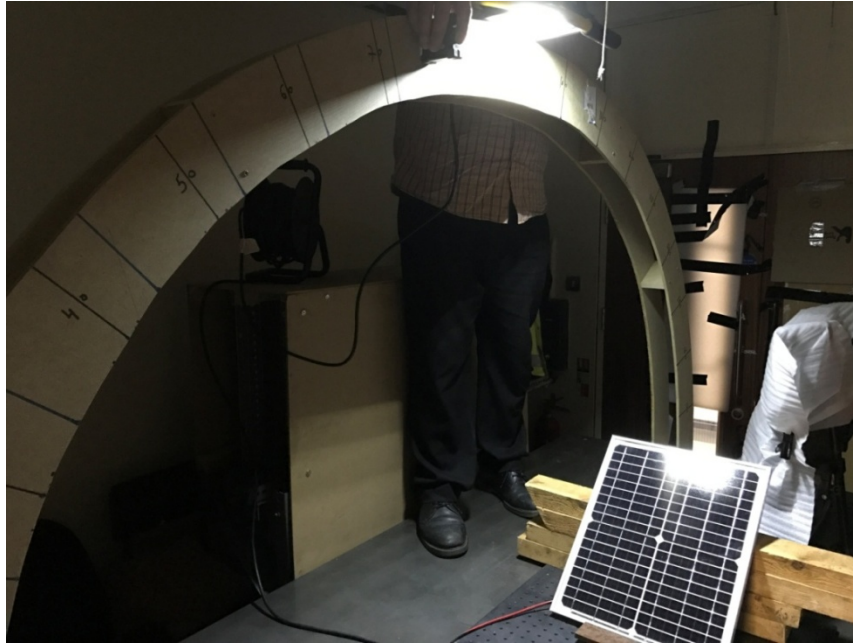


Figure 24: shows the indoor measurement done on the PV solar panel.

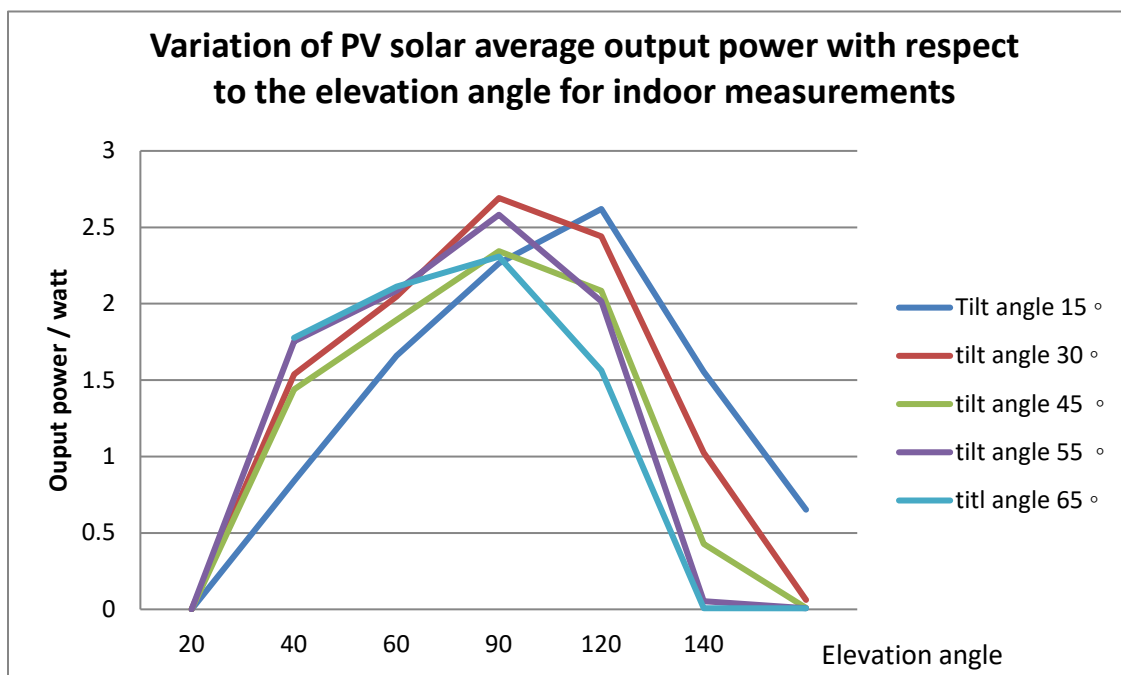


Figure 25: relationship between elevation angle and the output power at different tilt angle.

Indoor Measurement Experiments

First test

Second Test

Tilt angle
15°

tilt angle 15°

Elevation angle	calculated output voltage	calculated output current	measured output power	Elevation angle	calculated output voltage	calculated output current	measured output power	Average power for both tests
20	4.81	0.18	0.87	20	4.79	0.17	0.81	0.84
40	5.73	0.29	1.66	40	5.72	0.29	1.66	1.66
60	6.11	0.37	2.26	60	6.13	0.37	2.27	2.26
90	6.38	0.41	2.62	90	6.4	0.41	2.62	2.62
120	5.66	0.28	1.58	120	5.64	0.27	1.52	1.55
140	4.35	0.15	0.65	140	4.34	0.15	0.65	0.65
tilt angle 30 °				tilt angle 30 °				tilt angle 30 °
Elevation angle	calculated output voltage	measured output current	measured output power	Elevation angle	calculated output voltage	measured output current	measured output power	Average power for both tests
20	5.6	0.27	1.51	20	5.8	0.27	1.57	1.54
40	6.12	0.34	2.08	40	6.1	0.33	2.01	2.05

60	6.56	0.41	2.69	60	6.57	0.41	2.69	2.69
90	6.43	0.38	2.44	90	6.42	0.38	2.44	2.44
120	5.13	0.2	1.026	120	5.13	0.2	1.03	1.03
140	2.1	0.03	0.06	140	1.99	0.03	0.06	0.06
tilt angle 45 °				tilt angle 45 °				tilt angle 45 °
Elevation angle	calculated output voltage	measured output current	measured output power	Elevation angle	calculated output voltage	measured output current	measured output power	Average power for both tests
20	5.53	0.26	1.44	20	5.54	0.26	1.44	1.44
40	5.91	0.32	1.89	40	5.93	0.32	1.89	1.89
60	6.33	0.37	2.34	60	6.34	0.37	2.35	2.34
90	6.24	0.34	2.12	90	6.21	0.33	2.05	2.09
120	3.91	0.11	0.43	120	3.89	0.11	0.43	0.43
140	1.02	0.01	0.01	140	1.02	0.01	0.01	0.01
tilt angle 55 °				tilt angle 55 °				tilt angle 55 °
Elevation angle	calculated output voltage	measured output current	measured output power	Elevation angle	calculated output voltage	measured output current	measured output power	Average power for both tests

20	6.14	0.29	1.78	20	6.17	0.28	1.73	1.75
40	6.4	0.32	2.05	40	6.43	0.33	2.12	2.08
60	6.78	0.37	2.51	60	6.81	0.39	2.66	2.58
90	6.38	0.31	1.98	90	6.41	0.32	2.05	2.01
120	1.79	0.03	0.05	120	1.8	0.03	0.05	0.05
140	0.8	0.01	0.01	140	0.81	0.01	0.01	0.01
tilt angle 65 °				tilt angle 65 °				tilt angle 65 °
Elevation angle	calculated output power	measured output power	measured output power	Elevation angle	calculated output power	measured output power	measured output power	Average power for both tests
20	6.12	0.29	1.77	20	6.14	0.29	1.78	1.78
40	6.4	0.33	2.11	40	6.4	0.33	2.11	2.11
60	6.59	0.35	2.31	60	6.6	0.35	2.31	2.31
90	5.89	0.26	1.53	90	5.91	0.27	1.60	1.56
120	0.77	0.01	0.01	120	0.75	0.01	0.01	0.01
140	0.67	0.01	0.01	140	0.68	0.01	0.01	0.01

Table 8: shows the data from indoor measurements.

4.2 Evaluate the maximum output power

To evaluate the output power of the PV solar panel, it is essential to understand which parameters have influence on it.

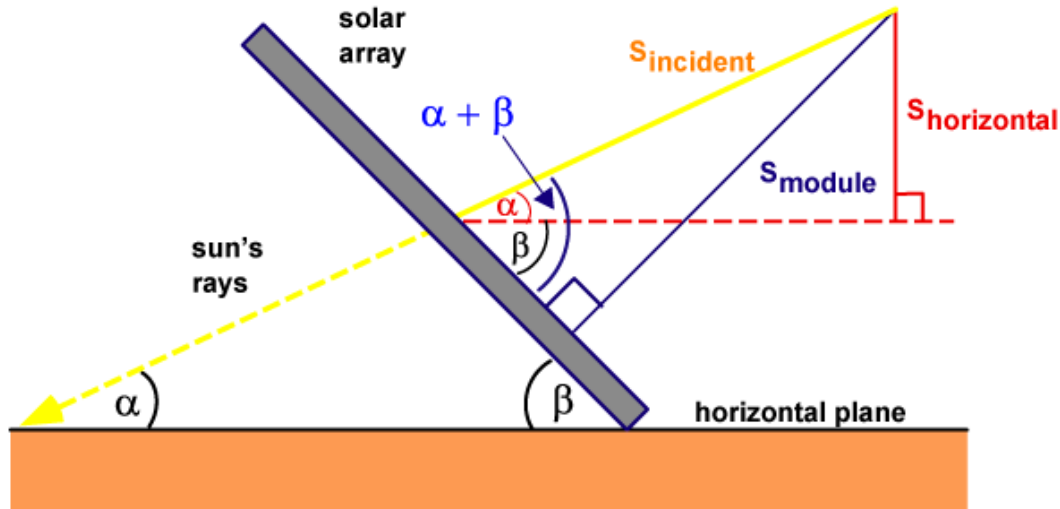


Figure 26: the solar array position and tilt angle (Honsberg & Bowden, 2017).

$$S_T = S_{T,STC} \times \sin(\alpha + \beta) \quad 4-3$$

Where β is corresponding to the tilting angle

$$\alpha = 90 - \Phi + \delta \text{ where}$$

Φ is the latitude angle at the site

δ is the declination angle

The declination angle δ is calculated as follows

$$\delta = 23.4^\circ \times \sin \left[\frac{360}{365} (284 + d) \right] \quad 4-4$$

Where d is the day of the year.

By substituting the last equation by the equation for calculating the output power from a solar array and simplifying it, the following equation will be achieved which can be used to calculate the output power of a PV solar array per square meters:

$$P_{PV} = P_{PVcell} \times f_{PV} \left(\sin \left(90 - \phi + \left(23.4^\circ \times \sin \left[\frac{360}{365} (284 + d) \right] \right) + \beta \right) \right) [1 + T_{cert} (T_C - T_{C,STC})] \quad 4-5$$

The PV solar panel has the following specifications: P_{vcell} , 185 W_p, f_{pv} , 25% and T_{cert} is -0.45%.

It is observed that there is a direct relation between the tilt angle β and the output power produced by PV solar array. Moreover the PV solar panel's temperatures as well as the number of the day in a year and the latitude's angle have the influence on the PV solar output power.

The output power can be calculated using equation 4-5. By substituting the variables in the last equation by the parameters taken from the outdoor measurement the following output power was calculated as shown in tables 9, 10, 11, 12 and 13 for the chosen five days during the outdoor measurements. According to the tables 9, 10, and 11, the maximum output power was observed when the tilt angle was 40°. The output power was measured for 4 times in 5 days, see the chart in figure (27), showing the maximum output power at tilt angle 40° in day 31. By comparing the theoretical calculations with the practical measurements taken from outdoor, it is revealed that the maximum output power is when the tilt angle is 35° starting from day 45, this is because of the site, where the measurements taken was outskirts of Riyadh which is not exactly the same altitude angle used in to calculate theoretically the output power from the chosen PV solar and by considering different days where measurement could be conducted the output power from PV solar panel becomes better at tilt angle equal 35°.

Day 31	Temperature	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Tilt angle β in rad	Pv																	
0		36.56	36.4	36.25	36.1	35.94	35.79	35.64	35.48	35.33	35.18	35.02	34.87	34.72	34.56	34.41	34.25	34.1
0.610865238		49.16	48.95	48.74	48.54	48.33	48.12	47.92	47.71	47.51	47.3	47.09	46.89	46.68	46.47	46.27	46.06	45.85
0.698131701		49.53	49.33	49.12	48.91	48.7	48.49	48.29	48.08	47.87	47.66	47.45	47.25	47.04	46.83	46.62	46.41	46.21
0.872664626		49.16	48.95	48.74	48.54	48.33	48.12	47.92	47.71	47.5	47.3	47.09	46.89	46.68	46.47	46.27	46.06	45.85
1.047197551		47.28	47.09	46.89	46.69	46.49	46.29	46.09	45.89	45.7	45.5	45.3	45.1	44.9	44.7	44.51	44.31	44.11

Table 9: output power during day 31.

Day 33	Temperature	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Tilt angle β in rad	Pv																	
0		36.87	36.71	36.56	36.4	36.25	36.09	35.94	35.79	35.63	35.48	35.32	35.17	35.01	34.86	34.7	34.55	34.39
0.610865238		49.21	49.01	48.8	48.59	48.39	48.18	47.98	47.77	47.56	47.36	47.15	46.94	46.74	46.53	46.32	46.12	45.91
0.698131701		49.55	49.34	49.14	48.93	48.72	48.51	48.3	48.09	47.89	47.68	47.47	47.26	47.05	46.85	46.64	46.43	46.22
0.872664626		49.09	48.89	48.68	48.47	48.27	48.06	47.86	47.65	47.44	47.24	47.03	46.83	46.62	46.41	46.21	46	45.8
1.047197551		47.14	46.94	46.75	46.55	46.35	46.15	45.96	45.76	45.56	45.36	45.16	44.97	44.77	44.57	44.37	44.17	43.98

Table 10: output power during day 33.

Day 41	Temperature	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Tilt angle β in rad	Pv																	
0		38.19	38.03	37.87	37.71	37.55	37.39	37.23	37.07	36.91	36.75	36.59	36.43	36.27	36.11	35.95	35.79	35.63
0.610865238		49.42	49.21	49	48.8	48.59	48.38	48.17	47.97	47.76	47.55	47.34	47.14	46.93	46.72	46.51	46.31	46.1
0.698131701		49.58	49.37	49.16	48.95	48.75	48.54	48.33	48.12	47.91	47.71	47.5	47.29	47.08	46.87	46.67	46.46	46.25
0.872664626		48.77	48.56	48.36	48.15	47.95	47.74	47.54	47.33	47.13	46.93	46.72	46.52	46.31	46.11	45.9	45.7	45.49
1.047197551		46.47	46.28	46.08	45.89	45.69	45.5	45.3	45.11	44.91	44.72	44.52	44.33	44.13	43.94	43.74	43.55	43.35

Table 11: output power during day 41.

Day 45	Temperature	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Tilt angle β in rad	Pv																	
0		38.89	38.73	38.56	38.4	38.24	38.08	37.91	37.75	37.59	37.42	37.26	37.1	36.93	36.77	36.61	36.44	36.28
0.610865238		40.36	40.36	40.36	40.36	40.36	40.36	40.36	40.36	40.36	40.36	40.36	40.36	40.36	40.36	40.36	40.36	40.36
0.698131701		34.01	34.04	34.06	34.09	34.12	34.14	34.17	34.2	34.22	34.25	34.28	34.3	34.33	34.36	34.38	34.41	34.44
0.872664626		33.77	33.77	33.77	33.77	33.77	33.77	33.77	33.77	33.77	33.77	33.77	33.77	33.77	33.77	33.77	33.77	33.77
1.047197551		34.81	34.8	34.8	34.79	34.79	34.79	34.78	34.78	34.77	34.77	34.76	34.76	34.76	34.75	34.75	34.74	34.74

Table 12: output power during day 45.

Day 48	Temperature	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Tilt angle β in rad	Pv																	
0		39.42	39.26	39.09	38.93	38.76	38.6	38.43	38.27	38.1	37.93	37.77	37.6	37.44	37.27	37.11	36.94	36.78
0.610865238		40.91	40.91	40.91	40.91	40.91	40.91	40.91	40.91	40.91	40.91	40.91	40.91	40.91	40.91	40.91	40.91	40.91
0.698131701		34.39	34.42	34.44	34.47	34.5	34.53	34.55	34.58	34.61	34.64	34.66	34.69	34.72	34.75	34.77	34.8	34.83
0.872664626		34.14	34.14	34.14	34.14	34.14	34.14	34.14	34.14	34.14	34.14	34.14	34.14	34.14	34.14	34.14	34.14	34.14
1.047197551		35.22	35.22	35.21	35.21	35.2	35.2	35.2	35.19	35.19	35.18	35.18	35.17	35.17	35.16	35.16	35.15	35.15

Table 13: output power during day 48.

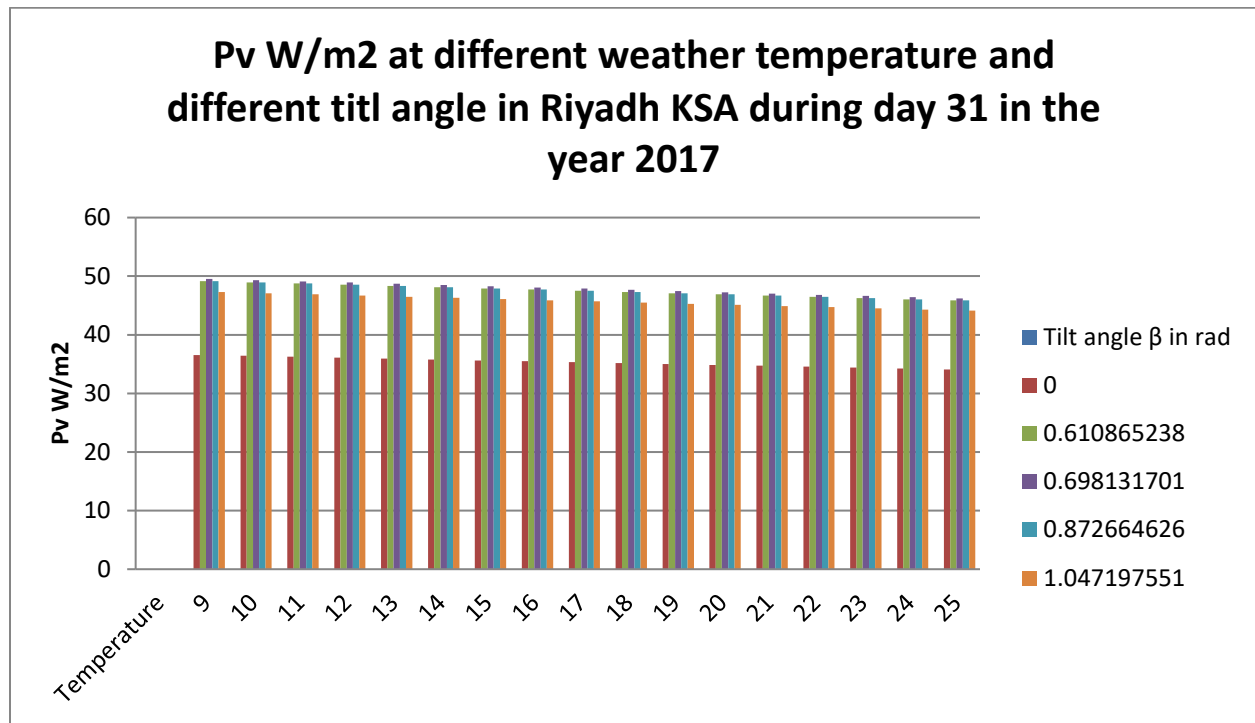


Figure 27: shows the maximum output power was calculated when the tilt angle was 40 ° which is equivalent to radians 0.698131701.

When the output power for the same day 31 is calculated theoretically for different locations in the world such as Sydney, Buenos Aires and Swansea, it is obviously revealed that the maximum power is at tilt angle 50 °, 50 ° and 60 ° correspondingly. This is because the solar irradiation reaches the maximum at these tilt angles in the given day of the year, see figures 28, 29 and 30. Moreover the different cell temperatures shown that the power varies which have influence on the amount of the output power from the PV solar panel. Therefore, cell temperature is other factor which is directly proportion to the output power. The different locations have different GPS coordination which it has a direct impact on the tilt angle and the output power as seen earlier.

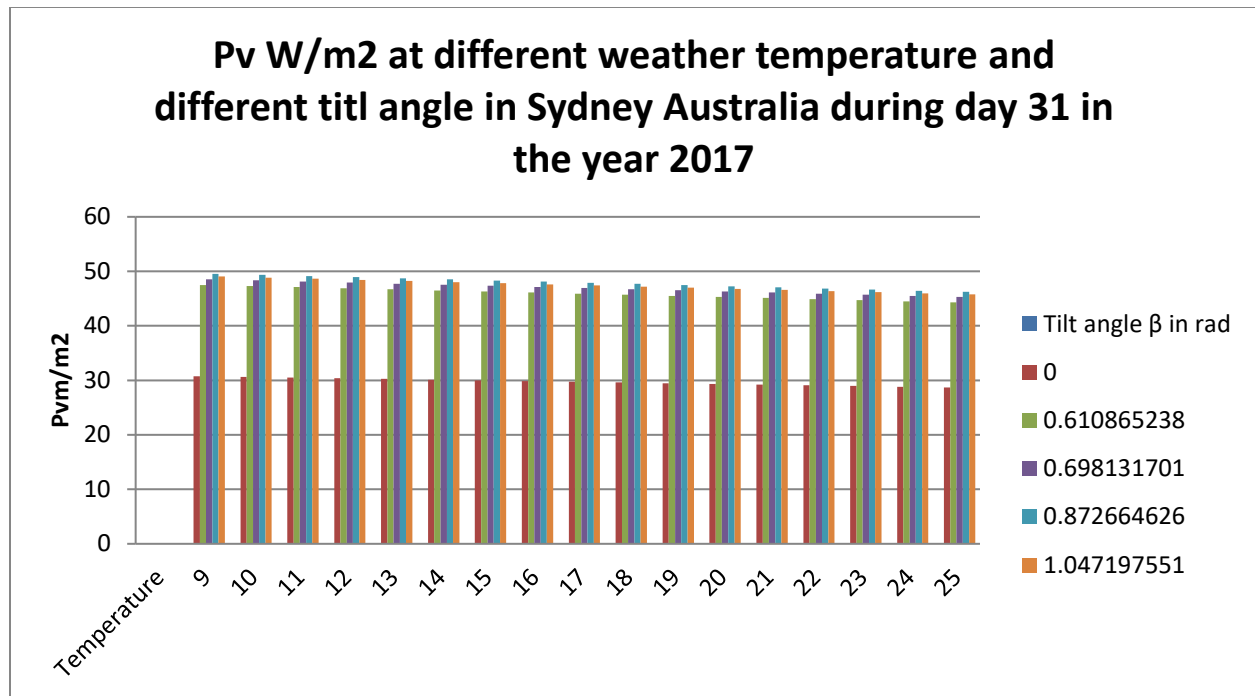


Figure 28: Theoretical calculation of the output power of the PV solar panel in Sydney.

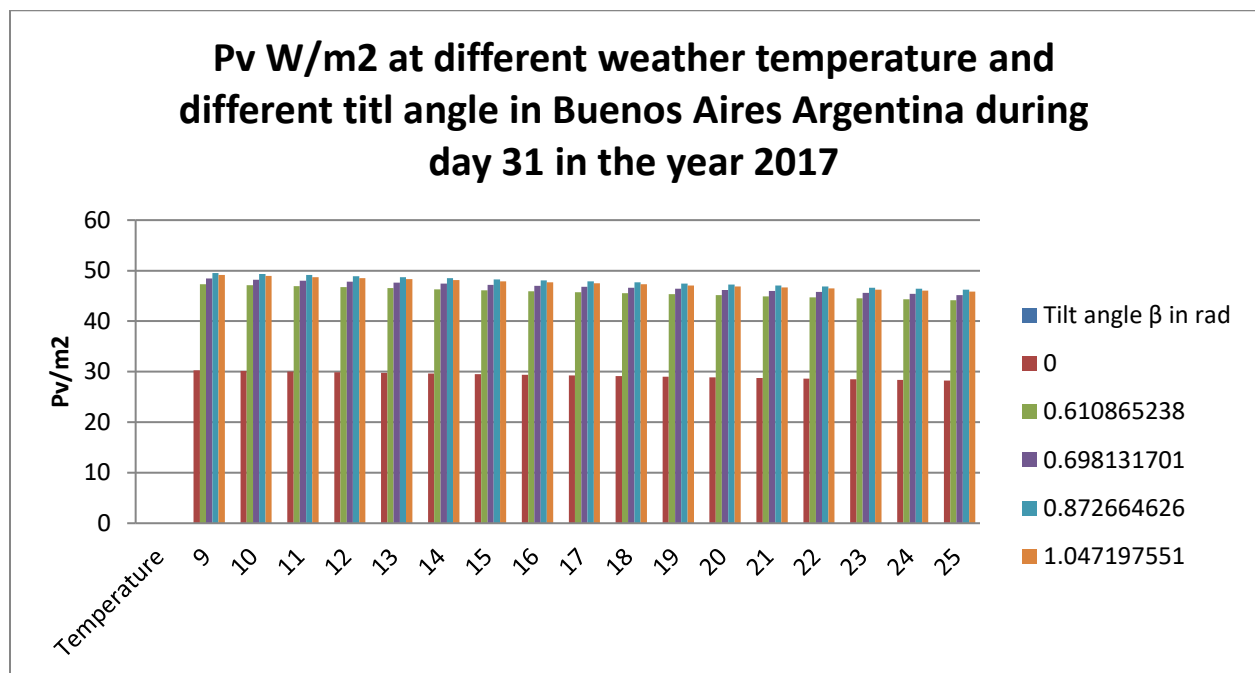


Figure 29: theoretical calculation of output power of the PV solar panel in Buenos Aires.

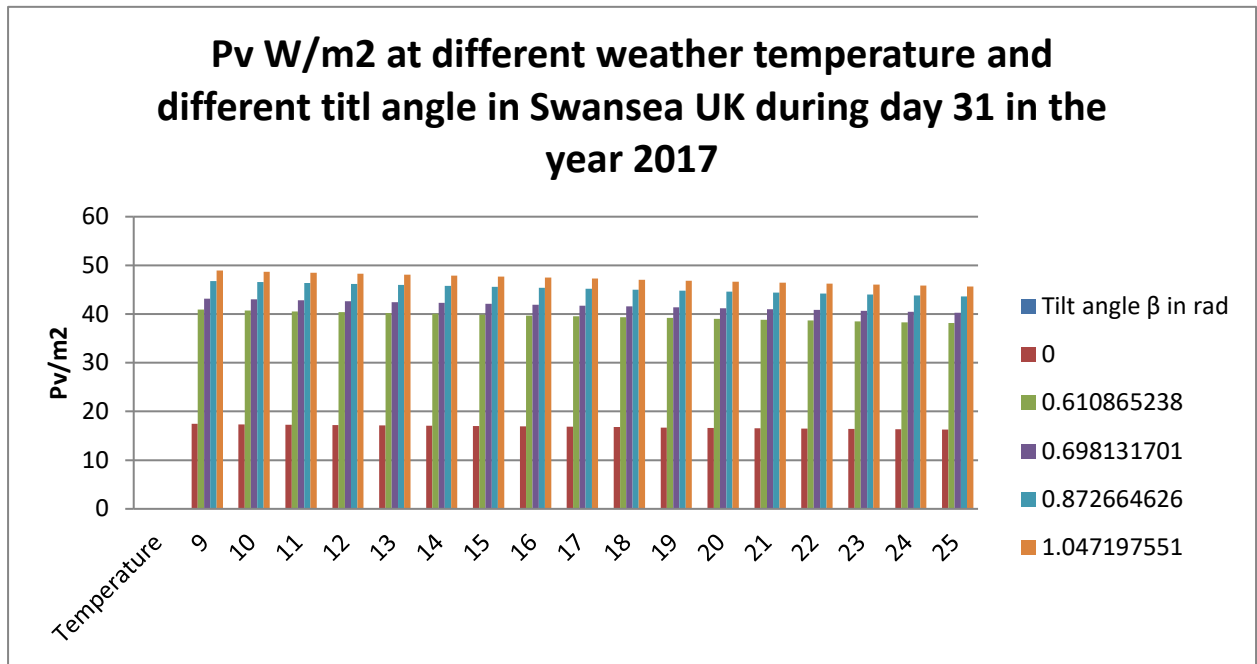


Figure 30: theoretical calculation of output power of the PV solar panel in Swansea.

Chapter 5

Discussion

5.1 Evaluate the methodology to find an optimum tilt

There are many ways to find the optimum tilt angle in order to get the maximum output power from PV solar panels. To evaluate which methodology is the most suitable one, the following chart in figure (31) can be used.

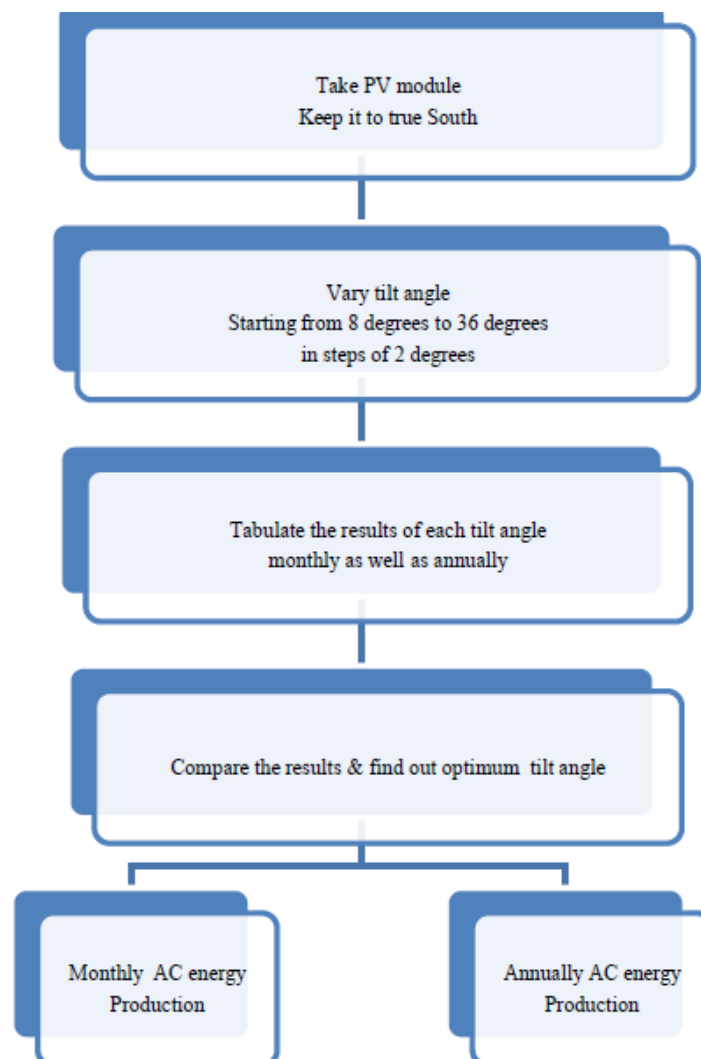


Figure 31: A methodology to find an optimum tilt angle (Radhika & Suman, 2015).

It is obvious that the panel has to face southerly direction in order to ensure the highest sunlight irradiation. Moreover, the measurements should be repeated in different time so that data can be analysed efficiently. The high amount of data the more valuable results will be achieved which can be used to decide for the optimum tilt angle, as this will prove that the choice for a tilt angle is valid. According to Radhika & Suman (2015), the tilt angle should be changed every 8° this will ensure that the results are more realistic. However, when the measurements were carried out in Riyadh, there was a focusing on the tilt angles within the range between 35° - 40° . This is because of the optimum angle should be within this range according to the theoretical calculations of the output power. Moreover, the daylight time was also taken into consideration when the output power was measured in order to find out when was the maximum power at the given optimum tilt angle.

5.2 Optimum tilt angle

The optimum tilt angle is the one where a PV solar panel is mounted on a base in order to measure the maximum output power of the PV solar panel at different locations as seen in the previous section. In order to gain the highest output power, the optimal tilt angle is measured at different PV solar tilt angles as discussed in the last paragraph and the measurement should be carried out during months in a year. Chandrakar & Tiwari (2013), showed that for a given location the optimum tilt angle is changed during the months in a year because of the solar radiation and the length of the daylight hours changes throughout the year. According to the next figure (32), the range of the tilt angles will be close to the latitude during the end of March to the beginning of April and during the end of September and beginning of October. Moreover the highest radiation was recorded during the middle of May and end of July. Hence the optimal tilt angle was the lowest for this range. Figure (33) shows at which tilt angle should the PV solar panels mounted in order to get the maximum output power according to the last authors.

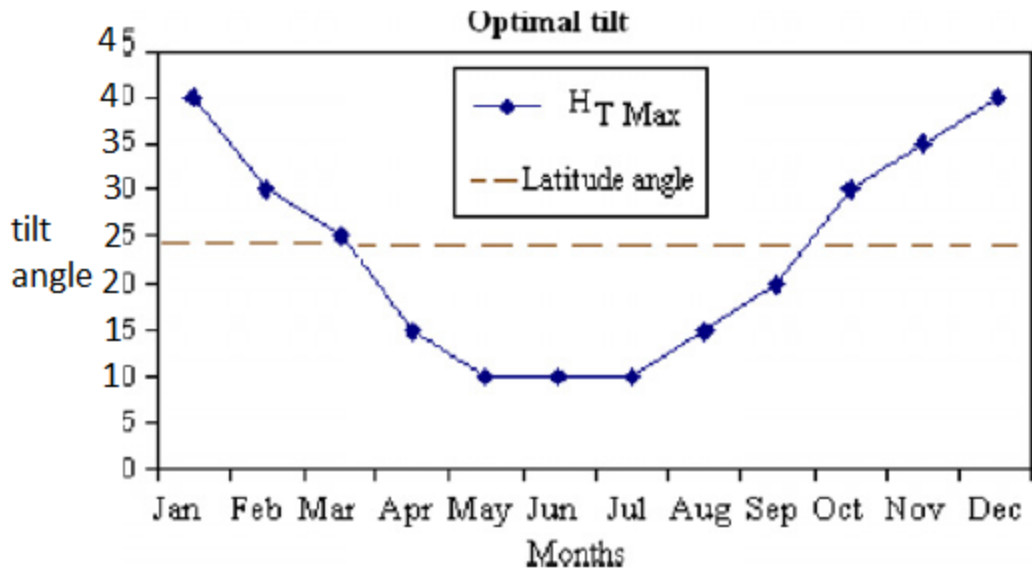


Figure 32: shows the optimal tilt angle during a year at CHHATISGARH SITE (Chandrakar & Tiwari, 2013).



Figure 33: shows how the tilt angle is adjusted during a year in order to achieve the best performance (Chandrakar & Tiwari, 2013).

5.3 Analyse a mathematical model for calculating the tilt angle

According to Yang & Lu (2007) a model is investigated to calculate the tilt angle and azimuth angle. They researched the correlation between the output power at certain tilt angles and the weather condition. The solar irradiation at specific hour is calculated as follows according to Yang & Lu:

$$S_{tt}(i) = S_{bt}(i) + S_{dt}(i) + S_r(i) \quad 5-1$$

Where $S_{bt}(i)$ is the beam irradiation at hour.

$S_{dt}(i)$ is the total diffuse solar irradiance.

$S_r(i)$ is the solar irradiation reflection.

All solar irradiance has unit w/m².h. The optimal tilt angle is calculated by solving the following equation;

$$\frac{d}{dB} (\sum_{i=1}^m S_{tt}(i))_{\beta_{opt}} = 0 \quad 5-2$$

Where m is the maximum hour the solar panel operates. The beam solar irradiation is calculated as follows:

$$S_{bt} = S_{bh} \frac{\cos \theta}{\cos \theta_z} = S_{bh} R_b \quad 5-3$$

Where S_{bh} is the beam solar irradiation in a horizontal plan, while θ and θ_z are the angle of incident and the angle of incident on a horizontal surface correspondingly. R_b is a geometry factor.

The reflected solar irradiation S_r is calculated using the following equation:

$$S_r = \frac{\rho_o}{2} S_{th} (1 - \cos \beta) \quad 5-4$$

S_{th} is the total irradiance on a horizontal plane. If the weather is not snowing then $S_{th} = 0.2$, otherwise it will have a value between 0.35-0.95.

$$S_{dt} = 0.5 S_{dh} [1 + \cos(\beta)] (1 - A_I) \left(1 + f * \sin^3 \left(\frac{\beta}{2} \right) \right) + S_{dh} A_I R_b \quad 5-5$$

Where S_{dt} is the solar irradiation diffusion on a horizontal plan and

$$A_I = \frac{S_{bn}}{S_{on}} = \frac{\left(\frac{S_{bh}}{\cos \theta_z} \right)}{\left(\frac{S_o}{\cos \theta_z} \right)} = \frac{S_{bh}}{S_o} \quad 5-6$$

$$f = \sqrt{\frac{S_{bh}}{S_{th}}} \quad 5-7$$

$$S_o = S_{sc} \left[1 + 0.033 \cos \left(\frac{360n}{365} \right) \right] (\cos \delta \cos \varphi \cos \omega + \sin \delta \sin \varphi) \quad 5-8$$

S_{sc} is a solar constant which is 1353 w/m²

The last model should include S_{bh} and S_{dh} and most observation are associated with an hourly radiation. The ratio $\frac{S_{bh}}{S_{th}}$ is the diffuse ratio. For this model a weather data are used as a requirement to calculate the output power of the PV solar panels.

5.4 Validate optimal tilt angle

When the optimal angle is determined theoretically as seen in the previous section, there is a need to validate the value of the tilt angle which returns to the maximum output power. The validation is always done by measuring or calculating the output power produced by a PV solar panel at a certain time and location. Kaldellis et al (2012) showed the validation is carried out when the output power reaches a maximum value at a given tilt angle and at a certain hour in a day. Many experiments were conducted in Greece while the optimal tilt angle was observed which it was 60° . A numerical sizing algorithm was used in order to design the mounting of PV solar panels. According to the experiment, it is expected that the maximum output of PV solar panels can be observed during the winter time when there is sunlight with low sun radiation. An optimum tilt angle is the one which returns the highest electrical energy $\text{w/m}^2\cdot\text{h}$ at a given day and time. Moreover, different experiments were conducted at different time to ensure the validity of the project. Similarly, when the measurements were conducted in Riyadh in KSA, the maximum output power was measured when the tilt angle was 35° . By repeating the measurements in 4 different days at different tilt angles, each day the output power was measured in different time. However, it was validated that the 35° is the optimal tilt angle.

5.4.1 Photov-III sizing algorithm

This is an algorithm developed by Kaldellis et al (2012) in order to validate the optimal tilt angle. It is based on the production of the output power of the Z PV panels with a battery capacity ' $Q_{\max}$ '. The algorithm had requirements such as the energy autonomy during a year and the area in which the output was examined at different tilt angles. The measurements are examined in such a way that a number of panels Z and batteries $Q_{\max}$ was executed for tilt angles between 0° and 90° in intervals of 15° in a one month, six months or a year and each time the z-Q* is calculated which represents the energy autonomy. However, the optimal tilt angle is predicted from the curve under no load restrictions. Each time selected the zero load rejection is obtained. When the zero rejection is not achieved the procedure is repeated until this condition will be fulfilled. Furthermore, when the number of PV solar panels increases, the battery capacity is reduced in such a way that the curve in figure (34) will continue asymptotically. It means that the maximum tilt angle is when the battery requirement is low. According to the last mentioned figure, if 160 PV solar panels are used with a battery capacity of 4850 Ah, the predicted tilt angle would

be 60° as shown in figure (34). Therefore the battery capacity required to maintain maximum energy from the PV solar panels should be reduced as there will be less demand on the power from the batteries at this optimum tilt angle.

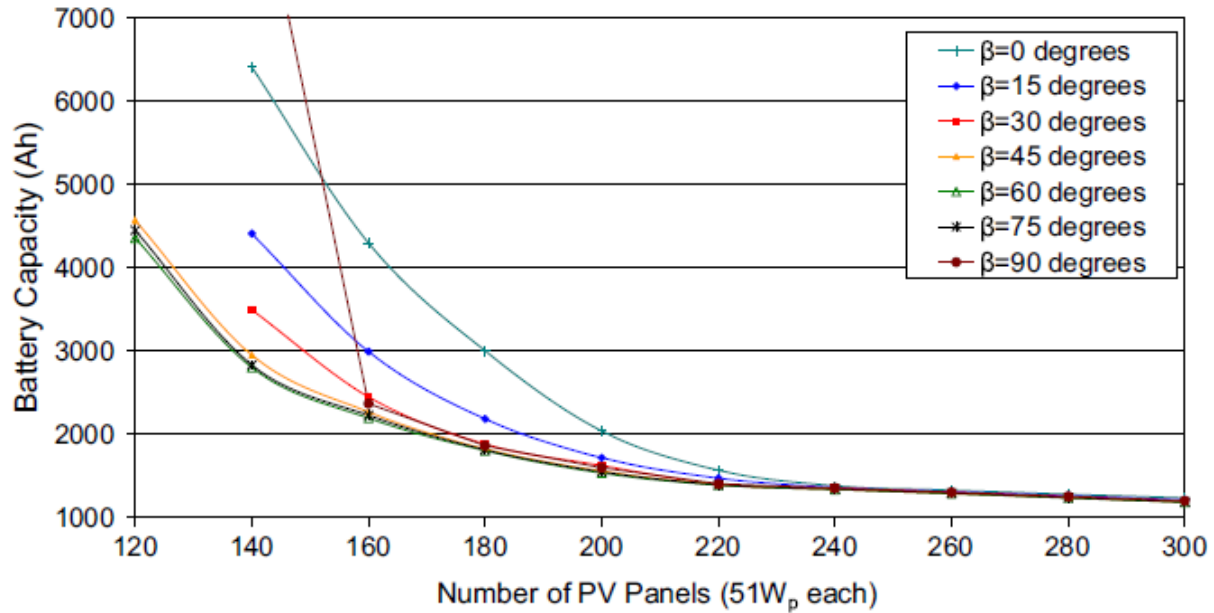


Figure 34: shows battery capacity Q_{max} verses number of PV panels Z for Various Panel Tilt Angles (Kaldellis et al.,2012).

5.5 Optimum inclination of PV panels

Since there is a relationship between the panel inclination and the required spacing between two arrays of PV solar panels, the optimum inclination is determined in such a way that the output power can be achieved at a certain tilt angle which leads to maximize the yield of the PV solar panels (Wissenbacher, 2015). According to Wissenbacher, the optimal fixed tilt angle for a PV solar panels equal to 0.9 times the latitude angle at a location faces to the South and installed in the Northern Hemisphere. For an optimum inclination, the angle has an impact on the required spacing between two arrays of PV solar panels. Consequently, the spacing should be designed that shadow between two neighbouring rows of PV panels is avoided. For example, an outdoor measurement was conducted in Malta in order to explore how changing the orientation has an impact on PV solar performance and the amount of output power produced. The results have been investigated to show the spacing requirements according to the azimuth and altitude angle, see figure (35).

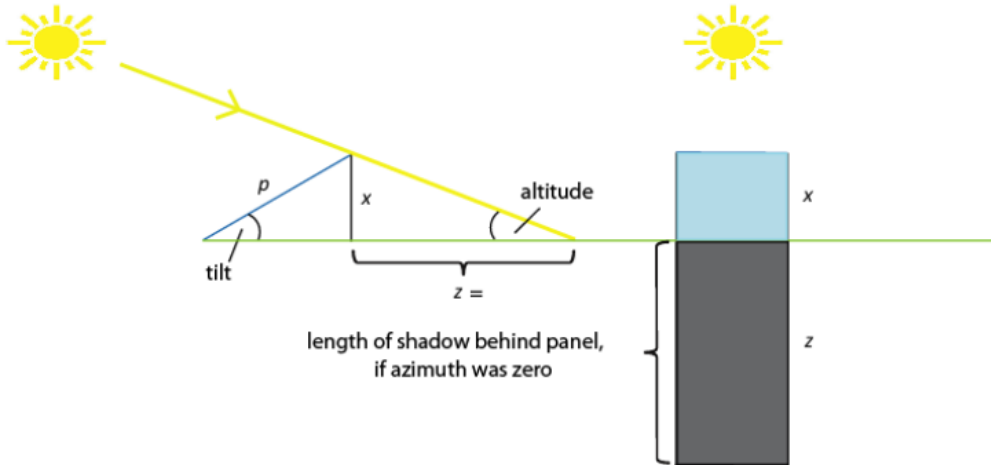


Figure 35: shows the length of shadow required between two rows of PV panels according to azimuth and altitude angles (Wissenbacher,2015).

To calculate the spacing between two PV solar panel arrays, the following steps should be followed according to Wissenbacher:

$$z = \frac{x}{\tan(\theta)} = y / \cos(\psi) \quad 5-9$$

Where ψ is the azimuth angle.

$$x = P \sin(\beta), \quad 5-10$$

Where P is a typical length of a PV solar panel and it is usually equal to 1.66 m.

$$\text{Hence, } y = P \sin(\beta) * \frac{\cos(\psi)}{\tan(\theta)}. \quad 5-11$$

However, spacing can be decreased when the tilt angle is reduced in such a way that $y = 2x$ according to (Wissenbacher, 2015), because the cross shading is reduced which leads to increasing the performance factor PF . A low tilt angle in specific locations is not preferred because the panel would be dirty quickly and dust will be accumulated on the surface of the panel which resulted a regular maintenance including cleaning to maintain a good operating efficiency. By keeping the tilt angle between $35^\circ - 45^\circ$, the PV solar module will be feasible, as less maintenance cost will be needed.

5.6 Mounting system analysis

The design of the mounting system for a PV solar panel should be sustainable and the product should be rigid and has no weak points. The SolidWork was used in order to draw a suggested mounting system using Aluminium T451 material, see figure (36). This material was chosen because it's Solution is heat-treated and naturally aged to a substantially stable condition, see appendix C for further details about the material suggested to be used in manufacturing the mounting system. The design shows that the tilt angle can be adjusted manually as shown in figure (38) by tighten and un-tighten the bolts seen underneath the panel. In order to evaluate the design. Moreover the design should be evaluated in order to find out whether there are weak points which causing displacement of the PV solar panels to a different tilt angle and will cause degrading in the operating performance when there is a wind as seen in figure (37). The forces attacking the surface of the PV solar panel and the base of the mounting system are the drag forces produced by the wind speed. Appendix C shows more images taken from the SolidWork design. The drag forces produced on the surface of the panel is measured at different wind speed (Bernard, 2009). Figures (39 A and B) show the brackets used to mounting the PV solar panel. Figure (40) shows the FEA analysis of the brackets and the frame to ensure that the mounting system is complying with the weight and the drag force produced due to the wind speed attacking the surface of the panel.

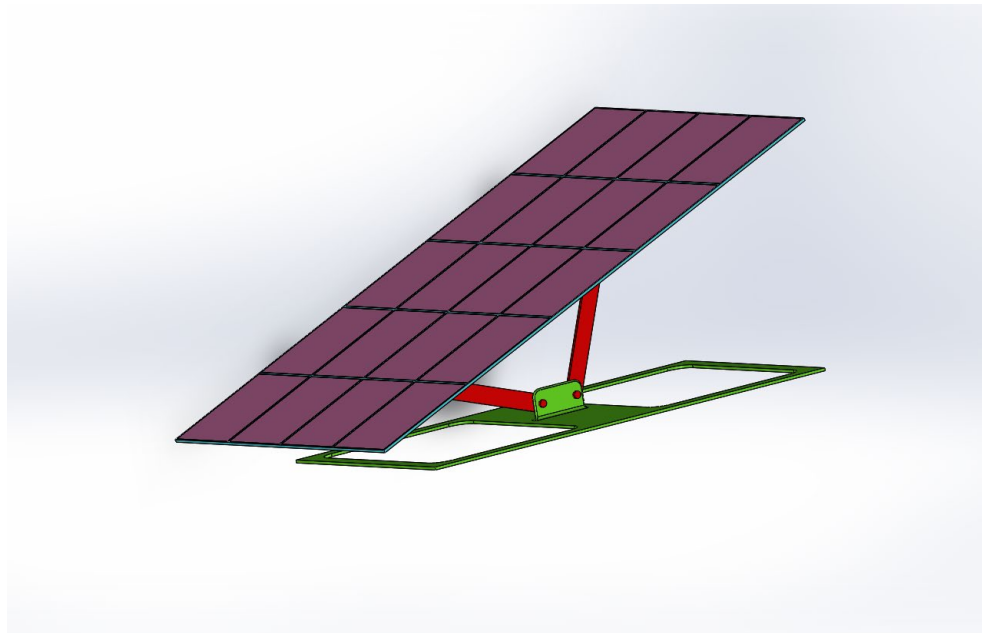


Figure 36: shows a design by SolidWork of the mounting system using Aluminum material.

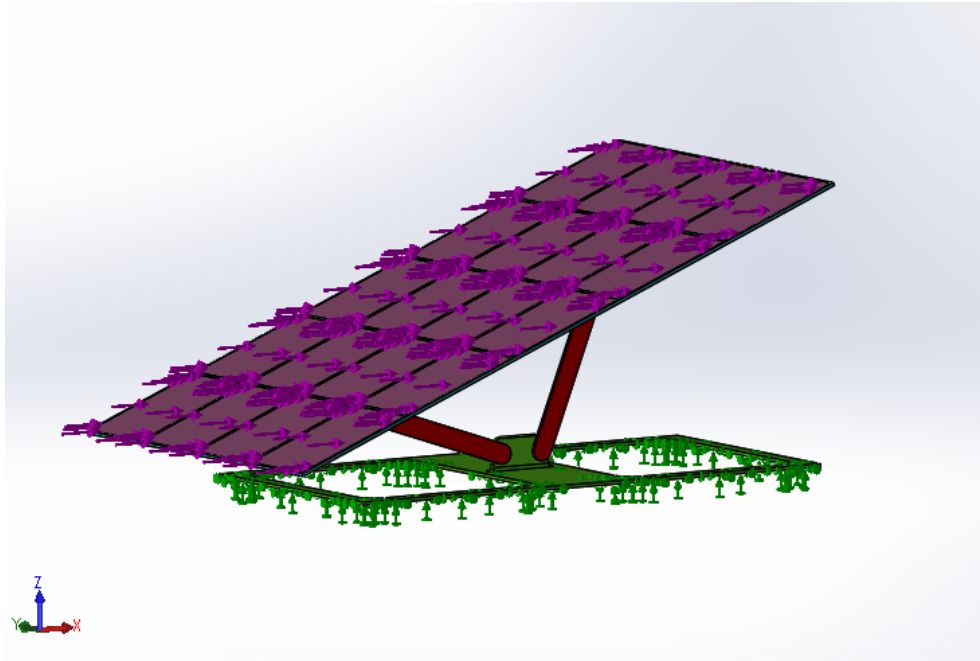


Figure 37: shows the forces attacking the surface of the PV solar panel.

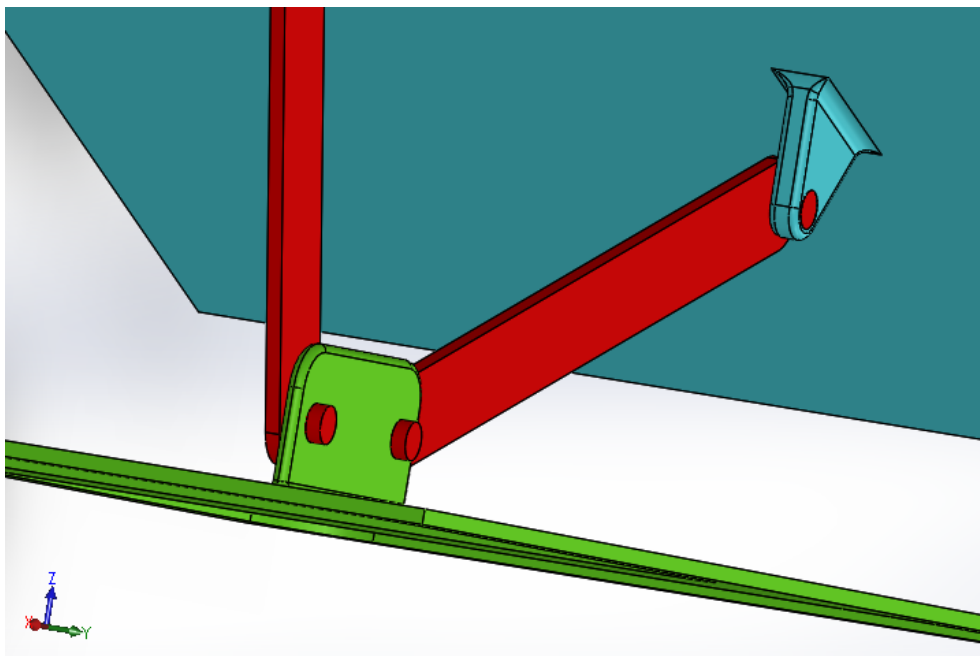
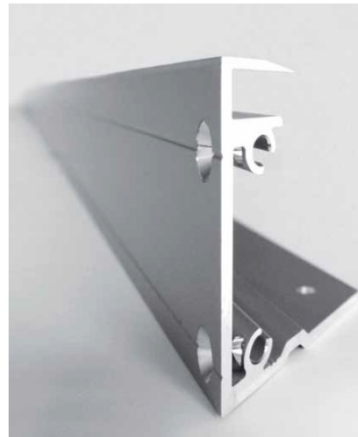


Figure 38: A SolidWork design to show how the tilt angle can be adjusted manually.

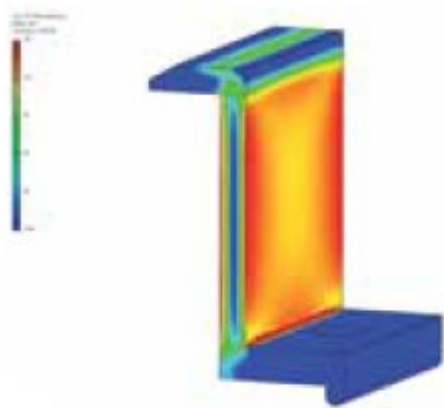


A

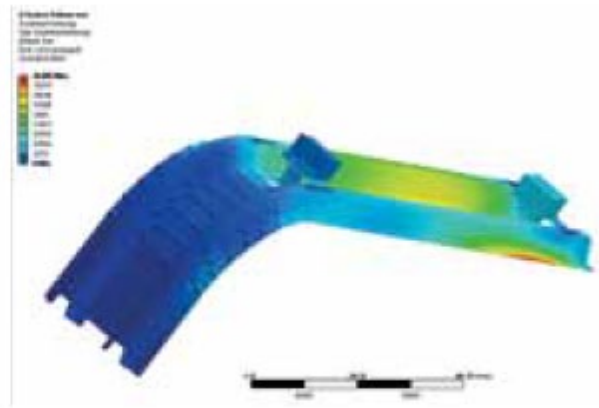


B

Figure 39: Frame and the brackets of the mounting system (20 years mounting system).



FEM-model: end clamp



FEM-model: Lambda Light

Figure 40: FEM analysis of the bracket and the frame (20 years mounting system).

FEA analysis done through the SolidWorks was conducted in order to investigate the performance of the Aluminium material chosen to build the mounting system. It has a von Mises for up to 9.738×10^6 while the yield strength is 2.757×10^7 . This information can be utilized in order to ensure the rigidity of the mounting system as it shown in figures (41 and 42).

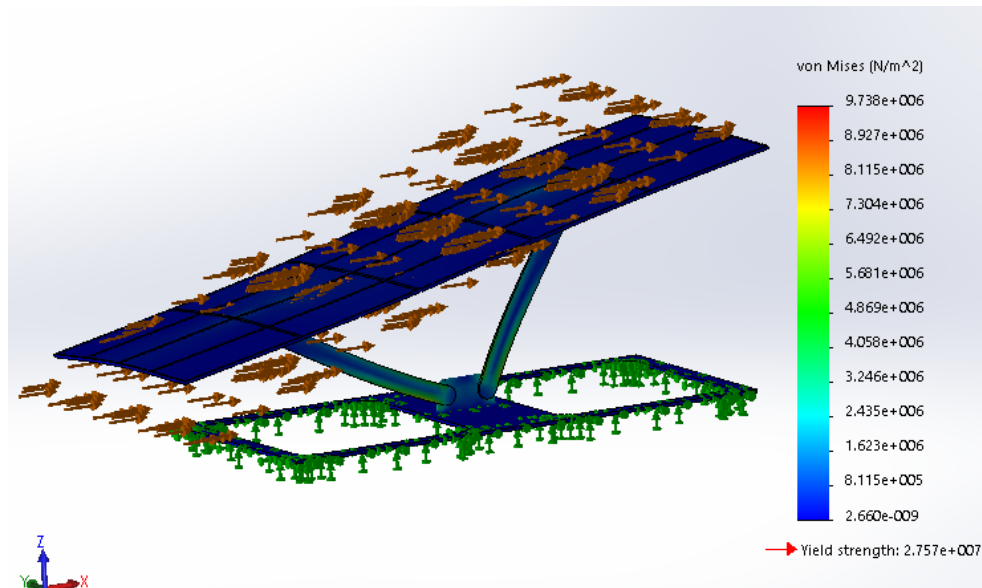


Figure 41: shows the result of the maximum stress and the yield strength.

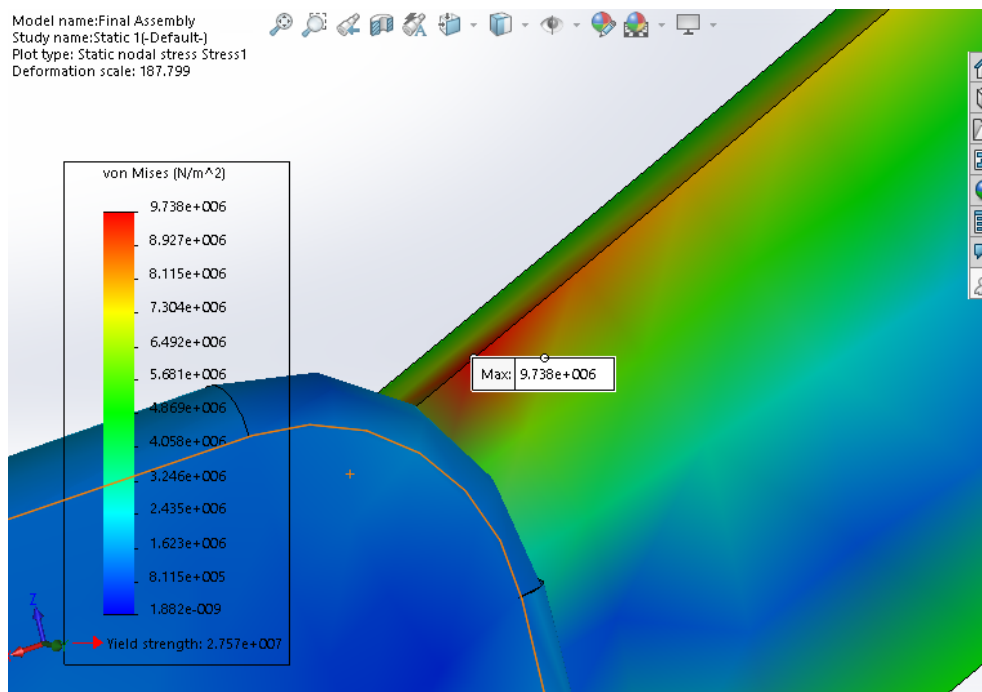


Figure 42: shows the result of the maximum Von Mises.

5.7 Analysis of a tracking system

As seen in the previous sections, the optimal tilt angle should not be fixed in order to ensure a production of a maximum output power from the PV solar panels. Therefore, a tracking system that changes the tilt angle whenever the sunlight radiation is changed and required to ensure the best performance of the PV solar panels according to Bazyari et al (2014). A suggested system which can be used in order to control the tilt angle is depicted in figure (43). The system should be built in with a mechanical mounting system in order to change the tilt angle by a degree suitable to ensure the maximum output power. The tracking system has a sunlight intensity sensor, servo motor and a control circuit. The sunlight intensity sensor sends a continuous signal about the intensity of the sunlight radiation to the control system during the continuous operation. The control system processes the signals from the sensor and sends a control signal to a servo motor in order to rotate it by certain steps within the azimuth direction. The servo motor moves in steps corresponding to a total of 90 degrees. The motor moves clockwise when the tilt angle needs to be changed close to 90 degree and anti-clock wise in order to ensure that the PV panel returns to the initial position during the sunset time and to ensure that the same operation is repeated next day. The mounting system has a tooth pulley which stops by a solenoid latch to keep the mounting system hold at one position when the sunlight radiation is fixed during a certain daytime. The system could be made smarter and more sensitive to the variation of the sunlight radiation if the radiation sensor is adjusted to measure any changes in the sunlight radiation during the day time, however, this is not preferred as it needs more maintenance including lubrications to the mechanical parts joining the servo motor by the mechanical base through the tooth pulley.

This tracking system solves the issues with the reducing the PV panel performance when the solar irradiation changes during the day, month or a year.

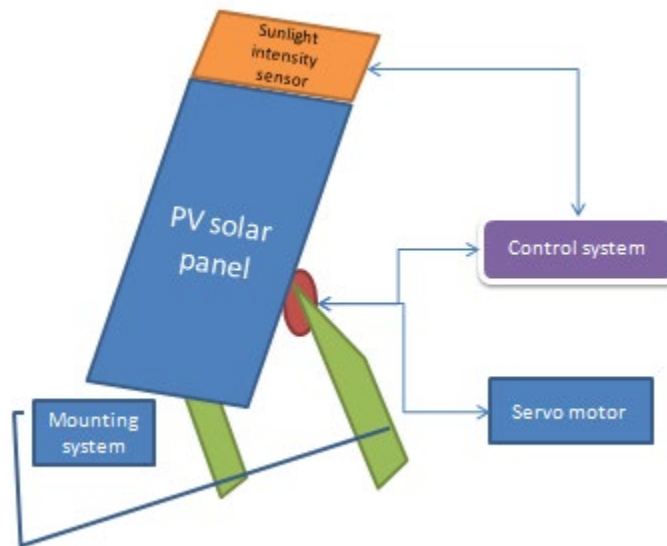


Figure 43: shows a suggested tilt's angle tracking system.

5.8 Develop a mounting system

In order to make the project more valuable a mounting system was developed using SolidWork, see figure (44). Aluminum material was used in the design because of the physical properties which are suitable for this type of applications, see appendix C. This information can be utilized in order to ensure the rigidity of the mounting system. The arc was designed like teeth with a slot between them, each tooth is corresponding to a tilt angle one there is a 20 degree difference between each tooth. The mounting is adjusted manually by inserting a steel pin which hold the brackets on the mounting system, see figures (45 and 46). This mounting system can be improved further when the arc is redesigned and converted into a track with multiple slots moved by a stepper motor and teeth pulley. This will make the tilt angle adjusted smoothly and automatically using the suggested track system in the previous paragraph.

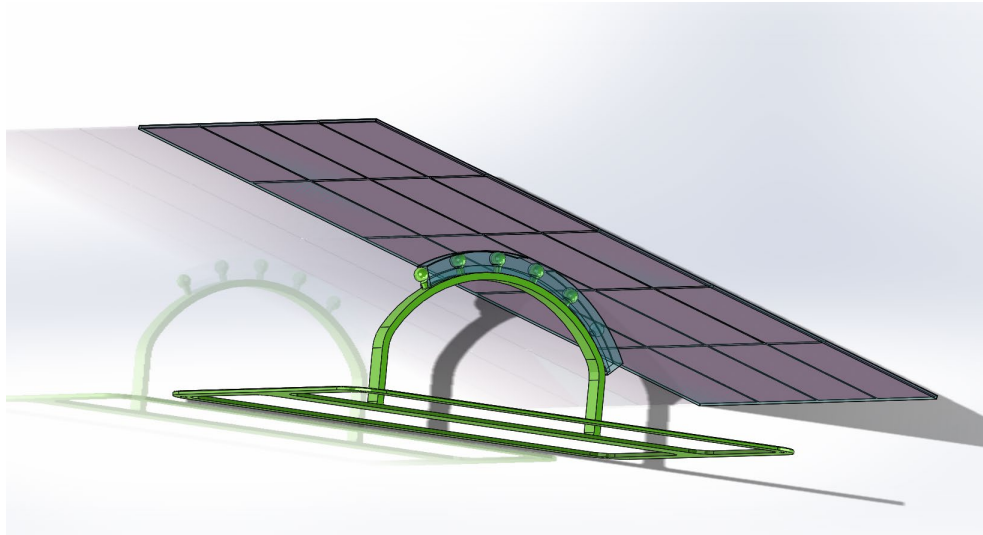


Figure 44: Develop a mounting using SolidWork

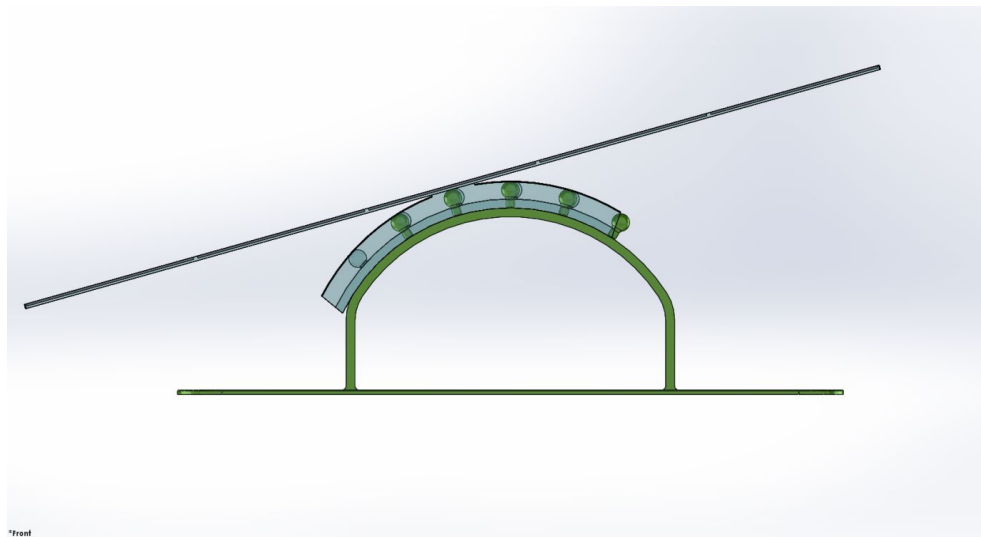


Figure 45: Design of the arc showing the teeth which are displaced by 6 apart.

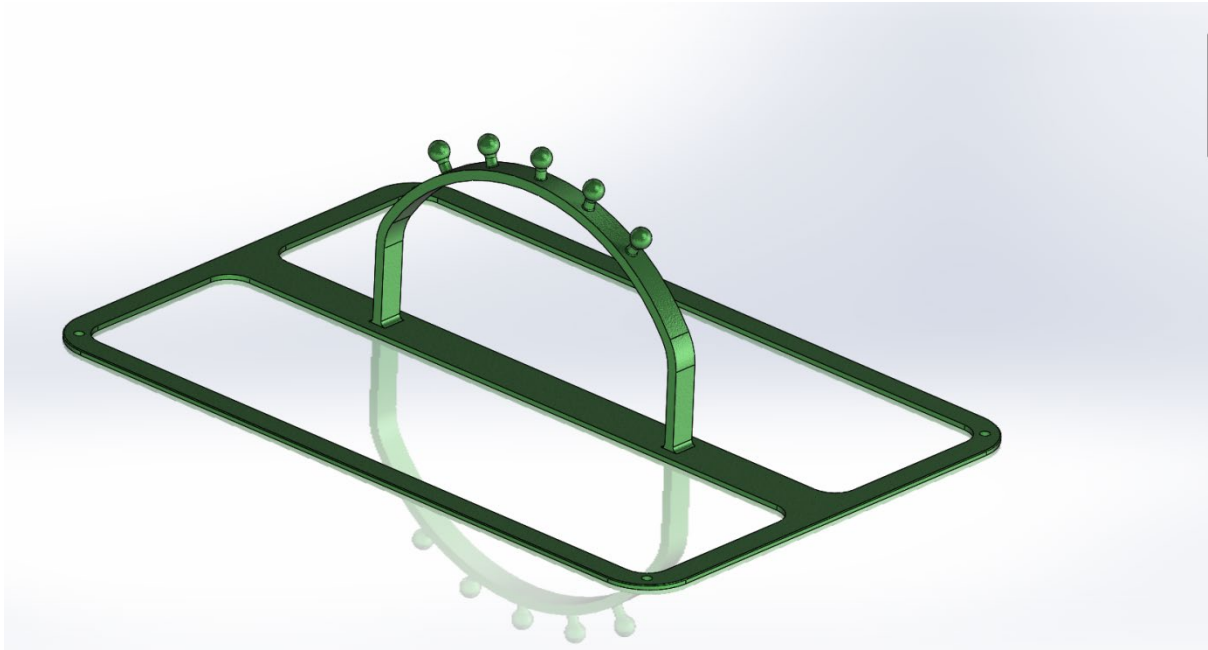


Figure 46: the design of the arc showing the teeth more visible.

Chapter 6

Conclusion and Recommendation

6.1 Conclusion

The optimum tilt angle is an important factor need to be chosen in order to ensure a maximum output power achieved from the PV solar panel. The optimum tilt angle can be calculated from the irradiation and the latitude of the location where the solar panel is mounted. However, in can be achieved from experimental measurements which can be made in order to calculate the output power of the PV solar panels. In this research two experiments were conducted; the first one was an outdoor conducted in Riyadh in KSA and the second one was an indoor which was conducted in the university lab in Swansea. The results shows the optimal tilt angle for the indoor test was 30° , as well as in Riyadh the optimal tilt angle was 35° , however, this is not the case when the output power was calculated theoretically which was 40° because the measurements were conducted outskirts of Riyadh city. The output of the same PV solar panel was calculated theoretically for different locations in the world in order to observe the tilt angle and the maximum output power produces. The indoor measurements were conducted in order to examine the impacts of the elevation angles and the tilt angles on the output of a PV solar panel. The elevation angle is considered, as it acted as sunlight. The measurements were taken during 5 days in order to ensure the data are valuable. Finally a tracking system is suggested in order to maintain an optimal tilt angel that produces the maximum output power.

6.2 Recommendation

It is highly recommended to investigate many tilt angles to decide for the best one which can produce the maximum power output. If there is no enough data about the solar radiation for the location where PV solar panels are aimed to use, the more tilt angles should be investigated in intervals in order to get accurate data. To upgrade the current PV solar models a tracking system could be added into the model as shown in the last chapter and add a smart controller that count the number of steps the tilt angle need to change in order to achieve the maximum output power. This could be done with the aid of digital signal processing 'DSP' and suitable mounting system.

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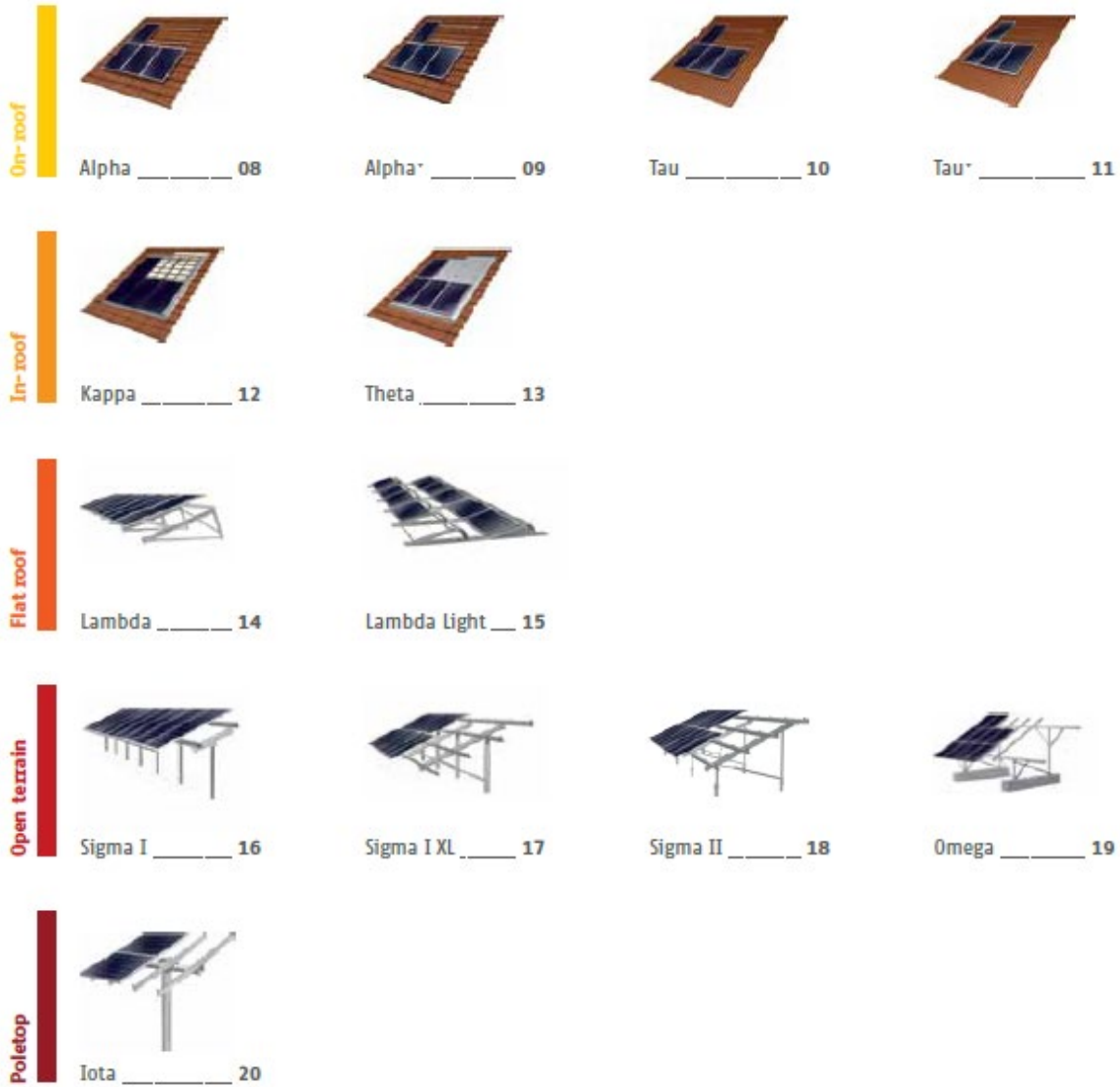
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Appendix

Appendix A



Appendix B

CHIKO MOUNTING SYSTEMS



Appendix C

Aluminum, 6061, T451

Typical uses

Trucks, towers, canoes, railroads cars, furniture, pipelines, and other structural applications where strength, weldability, and corrosion resistance are needed

Price

Price * 1.34 - 1.48 GBP/kg

Physical properties

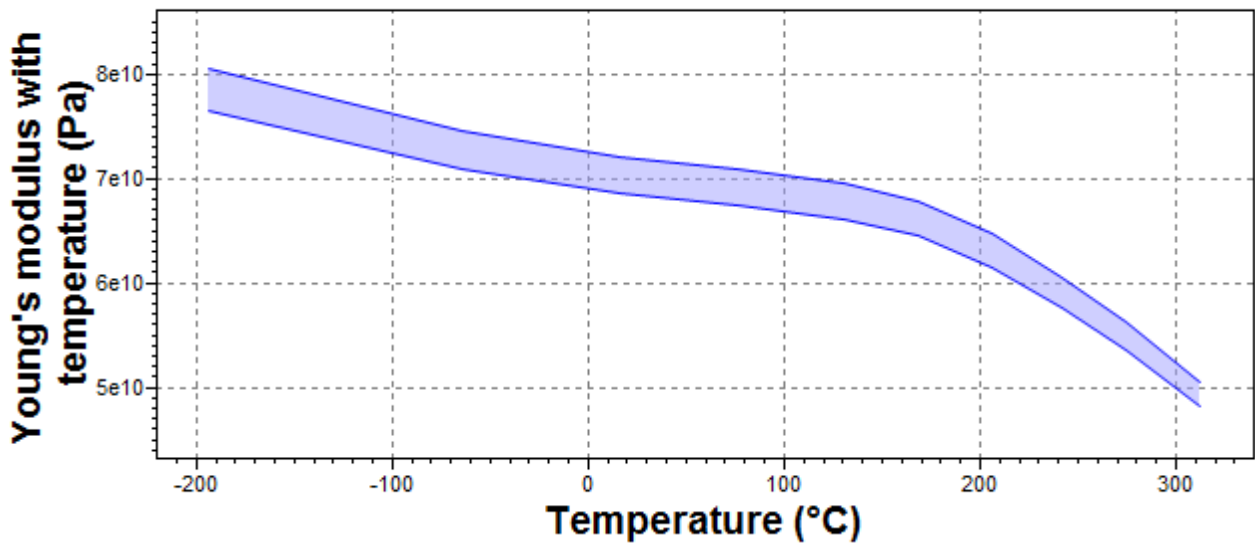
Density 2.7e3 - 2.73e3 kg/m^3

Mechanical properties

Young's modulus 6.8e10 - 7.15e10 Pa

Young's modulus with temperature 6.83e10 - 7.19e10 Pa

Parameters: Temperature = 26.9°C



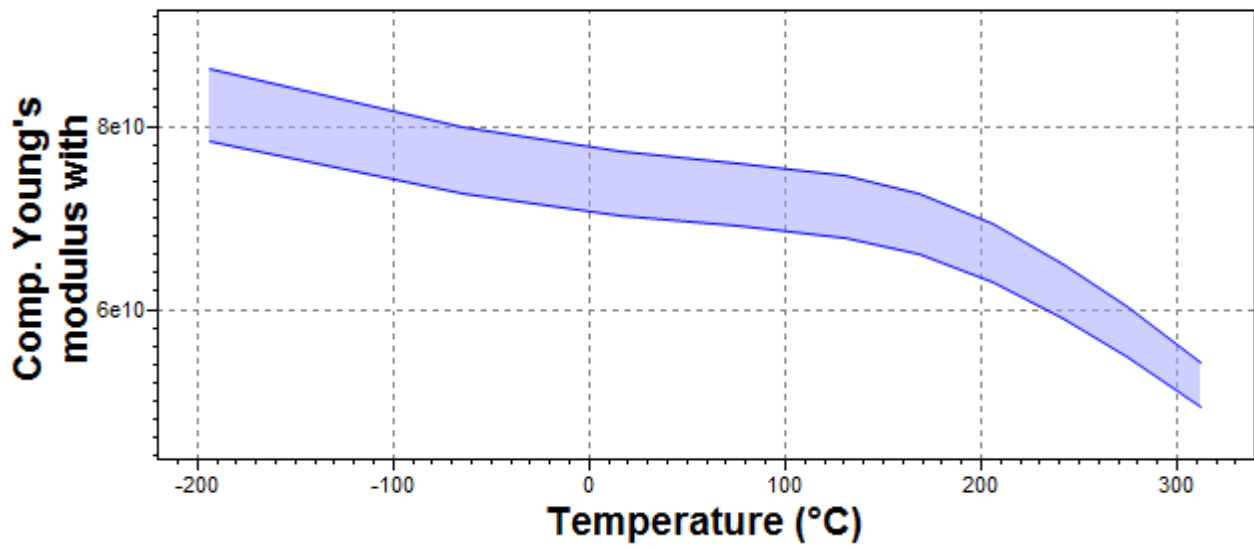
Yield strength (elastic limit) 1.03e8 - 1.24e8 Pa

Tensile strength 1.72e8 - 2.41e8 Pa

Elongation 0.16 - 0.186 strain

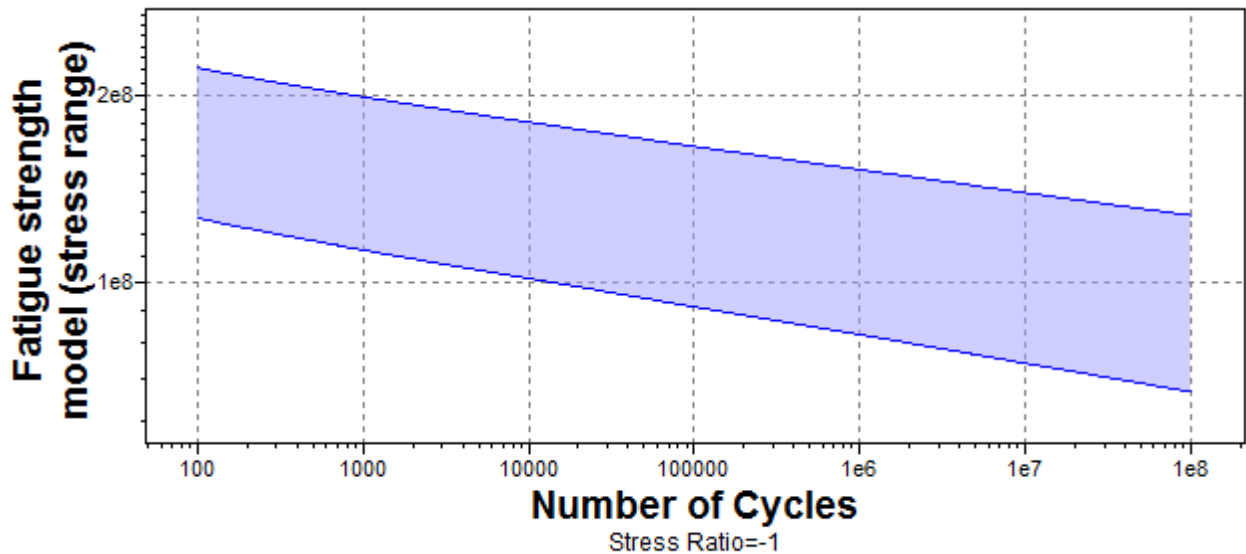
Comp. Young's modulus with temperature 7e10 - 7.7e10 Pa

Parameters: Temperature = 26.9°C



Compressive strength	* 9.7e7	-	1.72e8	Pa
Flexural modulus	* 6.8e10	-	7.15e10	Pa
Flexural strength (modulus of rupture)	1.03e8	-	1.24e8	Pa
Shear modulus	2.6e10	-	2.73e10	Pa
Bulk modulus	6.69e10	-	7.03e10	Pa
Poisson's ratio	0.33	-	0.343	
Shape factor	39			
Hardness - Vickers	70	-	76	HV
Fatigue strength at 10 ⁷ cycles	9.7e7	-	1.07e8	Pa
Fatigue strength model (stress range)	7.43e7	-	1.4e8	Pa

Parameters: Stress Ratio = -1, Number of Cycles = 1e7cycles



Thermal properties

Melting point	582	-	652	°C
Maximum service temperature	130	-	150	°C
Minimum service temperature	-273			°C
Thermal conductivity	161	-	174	W/m.°C
Specific heat capacity	934	-	972	J/kg.°C
Thermal expansion coefficient	2.34e-5	-	2.46e-5	strain/°C
Latent heat of fusion	3.84e5	-	3.93e5	J/kg

Processing properties

Metal casting	Unsuitable
Metal cold forming	Excellent
Metal hot forming	Excellent
Metal press forming	Acceptable
Metal deep drawing	Acceptable

Durability

Water (fresh)	Excellent
Water (salt)	Acceptable
Weak acids	Excellent
Strong acids	Excellent
Weak alkalis	Acceptable
Strong alkalis	Unacceptable
Organic solvents	Excellent
Oxidation at 500C	Unacceptable
UV radiation (sunlight)	Excellent
Galling resistance (adhesive wear)	Limited use

Notes