PHYSICS INTERNAL ASSESSMENT

What is the optimal tilt angle for a solar panel to generate the maximum power output?

WHAT IS THE OPTIMAL TILT ANGLE FOR A SOLAR PANEL TO GENERATE THE MAXIMUM POWER OUTPUT?

INTRODUCTION

As I wish to pursue engineering at University, I keep scrolling through fascinating articles which connect physics and the latest technology. And that's when I came across the article about the Toyota bZ4X, this electric SUV has an optional rooftop solar panel, this sparked an interest in me. These panels can add an extra 1800km of driving distance, which is not a small number. And that's when the idea of this investigation came about, regarding a particular orientation or an optimal angle it is placed in, to maximize the power output from it.

As we don't go in-depth about Solar energy and look at it only from the surface level of its working in the course. I decided to research it and find out the factors which affect the power output which are the latitude of the location, topography, climate, etc. This also led me to think that it took about 2 weeks in my condo to layout the solar panels to use to power the basic amenities. The reason for this might be testing out different angles based on the geographic location of the condo and finding the precise orientation. In this exploration, I aim to find if there exists a relation between the angle of incidence and the power output

BACKGROUND INFORMATION

A photovoltaic cell is an electrical device that absorbs the energy of light sources such as Solar energy and then directly converts it into Electrical energy used in our daily life appliances. This form of energy is renewable and non-exhaustible, making it one of the environment friendly forms of electricity. However due to the requirement of solar energy, many areas around the world are restricted as they don't receive enough light energy from the sun. However, these cells absorb the light and heat incoming from the sun, the thermal energy does not contribute to the power output, it rather affects the efficiency negatively, this is determined by the photovoltaic cell's temperature coefficient. These cells work on the photovoltaic effect, which is inspired by Einstein's photoelectric effect, which can be defined as the emission of flow of electrons from a semi-conductor material when it absorbs photons emitted by light sources. The cells we use, the photovoltaic response of single-junction cells is limited to the portion of the sun's spectrum whose energy is above the band gap of the absorbing material, and lower-energy photons are not used. (Knier)

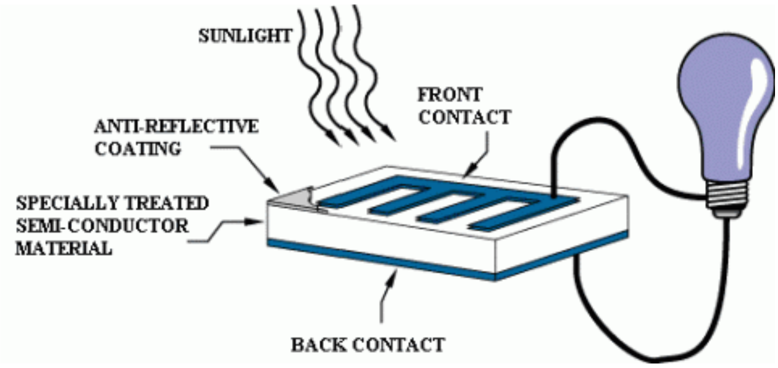


Figure 1 (Knier)

This diagram above explains how a solar cell works. The semiconductor material mentioned is usually n-type silicon because of its superior stability in an lighted and electric field environment. This forms an electric field, as soon as light hits this cell. The electrons leave from the atom. And when a conductor is connected to this, it forms a basic electric circuit and produces electric current.

Solar radiation geometry can be defined as the angle between a line extending from the centre of Sun to centre of Earth and the projection of this line upon Earth's Equatorial Plane. It is interesting because it also plays a big role in the development of photovoltaic cells. This introduces many other factors we must consider while evaluating the power output of a cell. The factor being evaluated in this paper is mainly the tilt angle, depends on the elevation of the cell as it is the vertical angle. This angle is changed according to the seasons, as the power output directly corresponds to the position of the sun.

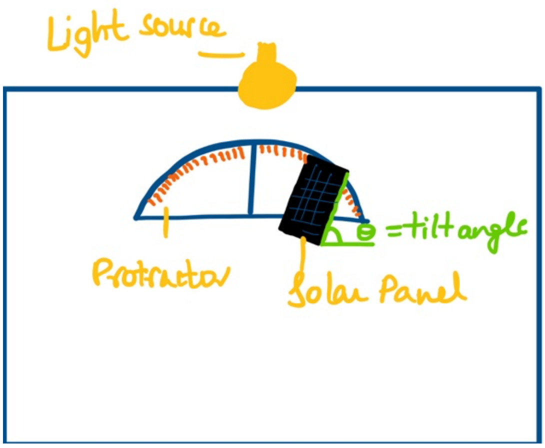


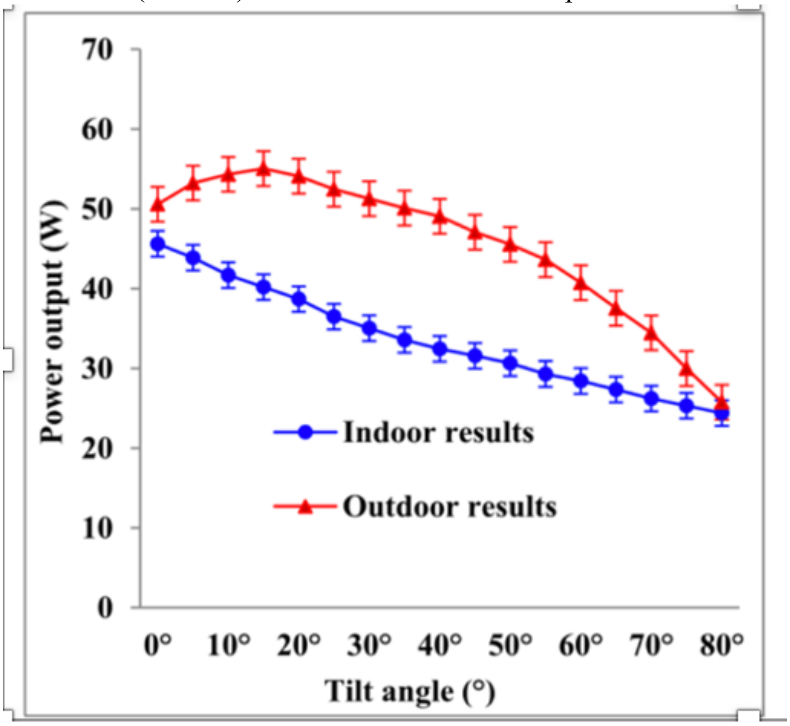
Figure 2 Rough labelled diagram of a tilt angle

HYPOTHESIS

The power output is expected to indirectly proportional to the cosine of the tilt angle. As the solar panel is at 0°, maximum light is hitting the solar panel generating the maximum amount of current possible leading to the maximum power output. Similarly, at 90° it is expected to produce the minimum electric current, and power output.

$$Power\ output \sim \cos(\theta)$$

The experiment has been conducted before in a university, their quantitative results will be used as the hypothesis. On the other hand, with every 5° increase in tilt angle, efficiency decreases by 0.54% for indoor case(Mamun). The blue trendlines are expected from this experiment.



Graph 1 (Mamun)

METHODOLOGY

Equipment	Uncertainty	Purpose
Solar Panel	-	To convert solar energy into electrical energy
Load resistor (1Ω	-	To maximize the power and improve output stability (
Ammeter (multimeter)	$\pm 0.005A$	To measure the current across the circuit, to use these values to calculate the power output
Voltmeter (multimeter)	$\pm 0.05V$	To measure the potential difference across the circuit, to use these values to calculate the power output
Box with a hole in the lid	-	To avoid any other source of light or radiation falling on the solar panel, except the one provided
Ray optic box	-	Acting as a light source directly hitting the solar panel through a hole in the box
Protractor	$\pm 1°$	To measure the tilt angle of the solar panel for different trials
Bench power unit supply	$\pm 0.195V$	To power the ray optic box providing the light in this setup
Lab jack	-	Just to place the solar panel on a total flat surface
Luxmeter	$\pm 3lux$	To calculate the intensity of the incoming light

Table 1 Apparatus required

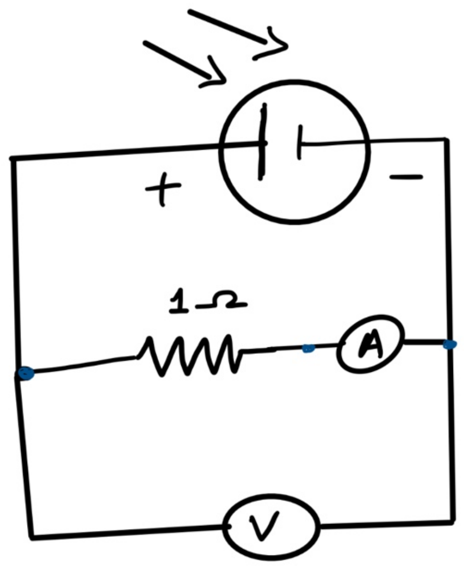


Figure 3 Experiment circuit diagram

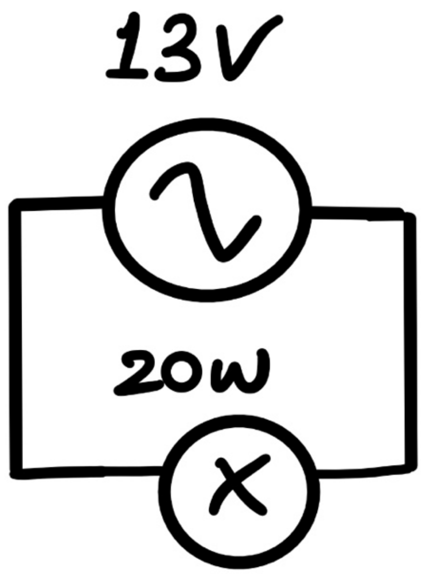


Figure 4 Light source circuit diagram

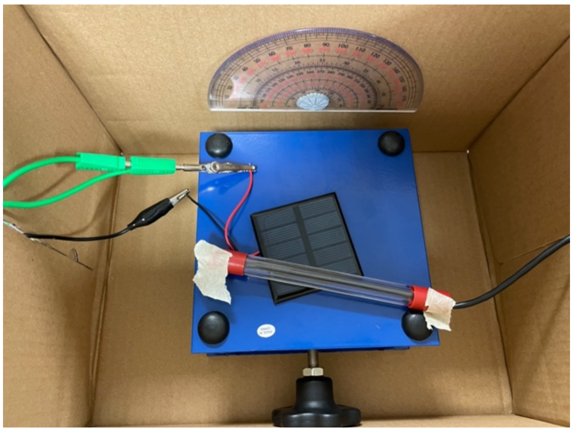


Figure 5 Solar panel pre-experiment setup

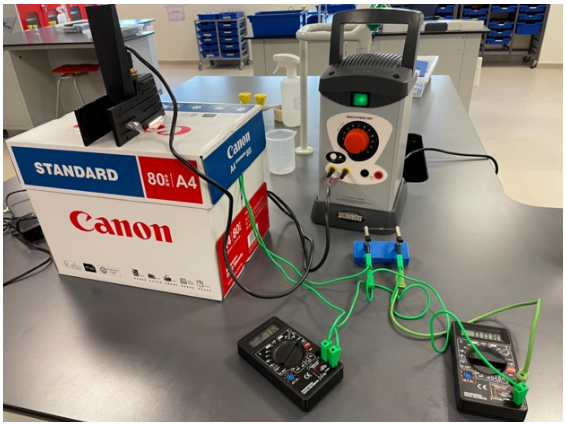


Figure 6 Final experiment setup

	Range/quantity	Units	Method for changing/measuring
Tilt Angle (independent variable)	10°- 90°	°	Using two protractors to measure the tilted angle every time
Current (dependent variable)	0-2A	Ampere	Multimeter was set to the current setting displaying the reading in amperes
Voltage (dependent variable)	0-2V	Volt	Multimeter was set to the current setting displaying the reading in volts

Table 2 Independent and dependent variables

What is controlled	How is it controlled	Why is it controlled
Incoming intensity of light	By keeping the power supplied to the ray optic box throughout It was 172 lux throughout As we know 1 Lux = $0.0079W/m^2$ Therefore, $1.36W/m^2$	All the sets and trials have equal intensity of light hitting the solar cell surface, the reflection of the light is same and can be neglected
Temperature of the set up	By performing the experiment in one seating, setting the room temperature to the desired value	The optimal temperature needs for the solar cell to be efficient is 25°C
Background light	By placing the set up in a box with its lid on, a small hole only for the ray optic box to fit through	To avoid any additional or incoming light which can hinder our values measured for the maintained Lightsource
Position of the ray optic box	By tracing it out on top of the box and sticking it	To assure the light directly hits the solar panel in a straight line for all the sets and trials.

Table 3 Controlled variables

Method

Firstly, start out by aligning the ray optic box right on top of the whole made in the lid of the box. The ray optic box is connected to the bench power unit supply and maximum power is given. Secondly, place a lab jack in the box and parallel to it, stick a protractor to use it for reference. The luxmeter and the solar panel are placed on the lab jack next to each other. The solar panel is then connected to a multimeter and a load resistor in series and another multimeter in parallel. The one in series acts as an ammeter and the one parallel acts as a voltmeter. For reference, a rough diagram of the circuit was drawn on the whiteboard.

Following this the tilt angle of the solar panel is changed, starting from 10° going up to 90°. The strength of this experiment is that five trials are taken for each tilt angle set, to give accurate and precise measurements, the average of these values will be taken. The data points were recorded manually on Microsoft excel sheet. It's important to remember that the lid must be put back on as soon as possible or else the solar panel can heat up and give us varied results with the change in temperature. The weakness of this experiment is the scope of maintaining the solar cell's temperature, as it is exposed to the ray optic box continuously, it might heat up and this can vary the power output values.

Equipment	Risk assessment	How to reduce the risks
Ray optic box	When used continuously, it can get heated up very quick. As it was placed on the cardboard box, possibility of it catch fire.	This was avoided by switching the ray optic box whenever not in use. And giving it some buffer time to cool down after using it.

Table 4 Safety assessment

Raw data

Tilt angle ($\pm 1°$)	Current ($\pm 0.005A$)					Relative Uncertainty on current (%)
	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	
10	2.720	2.540	2.660	2.670	2.710	0.031
20	1.230	1.160	1.210	1.190	1.160	0.029
30	1.150	1.130	1.100	1.170	1.140	0.030
40	1.120	1.110	1.090	1.070	1.080	0.022
50	0.950	0.930	0.960	0.940	0.950	0.015
60	0.850	0.840	0.840	0.830	0.860	0.017
70	0.760	0.790	0.750	0.790	0.770	0.025
80	0.690	0.680	0.660	0.630	0.670	0.045
90	0.210	0.290	0.200	0.260	0.240	0.187

Table 5 Raw data with the tilt angle and measured current

Tilt Angle ($\pm 1°$)	Voltage ($\pm 0.05V$)					Uncertainty on voltage (%)
	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	
10	0.80	0.70	0.80	0.80	0.80	0.064
20	1.10	1.00	1.00	0.90	1.10	0.098
30	0.90	1.00	1.10	0.80	0.90	0.159
40	0.80	0.70	0.90	0.70	0.90	0.125
50	0.80	0.80	0.70	0.80	0.70	0.065
60	0.70	0.70	0.70	0.70	0.60	0.073
70	0.60	0.60	0.50	0.60	0.70	0.167
80	0.52	0.50	0.60	0.50	0.50	0.095
90	0.14	0.10	0.20	0.30	0.10	0.595

Table 6 Raw data with the tilt angle and the measured voltage

Processed Data

Tilt Angle ($\pm1°$)	Cosine of the tilt angle	Average Power output	Uncertainty on power(%)
10	0.984	2.074	0.096
20	0.939	1.213	0.127
30	0.866	1.069	0.190
40	0.766	0.875	0.147
50	0.642	0.718	0.081
60	0.500	0.573	0.091
70	0.342	0.463	0.192
80	0.173	0.348	0.140
90	0	0.040	0.782

Table 7 Processed data with the tilt angle and average power output

Calculations and uncertainty processing

$$Average\ voltage\ or\ current = \frac{sum\ all\ 5\ values}{5}$$

E.g. Average current when tilt angle is 50° = $\frac{0.950+0.930+0.960+0.940+0.950}{5} = 0.946$

Average voltage when tilt angle is 50° = $\frac{0.80+0.80+0.70+0.80+0.70}{5} = 0.76$

The power was calculated using the Ohm's law :-$Power = Voltage \times Current$

E.g. Power output when tilt angle is 50° =$0.946 \times 0.76 = 0.718$

Lastly, the uncertainty of the power output is calculated by adding the percentage uncertainties in the current value and voltage value together.

E.g. $Uncertainty\ in\ current\ at\ 50° = \frac{\max value - \min value}{2} = \frac{0.960-0.930}{2} = \pm 0.015$

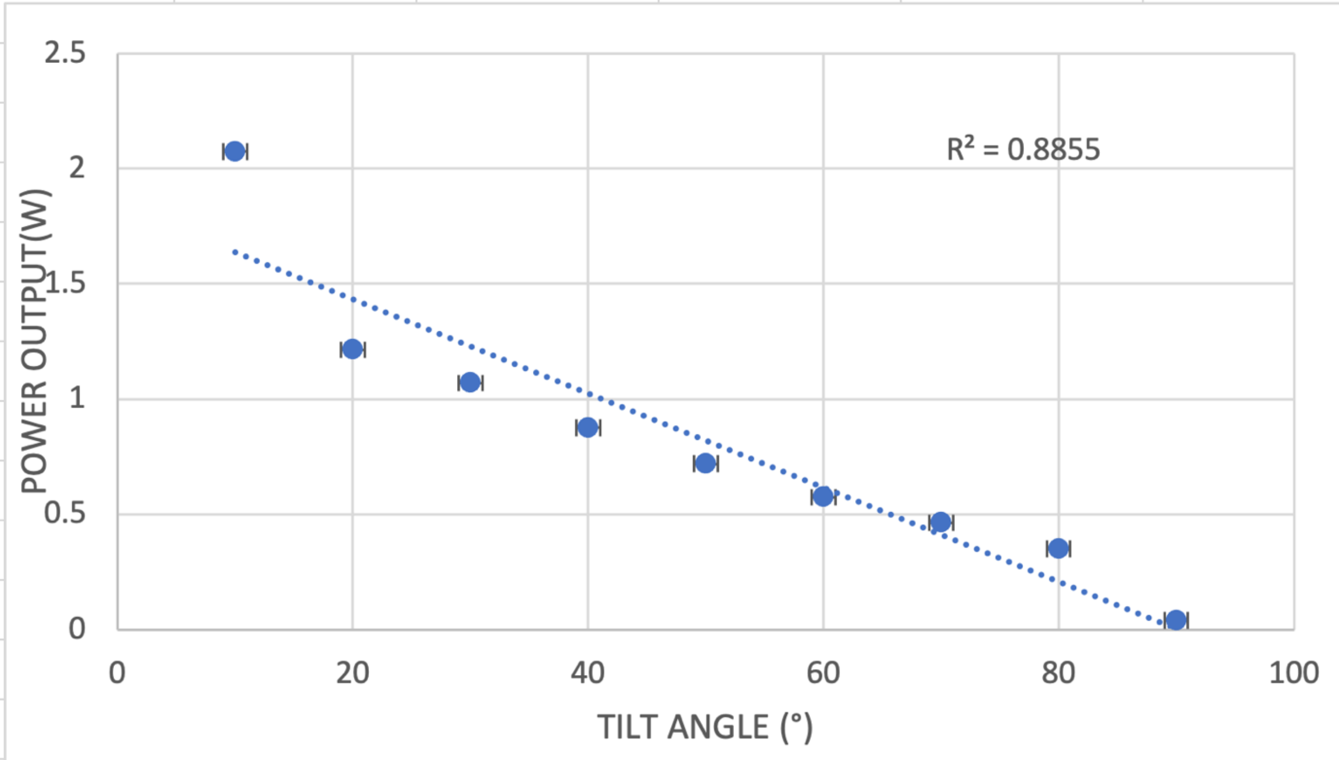
$$Uncertainty\ in\ Voltage\ at\ 50° = \frac{\max value - \min value}{2} = \frac{0.80-0.70}{2} = \pm 0.05$$

Uncertainty in Power at 50°=$relative\ uncertainty\ on\ current + relative\ uncertainty\ on\ voltage = \frac{0.015}{0.946} + \frac{0.05}{0.76} = 0.081$

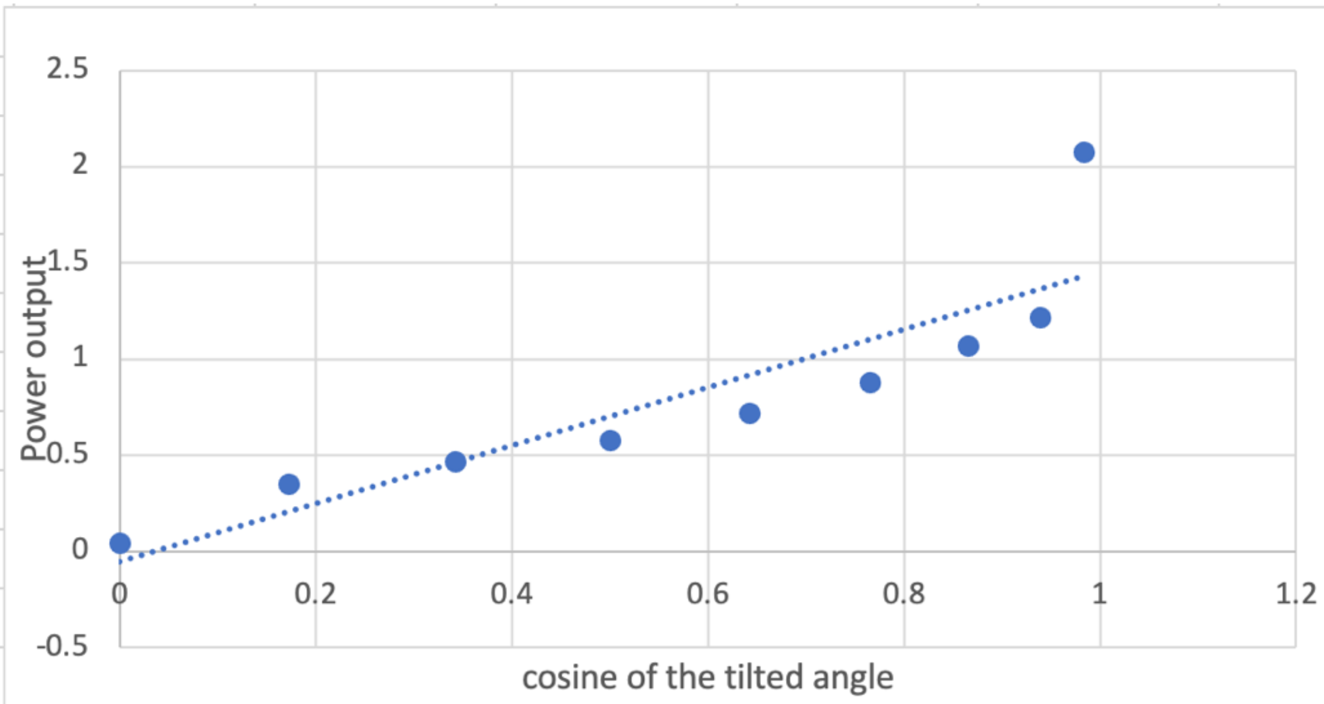
Graph

Graph 2 is the resultant graph which has the tilt angle on the x-axis and the power output on the y-axis. It displays a declining trendline. So when the tilt angle is increased, the power output decreases. The two variables are inversely proportional. The r-squared value is about 0.89 which means that the two variables have a strong correlation and depend on each other. As the propagated errors are very small in value, the error bars are negligible and not quite noticeable on the graph. If the first datapoint is excluded which is acting as an anomaly here, the trendline will be more accurate.

Graph 3 is the resultant graph to prove the hypothesis right which is plotted between the cosine of the tilt angle and the power output, this shows a direct proportionality, the cosine of the tilt angle increases with the increase in power output. Similarly, if the last datapoint is excluded, the result will be more precise. As the cosine of 10° is almost close to 1, leading to the maximum power output.



Graph 2 Power Output v/s Tilt angle



Graph 3 Cosine of tilted angle v/s Power output

EVALUATION

The resultant graphs have successfully proved the hypothesis right. Tilt angle and power output are inversely proportional because the main factor is the amount of light energy the solar cell receives, the efficiency improves. The. Larger area covered by light is better for the performance of the solar cell. The maximum power output is found to be at 10°, this is because at this angle the light energy falling on the panel destructively interferes with the silicon layer of the cell. The path difference is the appropriate value for it to minimize the reflected light and maximise the transmitted light energy. Hence this is the optimal angle corresponding to the maximum efficiency. The quantitative results match the hypothesis and the result of the research paper to a certain extent, however with smaller numbers and a different set of parameters.

The maximum power output is when the angle is about 10°, the optimal angle. The main reason behind this is at this angle, maximum light energy is reaching the solar panel. This leads to maximum energy to supply electrical power.. This means that the highest possible number of photons are being emitted with high energies causing the electron to flow at an efficient rate and generating a good amount of electrical energy. When the angle is 90°, almost none of the light energy is even reaching the solar panel leading to minimal power output, the power output which is observed in the experiment is mainly due to the heat caused by the absorbance of the light energy.

One of the main implications is that it corresponds to the 10-degree-rule which is used while calculating the gain in solar energy as it is said that at this tilt angle the light energy and heat is gathered as much as possible. This matches the trend found in the reference paper, however as it is a paper done in a university the equipment used was more professional and they could set ambient surrounding, the test conditions are the main reason my results have a large uncertainty.

The conclusion is that tilt angle plays a big role in the efficiency of a solar panel and needs to be monitored continuously to maximize the power output, however this depends on the latitude, and other geographical factors. The data is not vaguely spread out and displays a clear trend if the obvious anomalies are excluded. The error bars would touch the best line fit only when the fluctuation in the temperature and more number of significant figures can be recorded during the experiment.

STRENGTHS, WEAKNESSES AND EXTENSIONS

The main strengths of my experiment were the number of trials which was five. The multiple values provides an average value making the overall results more accurate as it is known that the results are not being affected by any random events and are constant every time we perform the experiment. It can be concluded that the findings are true and reliable then. Secondly, the method of using a closed box which blocked any other light source and lead to minimizing the scope of reflection light makes the results more accurate. Thirdly the fact that it matches the reference paper's graph trendline shows that the certain similar test conditions and the tilt angle plays a big role and is a reliable factor to vary the performance.

Weaknesses	Why is it a weakness	How to avoid it
Dust on the solar panel (random)	As the dust might block some light energy from being absorbed by the solar panel.	To clean the solar panel before every trial of the experiment.

Temperature of the solar panel (systematic)	Every solar panel has an optimal temperature where it is the most efficient, the temperature of the panel keeps on fluctuating leading to varied performance.	To monitor and set it to the optimal temperature of the solar panel depending on its material of it.
Position of the solar panel (random)	The light energy might be exposed to different area in every trial while setting the tilt angle.	By tracing a position on the lab jack and placing the solar panel back before every trial.
Material of the solar panel (systematic)	As the coating of the solar panel might be different from the one used in the reference paper the destructive interference takes place at different angles which correspond to the maximum efficiency.	By using the solar cell which has the same material and same thickness of coating as the one used in the reference paper.
Time of the experiment (random)	If the experiment is observed for a longer time, then the solar panel gets heated up and has a better performance.	Every trial should be performed for the same amount of time and the solar cell should be left out for a while to cool it down.
Tilt angle of the solar panel (random)	As the solar cell has wires under it, it was not completely flat on the plane, leading to an uncertainty in the measured tilted angle.	By starting the range of the tilted angle from 10° instead of 0°. There is less scope of error in this case. And also using a protractor with an articulated arm.
Test conditions – one of the main weaknesses producing the uncertainty (systematic)	Few of the more important factors are latitude and elevation angle of the respective location the experiment takes place.	To use a paper for reference which performs the experiment in the same country.
Light source	The light source on the spectrum have different wavelengths and frequencies, which means different amount of photons are emitted by each one of them leading to different energy which cause electrons to flow at a different rate.	Using the same light source and preferably at the same voltage in order to be precise and accurate to compare with the reference paper.

One of the main extensions is considering an appropriate location and using secondary databases to actually analyse and derive a relation through what real life solar panel set ups actually use. This will give us more accurate data, as it will be based on the solar energy from the sun and data regarding the solar irradiance can also be found. The latitudes of the location will give us scope of finding specific outcomes. As it is based on real life experiments, it is easier to calculate the specific efficiencies of the panel and also go in depth regarding other factors which can be involved such as the position of the sun which the seasons change.

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