Physics Extended Essay

To What Extent does the angle of incidence of a laser effect the current output on a Solar Panel?

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Introduction

Growing up in a family of electrical engineers, I have always been fascinated by the concept of electricity and its many applications. Electricity is ubiquitous, from the technology we use daily to the functioning of our bodies. It is an essential part of life and this is why I find it so intriguing. For my physics Extended Essay, I decided to combine my interest in electricity with another captivating topic, light. Light rays are invisible to the naked human eye, yet they illuminate the world and enable us to see through it. Moreover, light plays a crucial role in the production of electricity, especially through solar panels. During an internship at a solar panel company, I learned about the various components and inner workings of these panels. I noticed that the engineers were meticulous about calculating the efficiency of the panels at different angles of sunlight to reduce costs. This experience inspired me to investigate one fundamental question that stuck with me even after my internship ended: at what time during the day is the current of electricity the highest in solar panels? To satisfy my curiosity, I have conducted an experiment that explores the relationship between a solar panel’s current output and the angle of sunlight throughout the day. To answer my question about the time of day when the current of electricity is the highest in solar panels, I decided to conduct an experiment that would replicate the sun's angle of incidence on the panel. However, conducting such an experiment in real-time would introduce a lot of uncontrolled variables, which would make it difficult to achieve accurate and consistent results. Therefore, I had to think of an alternative method that would allow me to control the variables and produce reliable data. After consideration, I decided to use a laser beam as a substitute for the sun in my experiment. By focusing the laser beam on the solar panel at different angles and measuring the output current, I could accurately simulate the effect of the sun's position in the sky on the panel's current output. This approach would enable me to precisely control the variables and repeat the experiment as many times as necessary to achieve meaningful results. Through this experiment, I aim to expand my knowledge of engineering and better understand the principles of electricity. I believe that this investigation will allow me to delve deeper into the intricate relationship between light and electricity, and help me appreciate the underlying mechanisms that drive the operation of solar panels.

Background Information

The development of solar energy spans over a century. Initially, it was mainly used to generate steam for powering machines. However, it was not until Edmond Becquerel discovered the "photovoltaic effect" that solar energy could be directly converted into electrical energy. After Becquerel's breakthrough, Charles Fritts invented the first practical solar cell in 1893, which consisted of selenium sheets covered with a thin layer of gold. This marked the humble beginnings of the modern solar panel we use today in our day to day lives. In 1941, Russell Ohl, an American inventor working for Bell Laboratories, invented the first silicon solar cell. In 1954, the same company produced the first solar panel based on Ohl's design. Initially, solar panels were primarily used in space satellites. However, in the 1970s, they became commercially available for everyday use, with many people's first experience of solar panels coming in the form of calculators. Nowadays, solar panels and systems are being widely used to power a range of applications, including small solar systems for households in developing countries, schools and hospitals in developing countries, medical or veterinary cooling systems, power supply for remote homes or summer villas in developed countries, telecommunication equipment, water pumps, street infrastructure equipment such as streetlamps, bus station dashboards, parking meters, recreational vehicles, remote meteorological stations, airports, and much more. [6]

Solar Cell

A photovoltaic cell, also known as a solar cell, is a device that uses the photovoltaic effect to convert light energy into electrical energy. The bulk of solar cells are made of silicon, which has evolved from amorphous to polycrystalline to crystalline forms while also becoming more efficient and less expensive. Solar cells, unlike batteries or fuel cells, don't need fuel or chemical reactions to produce energy, and unlike electric generators, they don't have moving parts. Solar panels can be set up in arrays, which are big collections of cells that can function as central power plants by harnessing solar energy, converting it to electricity, and then dispersing it to industrial, commercial, and domestic customers. An antireflection layer is utilized to effectively absorb and transfer light to the energy-conversion layers beneath. The absorber layer, which is the device's central component, is encircled by the top and back junction layers. To create an electric circuit, two additional electrical contact layers are needed, one on the cell's face where light enters and the other on the back of the cell. The back layer is made of metal and acts as an electrical contact, while the front layer is typically a grid pattern made of an excellent conductor.[4]

Solar Panel

The sun is the source of solar energy. Solar panels are light-absorbing devices that transform sunlight into electricity or heat. These panels (also known as "PV panels") convert sunlight, which is made up of energy-bearing particles known as "photons" into electricity that may be utilized to power electrical devices. A solar panel is made up of solar (or photovoltaic) cells that generate energy via the photovoltaic effect. On the surface of solar panels, these cells are organized in a grid pattern. As a result, it may alternatively be defined as a collection of photovoltaic modules put on a supporting framework. A photovoltaic (PV) module is a 6x10 solar cell packed and linked assembly. [1]

Design of Solar Panels

In order to protect them from weathering, solar cells usually have a surface area of a few square centimetres and are covered in a thin layer of glass or clear plastic. They are frequently connected in series to increase voltage or in parallel to increase current because a normal solar cell measuring 10cmx10cm only produces about two watts of electrical power (15–20% of the light energy that strikes its surface). A photovoltaic (PV) module, also known as a solar module, is made up of 36 interconnected photovoltaic cells contained in a glass capsule and supported by an aluminium frame. [5]

Laser Beam

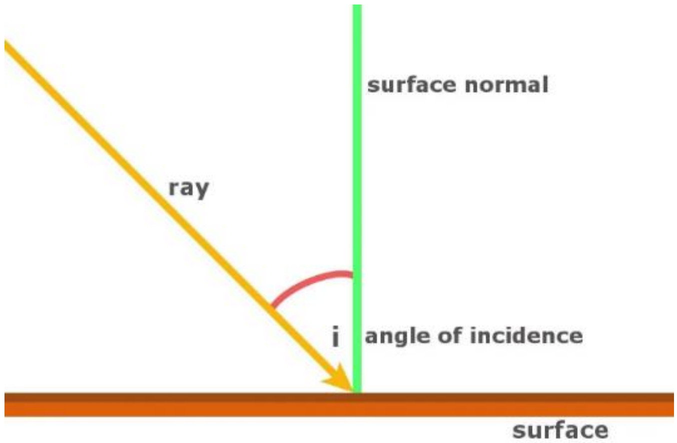
A laser is a highly advanced tool that can produce a narrowly concentrated, intense beam of light. The waves in this monochromatic beam of light are in phase with one another and usually span a small range of wavelengths. In contrast to regular light, laser light is amplified, enabling it to be concentrated into a razor-sharp beam. Different kinds of lasers have been created, and each has a special set of characteristics that make it suitable for a specific application. The technique of stimulated emission is essential to laser technology. An atom or molecule can release a photon of light with a particular wavelength and direction when it is stimulated by an exterior source of energy, such as an electrical discharge or light. This process is precisely regulated in a laser to produce a highly coherent stream of light by ensuring that the photons released by the stimulated atoms or molecules are in phase with one another. The laser beam is generally repeatedly cycled through a resonant cavity to increase its coherence and narrowness. This hollow is made to reflect light back and forth in a controlled way, magnifying the beam and enabling it to increase in intensity to high levels. The resulting laser beam is extremely focused and has a variety of uses, including material cutting and welding as well as precise measurements and medical operations. [2]

Angle Of Incidence

When light enters the prism, it changes direction, and when it left, it changes again. Prisms aren't the only ones who bend light in this way. It happens a lot with translucent and transparent materials. We've even given the angles at which light enters and passes through the material its own names. The angle of incidence refers to the angle at which light enters. The angle of incidence is the angle formed by the approaching beam of light and the normal vector of the substance with which it is coming into contact. A perpendicular vector from a plain or surface of an item is called the normal vector.

There are three possible outcomes for light once it meets up with an object. Absorption is the first. The light ray does not go any farther in absorption; it is absorbed into the item and converted into energy. When the sun shines on a solar panel, the PV cells in the panel absorb the energy from the sun. This energy causes electricity to flow by forcing electrical charges to shift in response to an internal electrical field in the cell.

We know that the surface's normal is always 90 degrees. The light ray is assumed to make a 10° angle with the surface. As a result, the incidence angle is 90°-10°=80°.[3]



(figure 1: the angle of incidence of ray and its refraction is illustrated above)

Materials

Material	Size (± uncertainty)	Quantity
Glass Protractor	20 cm(±0.1^0)	1
Solar Panel	70cm^2	1
5mW Red diode colored Laser	Na	1
Ammeter	(±0.01A)	1

(figure 2: the materials used in the experiment is given above)

Variables

Independent Variable	Angle of Incidence of the Laser (in degrees°)
Dependent Variable	Current (in miliamperes*)*

Controlled Variables	**Reason for control**	**Method for control**
Solar Panel	In order to get the most accurate result from the refracted beam same type of solar panel must be used as different solar panels greatly differ in current output. This is because the work function (Φ) is different for different types surfaces.	Identical solar panels will be used throughout the experimentation process
Laser	In order to prevent energy differences as different colours each emit different wavelengths and frequencies which yield different energy outputs potentially causing systematic as well as random errors.	Same coloured 5mW red diode laser will be used for all the respective trials and angles.
Same Environment	To make sure no excess heat is absorbed by the solar panel as this will affect the output of the current	The experiment will be conducted in the same environment and made sure there are no external light sources which can cause excess heat and photon interaction
Room Darkness	In order to prevent excess photons entering the solar panel which will increase the current as well as keep the random errors in the experiment to the minimum.	The experiment will be conducted in the same environment with any light source being turned off
Ammeter	In order to ensure that the readings are precise and accurate as possible. Because different kinds of ammeters differ in their readings of the same value as a result of factors such as its internal resistance, type of material and the radius of an ammeter. This will reduce systematic errors in the experimentation process.	Identical ammeter will be used when reading the current output values.

(figure 3: the variables of the experiment and their explanation is given)

Hypothesis

It will be seen that there is a direct proportional relationship between the angle of incidence of the laser and the current output of the solar panel as the angle of incidence of the laser increases from 0^0 to 90^0, there will be a linear increase in the current of the solar panel measured by the ammeter. Furthermore, the greatest amount of current will occur at an angle of incidence of 90 degrees, while the least amount of current production will occur at an angle of incidence of 0^0. When the angle of incidence is 0^0, the laser beam is parallel to the surface of the solar panel, and therefore, the current of the solar panel is expected to be the least as no photons enter the panel. As the angle of incidence increases, the laser beam becomes increasingly perpendicular to the surface of the solar panel, and a greater number of photons enter the panel which is expected to increase the current. This correlation can be represented graphically, and the resulting graph is expected to show a linear trend with a positive slope.

Risk Assessment

Hazard	**Control Measure**
Safety	Goggles were worn during the experimentation process to prevent possible damage to the cornea, lens, and retina as well as to reduce exposure to radiation and the irritation effect caused by the red diode laser.
Environmental	The Excess solar panel pieces were disposed properly to make sure no living organism is harmed after the experimentation process and to ensure that no organism gets harmed through accidentally consuming the heavy metals in the solar panel.
Ethical	There were no Ethical issues identified in the experiment.

(figure 4: the safety hazards and the measures taken to control them are illustrated above)

Procedure

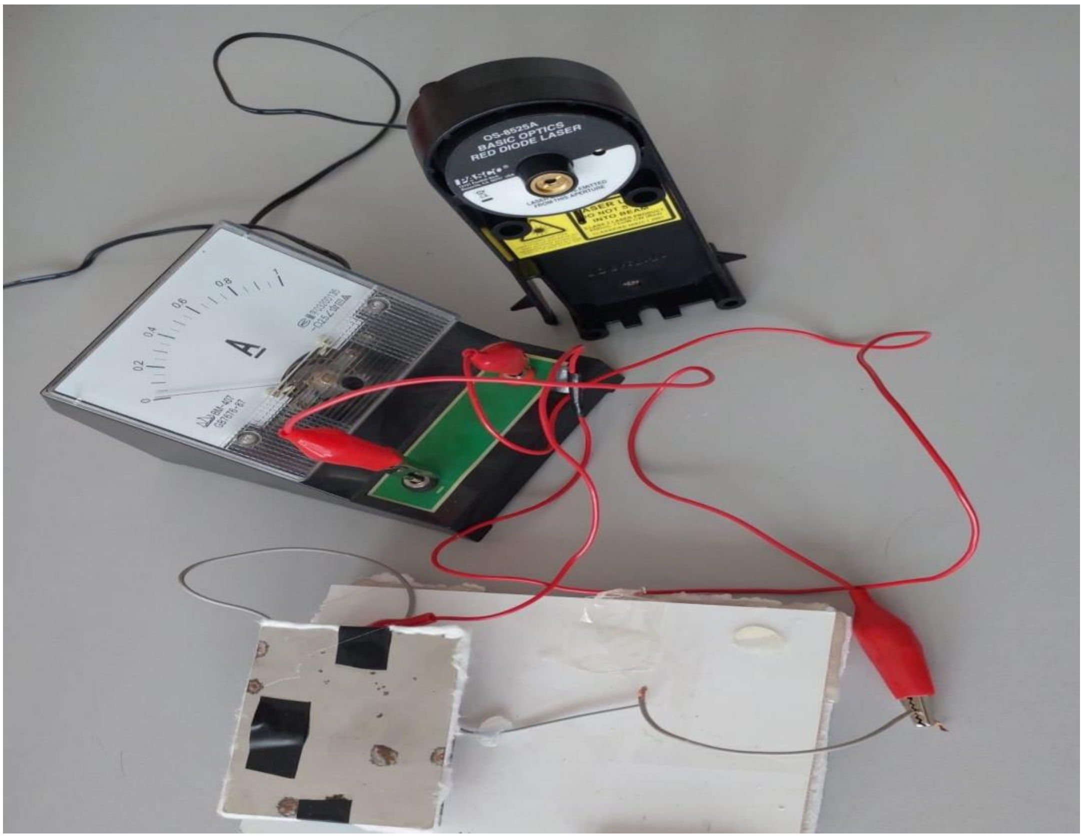
1-A dark environment will be established to prevent any extraneous sources of light that could potentially influence the current through the emission of photons. Temperature readings will be recorded at 10-minute intervals in order to prevent overproduction of energy in the panels as a result of excess heat absorption

2-The solar panel will be positioned behind a protractor, and the red diode laser will be turned on and calibrated for the experiment. Safety goggles will be worn to minimize exposure to radiation and irritation to the eye, and the protractor will be set perpendicular to the laser to ensure accurate measurements.

3-The experiment will commence with the laser positioned at 0°, as measured by the protractor. The angle of incidence between the laser and solar panel will be increased by 15° for each subsequent trial, with the current recorded at each angle. The experiment will conclude when the angle of incidence reaches 90°, and the current will be measured using the ammeter.

5-Each angle will be measured five times to minimize random errors and ensure the production of reliable results before progressing to the next angle, as measured by the protractor.

6-The results will be analysed and sent to "logger pro" for further calculations and graphing.



(figure 5: the experimental diagram setup is illustrated above in the picture)

Raw Data: The graph of angle of incidence of the laser and the current produced is illustrated below (mA)

Angle of incidence of the laser (± 1^0)	Trials	Current (± 0.01mA)	Solar Panel area (cm^2)	Laser strength (mW)
0^0	1	0.12	100	5
	2	0.23	100	5
	3	0.15	100	5
	4	0.19	100	5
	5	0.21	100	5
15^0	1	168.22	100	5
	2	173.47	100	5
	3	184.57	100	5
	4	159.65	100	5
	5	195.45	100	5
30^0	1	348.28	100	5
	2	344.51	100	5
	3	336.55	100	5
	4	341.46	100	5
	5	351.98	100	5
45^0	1	520.76	100	5
	2	527.92	100	5
	3	534.43	100	5
	4	522.54	100	5
	5	539.12	100	5
60^0	1	745.41	100	5
	2	753.66	100	5
	3	757.49	100	5
	4	750.68	100	5
	5	748.23	100	5
75^0	1	835.47	100	5
	2	838.36	100	5
	3	833.48	100	5
	4	841.21	100	5
	5	837.23	100	5
90^0	1	910.32	100	5
	2	903.75	100	5
	3	921.65	100	5
	4	915.27	100	5
	5	908.38	100	5

(figure 6: the raw data of the experimental results are illustrated above)

Processed Data

The formula $A = \frac{1}{n}\sum_{i=1}^{n} a_i$ is used to calculate the mean (arithmetic average).

The formula $\sigma = \sqrt{\frac{\sum(x_i - \mu)^2}{N}}$ is used to calculate standard deviation (the average distance from the mean).

(Note: The numbers are rounded to 3 significant figures)

The standard deviation for the current produced on the solar panel for 0^0 is 0.04 and the mean current output is 0.18 mA

The standard deviation for the current produced on the solar panel for 15^0 is 12.5 and the mean current output is 176 m*A*

The standard deviation for the current output on the solar panel for 30^0 is 5.34 and the mean current output is 344 mA

The standard deviation for the current produced on the solar panel for 45^0 is 6.97 and the mean current output is 529 mA

The standard deviation for the current output on the solar panel for 60^0 is 4.20 and the mean current output is 751 mA

The standard deviation for the current output on the solar panel for 75^0 is 2.46 and the mean current output is 838 mA

The standard deviation for the current output on the solar panel for 90^0 is 6.15 and the mean current output is 911 mA

Using the Pearson Correlation Coefficient Formula

The Pearson product-moment correlation coefficient (or Pearson correlation coefficient, for short) is a measure of the strength of a linear association between two variables and is denoted by *r*. Basically, a Pearson product-moment correlation attempts to draw a line of best fit through the data of two variables, and the Pearson correlation coefficient, *r*, indicates how far away all these data points are to this line of best fit (i.e., how well the data points fit this new model/line of best fit). The Pearson correlation coefficient is found by;

$$\mathbf{r} = \frac{\mathbf{n}(\sum \mathbf{xy}) - (\sum \mathbf{x})(\sum \mathbf{y})}{\sqrt{[\mathbf{n}\sum \mathbf{x}^2 - (\sum \mathbf{x})^2][\mathbf{n}\sum \mathbf{y}^2 - (\sum \mathbf{y})^2]}}$$

$r \cong 0.990$ mA

$r^2 \cong 0.980$ mA

Linear Regression

Linear regression analysis is used to predict the value of a variable based on the value of another variable. The variable you want to predict is called the dependent variable. The variable you are using to predict the other variable's value is called the independent variable. This form of analysis estimates the coefficients of the linear equation, involving one or more independent variables that best predict the value of the dependent variable. Linear regression fits a straight line or surface that minimizes the discrepancies between predicted and actual output values

Doing linear regression in the format of y=ax+b we find

a≅ 10.627 mA

b≅ 28.8 mA

(Correlation value is very close to ~1.00 this shows that there is a very strong positive correlation between the current produced in a solar panel and its angle of incidence in miliamperes)

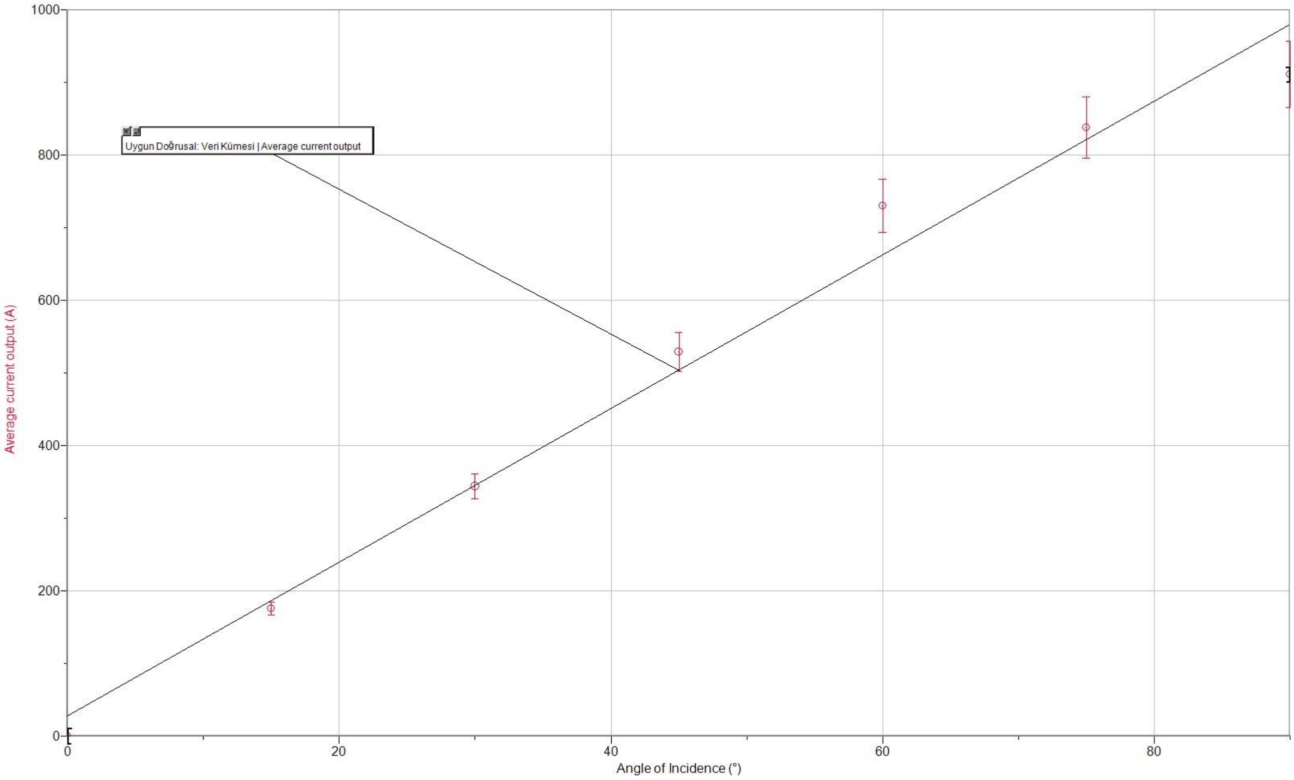
Processed Tables

Angle Of incidence(±1^0)	**Average current output(± 0.01mA)**
0^0	**0.18 mA**
15^0	**176 mA**
30^0	**344 mA**
45^0	**529 mA**
60^0	**751 mA**
75^0	**838 mA**
90^0	**911 mA**

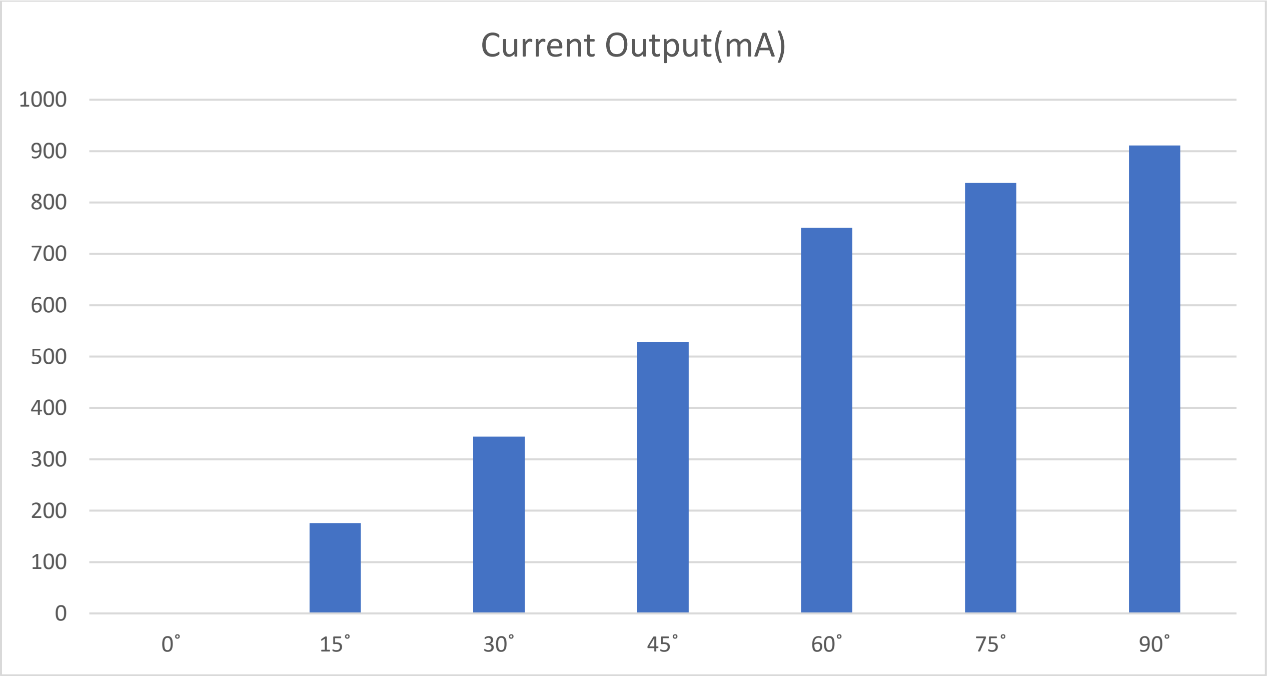
Angle Of incidence(±1^0)	**Standard Deviation**
0^0	**0.04 mA**
15^0	**12.5 mA**
30^0	**5.34 mA**
45^0	**6.97 mA**
60^0	**4.20 mA**
75^0	**2.46 mA**
90^0	**6.15 mA**

Processed Graphs

(figure 7: The graph of angle of incidence and the current output in miliamperes is given below)



(figure 8: The bar graph of angle of incidence and the current output in miliamperes *is given below)*



Conclusion

The purpose of this experiment was to investigate the relationship between the angle of incidence and the current output of a solar panel. The results of the experiment clearly demonstrate that there is a direct correlation between the two variables, indicating that the angle of incidence has a significant impact on the amount of current produced by the solar panel. The findings also suggest that the optimal angle of incidence for producing maximum current output is 90^0

It is important to note that the correlation between the angle of incidence and the current output is very strong ($r \cong 0.990$).Moreover, when the data was fitted into a linear regression in the format of $y= ax+b$ ($a \cong 10.6mA$ $b \cong 28.8mA$), which demonstrated that, on average, for every 1^0 increase in the angle of incidence correlates to a 10.1 miliamperes increase in the current produced in the panel. However, it is important to note that the value of current produced (in miliamperes) when the angle of incidence is 0^0 is an outlier as no photons reach the panel and produce close to 0 current.

The hypothesis is supported by my findings, as the increase in current output with increasing angle of incidence was predicted. However the results of this experiment also highlight some of the limitations and shortcomings of the experimental design. For example, it was found that there were errors in the form of random and systematic errors throughout the experimentation process. In particular, a parallax error occurred in the measurement of the protractor at 45^0, causing the standard deviation to be much higher compared to the rest of the other trials. Additionally, in some of the angles (15^0-75^0) the protractor was not held perpendicular with respect to the laser, causing a random error and changing the result of the data set. Furthermore, the environment in which the experiment was conducted had an untenable light source, causing all of the values of current to be higher than expected and leading to systematic errors in the process. For some of the trials, the laser was not held stably, resulting in values that were either higher or lower than usual. The findings of this experiment suggest that the angle of incidence has a significant impact on the current output of a solar panel. The results also highlight the importance of controlling for extraneous variables, such as light source and measurement tools, to ensure the accuracy of the data. By addressing these limitations, further research could be conducted to expand our understanding of the relationship between the angle of incidence and the current output of a solar panel, and to identify ways to optimize the performance of solar panels for maximum current production which will all be discussed further in the *"Evaluation"* section.

Evaluation

Strengths	Reason it's believed to be a strength
Methodology	The methodology of the experiment had no major systematic issue which gave more accurate results.
Amount Of Data	Each trial was conducted 5 times greatly reducing the possibility of random error throughout the experimentation process.

Limitations	Effect of Limitation on the result of investigation	Suggested improvement and why it will improve the investigation
External light sources	The external light source greatly decreased the reliability of the result as it caused increased values for all trials	The experiment should be done on a dark environment and made sure that there is no external light source other than the laser. This will reduce the number of photons interacting with the panel, thus, greatly improving the reliability of the results and reducing the possibility of increase in the standard deviation values.
Unstable room temperature	The experiment was conducted in an environment where the temperature was unstable causing some values of current to increase or decrease depending on the temperature of the panel as the panel absorbed the heat	For the most accurate result the experiment should be conducted on a laboratory and the room temperature should be set to 23^0 for all the respective trials. Furthermore, the temperature should be checked every 10 minutes to make sure that there is no increase/decrease in the temperature. This will greatly increase the reliability of the experiment and reduce the possibility of systematic error.
Protractor	The protractor was not stabilized at a set position, so the angle measurements were inaccurate to an extent which caused the current output to be slightly higher between 0^0-75^0	In order to make sure all the angles are measured correctly Set the protractor's dot in the center with the angle's vertex. Then the protractor should be aligned so that the angle is aligned with 0^0 .In order to determine where the other side of the angle crosses the number scale, the protractor should be read. Following these steps will greatly reduce the chance of parallax error in angle calculations.

(figure 9: the strengths, shortcomings and suggested improvements to the experiment is given above)

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