Extended Essay

IB Physics Higher Level

Effect of Foreign Substances on the Efficiency of Solar Panel

Research Question: What is the effect of foreign substances (dust, ash) on the efficiency of solar panels?

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Research Question

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Introduction

The topic interests me based on developing an interest in practical applications of concepts taught in physics in situations found in the real world. My interest in energy dynamics has intrigued me from online sources where I found that solar energy is the greenest and the most sustainable source of energy. There has been a tremendous and increased reliance on renewable sources of energy in the recent past for domestic and industrial use to fulfill the global demands for clean energy. Solar panels are often exposed to different environmental factors, including airborne particles and dust (Mustafa et al., 2020). Understanding the underlying dynamics of these potential effects on the solar panel could be instrumental in the pursuit of developing effective maintenance strategies and designs for solar panels for improved productivity and reliability.

Aim of the Investigation

The aim of this study is to find out the effect of foreign substances on the efficiency of solar panels.

Background Theory

Solar panels have a long history, are energy efficient, and are renewable. The solar panels were discovered by Edmond Becquerel, a French physicist, in 1839, and since then, they have undergone a massive evolution, leading to the current designs in the market (Solar Energy Systems, 2019). Essentially, solar panels are considered among the most appropriate energy sources in the quest for green energy solutions. They convert sunlight into electrical energy that can be utilized in domestic and industrial applications. Moreover, solar energy is finite and renewable because it can always be produced as long as there is sunshine and has quite a small carbon footprint since it can last at least 25 years (Solar Energy Technologies Office, 2024).

Solar panels have unique basics for converting solar energy. Ideally, solar panels are able to generate both heat and electricity through the photovoltaic (PV) effect. This effect, discovered by Edmond Becquerel, works effectively based on the materials used in the construction of the panels. Usually, solar panels are made using silicon, which is a semiconductor (Greentech, 2023). A solar panel has two layers of silicon, a p-type and n-type layers. The p-type layer contains holes, while the n-type contains electrons. When the two layers are placed closely together, they tend to create electric fields that enable energy conversion (Mehmood et al., 2021). These parts of the solar panels are shown in **Figure 1** below.

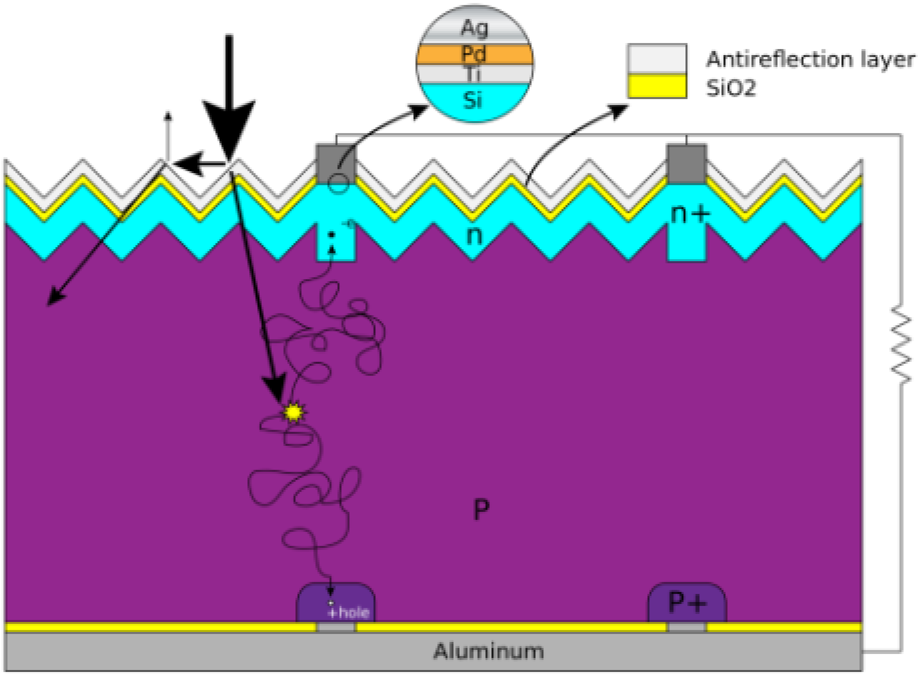

Figure 1: Major Parts of a Solar Panel (Mehmood et al., 2021)

Beyond these layers, solar panels contain additional materials to enhance performance levels. In particular, the panels have a passive layer on the back surface, which reduces the combination of electrons and the holes before excitation (Meena et al., 2024). Anti-reflective coatings are also added onto the surface of the cells in order to reduce possible losses of incident lights, thereby leading to enhanced generation of electrical power.

Efficiency is a critical component in the use of a solar panel. In their use, solar panels reduce utility bills and produce environmentally friendly and clean energy. However, their efficiency is majorly based on the quality of the photovoltaic (PV) cells. The rate of conversion of solar energy falling on the panel to usable electricity constitutes solar efficiency. The higher the efficiency of the solar panel, the higher the quantity of electrical energy output (Solar Energy Technologies Office, 2024). In the recent past, the efficiency of solar panels has risen from 15 % sunlight energy conversion to 20 %, with the most effective solar panels reaching their efficiency to approximately 33 % (University of Michigan, 2020). The power rating of the solar panels has also increased over the years from 250 W to 370 W (Aggarwal, 2023). The efficiency of a specific solar panel in use can determined as a function of output power (Watts), the input power, and the area. Power output is the quantity of electrical power that is being produced from the solar panel under standard test conditions (Chetan Kumbhar, 2023). The input power is the power density of the sunlight energy being received by the panel from the sun. The theoretical value of input power is 1000 W/m^2 (Michael et al., 2020). On the other hand, the area is the physical size of a solar panel. For regular solar panels, the width and length dimensions of the solar panels can be used to determine the precise area of the panel. Therefore, this area is considered a critical consid eration in the analysis of efficiency of efficiency and energy generation. Thus, according to Chetan Kumbhar (2023):

$$Efficiency\ of\ a\ Solar\ Panel, \eta = \left(\frac{Output\ Power}{Input\ Power}\right) \times Area \times 100$$

$$= \frac{Output\ Power \times Area}{Input\ Power} \times 100$$

$$= \frac{Output\ Power \times Area}{1000} \times 100$$

The output power is a function of voltage drop (V) and current (I) such that:

$$Output\ Power = V \times I$$

Thus, the calculation of efficiency of the solar panel would be such that:

$$Efficiency\ of\ a\ Solar\ Panel, \eta = \frac{VI \times Area}{1000} \times 100$$

$$= \frac{VI \times Area}{10}$$

This equation will be utilized in succeeding sections of this study to determine the overall efficiency of a solar panel under the variation of foreign substances (dust and ash).

Hypothesis

In developing this study, it is hypothesized that the foreign substances will significantly impact the solar panel's efficiency. It is expected that an increase in the amounts of dust and ash on the surface of the solar panel will lead to an increased obstruction of sunlight energy falling on the solar panel, reducing power output and, subsequently, efficiency.

Variables

Independent Variable, IV

- Foreign substances: Dust and ash will be the foreign substances used in this study. Their amounts will be varied from 0.0 g up to 40.0 g in increments of 10.0 g, ensured through an electronic beam balance (± 0.1 g).

Dependent Variable, DV

- The efficiency of the solar panel: The efficiency will be determined from the measured voltages and currents in the solar panel when the amounts of dust and foreign substances vary. The voltages and currents in each variation will be measured with a digital multimeter (± 0.01 A, ± 0.01 V).

Control Variables, CV

Control Variable	Effect on the Experiment	Control/Measurement
Ambient temperature	Variations in ambient temperature can affect the performance of the solar panel by influencing the efficiency of photovoltaic cells. High or low temperatures may cause power output fluctuations, leading to unreliable results.	When performing the experiment, temperature will be monitored using a thermometer. The experiment will be conducted in a temperature-controlled environment to minimize temperature fluctuations.
Angle of the panel	If the angle of the solar panel is not controlled, it will affect the amount of sunlight it receives, altering the intensity of the light hitting the panel. This alteration can result in varying voltage and current readings.	When performing the experiment, the solar panel will be mounted at a fixed angle using a stand or mounting system. The panel will be positioned at the same angle and orientation (facing the same direction) during all trials.
Light intensity	Variations in sunlight or artificial light intensity could alter the amount of energy available for the solar panel to convert, leading to inconsistent efficiency measurements.	When conducting this experiment natural sunlight was used throughout the experiment. All the tests were performed at the same time of day under clear weather conditions.

Type of solar panel	Different solar panel models have varying efficiencies and electrical characteristics, which could lead to inconsistent results if multiple models are used.	The same solar panel will be used for all trials when performing the experiment. The model and specifications of the panel will be recorded and kept constant to ensure uniformity in performance.
Time factor	The intensity and angle of sunlight change throughout the day due to the Earth's rotation. If the experiment is conducted at different times, this will lead to variations in the light intensity, affecting the measurements.	When performing the experiment, the tests will be conducted at the same time of day, ensuring consistent solar exposure. If the experiment is performed indoors, the same artificial light source will be used at a fixed intensity for each trial.

Table 1: Main Control Variables Considered, their Effect and Control Mechanisms

Methodology

List of Equipment/Materials

- A Digital multimeter, DMM ($\pm$ 0.01 A/V) to be used in measuring current/voltage
- An electronic beam balance ($\pm$ 0.1 g) is to be used in measuring the mass of the substances
- A 12 V solar panel of area 85 cm by 45 cm to be used in assessing efficiency
- Two connecting cables are to be used in linking the DMM with the solar panel
- Red and black probes to be used to link the DMM with the solar panel
- A stopwatch ($\pm$ 0.01 s) to be used in measuring time
- A sample of 500 g of dust to be used as one of the foreign substances in the experiment
- A sample of 500 g of ash to be used as one of the foreign substances in the experiment

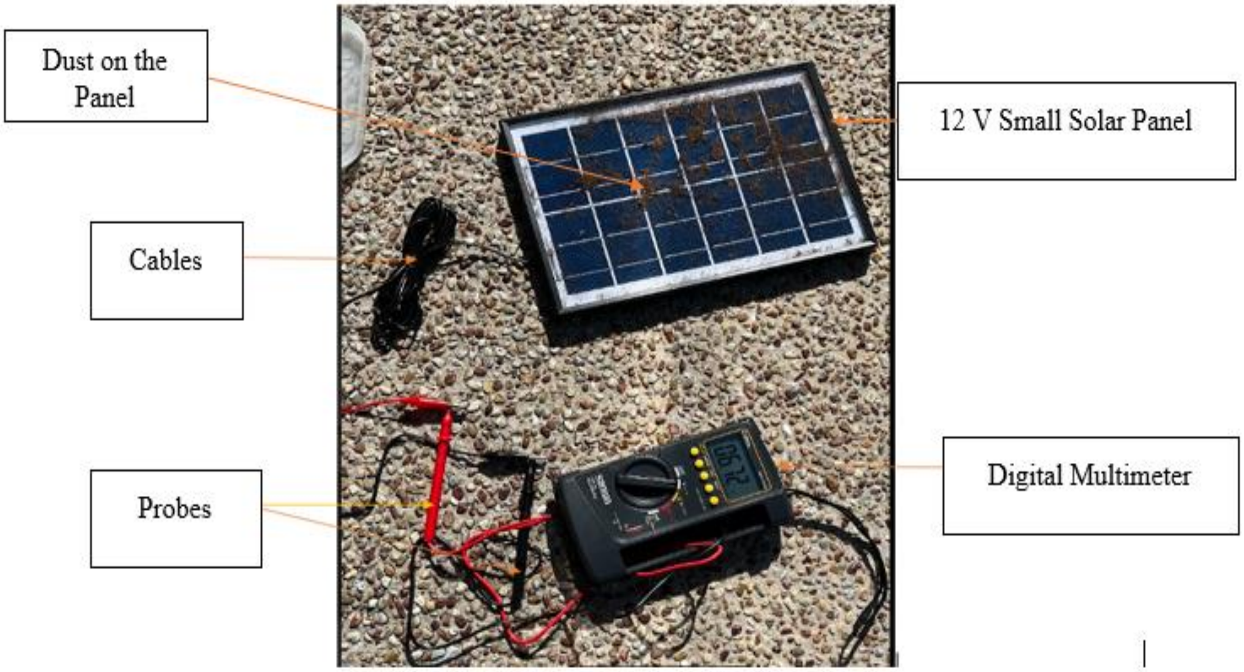

Figure 2: A Photo Showing the Main Equipment and Materials Used

Procedure

1. Baseline Measurement

a) A soft cloth was first used to clean and dry the surface of the panel removing any embedded substances.

b) The panel placed on a completely flat surface in the direction of sunlight.

c) The panel was allowed to be shone by direct sunlight for 5 minutes aided by stopwatch ($\pm$ 0.01 s).

d) The digital multimeter was then used to measure accurately the voltage drop and the current dissipating through the panel.

e) Repeat steps (a) to (d) for two more trials.

2. Application of Foreign Substances Application

a) An electronic beam balance was used to accurately measure 10 g of dust.

b) The weighed amount of dust was then transferred onto the solar panel.

c) The panel was then exposed to the sunlight for a period of 1 minute, ensured by the use of the stopwatch ($\pm$ 0.01 s).

d) The voltage and the current in the solar panel were then measured using the multimeter, and the results obtained were recorded.
e) Repeat steps (a) to (d) for two more trials.
f) Step (a) to step (e) were repeated using 20 g, 30 g, and 40 g of dust.
g) Steps (a)- (f) were repeated using ash, and all the results obtained were recorded in the data tables.

Safety Precautions

- Eye protection: A pair of eye goggles were worn while performing the experiment as a safety measure against possible eye damage from the foreign substances used.
- Skin protection: The skin could be damaged due to long exposure to sunlight during the experiment. To prevent this possible damage, clothing that covered the entire body had to be worn.
- Possible electrocution: While conducting the experiment, the body could be electrocuted. To minimize chances of this risk, all the probes and the connecting cables had to be cross-checked before being applied to connecting the solar panel and the multimeter.

Results and Findings

Raw Data

Mass of Dust $(\pm 0.1\mathrm{g})$	**Voltage Measured, V** $(\pm 0.01\ \mathrm{V})$			**Current Measured, I** $(\pm 0.01\ \mathrm{A})$		
	Trial 1	**Trial 2**	**Trial 3**	**Trial 1**	**Trial 2**	**Trial 3**
0.0	18.50	18.62	18.42	2.10	2.04	2.12
10.0	18.01	18.12	17.92	1.92	1.92	1.90
20.0	17.52	17.64	17.48	1.84	1.82	1.83
30.0	17.01	16.92	17.04	1.61	1.64	1.63
40.0	16.50	16.42	16.34	1.40	1.54	1.62

Table 2: Voltages and Current Measured for the Solar Panel Upon Applying Dust

Mass of Ash$(\pm 0.1\mathrm{g})$	**Voltage Measured, V** $(\pm 0.01\ \mathrm{V})$			**Current Measured, I** $(\pm 0.01\ \mathrm{A})$		
	Trial 1	**Trial 2**	**Trial 3**	**Trial 1**	**Trial 2**	**Trial 3**
0.0	18.50	18.62	18.42	2.10	2.04	2.12
10.0	18.34	18.04	17.92	1.96	1.91	1.96
20.0	17.42	17.55	17.63	1.85	1.82	1.89

30.0	16.93	17.04	16.82	1.52	1.57	1.55
40.0	16.42	16.52	16.34	1.43	1.48	1.40

Table 3:Voltages and Current Measured for the Solar Panel Upon Applying Ash

Processing Data

Data processing involves performing several calculations. The first set of calculations determined the average voltage drop and currents in the solar panels across the masses of both ash and dust foreign substances. The uncertainties of these measurements were also calculated. The formulas used and the sample calculations are presented in **Table 5** below.

Table 4: Average Voltage Potential and Currents in the Solar Panel

The calculation average voltage and current	Uncertainties
For voltage: $Average\ Voltage, V = \frac{V_1 + V_2 + V_3}{3}$ For current: $Average\ Current, I = \frac{I_1 + I_2 + I_3}{3}$	$Uncertainty\ of\ voltage, \Delta V = \frac{V_{max} - V_{min}}{2}$ $Uncertainty\ of\ current, \Delta V = \frac{I_{max} - I_{min}}{2}$
Example for the dust at m = 10.0 g	
For voltage: $Average\ Voltage, V = \frac{18.01 + 18.12 + 17.92}{3}$ $= 18.02\ V$ For current: $Average\ Current, I = \frac{1.92 + 1.92 + 1.90}{3}$ $= 1.91\ A$	$Uncertainty\ of\ voltage, \Delta V = \frac{18.12 - 17.92}{2}$ $= 0.10\ V$ $Uncertainty\ of\ current, \Delta V = \frac{1.92 - 1.90}{2}$ $= 0.01\ A$

The calculations for all the other variations of masses of ash and dust were performed using the same formulas, and the results obtained were recorded in the following data table.

Table 5: Processed Data for the Average Voltage and Current for the Dust Substance

	Voltage Drop (V)	**Current Dissipation (A)**

Mass of Dust ($\pm\, \mathbf{0.1g}$)	Average Voltage, V	Uncertainty, ΔV	Average Current, I	Uncertainty, ΔI
0.0	18.51	0.10	2.09	0.04
10.0	18.02	0.10	1.91	0.01
20.0	17.55	0.08	1.83	0.01
30.0	16.99	0.06	1.63	0.01
40.0	16.42	0.08	1.52	0.11

Table 6: Processed Data for the Average Voltage and Current for the Ash Substance

Mass of Ash ($\pm\, \mathbf{0.1g}$)	Voltage Drop (V)		Current Dissipation (A)	
	Average Voltage, V	**Uncertainty, ΔV**	**Average Current, I**	**Uncertainty, ΔI**
0.0	18.51	0.10	2.09	0.04
10.0	18.10	0.21	1.94	0.03
20.0	17.53	0.10	1.85	0.03
30.0	16.93	0.11	1.55	0.03
40.0	16.43	0.09	1.44	0.04

The processed data were then used to calculate the power output and the associated propagated uncertainties. The formulas used in these calculations are presented in **Table 8** below.

Table 7: Calculations of Output Power of the Solar Panel and the Associated Uncertainties

The calculation average voltage and current	Uncertainties
$Power\ Output, P_{out.} = VI$	$Uncertainty\ of\ Power\ Output, \Delta P = \frac{\Delta V}{V} + \frac{\Delta I}{I}$
Example for the dust at m = 10.0 g	
$Power\ Output, P_{out.} = 18.02 \times 1.91$ $= 34.42\ W$	$\Delta P = \frac{0.10}{18.02} + \frac{0.01}{1.91}$ $= 0.01\ W$

Similar calculations were made for all the other variations of masses and extended to the processed data of ash substance. The results obtained are presented in the following table.

Table 8: Power of the Solar Panel in the Different Foreign Substances

Mass ($\pm$ 0.1g)	**Power Output of Dust Substance**		**Power Output of Ash Substance**	
	P_{out} (W)	**ΔP (W)**	**P_{out} (W)**	**ΔP (W)**
0.0	38.69	0.02	38.69	0.02
10.0	34.42	0.01	35.11	0.03
20.0	32.12	0.01	32.43	0.02
30.0	27.69	0.01	26.24	0.03
40.0	24.96	0.08	23.66	0.03

The processed data of the power output and the geometrical area of the solar panel were used to compute the efficiencies of the solar panels across the different masses of the two selected foreign substances.

Table 9: Calculation of the Efficiency and Propagated Uncertainty

The calculation efficiency of the solar panel	Propagated Uncertainty
$Efficiency, \eta = \frac{P_{out.} \times Area}{1000} \times 100$ From the manufacturer's design, the panel measured 85 cm by 44 cm	$Propagated\ Uncertainty, \Delta\eta \ = \frac{\Delta P}{P_{out.}} \times 100$
For example, for the dust at m = 10.0 g	
$Efficiency, \eta = \frac{34.42 \times \left(\frac{85}{100} \times \frac{44}{100}\right)}{1000} \times 100$ $= 1.29\ \%$	$\Delta P \ = \frac{0.01}{43.42} \times 100$ $= 0.02\ \%$

The efficiencies of the other variations of the masses of the solar panels were calculated using the same approach, and the results obtained were recorded in the following data table.

Table 10: Calculated Efficiencies of the Solar Panel for the different Substances

	Efficiency of the Panel for Dust Substance	**Efficiency of the Panel for Ash Substance**

Mass ($\pm$ 0.1g)	Efficiency, η (%)	Δ η (%)	Efficiency, η (%)	Δ η (%)
0.0	1.45	0.05	1.45	0.05
10.0	1.29	0.03	1.31	0.09
20.0	1.20	0.03	1.21	0.06
30.0	1.04	0.04	0.98	0.11
40.0	0.93	0.32	0.88	0.13

Graph Obtained from the Data

The data obtained and presented in **Table 11** above were imported into LoggerPro's graphing software and used to create a line graph of the efficiency of a solar panel against the masses of ash and dust foreign substances. The values of the uncertainties were used as the error bars on these graphical plots, as demonstrated in **Figure 3** below.

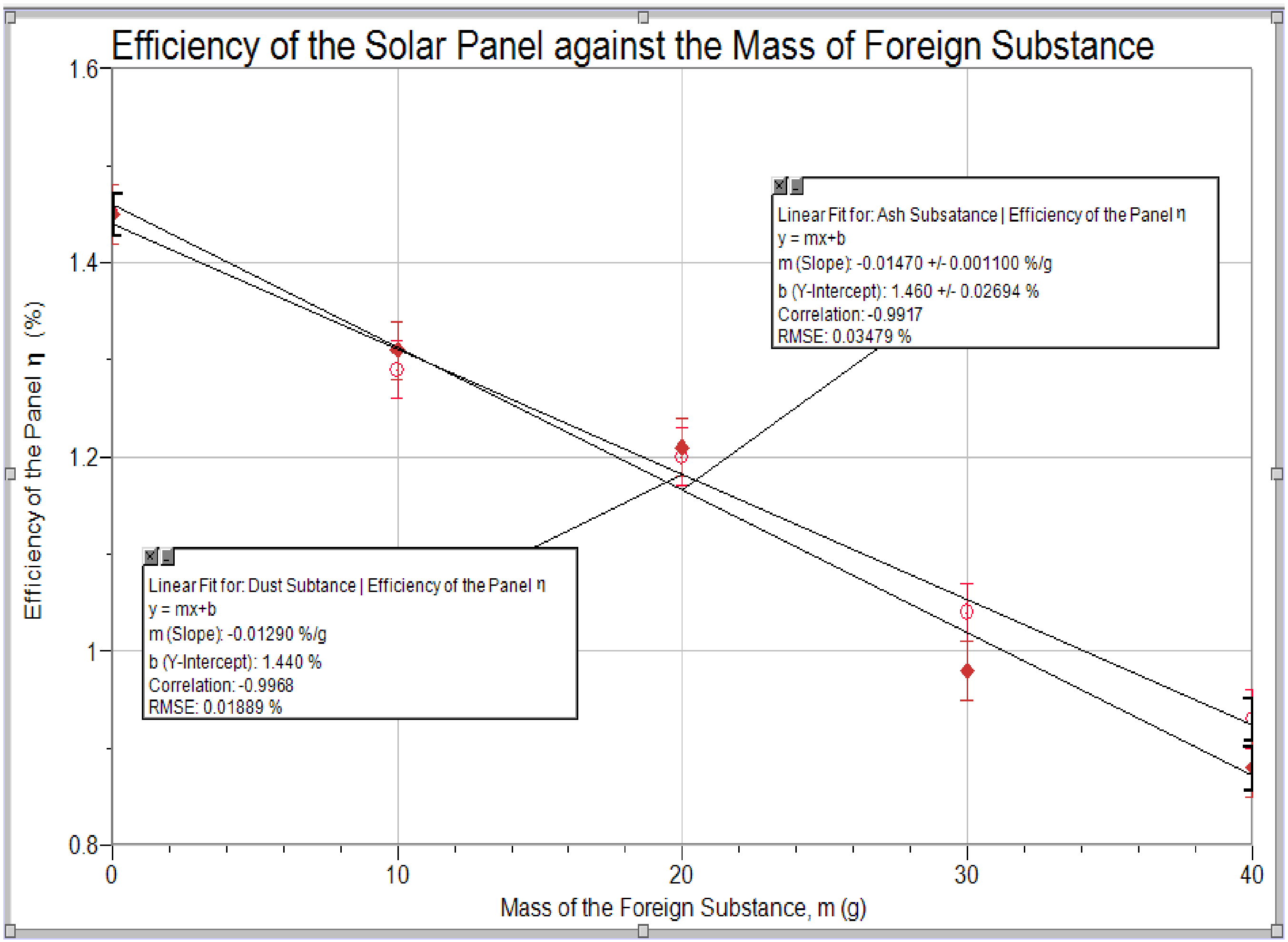

Figure 3: A Graph of Efficiency of the Solar Panel against Mass of Foreign Substance

Data Analysis

The graph plotted above shows that there was a progressive decline in the efficiency of the solar panel as the masses of the two foreign substances increased. This trend was evidenced by the negative slopes of the two trendlines in **Figure 3** above. The efficiencies of the solar panels without the addition of foreign substances were 1.45 %, decreasing to 0.93 % and 0.88 % for the dust and ash substances, respectively, at 40.0 g. The sharp declines in the efficiencies of solar panels are a demonstration of the cumulative effect of foreign substance coverage on the photovoltaic effect of the conversion of solar energy into electrical energy. The reductions in the efficiencies of the two dust particles were comparatively different, with the slope of the ash substance being - 0.01470 compared to the slope of -0. 01290. This comparative difference shows that the efficiency of the solar panel in the ash substance was higher compared to that of the dust substance. This trend was consistent with the study hypothesis. In practice, it has been expected that an increase in the amounts of dust and ash on the surface of the solar panel would lead to an increased obstruction of sunlight energy falling on the solar panel, reducing power output and, subsequently, efficiency. The comparative difference between the trends in the ash and dust substance could be linked to the fact that the ash substance is darker with an opaque of higher intensity compared to the dust substance. The low values of root mean square errors (RMSE) of the two plots of 0.01889 and 0.03479 for the dust and ash substances showed that the experimental data collected and processed in this extensive study closely aligned with the linear models. In addition, the two RMSE values showed high accuracy and reliability in the experimental data, further confirming the systematic impact of the two foreign substances on the efficiency of the solar panel. The error bars in the two characteristic graphs were also relatively low and did not overlap on the trendlines. These observations were indications of high accuracy and reliability in the processed data.

Conclusion

The aim of this study was to find out the effect of foreign substances on the efficiency of solar panels. It had been hypothesized that the foreign substances would significantly impact the solar panel's efficiency. There was also an expectation that an increase in the amounts of dust and ash on the surface of the solar panel would lead to an increased obstruction of sunlight energy falling on the solar panel, reducing power output and, subsequently, efficiency. The results of the experiment showed that there was a progressive decline in the efficiency of the solar panel as the masses of the two foreign substances increased. The efficiencies of the solar panels without the addition of foreign substances were 1.45 %, decreasing to 0.93 % and 0.88 % for the dust and ash substances, respectively at 40.0 g. The sharp declines in the efficiencies of solar panels are a demonstration of the cumulative effect of foreign substance coverage on the photovoltaic effect of the conversion of solar energy into electrical energy. The reductions in the efficiencies of the two dust particles were comparatively different, with the slope of the ash substance being - 0.01470 compared to the slope of -0. 01290. This comparative difference shows that the efficiency of the solar panel in the ash substance was higher compared to that of the dust substance. Hence, the hypothesis of the study was supported. The findings of this study were consistent with the theoretical insights of Aghaei et al. (2022), who found that soiling and shading of solar panels blocking any section of a solar panel reduces the output of the panel.

Evaluation

Evaluation of Strengths

- Systematic variation: The decision to systematically vary the masses of the dust and ash substances from 0.0 g to 40.0 g in increments of 10.0 g was effective as it ensured there was a consistent and larger scope in the measurement of the impacts of foreign substances on the efficiency of the solar panel.
- A large number of control variables: The control of temperature, cleanliness, and angular inclination minimized the possible impacts of the external factors on the efficiency of the panel, increasing the reliability of the results.
- Repeatability: The decision to use three trials of measurements of voltage drop and current in each variation of the independent variables effectively reduces the impact of random errors in the calculation of average measurements, increasing the level of accuracy of the final results.
- Precision Measurements: The digital multimeter and electronic beam used in the experiment had low uncertainties of (± 0.01 A, ± 0.01 V) and ± 0.1 g, which increased the precision and accuracy of measurements.
- Inclusion of baseline measurements: The inclusion of measurement of voltage and current at 0.0 g variation of mass provided a reference to the foundation of comparison of power output with the inclusion of foreign substances, enhancing clarity in the observed effects.

Evaluation of Weaknesses

Table 11: The main Limitations/Weaknesses and Suggested Improvements

Weakness	Effect on the Experiment	Suggested Improvement
Limited range	By testing only dust and ash, the study fails to account for other real-world pollutants like bird droppings, pollen, or industrial soot. This limits the scope of the conclusions and their applicability to diverse conditions.	Incorporate a wider range of foreign substances commonly encountered in different environments. This variation would make the results more representative of real-world scenarios.
Lab setting	Conducting the experiment in a controlled environment eliminates environmental factors like wind, humidity, and variable sunlight intensity. These factors significantly influence solar panel efficiency in practical applications.	Perform outdoor trials in various real-world settings, such as urban, rural, and industrial areas. Include environmental variables to assess their combined effects on efficiency.
Use of single panel	Use of only one type of solar panel limited the findings to a single technology. Different panel types may respond differently to soiling due to variations in design and material properties.	Test multiple types of solar panels, such as polycrystalline and thin-film, to compare their efficiency losses under similar conditions. This would enhance the study's broader applicability.
Possible variation of light	If using natural sunlight, variations in light intensity due to clouds or time of day might introduce inconsistencies in the data.	Use a calibrated solar simulator to ensure consistent and accurate light exposure throughout the experiment.

Suggested Extension

The approach used in this study could be extended to investigate the combined effects of humidity and shading on the power output and efficiency of the solar panel. Such an investigation would allow a comprehensive determination of factors that affect the efficiency of photovoltaic cells.

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