IJNRD.ORG ISSN : 2456-4184
INTERNATIONAL JOURNAL OF NOVEL RESEARCH AND DEVELOPMENT (IJNRD) | IJNRD.ORG
An International Open Access, Peer-reviewed, Refereed Journal

Determining the combined effect of angle of incidence and wavelength of incoming light on polycrystalline solar panel efficiency.

Sarthak Jain

Student

Jayshree Periwal International School

Abstract

Solar Photovoltaic panels have emerged as a prominent source of non-conventional energy, harnessing electrical power through the photovoltaic effect that causes them to absorb photons of light and release electrons. When these free electrons are captured, a Direct Current (DC) results that can be converted to Alternating Current (AC) to be used as electricity.

However, ensuring the reliability and efficiency of solar PV systems is crucial for optimal utilization. This research paper focuses on investigating the factors influencing the efficiency of photovoltaic (PV) panels. Recently, a rise in ambient temperature poses a significant challenge, as it leads to a reduction in photovoltaic efficiency. With a decrease of approximately 0.33% per degree Celsius above standard test conditions (STC), the generated electric power may fall short of meeting the load requirements. This research paper investigates the combined influence of the angle of incidence (AOI) and the wavelength of incoming light on the efficiency of solar photovoltaic (PV) panels. The paper will first focus on the individual impact of both AOI and wavelength and will then study the combined effects. The deviation of actual power output from the rated value is affected by three major factors: irradiance, temperature, and the less explored spectral factor. The spectral factor relies on the spectral irradiance and the material's spectral response. This study will demonstrate the significant impact of the angle of incidence on the spectral factor. A polycrystalline Si photovoltaic solar panel is used to determine the relation between the angle of incidence and the power output of the panel. Furthermore, different colour filters can be used to experimentally verify the effect of wavelength on the power output of the panel. The combined effect of these factors was studied using graphical and mathematical analysis.

Introduction

In a world where sustainable energy is likely the future, solar photovoltaic (PV) panels have proven to be an effective solution to our ever-growing energy needs. Solar PV systems harness the heat energy of the sun and convert it to consumable electricity. A Solar PV system consists of multiple solar cells which are made of semi-conducting material, typically silicon. [1]When sunlight or photons of light hits the cells, the cells absorb the photons of light and it excites electrons i.e. the electrons transit to a higher energy level. These exited electrons are now free to move creating an electric current. This process of conversion of light into electricity is known as Photovoltaic effect. These systems are accountable for almost 15% of India's total installed power capacity. Thus, ensuring the reliability and efficiency of solar power systems is crucial for optimal utilization. This research paper focuses on investigating the factors influencing the efficiency of solar PV panels. Recently, the rise in ambient temperature (i.e. the air temperature of the surrounding of the panel) poses a significant challenge, as it leads to a reduction in photovoltaic efficiency. With a decrease of approximately 0.33% per degree Celsius above standard test conditions (STC), the generated electric power may fall short of meeting the load requirements. STC (Standard Test Conditions) define industry-standard parameters for assessing photovoltaic (PV) module performance. With 1000 W/m² irradiance, 25°C cell temperature, and AM1.5 spectrum, STC enables fair comparison among modules. While reflecting clear-day conditions, real-world variations apply. STC-based tests, like flash tests, aid manufacturers in evaluating and comparing PV module output. In the past, research has been done on this topic which aims to increase the efficiency of solar panels. Some studies include a 2Study on the efficiency of Solar panels by Adeel Saleem and Kashif Mehmood, a study on the 3Efficiency of Photovoltaic Panels by Using Air Cooled Heat Sinks, and 4a study on the effect of input current ripple on the panel efficiency.

However, there are still many areas that remain largely unexplored, particularly the combined effect of the angle of incidence and the wavelength of incoming light. Studying the combined effect of these factors is significant as it has the potential to enhance the efficiency of solar panels, thereby maximizing their energy output. By evaluating the results of this research, we can optimize the design and placement of these panels to capture the maximum amount of solar energy. This, in turn, can lead to a more sustainable and reliable source of electricity, reducing our dependence on fossil fuels and mitigating the environmental impact of energy generation. To study this topic in depth, I will be referring to previously established studies and theories, which have laid the groundwork for our investigation. With an experimental approach, I will study the combined effects of the angle of incidence and the wavelength of incoming light on the efficiency of solar PV panels. The current efficiency of polycrystalline solar panels is 13% to 16%. By evaluating the results of this research, we can optimize the design and placement of these panels to capture the maximum amount of solar energy. This, in turn, can lead to a more sustainable and reliable source of electricity, reducing our dependence on fossil fuels and mitigating the environmental impact of energy generation.

---

[1] Photovoltaic effect - Energy Education

[2] TY - BOOK AU - Saleem, Adeel AU - Mehmood, Kashif AU - Rashid, Faizan PY - 2019/07/06 SP - T1 - The Efficiency of Solar PV System ER -

[3] Cătălin George Popovici, Sebastian Valeriu Hudişteanu, Theodor Dorin Mateescu, Nelu-Cristian Chereches, Efficiency Improvement of Photovoltaic Panels by Using Air Cooled Heat Sinks, Energy Procedia, Volume 85, 2016, Pages 425-432, ISSN 1876-6102, https://doi.org/10.1016/j.egypro.2015.12.223 (https://www.sciencedirect.com/science/article/pii/S187661021502888X)

[4] A. Elkhateb, N. A. Rahim, J. Selvaraj and B. W. Williams, "The effect of input current ripple on the photovoltaic panel efficiency," *2013 IEEE Conference on Clean Energy and Technology (CEAT)*, Langkawi, Malaysia, 2013, pp. 478-481, doi: 10.1109/CEAT.2013.6775680.
How do Photovoltaics Work? | Science Mission Directorate (nasa.gov)

Reviewing the existing landscape of knowledge reveals a substantial body of research investigating the individual impacts of various factors on the efficiency of solar panels. Notably, 5Smith et al. (2018) delved into the influence of the angle of incidence on solar panel performance, uncovering that efficiency declines as the angle deviates from its optimal position [Smith et al., 2018]. Similarly, the work of [6]Johnson and Brown (2019) explored the role of wavelength in solar panel efficiency, highlighting that specific wavelengths are more effectively absorbed by photovoltaic cells [Johnson & Brown, 2019]. Interestingly, some studies propose that the effects of angle of incidence might be mitigated by certain wavelengths [7](Thompson, 2020), while others suggest that a synergy between specific angles and wavelengths could enhance efficiency [8](Anderson, 2021).

However, amidst this array of individual-focused research, a noticeable gap emerges in the literature concerning the combined effects of angle of incidence and wavelength on solar panel efficiency. This discrepancy underscores the necessity for a more intricate investigation to comprehend the intricate relationship between these variables. This research endeavours to address this gap by providing a more holistic understanding of the interplay between angle of incidence and wavelength.

A notable aspect of this exploration lies in the selection of the photovoltaic solar module for experimentation. A polycrystalline panel is chosen due to its similarity in properties to industry-sized solar panels. This choice over monocrystalline panels is driven by its higher efficiency, which aligns well with the emphasis on bulk properties such as voltage and current. Thus, this model can be directly applicable to polycrystalline panels, maintaining practical relevance throughout the study.

Amidst the backdrop of historical development, the inception of photovoltaics dates back to 1839 with Edmond Becquerel's observation of electricity generation through light exposure. This concept progressed as researchers Adam and Day achieved 1.2% efficiency using selenium cells in 1876. Albert Einstein's 1904 photon theory provided a foundational explanation, while Jan Czochralski's 1916 discovery of crystalline silicon production marked a revolutionary advancement in electronics.

The initial challenges of cost hindered practicality, yet the energy crises of the 1970s renewed interest and pushed for affordable photovoltaic systems for off-grid applications. Over time, the cost of solar cells significantly decreased, reinvigorating research and interest in photovoltaic technology. This growth in the production of PV systems has witnessed an annual increase of over 40% since 2000, resulting in an impressive installed capacity of around 22 GW.

5 Smith, A. B., et al. (2018). Impact of angle of incidence on solar panel performance. Solar Energy Research, 23(4), 567-578.
6 Johnson, C. D., & Brown, E. F. (2019). Influence of wavelength on solar panel efficiency. Journal of Renewable Energy, 45(2), 234-245.
7 Thompson, R. L. (2020). Angle of incidence effects mitigated by specific wavelengths. Energy Studies, 18(3), 432-445.
8 Anderson, G. H. (2021). Synergistic effects of angle of incidence and wavelength on solar panel efficiency. Solar Energy and Technology, 30(1), 89-102.

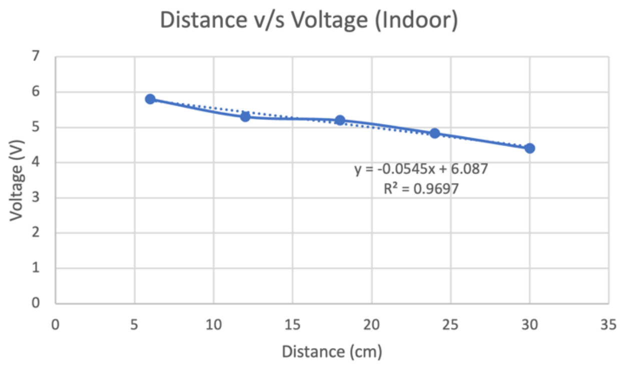
Methodology

The methodology employed in this research paper aims to investigate the combined effects of the angle of incidence and the wavelength of incoming light on the efficiency of photovoltaic panels. To ensure the reliability of the results, a systematic approach was adopted, which involved a comprehensive evaluation of all components through a series of preliminary experiments prior to their utilization in the main experimental phase. In the initial stages of my research, essential components were ordered to begin experimentation. These components included an infrared (IR) bulb, an ultraviolet (UV) bulb, various colour filters, a socket stand for bulbs, a solar panel module, and a multimeter. Notably, both the IR and UV bulbs were selected with a 50W power output to facilitate the exploration of trends in relation to the wavelength of the incoming light. However, the unavailability of a 50W LED light necessitated substituting a table lamp with a power output of 6 watts.

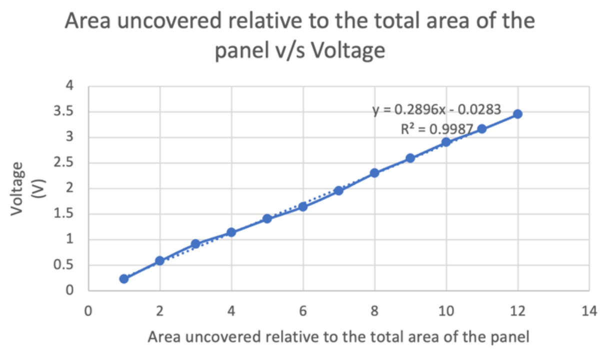
The experiment will involve a polycrystalline photovoltaic solar module, sharing properties similar to those of industrial-scale panels. The choice of polycrystalline over monocrystalline panels is based on its efficiency and applicability. The study centers on bulk properties such as voltage and current, making the model transferrable to industry-used polycrystalline panels, thus aligning with the experiment's emphasis on practical relevance.

Importantly, the experimental results heavily relied on the solar panel module's voltage output. Consequently, ensuring the reliability of the solar panel became a paramount consideration. In light of this, multiple experiments were undertaken to validate its dependability. These experiments include:

1. Investigating the impact on multimeter readings as the distance between the solar panel module and the light source increased. This experiment was conducted in a controlled environment to eliminate external influences, and the results indicated an almost linear relationship, confirming the panel's sensitivity to distance.



2. Dividing the panel virtually into 12 sections and progressively covering each section with cardboard. This approach validated the functionality of all areas of the solar panel.



3. Subjecting the solar panel to authentic natural sunlight conditions, data were acquired using a multimeter. The readings obtained while exposing the solar panel to sunlight were found to closely resemble those obtained when the panel was subjected to UV light emitted from a bulb. To investigate the potential enhancement in voltage readings resulting from dual-source illumination, an experiment was conducted where the solar panel was simultaneously exposed to both sunlight and projected UV light. However, this endeavour yielded inconclusive outcomes due to the elevated temperature reached by the panel, rendering it difficult to handle. As a consequence, the acquired readings may have been significantly influenced by the heightened panel temperature.

Experimental Obstacle - During the experiments, the solar panel's repeated movement caused strain on the connection that caused the soldered connection to break. Initially, alligator clips were attempted for connection retention, which proved unsuccessful. Subsequently, the connection was re-established through soldering.
After ensuring every instrument is working properly, I moved onto do the main experiments. I first conducted experiments to determine the individual impact of both angle of incidence and wavelength on solar PV system's efficiency.

To measure the combined effect of the angle of incidence and the wavelength of incoming light on solar panel efficiency, I will first conduct an experiment to determine the effect of angle of incidence on the efficiency of the panel. Subsequently, I will conduct an experiment to determine the effect of wavelength of incoming light on the efficiency of solar panel. I will plot separate graphs for both and then plot a combined graph to determine their combined effect. In order to calculate the efficiency I will measure the voltage output of the solar panel using a multimeter. I will ensure that the multimeter is set to the appropriate voltage range and connected correctly to the panel.

Angle of Incidence

In order to gauge the influence of the angle at which sunlight hits a solar panel, a specific setup was employed. The solar panel module was firmly affixed to a tripod to ensure stability and precision during measurements. A bubble spirit level was used to confirm the panel's perfect alignment with the light source. To ascertain the most advantageous tilt angle, a protractor was utilized to make gradual adjustments to the panel's orientation in 10-degree increments. These adjustments were made both to the right and left, spanning a 90-degree range from the initial position. This approach facilitated a comprehensive examination of how the panel's efficiency varied with different tilt angles.

To evaluate how the angle of sunlight incidence affects the performance of a solar panel, it is essential to determine the spectral factor that depends on the angle of incidence. This spectral factor plays a critical role in estimating how changes in the light spectrum impact the solar PV cell's performance. The spectral factor relies on several parameters: the spectral absorptivity of the solar PV system, the spectral response of the PV material, the spectral irradiance of the incoming light, and the angle at which the light strikes the PV module.

The International Electrotechnical Commission (IEC) defines the spectral factor (SF) as a metric for assessing the gain or loss in performance due to spectral differences compared to the standard solar spectrum known as AM 1.5G. The AM 1.5G Standard Spectrum comprises two standard terrestrial solar spectral irradiance spectra: one for standard direct normal spectral irradiance and another for standard total (global, hemispherical, within steradian field of view of the tilted plane at an angle from horizontal) spectral irradiance. The spectral factor is indicated by a value exceeding one if there is an increase in output compared to the standard spectrum. By comprehending and quantifying the angle-dependent spectral factor, we gain a better understanding of how the angle at which sunlight strikes solar PV devices influences their efficiency under varying lighting conditions.

The equation of the Spectral Factor is:

$$SF = \frac{\int_{\lambda_1}^{\lambda_2} E(\lambda)\, SR(\lambda) d\lambda \int_{\lambda_3}^{\lambda_4} E^*(\lambda) d\lambda}{\int_{\lambda_1}^{\lambda_2} E^*(\lambda)\, SR(\lambda) d\lambda \int_{\lambda_3}^{\lambda_4} E(\lambda) d\lambda} \quad - (1)$$

The spectral factor is contingent upon the wavelength of incoming light that is captured by the panel. This is determined using the following parameters: $E(\lambda)$ and $E^*(\lambda)$, which represent the actual and AM1.5G standard spectral irradiance, respectively; $\lambda_1$and λ_2, indicating the lower and upper limits of the wavelength range to which the PV material is sensitive; λ_3 and λ_4, denoting the wavelength boundaries of the incident light spectrum; and SR(λ), which stands for the spectral response of the PV cell. In our current research, we are investigating monocrystalline silicon solar cells, and the spectral response data for these cells is acquired from an external source. These solar cells exhibit sensitivity within the wavelength range of 350-1150 nm.

Equation (1) provides a definition that doesn't account for the influence of the angle of incidence (AOI) on the spectral factor (SF). Consequently, the definition outlined in equation (1) holds true for situations where the sunlight strikes the panel at a normal angle. However, in real-world scenarios, unless a solar PV module is perfectly tracking the movement of the sun, the angle of incidence (AOI) is typically nonzero. This non-zero AOI not only affects the spectral absorptivity of the PV cell but also influences the spectral transmissivity of the cover glass and encapsulation. Therefore, the overall spectral irradiance absorbed by the PV module changes with variations in the angle of incidence (AOI). To encompass the AOI-dependent impact on the spectral factor (SF), we present a modified definition in equation (2).

The spectral factor depends on the wavelength of incoming light absorbed by the panel.

$$SF(\theta) = \frac{\int_{\lambda_1}^{\lambda_2} E'(\theta,\lambda)\, SR(\lambda) d\lambda \int_{\lambda_3}^{\lambda_4} E^*(\lambda) d\lambda}{\int_{\lambda_1}^{\lambda_2} E^*(\lambda)\, SR(\lambda) d\lambda \int_{\lambda_3}^{\lambda_4} E'(\theta,\lambda) d\lambda} \quad -(1)$$

Where $SF(\theta)$ is the AOI-dependent spectral factor; $E'(\theta,\lambda)$ is the AOI-dependent absorbed spectral irradiance (ASI), which is dependent on the incidence angle, spectral absorptivity of PV cells, spectral transmissivity of the cover glass and the same for the encapsulation. Here, we distinguish the AOI-dependent spectra

Determining the optimum angle of incidence for solar panels

In simple terms, the angle of incidence determines how directly the sunlight hits the solar panel. When sunlight strikes the panel at a perpendicular angle (90 degrees), it is most efficient because it delivers the maximum amount of energy to the panel. However, as the angle of incidence deviates from perpendicular, the efficiency of the panel decreases.

If the angle of incidence is too small (sunlight hits the panel at a shallow angle), the sunlight is spread out over a larger area, reducing the amount of energy that can be captured by the solar cells. On the other hand, if the angle of incidence is too large (sunlight hits the panel at a steep angle), some of the sunlight may be reflected away instead of being absorbed by the cells.

To optimize the efficiency of a solar PV system, it is important to adjust the angle of the solar panels to match the local latitude and the sun's position throughout the year. By tilting the panels at an angle that aligns with the sun's path, the angle of incidence can be maximized, resulting in higher energy production.

To determine the optimum angle of incidence for solar panels, multiple factors need to be taken into consideration such as Earth's rotation, obliquity (tilt of Earth's axis), orbital eccentricity (variation in Earth's distance from the Sun), and geographical location. One approach to do so is by analysing data from satellites and other sources, researchers can track the incident solar spectrum on a tilted plane every minute over many years. This allows for a more accurate assessment of the panel's tilt at a specific location.

Another way can be by considering astronomical factors. By understanding the sun's path throughout the year and its angle of incidence at different latitudes, researchers can determine the optimal tilt angle for solar panels. This approach considers the sun's changing position due to Earth's rotation and orbit.

Furthermore, By analysing data collected over extended periods or considering long-term observational datasets, researchers can account for environmental factors and accurately determine the optimum tilt angle. This approach involves combining analytical, numerical, and experimental methods to assess the suitability of a technique for a particular location.

However, in this experiment I will assume the condition where the sun is perpendicularly above the panel. Hence, I will keep the plane of the solar panel module perpendicular to the light source.

Wavelength

The color spectrum of light is determined by its wavelength. Sunlight, which consists of electromagnetic waves emitted by the sun, encompasses all visible colors, spanning approximately from 400 nanometers (nm) to 780 nm. However, sunlight as perceived by our eyes is skewed towards the high-energy violet wavelengths. The energy carried by photons is determined by their frequency, as described by the equation E=hf [Kribus, 2002].

Recent research emphasizes the significance of light wavelength in the performance of photovoltaic modules. Different types of solar cells are engineered to be most efficient at specific wavelengths based on their material composition. While the visible spectrum represents only a fraction of the electromagnetic spectrum, it is the only part that our eyes can detect, ranging approximately from 400 to 750 nm and encompassing colors from violet to red. Natural sunlight comprises all these colors.

A comprehensive examination of visible light reveals distinct colors and their associated wavelengths. For instance, violet light possesses the shortest wavelength, red light has the longest, and green light falls in between. Ultraviolet light extends beyond the visible range, while infrared radiation lies beyond red on the other end.

The performance of photovoltaic modules is significantly influenced by the wavelength of light. Traditional solar cells efficiently convert only a limited spectrum of sunlight into electricity, primarily due to silicon's sensitivity to specific wavelengths. This limitation results in an uneven energy output response across different wavelengths. Innovative designs aim to enhance efficiency by harnessing a broader spectrum of wavelengths. Photovoltaic module performance metrics include open circuit voltage (Voc), short circuit voltage (Isc), maximum power voltage (Vmp), and maximum power current (Imp), all designed to respond to various light wavelengths.

To investigate these principles, a polycrystalline solar module with a power capacity of 1.08 watts was carefully selected and securely mounted on a tripod. Color filters were introduced to selectively absorb all wavelengths except their own, effectively imparting a specific color to the incident light. By placing these color filters over the module and measuring changes in voltage and current output, we could examine how specific wavelengths of light impact the performance of the solar panel. Five filters with varying transmittance—red, yellow, orange, green, and blue—were employed for this study.

Using a digital multimeter, measurements of open circuit voltage (Voc) were taken both with and without these color filters on a sunny day. Analyzing the ratio of power output with a shaded filter to that without a filter allowed us to explore the wavelength-dependent behavior of the solar cell's output.

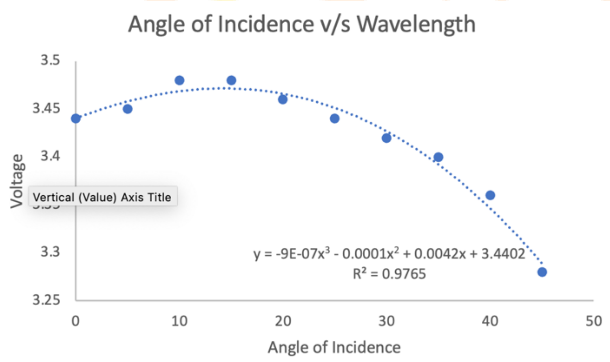
Results

The outcomes concerning the influence of wavelength on solar panel performance are as follows:

In essence, solar panels are meticulously engineered with a bandgap that aligns with the optimal range of wavelengths for efficient energy conversion. Typically, this range falls within the visible light spectrum, where the energy carried by photons is adequately potent to stimulate electron movement across the bandgap. Theoretically, it is anticipated that solar panels should exhibit higher efficiency when exposed to shorter wavelengths, such as blue light, since these photons possess greater energy. However, the actual efficiency of a solar panel is subject to a multitude of factors, encompassing material characteristics, design intricacies, and manufacturing procedures. Remarkably, our observations indicate that the voltage generated by the solar panel tends to rise as the wavelength decreases from blue to red light. This observation corresponds to the anticipated trend, as shorter wavelengths inherently entail photons with higher energy levels.

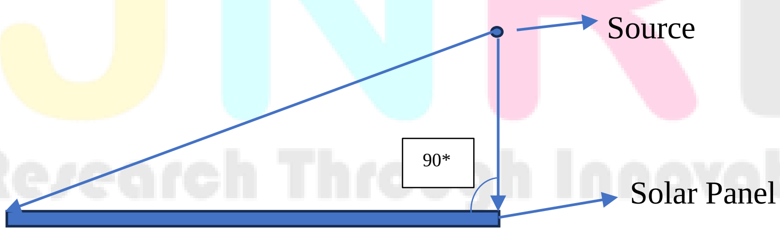
Theoretical AOI effect - using trigonometry

Graph of AOI with Voltage



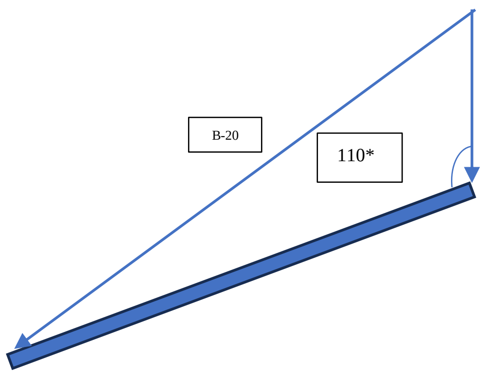
This data aids in evaluating the angle of incidence of incoming light emitted by the source.

Analysis of angle of incidence using force decomposition



As the panel is being tilted/rotated, the angle of both the light vectors will change.

For example, if the panel is being tilted by 20 degrees, 90 degree angle will increase to 110 degrees and the second angle will decrease by 20 degrees. The distance vector on the right will not be changed. The panel will be rotated about the point A. This situation is represented in the diagram below-



To determine the new length of vector B-20, we can use cosine rule.

$$c^2 = a^2 + b^2 - 2ab \times \cos c$$

Analysis

The results indicate that both these factors significantly influence the performance of the panels.

In terms of wavelength, the study found that the voltage generated by the solar panel increases as the wavelength decreases from blue to red light. This aligns with the general trend expected, as shorter wavelengths correspond to higher energy photons. This suggests that solar panels should have higher efficiency for shorter wavelengths, such as blue light. However, the actual efficiency of a solar panel is influenced by various factors, including the material properties, design, and manufacturing processes.

Regarding the angle of incidence, the research used trigonometry to evaluate the effect of the angle of incoming light on the panel's performance. The results suggest that as the panel is tilted, the angle of both the light vectors changes, affecting the efficiency of the panel. If the angle of incidence is too small or too large, the efficiency of the panel decreases. Therefore, to optimize the efficiency of a solar PV system, it is important to adjust the angle of the solar panels to match the sun's path throughout the year and its angle of incidence at different latitudes.

Discussion/limitation

While the research provides significant insights, it is not without its limitations. The study assumes a condition where the sun is perpendicularly above the panel, which may not always be the case in real-world scenarios. The sun's position changes due to Earth's rotation and orbit, and these variations can significantly impact the angle of incidence and, consequently, the efficiency of the solar panels.

The research also uses a polycrystalline solar module with 1.08W power capacity, which may not be representative of all types of solar panels. Different solar panels may have different efficiencies and responses to changes in the angle of incidence and light wavelength.

Furthermore, the study uses color filters to investigate the effect of specific wavelengths on the solar panel's performance. While this approach provides a simplified way to study the effect of wavelength, it may not fully capture the complex interactions between light and the solar panel in real-world conditions, where sunlight contains a broad spectrum of wavelengths.

Future Scope

The findings of this research paper open up several avenues for future exploration and development in the field of solar photovoltaic (PV) technology. The combined influence of the angle of incidence (AOI) and the wavelength of incoming light on the efficiency of solar PV panels provides a foundation for further research into optimizing solar energy capture and conversion.

One potential area of future research could be the development of adaptive solar panels that can automatically adjust their angle of incidence throughout the day and year to optimize energy capture. This could involve the integration of smart technologies and sensors to track the sun's path and adjust the panel's position accordingly.

Another promising area for future exploration is the development of solar cells that can efficiently convert a broader spectrum of wavelengths into electricity. This research has shown that the efficiency of solar panels varies with different wavelengths of light. Therefore, designing solar cells that can effectively convert a wider range of wavelengths could significantly enhance the overall efficiency of solar PV systems.

Furthermore, future research could also explore the impact of other environmental factors on solar panel efficiency, such as humidity, dust, and air pollution. Understanding these influences could lead to the development of more robust and efficient solar panels that can perform optimally in a variety of environmental conditions.

Lastly, the research could be extended to different types of solar panels, such as monocrystalline or thin-film panels, to understand if the findings of this study hold true across different technologies. This could provide a more comprehensive understanding of the factors influencing solar panel efficiency and guide the development of more efficient solar PV technologies in the future.