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The Effect of the Refractive Index of Solar Panel Glass on the Amount of Energy Received and the Optimal Angle of the Panel

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ABSTRACT

Using renewable energy is one of the sustainable solutions to deal with the problems caused by the excessive use of fossil fuels. In recent years, the use of solar electricity has developed more than other methods of using renewable energy due to its applicability on a small to large scale. Solar panels, as part of solar power systems that convert solar radiant energy into electrical energy, are installed at an optimal angle to receive the most energy. The purpose of the present study is to study the effect of the refractive index of solar panel glass on the amount of energy received and its optimal angle. The results showed that increasing the refractive index of the glass coating of solar panels will cause a significant reduction in the annual energy received. The annual energy received for a panel installed at an angle of 20 degrees at a latitude of 30 degrees is about 12.591×10^9 W. Considering a refractive index of about 1.2, the energy received is reduced to 10.530×10^9 W (about 16.4%). A refractive index of 1.6 also causes a reduction of about 42.7% of the energy received. Considering an increase in the refractive index of 1.4 led to an increase of about 2 degrees in the optimal angle.

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1. Introduction

In recent years, the use of adsorbents for environmental treatment and solar energy as a sustainable and cost-effective solution for energy supply has become more significant than ever [1-4]. With increasing concerns about climate change, depletion of fossil fuels and air pollution, solar energy has been recognized as a clean, renewable and unlimited source [5]. Also, technological advances and reduced production costs have made the use of solar panels

affordable for households and industries [6]. Many countries are encouraging people to install solar systems by providing financial facilities and incentives to both reduce energy costs and contribute to environmental protection [7]. Therefore, moving towards solar energy is not only a smart economic choice but also a necessity for a green and sustainable future [8]. Solar energy has grown the fastest in recent years compared to other renewable sources such as wind energy, hydroelectricity, and biomass [9-12].

One of the key advantages of solar energy compared to other renewable sources is its ability to be installed on both a small and large scale [13]. Wind and hydropower plants usually require large spaces or specific geographical conditions, while solar panels can even be installed on the roofs of houses [14]. The cost of solar electricity also shows that solar energy is an attractive option for the future of clean energy, not only in terms of scale, but also in terms of economics. Solar energy is also available and usable in wider areas than other types of renewable energy, such as wind energy, wave energy, geothermal energy, etc. [15]. Installing solar panels at the optimal angle is one of the key factors in increasing the efficiency and productivity of solar systems. The angle of installation of the panels has a direct impact on the amount of sunlight received and, if properly adjusted, can significantly increase the electrical energy produced by the solar panel. This angle depends on various factors such as geographical location (latitude and altitude), season of the year, and direction of solar radiation. In scientific studies, the calculation of the optimal angle of solar panels is mainly based on radiation models, climate data, and mathematical optimization [16]. Researchers usually calculate the amount of direct, diffuse, and reflected radiation using radiation models and considering geographical parameters (latitude, longitude, and altitude). It is important to note that direct radiation has the largest share and therefore the greatest impact, and as a result, only this type of radiation has been examined in some studies [17]. Typically, modeling conducted to determine the optimal panel angle, considering various simplifying conditions, seeks to determine the angle under which the highest annual energy input and consequently the highest electrical energy produced is obtained. The results of various studies show that in areas located at medium latitudes (such as Iran), the optimal angle is usually considered equal to the latitude of that area (± 15 degrees) in order to absorb the maximum amount of energy throughout the year [18]. Therefore, carefully examining and calculating the installation angle of solar panels not only reduces costs but also significantly increases the profitability and efficiency of solar projects.

The results of the research have led to the development of various commercial software such as PVsyst, Helioscope and PVSOL, which are used to calculate the optimal angle of solar panels. This software suggests the optimal installation angle of solar panels by simulating geographical and climatic conditions. However, software has limitations, including the high cost of purchasing a license (especially for professional versions), complexity in use for non-specialist users, and dependence on accurate meteorological data. These issues cause the results obtained from their use to be associated with errors in some cases and under specific conditions. Some of these tools have limited customization capabilities for non-standard system configurations and do not fully consider factors such as dynamic shading or long-term climate changes in their calculations. These challenges sometimes mean that the results obtained do not fully correspond to real conditions [19].

Solar panels consist of various components, including photovoltaic cells, a glass cover, an aluminum frame, a polymer backing, wiring, and connectors. The glass cover of solar panels, which is in direct contact with the environment, protects the photovoltaic cells from environmental factors such as weather, dust, and impact. However, the presence of a glass cover causes solar radiation to be reflected from the panel surface and not reach the photovoltaic cells

during the early and late hours of the day (when the angle of incidence on the solar panel is high). Therefore, it seems that one of the factors that affects the amount of energy received by solar panels is the refractive index of the glass coating of solar panels. However, a review of studies shows that the effect of this parameter on the efficiency of solar panels has not been studied much. Advanced commercial software such as PVsyst and PVSOL also model the effect of the angle of refraction of the panels on the system efficiency to some extent, but this analysis is usually simplified and based on the overall panel data. These software mainly use standard reflection coefficients (e.g. 91-94% light transmission for Anti-Reflective Coating glass), but rarely allow for accurate calculation of the effect of the angle of refraction based on the exact characteristics of the materials (e.g. refractive index of glass or Nano-coatings).

In calculating the optimal panel angle, this software focuses more on the geometry of solar radiation and shading and ignores the effects of light polarization or angular variations in reflection in different coatings. As a result, although solar software is useful for general calculations, to optimize technical details such as the effect of the glass refraction angle, it may be necessary to supplement the data with other methods. Therefore, considering the existing shortcomings, the main objective of this research is to investigate the effect of the refractive index of the glass of solar panels on the amount of energy received and their optimal angle.

2. Methodology

The refractive index of the glass coating on solar panels directly influences the amount of energy received. The critical angle of the glass coating can be determined using its refractive index. The critical angle is the maximum angle of incidence at which radiation can pass through the glass. In other words, the glass surface acts as a mirror for radiation at angles greater than the critical angle. Therefore, if the angle of incidence exceeds the critical angle, the radiation will be reflected off the glass surface and will not pass through. This is illustrated schematically in Fig. 1.

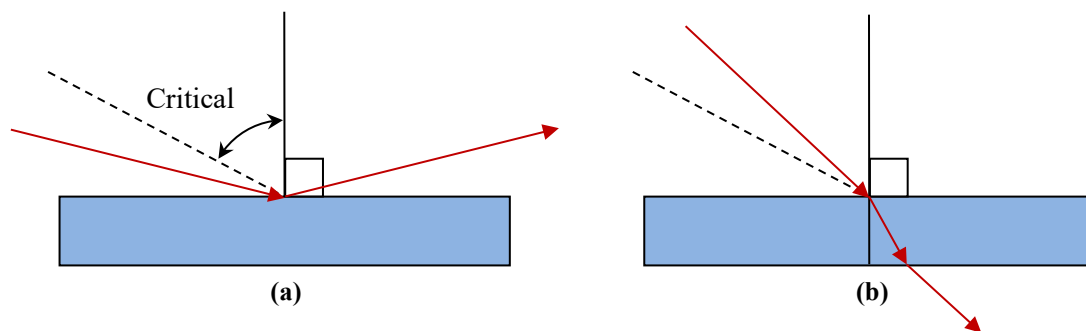


Fig. 1. (a) Reflection of incident rays with an angle of incidence greater than the critical angle; (b) transmission of incident rays with an angle of incidence less than the critical angle

Since the refractive index of commercial glass is about 1.6 or higher, anti-reflective coatings with optimized refractive indices (usually between 1.2 and 1.5) can minimize light reflection and enhance the average light transmission to photovoltaic cells. Research indicates that using nanostructured coatings with variable refractive indices can boost light absorption efficiency at different angles of irradiation (especially at the start and end of the day). This improvement is particularly notable when the irradiation is oblique (low-angle), as reflection losses are greater in these conditions. Therefore the range of 1.2 to 1.6 was selected as the range of refractive index change in this study. The present study was conducted to examine the effect of the refractive index on the amount of energy received and the optimal angle of the solar panel. Initially, considering the latitude of the study location, the changes in the angle

of direct sunlight during a day are calculated for a panel positioned at a specific angle to the horizon, from the start to the end of the day, with a time step of 1 minute. Next, to account for the effect of the refractive index, if the angle of sunlight on the panel surface exceeds the critical angle related to the specified refractive index, the amount of energy received is considered zero in the calculations. In these calculations, the relationship between the refractive index of glass and the critical angle is derived using the following equation.

$$\theta_c = \text{Sin}^{-1}\left(\frac{n_2}{n_1}\right) \quad (1)$$

In this relation, θ_c is the critical angle, n_1 and n_2 are the refractive indices of glass and air, respectively. According to this relation, as the refractive index increases, the critical angle decreases. The refractive index of solar panels depends on the type of glass and the coating used in them. If commercial glass is used, which has a refractive index of about 1.6, the critical angle is about 38 degrees. The use of solar glasses and nanometer anti-reflective coatings has caused the refractive index to decrease to values of about 1.15, in which case the critical angle increases to about 60 degrees. However, most commercially available panels have a critical angle between 42 and 56 degrees. In the next step, all the calculations mentioned above are performed from the first to the last day of the year, and the total annual energy received by the panel at a specific installation angle is obtained. Finally, by comparing the total annual energy at different angles of the panel, the angle under which the maximum amount of energy is received will be introduced as the optimal angle of the panel, taking into account the effects of the refractive index. To investigate the effect of the refractive index of the glass coating of solar panels on the optimal angle and received energy, results were compared with the case where the effect of the refractive index was ignored in the calculations.

3. Results and discussion

The presence of a glass coating on solar panels to protect the photovoltaic cells from environmental conditions causes solar radiation to be reflected from the panel surface during the early and late hours of the day (when the angle of incidence is greater than the critical angle). Table 1 shows the energy changes received by the panel from direct solar radiation at different refractive indices of the glass coating for a given day (the 100th day of the year) and a given angle of the panel (The panel angle of 20 degrees was chosen for day number 100 based on our previous study [16]). As is clear, with increasing refractive index, the energy received decreased.

Table 1. The effect of refractive index on the energy received from direct solar radiation on day 100 for a panel with an installed angle of 20 degrees

Refractive index		1.2	1.4	1.6
Energy received ($\times 10^7$ W)	Considering the critical angle	3.1398	2.6546	2.2772
	Regardless of the critical angle	3.8252		

On a given day, as the sun rises on the panel surface, the sun's rays strike the panel surface at an angle of 90 degrees. The angle of incidence decreases steadily over time from its maximum value of 90 degrees. But as long as the angle of incidence is greater than the critical angle, the radiation is reflected from the surface of the glass covering of the panel. Over time, the angle of incidence eventually becomes less than the critical angle, and the reflection phenomenon disappears.

At solar noon, the angle of incidence experiences its lowest value. As time passes from solar noon to sunset, the angle of incidence increases again. At a certain point, the angle of incidence again becomes greater than the critical angle. Therefore, from that time until sunset, the sun's radiation is reflected from the panel surface.

In fact, as the refractive index increases, the critical angle decreases. Lowering the critical angle shortens the time interval during which solar radiation passes through the glass surface, leading to a decrease in received energy. In other words, as the refractive index increases and the critical angle decreases, the duration of the times of day when solar radiation is reflected from the glass surface expands. The results in Table 1 show that the amount of energy received during a specific day decreases as the refractive index of the glass increases. According to Table 1, on the 100th day of the year, the energy received by a panel mounted at a 20-degree angle, considering refractive indices of 1.2, 1.4, and 1.6, is 17.92%, 30.60%, and 47.47% less, respectively, than when the effect of the critical angle is ignored. The impact of the refractive index on the total annual energy received at a given panel angle is shown in Table 2. These results, derived from summing the energy received over all days of the year, demonstrate that, as with Table 1, increasing the refractive index results in a reduction in the total annual energy received.

Table 2. The effect of refractive index on annual energy received from direct solar radiation for a panel with an installed angle of 20 degrees

Refractive index		1.6	1.4	1.2
Energy received ($\times 10^9$ W)	Considering the critical angle	7.2180	8.6875	10.530
	Regardless of the critical angle	12.591		

According to the results in Table 2, the annual energy received by a panel installed at an angle of 20 degrees, considering refractive indices of 1.2, 1.4, and 1.6, is 16.37%, 31%, and 42.67% less than in the case where the effect of the critical angle is ignored, respectively.

To examine the effect of the refractive index on the solar panel optimal angle, it is first necessary to determine the optimal angle for Zahedan city's latitude. The method for finding this angle involves calculating the annual energy received at various angles, and the angle with the highest energy is identified as the optimal. Fig. 2 illustrates the variations in annual energy received at different panel angles for Zahedan city.

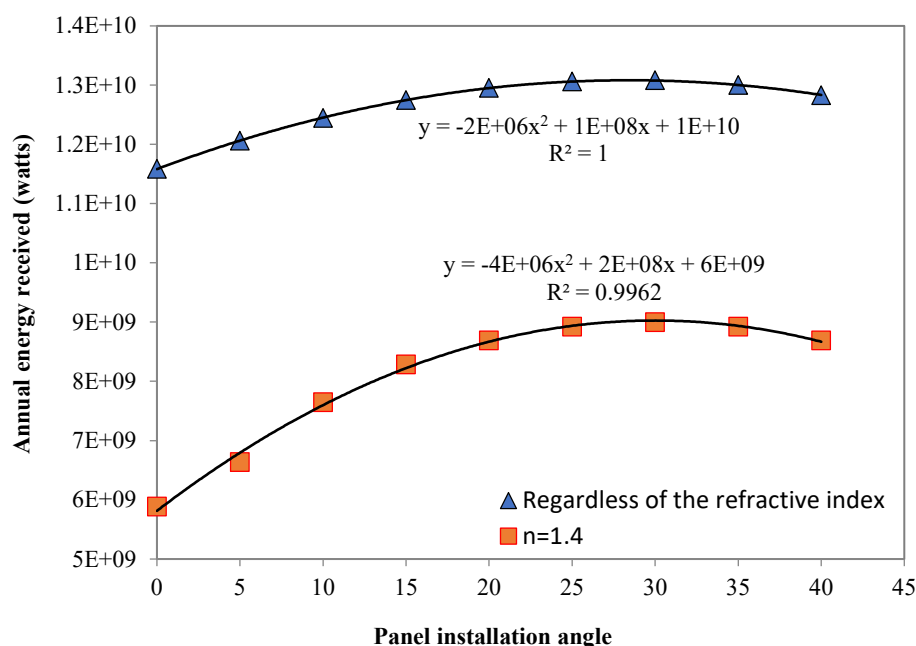


Fig. 2. The effect of refractive index on the optimal angle of the solar panel for a latitude of 30 degrees

According to the results obtained, the optimal angle of the solar panel is about 30 degrees (where the related curve reaches to its maximum value), considering the refractive index equal to 1.4. In contrast, the results show that by ignoring the effect of the refractive index, the optimal angle is 28 degrees (the point of maximum for the upper curve). Another important result obtained from Fig. 2 is that the curve corresponding to the case where the effect of the refractive index is taken into account was shifted significantly downwards. This indicates a significant reduction in the energy received in this case at all angles considered. This significant received energy reduction should be taken into account when designing solar power systems.

4. Conclusion

In this study, the effect of considering the refractive index of the glass coating of solar panels on the amount of energy received and the optimal angle of the panel was investigated. This glass coating is placed on the photovoltaic cells to protect them from environmental conditions. However, if the angle of solar radiation is greater than the angle of the glass coating, the radiation is reflected from the panel surface, reducing the amount of solar energy received. The angle of solar radiation decreases from its maximum value (i.e., 90-degree angle) on the panel surface as the sun rises, until solar noon, and experiences its minimum value at solar noon. As time passes from solar noon to sunset, the angle of incidence increases continuously, and at sunset, the angle of incidence on the panel returns to 90 degrees. The results of this study showed that as the refractive index increases (and consequently the critical angle decreases), the amount of time that solar radiation passes through the glass coating decreases. The greater the increase in the refractive index, the shorter this period and, consequently, the lower the amount of energy received. The results showed that the annual energy input of a panel with a glass coating with a refractive index of 1.6 is about 42.7% lower than the case where the effect of the refractive index is ignored. The results also show that considering the refractive index also affects the optimal angle of the panel. While the optimal angle of the panel, ignoring the phenomenon of solar radiation reflection from the panel surface, is 28 degrees for the city of Zahedan, for a panel with a glass coating with a refractive index of 1.4, the value of this parameter was determined to be about 30 degrees.

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