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Angle optimization of home solar panels for urban energy management

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ABSTRACT

BACKGROUND AND OBJECTIVES: Solar panels are always installed at an angle in which receive the maximum amount of energy. Small and even 1-degree changes in the angle of the installed panel have a significant impact on the annual energy received. The objective of this study was to study the evaluation of change in the sun's radiant energy on the surface perpendicular to the radiation during the day.
METHODS: Calculations of changes in the intensity of radiation on the surface of the panel are generally performed by assuming that the intensity of solar radiation is constant on the surface perpendicular to the radiation during the day (choosing the solar constant) and multiplying it by the cosine of the azimuth angle (which varies during the day). Since the sun's rays travel different lengths in the atmosphere at different times of the day, the intensity of the sun's radiation on the surface perpendicular to the radiation varies throughout the day. In this study, the effect of daily changes in the intensity of solar radiation on the surface perpendicular to the radiation, on the optimal angle of the solar panel has been investigated.
FINDINGS: The results showed that the daily optimal angle difference reported in this study compared to previous studies is more than 5 degrees in some cases. Also, installing the panel under the optimal daily angle (for day number 100) and the correct yearly angle resulted in receiving 128.56 kilowatts per square meter and 2.977 megawatts per square meter more energy, respectively.
CONCLUSION: According to the results of this research, the annual optimal angle for a geographic latitude of 30 degrees, taking into account the changes in solar radiation energy on the surface perpendicular to the radiation, is 26 degrees, which is 4 degrees different from the geographic latitude. Also, the results show that if the panel is installed at an angle of 30 degrees, the energy received annually is 16.122 megawatts per square meter less than if the panel is installed at an angle of 26 degrees.

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INTRODUCTION

The increasing population of cities has caused an increase in environmental pollution (Ehzari *et al.,* 2022; Samimi, 2024; Samimi *et al.,* 2023a) and a significant increase in energy consumption for domestic use (Samimi and Nouri, 2023; Cheraghipoor *et al.,* 2024; Samimi *et al.,* 2023b). Environmental pollution can be solved to some extent by physicochemical (Mohadesi *et al.,* 2024; Samimi and Safari, 2022; Sarmurzina *et al.,* 2023), and biological (Samimi *et al.,* 2021; Samimi and Shahriari-Moghadam, 2023; Samimi and Mansouri, 2024) methods, but the best way is to prevent the factors that cause urban pollution (Sulistyowati *et al.,* 2023; Seethong *et al.,* 2023; Mardianti and Purba, 2023). Air pollution in cities is one of the most important causes of excessive energy consumption (Salvaraji *et al.,* 2023; Ernyasih *et al.,* 2023). Supplying part of the energy needed by cities using renewable energy is one of the solutions for sustainable urban development (Ramli *et al.,* 2022; Bogachov *et al.,* 2022). Solar energy is one of the most important forms of renewable energy available in many areas compared to other types, even wind energy (Abrofarakh and Moghadam, 2024; Samimi and Moghadam, 2024a). Fresh water production using solar still devices (Moghadam and Samimi, 2022) or desalination of reverse osmosis units is one of the applications of using solar energy (Bdour, *et al.,* 2023; Samimi and Moghadam, 2024b). One of the methods of using solar energy is to convert it into electrical energy using the photovoltaic phenomenon (Kabir *et al.,* 2023; Fares *et al.,* 2022). Solar panels are tools that use this mechanism (photovoltaic phenomenon) to convert the radiant sun energy into electrical energy (Abdallat *et al.,* 2024). This technology has developed adequately in recent years; so extensive studies are being done to reduce the cost and increase the conversion efficiency. The efficiency rate of commercial panels available in the market is about 25 percent (%) and the average cost of solar electricity is about 3-6 cents per kilowatt–hour. Typically, photovoltaic panels to receive solar energy are installed on the roofs of houses, where they receive the most solar radiation. The panels must be equipped with a solar tracking system to get the most solar energy possible. Due to the high cost of these systems as well as requiring specialized maintenance, they are often not used for economic reasons. The panels installed permanently should be placed under an optimal angle to receive the maximum radiant energy from the sun throughout the year. So far, many studies have been conducted on optimizing the installation angle of solar panels and almost similar results have been reported (Despotovic and Nedic, 2015; Alqaed *et al.,* 2023; Gupta *et al.,* 2023). The studies show that the latitude of the installation location affects the annual optimal angle. Results of different studies in different places converge on the approximate similarity of the optimal angle and the latitude of the panel installation location. This means that although different studies may have suggested different values for the optimal angle, in most cases, the suggested value was in the latitude range of the place of investigation. In addition to the annual optimum angle, studies have also been conducted on the semi-annual, seasonal, monthly, and daily optimum angle. In some of these studies, results different from previous studies have been presented. For example, Moghadam *et al.* (2015) showed in their study that although in the northern hemisphere, the solar panel should be installed in the east-west direction and towards the south, on some days of the year, the optimal angle is towards the north. However, it is difficult to adjust the panel's angle every day under the optimal angle. Therefore, it is suggested that this work be done monthly, quarterly, or semi-annually. Determining the daily energy intake is the first step in calculating the annual energy intake. For this purpose, the changes in the intensity of the sun's radiation from the beginning to the end of a certain day are calculated. The energy received is calculated by integrating these changes in terms of time during the day. The literature review shows that the changes in the intensity of the sun's radiation in terms of time during the day were calculated in many studies using the product of the solar constant in the cosine of the zenith angle (Njoku *et al.,* 2023; Bailek *et al.,* 2018). In other words, the intensity of the sun's radiation during a certain day is considered constant. This is even though the intensity of the sun's radiation changes during the day (because it travels a different length in the atmosphere) and must be investigated. Small changes in the annual optimal angle will cause significant changes in the received energy throughout the year. Therefore, accurate determination of this angle is of great importance. This study aimed to determine the optimal angle of solar collectors by considering the changes in the intensity of the sun's radiation during the day. The current work has been performed in Zahedan, Iran in 2024.

MATERIALS AND METHODS

The intensity of solar energy radiation on the surface perpendicular to the sun's rays, outside the earth's atmosphere in one day, is constant which is known as the solar constant. This value changes on different days due to the change in the distance between the Earth and the sun, but these changes are less than 2%. However, the intensity of the sun's radiation on a surface perpendicular to the sun's rays on the earth (sea level) is completely variable during the day. A part of the sun's radiant energy is absorbed or scattered by hitting the particles in the atmosphere. According to Fig. 1, the sun's rays travel a much longer path in the atmosphere at sunrise to reach the earth's surface. Meanwhile, at noon, the sun's rays will travel the least possible path in the atmosphere on a given day. Therefore, during the day, the lowest radiation energy on the surface perpendicular to the radiation rays will be at sunrise and sunset, and the highest amount will be at noon.

RESULTS AND DISCUSSION

Intensity of the sun's radiation on a surface perpendicular to the radiation versus the zenith angle

According to Fig. 1, it is clear that the length of the sun's rays in the atmosphere depends on the sun's zenith angle. Table 1 presents the changes in the sun's radiation energy on the surface perpendicular to the radiation on the earth's surface (sea level) in terms of the sun's zenith angle. Fig. 2 shows the results of fitting the values of Table 1 with Eq. 1 (Moghadam *et al.,* 2011).

Table 2 shows the constants of Eq. 1 and the R, coefficient of determination (R^2), and adjusted R-squared (R_{adj}) values. Fig. 3 shows the changes in solar radiation energy on the surface perpendicular to the radiation in several days for a latitude of 30 degrees. As it is clear from Fig. 3, at the beginning and end of the day, the intensity of the sun's radiation is

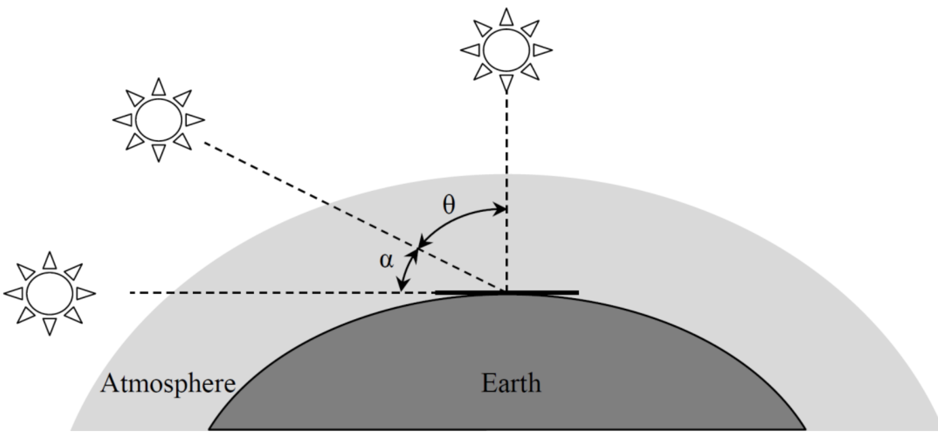
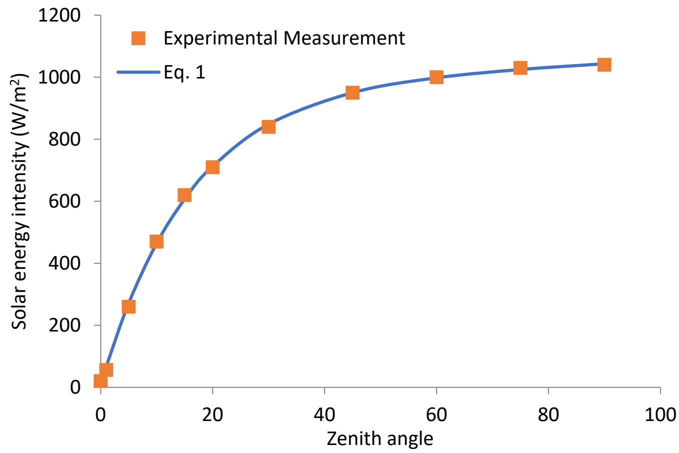


Fig. 1: Changes in the length of the sun's rays in the atmosphere at different times of the day

Table 1: The sun's radiant energy on the surface perpendicular to the radiation on the earth's surface versus the zenith angle

Zenith angle	Solar energy intensity (kW/m^2)
90	0.062
75	0.054
60	0.058
45	0.053
30	0.053
20	0.069
15	0.067
10	0.118
5	0.066
1	0.116
0	0.073



9Fig. 2: Comparison between the experimental values of changes in solar energy intensity at different zenith angles and the values obtained from Eq. 1

Table 2: Parameters of Eq. 1, and acceptability of fitting experimental data

Parameter of Eq. 1	Value
a	968.4
b	0.0008678
c	-961
d	-0.06298
Goodness of fit	Value
SSE	711.4
R-square	0.9995
Adjusted R-square	0.9993
RMSE	10.08

much lower than at other times during the day.

$$I = a \times exp\left(b \times \theta\right) + c \times exp\left(d \times \theta\right) \quad (1)$$

Where I is the intensity of the sun's radiation on the surface perpendicular to the radiation on the earth's surface (sea level) and θ is the sun's zenith angle. The constants of Eq. 1 and the fitting parameters are presented in Table 2.

The influence of variable daily sunlight intensity on the optimal angle

To find the optimal angle of solar panels during the day, the amount of energy received by the panel at different angles is calculated, and then the angle under which the most energy is received is introduced as the optimal angle. The same process is used to determine the optimal monthly, seasonal, semi-annual, and annual angles. The amount of energy received daily by the panel at a certain angle is obtained from the integral result of the energy changes received during the day versus time. In previous studies, the changes in the energy received by the panel at a certain angle have been related only to the changes in the radiation angle on the panel. In this way, the received solar energy is obtained by multiplying the solar constant by the cosine of the radiation angle on the panel. Variations of the radiation angle on a panel installed at an angle β concerning the horizon surface are obtained using Eq. 2 (Moghadam *et al.,* 2011).

$$\text{Cos}\,\theta = \cos(\phi-\beta)*\cos(\delta)*\cos(\omega)+\sin(\delta)*\sin(\phi-\beta) \quad (2)$$

Where θ is the angle of the summit side, ϕ is the latitude, β is the installation angle of the panel relative to the horizon, δ is the deviation angle, and ω is the hour angle. The deviation and hour angles

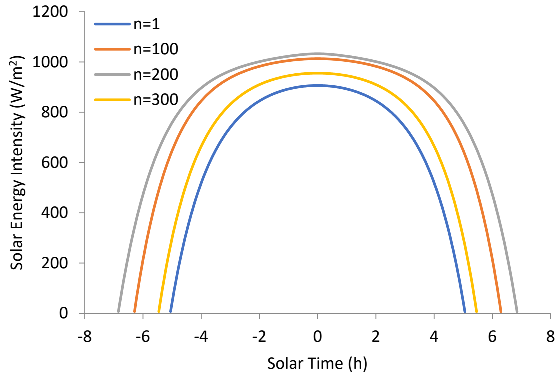


Fig. 3: Solar radiant energy on the surface perpendicular to the radiation versus time on several different days for a latitude of 30 degrees

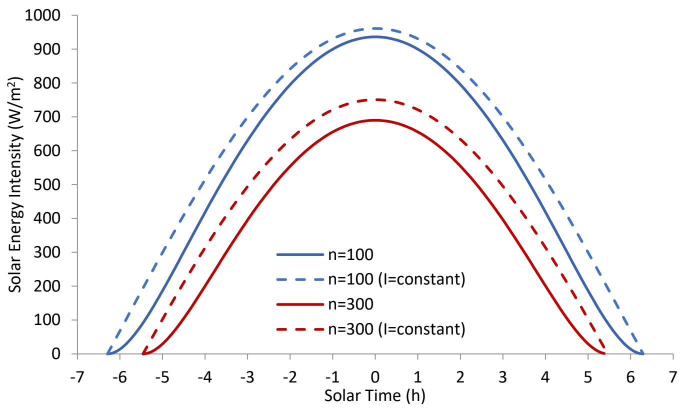


Fig. 4: The sun's radiant energy on the surface of the horizon considering variable daily radiation intensity (solid lines) compared to constant daily radiation intensity (dashed line)

are calculated using Eqs. 3 and 4, respectively (Moghadam *et al.,* 2011).

$\delta = 23.45\sin[360(284 +) / 365]$ (3)

$\omega = \pm (360/24)t$(4)

While the radiation angle varies during the day, the intensity of the sun's radiation (as shown in Fig. 3) also varies during the day. Fig. 4 shows the changes in the sun's radiant energy on the horizontal surface, considering the variable daily radiation intensity compared to the fixed daily radiation intensity, for two different days. As it is clear from the figure, taking into account the changes in radiation intensity during the day, the amount of energy received by the panel at the beginning and end of the day is less compared to the case of constant radiation intensity during the day. As a result, these moments of the day are less important in finding the optimal angle. Table 3 shows the amount of energy received by the panel for a specific day of the year at different installation angles in two modes of fixed and variable daily radiant energy. According to the values in Table 3, it can be seen that considering the change of radiant energy during the day, the optimal angle is -4, while in the case of constant radiant energy, the optimal angle is -9. The results show that if the correct optimal angle of -4 degrees is used, 128.56 kilowatts per square meter (kW/m^2) more energy is received during the day.

Table 4 shows the amount of energy received annually by the panel in two modes fixed and variable daily radiant energy. According to the values in Table 4, it can be seen that taking into account the variation of radiant energy during the day, the annual optimum angle for the panel installed at 30 degrees latitude is 26 degrees, while in the case of non-constant radiant energy, the optimal annual angle is 28 degrees. The

Table 3: Energy received by the panel at different angles for day number 100

β		-1	-2	-3	-4	-5	-6	-7	-8	-9	-10
Received energy (×10⁶ W)	Variable daily radiation	29.38422	29.40329	29.41339	29.41454	29.40673	29.38996	29.36424	29.32958	29.28598	29.23346
	Constant daily radiation	42.67506	42.77057	42.85305	42.92248	42.97884	43.0221	43.05226	43.06931	43.07323	43.06404

Table 4: Energy received by the panel at different angles for the whole year

β		30	29	28	27	26	25
Received energy ($\times 10^9$ W)	Variable daily radiation	8.523858	8.531706	8.537011	8.539772	8.539988	8.537658
	Constant daily radiation	13.08101	13.08516	13.0855	13.08202	13.07475	13.06367

results show that if the optimal angle of 26 degrees is used, 2.977 megawatts per square meter (MW/m^2) more energy will be received throughout the year.

CONCLUSION

Accurately determining the optimal angle of solar panels is the subject of many studies. In this study, the effect of daily changes in the intensity of solar radiation on the surface perpendicular to the radiation, on the optimal angle of the solar panel has been investigated. For this purpose, firstly, the experimental data of the changes in the intensity of the sun's radiation on the surface perpendicular to the rays of radiation on the earth (sea level) in terms of the azimuth angle were well fitted by a mathematical relationship. In this regard, the azimuth angle was the independent variable and the radiation intensity on the perpendicular surface was the dependent variable. Then, using this relationship, the changes in the sun's daily radiant energy were obtained on a panel installed at a certain angle. The total amount of energy received daily was calculated by integrating the radiant energy changes versus time during the day. The optimal daily angle was obtained from the comparison of the total daily received energy by the panel at different angles. The results showed that since at the beginning and end of the day, the intensity of the sun's radiant energy is lower than at other times of the day, these moments have less effect on the optimal angle. Also, the optimal angle obtained by taking into account the changes of the sun's radiant energy on the vertical surface during the day compared to keeping this value constant was more than 5 degrees in some cases. The optimal angle obtained from this research for day No. 100 at 30 degrees latitude was about -4 degrees, while previous studies wrongly suggested the optimal angle to be -9 degrees. The results showed that using the correct optimal angle of 128.56 kW/m^2 more energy to be received. Also, the annual optimal angle obtained from this research for the latitude of 30 degrees is 26 degrees, if the daily radiation intensity is considered constant on the surface perpendicular to the radiation, the optimal angle is mistakenly obtained as 28 degrees. The results showed that if the optimal angle of 26 degrees is used, 2.977 MW/m^2 more energy will be received by the solar panel per year.

AUTHOR CONTRIBUTIONS

M. Moghadam conducted the literature review, analysis and wrote the original draft. J. Nouri edited the manuscript. The corresponding author, M. Samimi, managed the project, performed the validation tests, and reviewed the manuscript.

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CONFLICT OF INTEREST

The authors declare no potential conflict of interest regarding the publication of this work. In addition, the ethical issues including plagiarism, informed consent, misconduct, data fabrication and, or falsification, double publication and, or submission, and redundancy have been completely witnessed by the authors.

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ABBREVIATION

%	Percent
α	Altitude (elevation) angle
β	Tilt angle of solar panel
δ	Declination angle
ϑ	Zenith angle
φ	Latitude
ω	Hour angle
h	Hour
I	Solar energy intensity perpendicular to sun's rays
kW/m^2	Kilowatt per square meter
MW/m^2	Megawatt per square meter
n	Day number of the year
RMSE	Root Mean Squared Error
R^2	Coefficient of determination
R_{adj}	Adjusted R-squared
SSE	Sum of Squares of Errors
t	Time distance to solar noon (in h)

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