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Optimal Tilt Angle of Photovoltaic Panels: A Case Study in the City of Rio de Janeiro

Alexandro Gomes (Corresponding author)

Postgraduate Program in Environmental Science and Technology

State University of Rio de Janeiro, Rio de Janeiro - RJ, Postal Code 23550-260, Brazil

E-mail: ag.fisica@hotmail.com

Maria Francisca do Nascimento Oliveira

Dept. Naval and Fishery, Postgraduate Program in Environmental Science and Technology

State University of Rio de Janeiro, Rio de Janeiro - RJ, Postal Code 23550-260, Brazil

E-mail: maria.francisca.oliveira@uerj.br

Marcelo Musci

Dept. Naval and Fishery, Postgraduate Program in Environmental Science and Technology

State University of Rio de Janeiro, Rio de Janeiro - RJ, Postal Code 23550-260, Brazil

E-mail: marcelo.musci@uerj.br

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Abstract

The optimal tilt angle of photovoltaic panels plays a crucial role in energy generation. However, the accumulation of dust on solar panels can significantly impact their performance and efficiency, leading to a reduction in energy production. Therefore, it is crucial to consider the effect of dust deposition on the optimal tilt angle of solar panels. Regarding panel installation, it is often observed that panels are positioned to follow the natural slope of the roofs, disregarding the optimal angle for maximizing solar radiation utilization. Numerous studies have investigated the impact of dust accumulation on the performance of photovoltaic panels and the optimal inclination angle for different regions and seasons. This study aims to analyze the optimal tilt angle of photovoltaic panels for maximum energy generation, considering undesired effects such as dust, dirt, water droplets, and other atmospheric factors. The authors have proposed an equation to calculate the optimal tilt angle of photovoltaic panels based on a case study conducted in different Rio de Janeiro City regions. The methodology employed in this study involves estimating solar incidence on the surface of the photovoltaic panels using the authors' proposed equation, which considers the latitude and longitude of the panel installation location. The results obtained were validated using software that generates hourly solar radiation data. The results indicate that an inclination of 30 degrees, calculated using the proposed equation, resulted in a 2% deviation from the optimal theoretical angle.

Keywords: Tilt of photovoltaic panels, Solar energy, Optimal tilt angle

1. Introduction

Photovoltaic solar panels, or photovoltaic panels, have been a crucial option to provide financial savings on the final consumer's electricity bill and decrease environmental impact. For this purpose, the angle of inclination of the photovoltaic panels is crucial for the best absorption of solar radiation (Mukisa & Zamora, 2021; Yadav & Cahndel, 2013).

Accommodating photovoltaic panels in shaded areas is not practical since the goal is to benefit as much as possible from solar incidence. Additionally, the modules should be installed as close as possible to the final consumption site, considering the economy with energy loss in transmission and material costs (Ramos & Lemos, 2020). Photovoltaic panels can be installed on poles, parking lot roofs, and not exclusively on residential and commercial roofs. The essential aspect is that they are higher areas and without shadow incidence.

Three basic principles attest to the effectiveness of installing a solar energy absorption system: orientation, area, and inclination. If these three factors are ignored, the system will not operate at maximum efficiency, and solar absorption will be compromised (Zhao et al., 2020).

Moreover, regular cleaning of solar panels is essential to maintain their performance and efficiency. Several studies have shown that cleaning solar panels can increase their energy output by up to 20%. Therefore, solar panels' optimal inclination angle should also consider the ease of cleaning and maintenance (Abdeen et al., 2017; Shenouda et al., 2022).

The tilt angle of photovoltaic panels plays a crucial role in capturing solar radiation that reaches their surface. The performance and efficiency of photovoltaic systems are significantly influenced by the tilt angle, which needs to be optimized while considering environmental factors such as dust and dirt accumulation. In recent years, many theoretical and experimental studies have been conducted to maximize the energy benefits of photovoltaic systems, Sado et al. (2021) conducted an experimental study where they mathematically calculated daily, monthly, and seasonal tilt angles and measured the incident radiation on the panels' surface, Li et al. (2017) developed a simulation model to determine the optimal tilt angle for photovoltaic panels in various climatic regions of China, Melhem & Shake (2023) utilized a mathematical model based on latitude and longitude to calculate the optimal tilt angle and compared the results with an online software that provides international solar maps, Liu et al. (2018) applied a solar radiation model to optimize the tilt angle of rooftop solar panels, taking into account factors such as latitude, solar radiation, and coverage areas, Hachicha et al. (2019) conducted studies on the accumulation of dust and dirt on photovoltaic panels in the United Arab Emirates due to their tilt angle, Simsek et al. (2021) investigated the impact of droplets on the performance of solar photovoltaic cells caused by dropwise condensation or rain falling on the panel's surface.

In conclusion, the optimal inclination angle for solar panels depends on various factors, such as the amount of dust deposition, region, and season. It is essential to consider the impact of dust accumulation on solar panels' performance and the ease of cleaning when determining the optimal inclination angle for a photovoltaic system.

1.1 Orientation of Photovoltaic Panels

It is relevant to determine the correct orientation of photovoltaic solar panels to optimize the incident capture of solar energy, providing greater exposure during the day of solar incidence. This way, photovoltaic panels can capture the maximum possible amount of incident energy (Nfaoui & El-Hami, 2018).

In the southern hemisphere, the most advantageous orientation for the set of photovoltaic panels is the geographic north, which is not the magnetic north pointed by the compass, since there is an angular difference between 20° and 30° between the geographic and magnetic north. Even though sets oriented to the west or east are more effective at some point in the year, they provide much smaller gains than those presented to the north because they lose radiation in the afternoon when directed to the east. When directed to the west, they lose radiation during the morning period (Dassi et al., 2015).

1.2 Area Used by Photovoltaic Panels

Equally important is to determine, through calculations, the area where the photovoltaic panels will be allocated, as the power generation capacity of the set is linked to the longest possible time of direct sunlight exposure (Farahmand et al., 2021). It is necessary to know the annual demand to determine the number of photovoltaic panels and make a monthly average of the building, considering if it already has occupants or employees. For projects in the preparation phase, assuming consumption based on the electrical installation project is acceptable, which will determine the power that will be established and the allocated area (Cunha, 2018).

1.3 Local Atmospheric Conditions

Local weather conditions also influence the efficiency of photovoltaic panels. Cloudy mornings, afternoons, and periods of fog or dust decrease the incidence of radiation, resulting in a loss of energy production capacity. Therefore, it is essential to note the best position of the panels about the seasons, minimizing these losses by considering the best position for the whole year (Odeh, 2018).

Thus, besides noting the north position, it is essential to consider the ideal slope during the calculations of the set, as a steeper slope will have better performance in winter, and a shallower slope will have better performance in summer. Minor adjustments can be made towards the East and West (Pandey & Channi, 2020).

Usually, roofs (roofs and slabs) remain the most suitable locations for solar panels. Because they fit well and do not occupy new areas, besides harmonizing the installed panels with the location's masonry, their inclination can be easily corrected through metallic structures (Pandey & Channi, 2020).

1.4 Unwanted effects

The reflection and absorption of solar radiation are subject to elements suspended in the atmosphere, such as pollution, dust, dirt, the ozone layer, and more. Consequently, the thicker the elements in contact with the solar panels, the greater the energy loss (Carneiro & Paixão, 2019). Local weather conditions also influence the effectiveness of photovoltaic panels. Very cloudy mornings or evenings and seasons with heavy fog, water droplets, and wind decrease the incidence of radiation, resulting in a loss of energy production capacity.

A study conducted in Saudi Arabia concluded that the optimal inclination angle for solar panels should be around 25-30° in dusty áreas (Hassan, 2022). Hachicha et al. (2019) mentioned that the performance of photovoltaic panels systems is generally affected by real weather conditions, and dust accumulation is one of the main concerns that may cause a significant deterioration of photovoltaic panels' efficiency. In the work of Simsek, Williams & Pilon (2021), the authors concluded that water droplets on the cover of solar cells could negatively affect the cell power generation and efficiency due to optical effects. Here, semi-transparent glass covers were prepared without or with surface treatments and covered with acrylic droplets with contact angles ranging between 25° and 77°. Negash & Tadiwose (2015) investigated the effect of tilt angle on the accumulation of dust on photovoltaic panels and energy production in the city of Bahir Dar, concluding that the flatter the solar module is placed, the more energy will be lost.

All these factors constitute the so-called "unwanted effects" in installing photovoltaic panels.

2. Tilt Angle Determination

Considering the longitude and latitude coordinates, it is established that the hour angle (W) is an angular variant whose value is zero when the local solar time is noon. According to Abood (2015), considering that the planet rotates 15° every hour, which is equivalent to 360°/24, then the hour angle will be:

$$W = (12 - T)\,.\,15° \quad (1)$$

Where:

W = hour angle (result in degrees)

T = local solar time (T varies between 0 and 24h).

According to Abood (2015), it is necessary to calculate the solar inclination to establish the angle the photovoltaic solar panel should have throughout the year, considering that the imaginary inclination of the Earth's axis interferes with the zenith angle at various latitudes.

Considering the Equinox and Solstice days, which mark the beginning of the seasons in both hemispheres, and also the true solar noon, which is established at the exact moment of the peak of the solar rays on the observer's meridian, there is a seasonal change in the planet's axis inclination of 23°27' (about 23.45°) concerning the normal to the plane of the ecliptic. The solar slope, observed by an observer at the Earth's equator on a particular day of the year (J), is given by equation (2):

$$\delta = 23{,}45 \,.\, \text{sen}\left[360 \,.\, \frac{(J-80)}{365}\right] \tag{2}$$

Where:

δ = solar slope value, in degrees.

J = indicates the order number of days, considering J = 1 in the first of January, taking February always as 28 days, thus resulting in 365 days in the year.

As the planet performs the translational movement around the Sun, the inclination of the imaginary terrestrial axis toward the line connecting the Sun to the Earth is modified. This results in the incidence of solar radiation in any region at angles that change considerably throughout the year. Equation (2) precisely demonstrates the angle variation throughout the year, assuming the solar convergence at the terrestrial equator, at noon, and throughout the year as the J variable changes.

The solar convergence angle on the photovoltaic system changes throughout the year, according to the solar altitude, requiring a specific inclination for better use of solar rays. However, most solar panels installed today use the slope angle of the roofs due to lack of knowledge, installer convenience, or material economy, considering the cost of more hardware in panel assembly. In addition to better utilizing the energy potential of the panels, the correct positioning of the system can reduce undesired effects and wind (Akhlaghi et al., 2017).

According to Medeiros & Martins (2020), the approximate ideal inclination for solar panel installation can be calculated using equation (3):

$$I = \varphi + \frac{\varphi}{3} \tag{3}$$

Where:

I = Inclination of the solar panel, in degrees;

φ = latitude, in degrees.

The equation generates an average inclination that varies between 25° and 30°. Wu (2020) emphasizes that installing panels with an inclination lower than 15° is not advisable. As cited by (Barbosa et al., 2018), it is crucial to avoid the accumulation of dirt, which can include animal feces, water droplets, remains of living beings, dust, microscopic organisms, and other types of materials that may hinder the incidence of solar energy on photovoltaic cells.

The work of Medeiros & Martins (2020) does not consider the existence of undesired effects as a variable in equation (3). Considering that the photovoltaic panels will be installed on the roofs of residential buildings and using only the latitude and longitude of the installation location, the authors propose equation (4) to calculate the optimal tilt angle of the photovoltaic panels.

$$|M| = \frac{\left(\varphi + \frac{\varphi}{3}\right) + \left(L - \frac{L}{3}\right)}{2} \quad (4)$$

Where:

M = annual angular average, in degrees;

φ = latitude, in degrees;

L = longitude, in degrees.

The proposed equation takes into account the ideal inclination in order to mitigate the undesirable effects described earlier.

This equation is being proposed because, as mentioned by Morais (2009), longitude should be considered when calculating the inclination of photovoltaic panels to adjust the optimal inclination angle, thus avoiding the undesired effects but maintaining the best possible solar incidence for the installation location. Considering the calculations presented in Medeiros & Martins (2020), longitude was included as another variable in calculating the inclination for installing fixed photovoltaic panels. The use of longitude followed the same line of reasoning as latitude, but in a symmetric way.

3. Methodology

The methodology employed in this study involves estimating solar incidence on the surface of the photovoltaic panels using equation (4), which is based on the latitude and longitude of the panel installation location. These estimates are then compared with the results obtained from software that generates hourly data on solar radiation.

The analysis will consider the assumption that all houses in the selected locations have roofs with a 30% slope or a 17° tilt angle, which aligns with the average slope of Brazilian roofs as described by Nascimento et al. (2016). Consequently, for the purpose of comparison, it is assumed that the photovoltaic panels installed in the three locations under analysis are oriented towards true North and tilted at 17°, mirroring the roof slope.

To validate Equation (4), three locations in the city of Rio de Janeiro were chosen as case studies, ensuring a reasonable distance between them. The selected districts are as follows: Bangu, known for having the highest local temperature, with geographical coordinates of latitude -22.874371° and longitude -43.466475°; Santa Cruz, located at the furthest extreme from the city of Rio de Janeiro, with latitude -22.920262° and longitude -43.674308°; and Urca, situated at the opposite extreme, with latitude -22.954517° and longitude -43.166838°. The corresponding values are summarized in Table 1.

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Table 1. Earth latitude and longitude values for three locals in the city of Rio de Janeiro

LOCAL	LATITUDE	LONGITUDE
Bangu	– 22.874371 °	– 43.466475 °
Santa Cruz	– 22.920262 °	– 43.674308 °
Urca	– 22.954517 °	– 43.166838 °

Source: Google Maps (n.d.). [Rio de Janeiro].

4. Results Validation

As mentioned, the most appropriate use of solar radiation throughout the year occurs when the solar panels are oriented towards the geographic North and have an angle determined by the mathematical relationship between latitude and local longitude, as described by equation (4). Solar radiation is calculated to measure the total amount of solar radiation that falls on the photovoltaic solar panel, allowing us to estimate the energy produced. Solar radiation data are presented by monthly average values of daily accumulated energy (Hoyer-Klick et al., 2011).

Thus, the methodology used to validate the results obtained in the case study will consist of comparing the results obtained with the calculation of equation (4) with the values of solar incidence on the surface of the photovoltaic panels obtained using the Radiasol2 software (Krenzinger & Bugs, 2010). This software allows the user to generate spreadsheets of meteorological data that can be used in simulation and sizing programs while also allowing for immediate observation of the effects caused by the orientation of solar radiation receiver surfaces. It should be emphasized that calculating solar radiation intensity on inclined surfaces is a laborious procedure due to the high number of arithmetic operations involved. In addition to trigonometric calculations, temporal and spatial distribution models of solar radiation are required. The Radiasol2 software internally utilizes mathematical models available in the literature.

5. Results and Discussions

Applying equation (4), for each of the selected locals within the city of Rio de Janeiro, we have the results listed in Table 2.

Table 2. Values, of the annual angular average, obtained with equation (4)

Local	Annual angular average
Bangu	29.738405 °
Santa Cruz	29.838277 °
Urca	29.691913 °

In the subsequent sections, the monthly average data of solar irradiation will be shown in different locations in the Rio de Janeiro City obtained by the Radiasol2 software.

5.1 Bangu

Table 3 shows the monthly average solar irradiation data for the Bangu district. The analysis was conducted for four angles, one horizontal plane (0 °), and three inclined planes. Of the inclined planes, the first corresponds to the average slope value of Brazilian roofs (17 °), the second corresponds to the value of 30 °, calculated by equation (4), and the last one represents a much steeper angle in order to observe the effect of increasing the angle to 45 °.

Table 3. Average daily solar irradiation – Bangu

Average daily solar irradiation (kWh/m^2.day)													
Tilt angle	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sept**	**Oct**	**Nov**	**Dec**	**Average**
0 °	5.33	5.32	5.00	4.30	3.83	3.30	3.38	4.15	4.46	4.85	5.16	5.65	**4.56**
17 °	5.35	5.31	4.97	4.25	3.70	3.18	3.27	4.06	4.44	4.84	5.16	5.68	**4.52**
30 °	5.06	5.11	4.90	4.36	4.00	3.47	3.53	4.29	4.43	4.67	4.91	5.35	**4.51**
45 °	4.61	4.51	4.13	3.44	2.86	2.46	2.56	3.20	3.66	4.11	4.43	4.90	**3.74**

Source: Data obtained in Radiasol2 software

By analyzing the data presented in Table 4, it is possible to observe that Santa Cruz district's highest average solar irradiation occurred at the 0 °angle and was 4.56 kWh/m2. The average value was close for the 17 °and 30 °angles, at 4.51 kWh/m2 and 4.51 kWh/m2, respectively. The lowest value observed was for the 45 °angle, which was 3.74 kWh/m.

When comparing the lowest and highest values, it is observed that there was a reduction of approximately 18% to the 0 °angle. The results support that an angle too steep to the solar rays does not absorb solar irradiation with the same efficiency as smaller angles.

As in the case of the Bangu district, the most favorable angle for harnessing solar energy in Santa Cruz district is 17 °, which presented an average solar irradiation similar to that of the 30 °angle.

However, according to explanations provided by Hassan (2022), Hachicha et al. (2019), and Simsek et al. (2021), installing solar panels with the same slope as the roof can compromise the long-term effectiveness of the system due to the accumulation of dust, dirt, and rain. These factors collectively contribute to the "undesirable effects" associated with photovoltaic panel installation.

5.2 Santa Cruz

Table 4 shows the average monthly data observed in recent years, considering a horizontal plane (0 °) and three inclined planes.

Table 4. Average daily solar irradiation – Santa Cruz

Average daily solar irradiation (kWh/m^2.day)													
Tilt angle	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sept**	**Oct**	**Nov**	**Dec**	**Average**
0 °	5,12	5,05	4,67	3,94	3,36	2,89	2,98	3,72	4,16	4,59	4,92	5,44	**4,23**
17 °	5,35	5,32	4,97	4,25	3,70	3,18	3,27	4,06	4,44	4,85	5,16	5,69	**4,52**
30 °	5,35	5,31	4,94	4,18	3,61	3,09	3,46	3,97	4,40	4,87	5,16	5,70	**4,49**
45 °	4,61	4,51	4,12	3,44	2,86	2,46	2,56	3,20	3,66	4,11	4,43	4,89	**3,74**

Source: Data obtained in Radiasol2 software

Through the analysis of the data, it was possible to observe that the highest average solar irradiation occurred at an angle of 17 ° and was 4.52 kWh/m2. For the 0 ° angle, the observed value was 4.23 kWh/m2; for the 30 ° angle, the value was 4.49 kWh/m2. The lowest value observed was for the 45 ° angle, which was 3.74 kWh/m2.

Comparing the lowest observed value of solar irradiation with the highest value, a reduction of 17.26% to the 17 ° angle (which presented the highest observed irradiation value). Once again, it is clear that the 45 ° angle does not absorb solar irradiation with the same efficiency as smaller angles.

For Santa Cruz district, the 17 ° angle (the same as the inclination of the roofs) presents the highest annual average irradiation of kWh/m2, demonstrating that a panel installed directly on the roof and taking advantage of its inclination would be the most advisable for better use of solar energy. However, comparing the irradiation value for the 17 ° angle with that for the 30 ° angle, it is noticed that the difference is minimal (only 0.03 kWh/m2). Again, the issue involves a solar panel with the same inclination as the roof favors the accumulation of dust, dirt, and raindrops, compromising the system's effectiveness over time. Thus, the angle obtained by equation (4) (more acute to the roof's inclination) would be more favorable to avoid the accumulation of dust, dirt, and raindrops and would have practically the same efficiency for a similar angle to the roof's inclination.

5.3 Urca

Table 5 shows the average monthly data observed in recent years, considering a horizontal plane (0 °) and three inclined planes.

Tabela 5. Average daily solar irradiation – Urca

Average daily solar irradiation (kWh/m^2.day)													
Tilt angle	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sept**	**Oct**	**Nov**	**Dec**	**Average**
0 °	5.33	5.32	5.00	4.3	3.64	3.30	3.38	4.00	4.27	4.56	5.16	5.64	**4.49**
17 °	5.35	5.31	4.97	4.25	3.7	3.18	3.27	4.06	4.44	4.85	5.16	5.68	**4.51**
30 °	5.09	5.22	5.00	4.32	3.43	3.46	3.11	3.92	4.32	4.77	4.9	5.41	**4.41**
45 °	4.61	4.5	4.13	3.44	2.86	2.46	2.55	3.2	3.66	4.11	4.43	4.89	**3.74**

Source: Data obtained in Radiasol2 software

Through data analysis, it is possible to observe that the highest average solar irradiation occurred at an angle of 17 °and was 4.51 kWh/m2. For an angle of 0 °, the observed value was 4.49 kWh/m2, and for an angle of 30 °, the value was 4.41 kWh/m2. The lowest value observed was at an angle of 45 °, which was 3.74 kWh/m2.

Comparing the lowest observed value of solar irradiation with the highest value, a reduction of approximately 17% to the angle with the highest observed solar irradiation, which was 17 °. Once again, like observed to Santa Cruz district, it is observed that the angle of 45 °does not absorb solar irradiation with the same efficiency as smaller angles.

For Urca district, the angle of 17 °, the same as the roof inclination, presents the highest average annual irradiation of 4.51 kWh/m2, demonstrating that a photovoltaic panel installed directly on the roof would be the most advisable for a better use of solar energy. However, comparing the irradiation value for the angle of 17 °with that for the angle of 30 °, it is noticed that the difference is only 0.1 kWh/m2, corresponding to a reduction of about 2% of the irradiation from the angle of 30 °to the angle of 17 °. Taking into account again the issue that a solar panel with the same inclination as the roof favors the accumulation of dust, dirt, and raindrops, compromising the efficiency of the system over time, the angle obtained by equation (4) (30 °), although reducing efficiency by 2% would be more favorable to avoid the weather conditions that also compromise the efficiency of a solar panel.

6. Final Considerations

In order to analyze the solar energy generated by photovoltaic systems installed in the city of Rio de Janeiro. A case study was conducted in three locations within the city, considering the physical concepts involved in solar energy production and positioning methods. A new calculation formula was proposed to determine the optimal panel tilt angle, taking into account the mitigating effects of unwanted factors. The results were tested and validated using the Radiasol2 software, revealing the significant importance of the solar panel angle in maximizing system potential. Unwanted factors, including dust, dirt, water droplets, and atmospheric conditions, pose challenges to rooftop photovoltaic panel systems. The study considered the installation of photovoltaic panels with a tilt angle of 17 °, which promotes the accumulation of undesirable elements, compromising long-term system effectiveness. However, the proposed equation yielded an angle of 30 °, which, despite a 2% reduction in efficiency, offers better protection against these undesired factors. Further research is needed to investigate the combined effect of these factors throughout the year and to develop appropriate cleaning technologies considering the local climatic conditions.

This study led to the development of a computer program called "InclinaSol," registered under number 512022001558-7 on June 28, 2022, by the National Institute of Industrial Property (INPI). The program was developed for mobile devices, and its function is to enable the calculation of the solar panel's inclination angle using equation (4). When using the program, it is only necessary to add the latitude and longitude of the location where the solar panel will be installed, returning the best inclination angle. The program was developed in JavaScript for the Android operating system.

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