INCLINASOL: AN APPLICATION FOR CALCULATING THE OPTIMAL ANGLE OF SOLAR PANELS

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ABSTRACT: Solar energy is one of the promising renewable energy sources that has the potential to meet future energy demand worldwide. This article analyzes the different parameters that influence the determination of the optimal tilt angle for maximum solar energy collection. It proposes a new equation to calculate the optimal tilt angle based on the latitude and longitude values of the solar panel installation site. A computer program, InclinaSol, was implemented taking into consideration undesired effects such as dust, dirt, and other atmospheric factors that can affect the solar panel's operating efficiency. Case studies were conducted for the districts of Guaratiba, Deodoro, and Copacabana, as they are located in different regions of Rio de Janeiro City. The choice of these locations was based on their geographical coordinates and territorial distance. The investigation is carried out considering installation angles of 0°, 17°, 30°, and 45°. Solar incidences on the surface of the solar panels were estimated using data calculated by the RadiaSol application, developed by the Solar Energy Laboratory of the Federal University of Rio Grande do Sul. The results obtained from the developed application showed that, for the city of Rio de Janeiro, installing a solar panel with the same average roof tilt angle of residential buildings (17°) is technically feasible. However, when considering the undesired effects, the tilt angle calculated by the application (30°) is more advantageous and results in solar irradiation values with a difference of at most 3.9% compared to the 17° tilt angle.

KEYWORDS: Solar panels. Renewable energy. Tilt of solar panels. Solar energy.

INTRODUCTION

Solar panels have been a fundamental option for providing financial savings on the final consumer's electricity bill, as well as for reducing environmental impact. For this purpose, the orientation of solar panels is of crucial importance for better absorption of solar radiation (Montalvão, 2009).

Placing solar panels in shaded spaces is not practical, as the goal is to benefit from maximum solar incidence. It's also important to install the modules as close as possible to the final consumption location to save on energy loss during transmission and material expenses (da Silva Lemos; Ramos, 2020). The panels can be installed on poles, as shown in Figure 1, on parking lot roofs, among other locations, not exclusively on residential or commercial roofs. The key is to have them in higher areas without shadow incidence.

Three basic principles confirm the effectiveness of installing a solar energy absorption system, namely: orientation, area, and inclination. If these three factors are ignored, the system won't operate at maximum efficiency because solar absorption and the appropriate sharing of energy will be affected (Torres, 2012).

Determining the right orientation is crucial to optimize the system so that the panels remain exposed to solar incidence for the maximum possible time. This way, they'll be able to capture the greatest amount of solar energy (Scherer, 2015).

In the southern hemisphere, the most advantageous orientation for the set of solar panels is geographical north, which differs from the magnetic north indicated by a compass by an angular difference ranging between 20° and 30°. Although systems oriented to the west or east are effective at certain times of the year, they provide much lower gains compared to those oriented to the north over the entire year. East-oriented systems lose irradiation in the afternoon, while west-oriented systems lose irradiation in the morning (Dassi, 2015).

Local weather conditions also influence the effectiveness of solar panels. Cloudy mornings and/or evenings, along with seasons of heavy fog or dust, reduce radiation incidence, resulting in an energy production loss. Therefore, taking into account the best position of the panels concerning the seasons helps minimize these losses, considering the best position for the whole year (Maciel, 2006).

Therefore, besides considering the north orientation, it's essential to take into account the ideal slope when calculating the solar panel array since a steeper incline will have better performance in winter, while a gentler slope will yield better results in summer. If needed, slight adjustments can be made towards east or west (Madeira, 2008).

Generally, roofs of houses (roofs and slabs) remain the most conducive locations for solar panels. This is because they fit well without occupying additional space, harmonize with the local masonry, and can easily have their inclination adjusted using metal structures (Maciel, 2006).

Figure 1 – Poles with solar panels on the Metropolitan Arc of the State of Rio de Janeiro

Source: Lins, 2016.

Also, the angle of inclination used for installation needs to be optimized taking into account 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 solar panel-based systems. Sado, A., Hassan, and Sado, S. (2021) conducted an experimental study where they mathematically calculated the daily, monthly, and seasonal inclination angles and measured the incident radiation on the panel's surface. Li et al. (2017) developed a simulation model to determine the optimal inclination angle for solar panels in different climatic regions of China. Melhem and Shake (2023) utilized a mathematical model based on latitude and longitude to calculate the optimum inclination angle and compared the results with an online software providing international solar maps. Liu et al. (2018) applied a solar radiation model to optimize the inclination angle of rooftop solar panels, considering factors such as latitude, solar radiation, and roof area. Hachicha, Al-Sawafta, and Said (2019) conducted studies on the accumulation of dust on solar panels in the United Arab Emirates due to their inclination angle. Simsek, Willians, and Pilon (2021) investigated the impact of droplets on the performance of photovoltaic cells caused by droplet condensation or rain that falls on the panel surface.

Therefore, the optimal inclination angle for the installation of solar panels depends not only on the panel's location, latitude, and longitude but also on various environmental factors such as dust and dirt accumulation, which should be considered during their installation.

ANGULAR DEMAND DETERMINATION

Taking into account the longitude and latitude coordinates, it is established that the solar hour angle (W) is an angular variant that is null when the local solar time is at noon.

According to Campos (2013), considering that the Earth rotates 15° every hour, which is equivalent to 360°/24, then the solar hour angle will be:

$$W = (12 - T) \,.\, 15° \qquad (1)$$

Where:

W = solar hour angle (result in degrees)

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

According to Campos (2013), it is necessary to calculate the solar inclination to establish the angle that the solar panel should have throughout the year, considering that the imaginary tilt of the Earth's axis affects the zenith angle (θZ) at different latitudes. Taking into account the Equinox and Solstice days, which mark the beginnings of the seasons in both hemispheres, and the true solar noon, which occurs at the exact moment of the sun's rays at the observer's meridian, and that there is a seasonal change in the planet's axis tilt of 23° 27' (about 23.45°) in relation to the normal to the plane of the ecliptic, the solar slope observed by an observer on Earth's equator on a specific day of the year (J) is given by the following equation:

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

Where:

δ = value of solar inclination, in degrees.

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

As the planet performs its orbital movement around the sun, the tilt of the Earth's imaginary axis in the direction of the line connecting the Sun to Earth changes. This results in solar radiation incidence at any region, at angles that vary considerably throughout the year. Equation 2 precisely demonstrates the variation of the angle over the year, assuming the standard solar convergence at the terrestrial equator, at noon, and over the year as the variable J changes.

According to Varejão-Silva (2006), the solar convergence angle on the solar panel system changes throughout the year, according to the solar altitude, requiring a specific inclination for optimal use of sunlight. However, most solar panels installed today use the roof slope angle due to a lack of knowledge, installer convenience, or material savings, considering the expense of additional hardware for panel assembly. In addition to better utilizing the panels' energy potential, the proper positioning of the system can reduce undesired effects and wind.

This study proposes establishing the best average annual angle, considering the solar panels are fixed in the installation site, and it is not advisable to install panels at an angle lower than 15° to prevent dirt accumulation. This can be seen in Equation 4, a variation of the equation used in (Medeiros & Martins, 2020).

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

Where:

M = average annual angle

ϕ = latitude

L = longitude

This equation is being proposed because, as Duarte et al. (2015) mention, longitude must be considered when calculating the angle of the solar panels to adjust the tilt angle, thus avoiding the effects of dust accumulation, dirt, and other undesired impacts while ensuring the best possible solar exposure for the installation site.

The proposed equation has been implemented in the InclinaSol app (Gomes, Oliveira, & Musci, 2022) for calculating the tilt of fixed solar panels, using latitude and longitude information for the installation site.

THE DEVELOPMENT OF THE INCLINASOL APP

The app allows the calculation of the solar panel tilt angle based on Equation 4. It requires the input of latitude and longitude of the solar panel installation site. The app locates the provided geographic coordinates on a map and computes the optimal tilt angle.

Built with HTML5 and the React Native framework (Meta, 2022), the app is designed for the Android® platform, utilizing the Google Geocoding Application Programming Interface (API) (Google, 2022). According to Venteu (2018), the use of this API provides significant advantages to developers, particularly in presenting geographic information on a smartphone screen. This visual representation is crucial since numerical latitude and longitude references can be challenging for app users to interpret.

Figure 2 illustrates (a) the initial screen of the InclinaSol app and (b) the display of the recommended angle for the solar panel installation at a specific geolocation.

Ângulo

Ângulo: 29.69195708018453

Latitude: -22.95451659719513,
Longitude: -43.16683804616332

(a) (b)

Figure 2 - (a) displays the initial screen of the InclinaSol app, while (b) shows the indication of the optimal angle for solar panel installation based on the provided geographical coordinates.

Source: Author, 2022.

METHODOLOGY

To create benchmarks at specific locations, three neighborhoods in the city of Rio de Janeiro were defined as case studies, which are reasonably distant from each other: Guaratiba, Deodoro, and Copacabana. Their locations are listed in Table 1.

LOCAL	LATITUDE	LONGITUDE
Deodoro	– 22,849999°	– 43,379999°
Guaratiba	– 22,986950°	– 43,611775°
Copacabana	– 22,969629°	– 43,185329°

Table 1 – Latitude and longitude values of three locals in the city of Rio de Janeiro

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

The validation of the case study using the InclinaSol application will involve comparing the obtained results with the values of solar incidence on the surface of the solar panels, acquired using the RadiaSol application developed by Krenzinger et al. (1997) at the Solar Energy Laboratory of the Federal University of Rio Grande do Sul. The study considers that all houses in the studied neighborhoods have roofs with a 17° inclination, as indicated by Nascimento et al. (2016) as the average slope of Brazilian roofs.

RESULTS AND DISCUSSIONS

With the use of the InclinaSol application for each of the selected neighborhoods within the city of Rio de Janeiro, the results are listed in Table 2.

LOCAL	Annual angular average
Deodoro	29,693332°
Guaratiba	29,861892°
Copacaban	29,708196°

Table 2 – Values of the annual average angle obtained using the InclinaSol application

Source: Author, 2021.

The comparison with the RadiaSol application is shown in Table 3 for the Deodoro district, in Table 4 for the Guaratiba district, and finally in Table 5 for the Copacabana district. In all tables, the analysis was considered for four angles, one being a horizontal plane (0°), and three inclined planes. Of the inclined planes, the first corresponds to the value of the average inclination of Brazilian roofs (17°), the second is the same value (30°) obtained by the InclinaSol application, and the last one is a much steeper angle (45°) to evaluate the effects of an increased angle of inclination.

Average Daily Solar Irradiance (kWh/m^2.day)													
Angle	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**June**	**July**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Average**
0°	5,33	4,74	5	5,02	5,16	5,13	5,03	5,52	5,47	5,41	5,48	5,05	**5,19**
17°	5,35	4,90	4,87	4,65	4,39	4,02	4,04	5,26	5,07	5,32	5,42	5,46	**4,89**
30°	5,59	4,62	4,6	4,35	4,29	4,11	4,31	4,53	4,86	5,68	5,89	5,96	**4,90**
45°	4,59	4,13	3,95	3,3	2,56	2,21	2,55	3,34	3,96	4,49	4,88	4,75	**3,72**

Table 3 – Average daily solar radiation – Deodoro/RJ

Source: UFRGS, 2021 – Data obtained from the RadiaSol application

Average Daily Solar Irradiance (kWh/m^2.day)													
Angle	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**June**	**July**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Average**
0°	5,33	4,43	5,08	5,02	5,36	5,13	5,13	5,62	5,97	5,42	5,42	5,48	**5,28**
17°	5,36	4,90	4,97	4,26	4,42	4,05	4,58	5,09	5,15	5,02	5,83	5,12	**4,89**
30°	5,29	4,92	4,87	4,87	3,94	3,97	4,59	4,59	4,88	5,59	5,91	5,49	**4,91**
45°	4,59	4,14	3,96	3,34	2,63	2,29	2,65	3,42	4,00	4,50	4,88	4,74	**3,76**

Table 4 – Average daily solar radiation – Guaratiba/RJ

Source: UFRGS, 2021 – Data obtained from the RadiaSol application

Average Daily Solar Irradiance (kWh/m^2.day)													
Angle	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**June**	**July**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Average**
0°	5,51	5,43	5,11	4,45	4,54	3,88	4,13	5,07	4,78	5,07	5,12	5,47	**4,88**
17°	5,56	5,52	5,18	4,43	3,63	3,34	3,59	4,56	4,81	5,12	5,20	5,54	**4,71**
30°	5,55	5,67	4,98	4,99	4,81	3,98	3,92	3,97	4,89	5,11	5,22	5,65	**4,90**
45°	4,95	4,70	4,06	3,09	2,16	1,76	1,88	2,67	3,53	4,25	4,49	4,90	**3,54**

Table 5 – Average daily solar radiation – Copacabana/RJ

Source: UFRGS, 2021 – Data obtained from the RadiaSol application

Permitting data analysis revealed that the highest average solar radiation occurred at the 0° angle, reaching 5.28 kWh/m2, 5.28 kWh/m2, and 4.88 kWh/m2 for the neighborhoods of Deodoro, Guaratiba, and Copacabana. Although panels installed horizontally, at 0° angle, can capture higher solar radiation (on average), tilts below 10° might accumulate debris and should be avoided. At angles of 17° and 30°, the average value for the three locations analyzed ranged between 4.71 kWh/m2 and 4.90 kWh/m2. The lowest observed value was at the 45° angle, which showed the poorest average for the three locations under study, ranging between 3.54 kWh/m2 and 3.76 kWh/m2.

Comparing the lowest observed solar radiation value with the highest, there was approximately a 28% reduction for the three locations concerning the 0° angle (highest observed solar radiation). This demonstrates that an angle significantly different from the solar rays does not absorb solar radiation as efficiently as smaller angles.

Given that tilt is a factor in determining the effective power of the solar panel system, a panel with a 0° tilt would be the most efficient in utilizing solar energy. However, this angle is more prone to accumulate dust, dirt, and raindrops, which could compromise the system’s efficiency over time.

The 17° angle, the same as the roof slope, exhibits almost the same average annual radiation in kWh/m2 as the 30° angle, with a maximum variance of 3.9% for the Copacabana neighborhood. This suggests that both tilts (17° and 30°) would be equally advisable for better utilization of solar energy. Once again, the challenge remains that a solar panel with the same inclination as the roof also favors the accumulation of dirt, dust, and raindrops, compromising the system’s effectiveness over time. Hence, the angle calculated by the InclinaSol app (obtained by equation 4), approximately 30° as presented in Table 2, is the most suitable to mitigate undesired effects that could hinder solar panel efficiency.

FINAL CONSIDERATIONS

This article developed an application based on a mathematical model to determine the optimal tilt angle to maximize the total incident solar radiation on a solar panel. The application takes into account the undesired effects to avoid the accumulation of dust, dirt, and raindrops on the solar panels. Subsequently, the results were tested and validated through the RadiaSol software in a case study conducted in three different locations in the city of Rio de Janeiro.

Based on the data provided by the InclinaSol application, it was concluded that the best angle for installing solar panels results in increased efficiency and higher electrical energy productivity. This verifies the importance of solar panel positioning for optimal utilization of the installed system's potential.

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