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Optimal solar panel tilt angle calculation and simulation in Indonesia: A Liu and Jordan sky isotropic model-based approach

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Abstract

The efficient utilization of solar energy is crucial for meeting the growing energy demands while reducing greenhouse gas emissions and dependence on fossil fuels. Solar panel tilt angle optimization plays a vital role in maximizing the energy output of photovoltaic (PV) systems. Determining the optimal tilt angle is essential as it directly affects the amount of sunlight captured by the solar panels. In the context of Indonesia, a country rich in solar resources and a rapidly expanding renewable energy sector, understanding the optimal tilt angle for solar panels is of paramount importance. This paper studies the optimal solar panel tilt angle calculation using Liu and Jordan Sky isotropic model-based approach. The numerical simulations were carried out for several main city locations of Indonesia. The objectives of the work are to address the suitable and optimal tilt angle of solar panels by proposing an approach based on the Liu and Jordan Sky Isotropic Model. The calculation result shows that the boundary for the tilted angle empirically satisfies all the mathematical domain of the inverse trigonometric functions. While, the optimal tilted angles will be differed for any location.

Keywords: Tilted angle; Solar panel; Liu and Jordan; Sky isotropic; PV

1. Introduction

Renewable energy plays a pivotal role in addressing Indonesia's energy challenges and fostering sustainable development. As the world's fourth most populous country and one of the largest energy consumers in Southeast Asia, Indonesia faces a pressing need to diversify its energy mix, reduce carbon emissions, enhance energy security, and promote economic growth. Embracing renewable energy sources offers a promising pathway to meet these goals while ensuring a sustainable and low-carbon future. Indonesia boasts vast renewable energy potential, including abundant solar irradiation, significant wind resources, substantial geothermal reserves, and extensive biomass availability. Harnessing these renewable resources presents an opportunity to meet the nation's energy demand while mitigating climate change, reducing dependence on fossil fuels, and improving energy access for remote and underserved communities. One crucial aspect of Indonesia's renewable energy transition is the need to curb its heavy reliance on coal as the primary source of electricity generation. Coal-fired power plants have contributed to Indonesia's increasing greenhouse gas emissions, air pollution, and environmental degradation. Shifting towards renewable energy sources will not only reduce emissions but also improve air quality, protect public health, and mitigate the adverse impacts of climate change. Furthermore, Indonesia's commitment to renewable energy aligns with its international climate change commitments, including the Paris Agreement [1]. By pursuing ambitious renewable energy targets, Indonesia can

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demonstrate global leadership in combating climate change, attract international investments and partnerships, and enhance its reputation as a responsible and sustainable nation. The efficient utilization of solar energy is crucial for meeting the growing energy demands while reducing greenhouse gas emissions and dependence on fossil fuels. Solar panel tilt angle optimization plays a vital role in maximizing the energy output of photovoltaic (PV) systems. Determining the optimal tilt angle is essential as it directly affects the amount of sunlight captured by the solar panels. In the context of Indonesia, a country rich in solar resources and a rapidly expanding renewable energy sector, understanding the optimal tilt angle for solar panels is of paramount importance.

The research by Yunus Khan, T. M. et al. (2020) focuses on determining the optimum location and the impact of tilt angle on the performance of solar PV panels. Through analysis and experimentation, the study evaluates various factors such as solar radiation, temperature, and panel efficiency to identify the optimal tilt angle for maximizing the energy output of PV panels. The research provides valuable insights into the importance of location selection and tilt angle optimization for achieving optimal performance and efficiency in solar PV systems [2]. Based on the research by Khan, P. W., Byun, Y. C., and Lee, S. J. (2022) focuses on predicting the optimal direction and tilt angle for PV panels using a stacking ensemble learning approach. By analyzing various input variables such as solar radiation, temperature, and panel efficiency, the researchers develop a predictive model that can accurately determine the optimal orientation and tilt angle for PV panels. The findings contribute to improving the design and performance of PV systems by providing valuable insights into maximizing energy generation based on specific environmental conditions and panel characteristics [3]. The research by Al-Sayyab, A. K. S., Al Tmari, Z. Y., and Taher, M. K. (2019) presents a theoretical and experimental investigation into the performance of PV cells, focusing on the optimal tilt angle in the context of Basra city. Through a case study, the researchers analyze various factors such as solar radiation, temperature, and PV cell efficiency to determine the optimal tilt angle for maximizing the performance of PV cells in Basra. The findings provide valuable insights for the design and installation of PV systems in the region, helping to enhance energy generation and efficiency [4]. The implementation of Optimal Solar Panel Tilt Angle in various country has been implemented by some researchers for China, Pakistan, and also United Arab Emirates such as the research by Hua, Y., He, W., and Liu, P. (2020) investigates the optimal tilt angles for solar panels in Gansu Province, Northwest China. Through a case study and data analysis, the researchers determine that the optimal tilt angle for solar panels in the region is 35 degrees. This angle provides the best balance between energy production and cost-effectiveness, helping to maximize solar energy generation in Gansu Province. The findings contribute valuable insights for solar panel installation and positioning, aiding in the design and implementation of efficient solar energy systems in the area [5]. The research by Ullah, A., Imran, H., Maqsood, Z., and Butt, N. Z. (2019) examines the optimal tilt angles for PV panels and investigates the impact of soiling on PV energy production in Pakistan. Through analysis and experimentation, the researchers evaluate various factors such as solar radiation, temperature, soiling effects, and panel efficiency to determine the optimal tilt angles for maximizing PV energy production in different regions of Pakistan. The study also explores the influence of soiling, particularly dust deposition, on PV performance. The findings contribute to improving the design and maintenance strategies of PV systems in Pakistan by providing insights into optimal tilt angles and addressing the challenges posed by soiling, ultimately enhancing energy generation and efficiency in the country [6]. The research by Hachicha, A. A., Al-Sawafta, I., and Said, Z. (2019) investigates the impact of dust on the performance of solar PV systems under the weather conditions of the United Arab Emirates (UAE). Through analysis and experimentation, the researchers examine the effects of dust deposition on solar radiation, PV panel efficiency, and overall energy production. The study provides insights into the detrimental effects of dust accumulation on PV system performance in the UAE, highlighting the importance of regular cleaning and maintenance to mitigate the negative impact of dust and optimize energy generation from solar PV systems in dusty environments [7].

The complex nature of the Indonesian climate, which includes diverse weather patterns and varying solar irradiance levels, presents a challenge in determining the most suitable tilt angle. This research aims to address this challenge by proposing an approach based on the Liu and Jordan Sky Isotropic Model to calculate and simulate the optimal tilt angle for solar panels in Indonesia. The Liu and Jordan Sky Isotropic Model takes into account various climatic factors, including solar irradiance, atmospheric conditions, and sky isotropy, to accurately estimate the solar energy potential in a specific location. By employing this model, we can analyze the impact of different tilt angles on the energy generation of solar panels in different regions of Indonesia. This approach allows us to identify the tilt angles that yield the highest energy output and contribute to the overall efficiency and economic viability of PV systems. The significance of determining the optimal tilt angle in Indonesia lies in its potential to drive the widespread adoption of solar energy and promote sustainable development. As Indonesia's energy demand continues to rise, harnessing the abundant solar resources can provide a clean and renewable energy source, reduce reliance on fossil fuels, and mitigate environmental degradation. The findings will enable them to make informed decisions regarding the design, installation, and operation of PV systems, ultimately accelerating the transition towards a more sustainable and energy-efficient future. In the subsequent sections of this research, the outline of the methodology used for calculating and simulating the optimal tilt angle based on the Liu and Jordan Sky Isotropic Model, and then present the results and analysis obtained from applying this approach to the region in Indonesia, and discussing the implications of findings and highlight the potential for further research and application in the field of solar energy optimization in Indonesia.

2. Methodology

Solar irradiance on tilted surface can be calculated using several existing mathematic models. The variables for solar irradiance are beam, ground-reflected, and diffuse component. Mathematical models to calculate the diffuse irradiance on tilt surface in general can be classified as sky isotropic and anisotropic model. The sky isotropic and anisotropic models differ in the assumption on distribution of diffuse sky radiation over the sky dome. The sky isotropic model assumes that the distribution is uniform while the anisotropic model assumes otherwise. One of the most common models is the sky isotropic model by Liu and Jordan as follow

$$R_b = \frac{\cos(\varphi-\beta)\cos\delta\sin\omega'_s+\left(\frac{\pi}{180^\circ}\right)\omega'_s\sin(\varphi-\beta)\sin\delta}{\cos\varphi\cos\delta\sin\omega_s+\left(\frac{\pi}{180^\circ}\right)\omega_s\sin\varphi\sin\delta}, \ldots\ldots\ldots \quad (1)$$

$$H_T = H\left(1-\frac{H_d}{H}\right)R_b + H_d\left(\frac{1+\cos\beta}{2}\right) + H\left(\frac{1-\cos\beta}{2}\right)\rho \ldots\ldots\ldots(2)$$

where R_b is ratio of monthly average beam radiation on tilted surface to monthly average beam radiation on a horizontal surface, φ is latitude, β is tilted angle,

$$\omega_s = \cos^{-1}(-\tan\varphi\tan\delta) \ldots\ldots\ldots(3)$$

is sunset hour angle on a horizontal surface,

$$\omega'_s = \cos^{-1}(-\tan(\varphi+\beta)\tan\delta) \quad \ldots\ldots\ldots\ldots(4)$$

is sunset hour angle on a tilted surface for southern hemisphere, replace $(\varphi+\beta)$ with $(\varphi-\beta)$ for northern hemisphere,

$$\delta = 23.45\sin\left(\frac{360(284+N)}{365}\right), \ldots\ldots\ldots\ldots(5)$$

with N is number of days in a year with representative day proposed by Klein as shown in Table 1,

H_T = monthly-average daily total radiation on an inclined surface,
H = monthly-average daily total radiation on a horizontal surface,
H_d = monthly-average daily diffuse radiation on a horizontal surface,
ρ = ground reflectance (normally, $\rho = 0.2$).

Table 1 Number of days in a year with representative day proposed by Klein

Month	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**June**	**July**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Date	17	16	16	15	15	11	17	16	15	15	14	10
N	17	47	75	105	135	162	198	228	258	288	318	344

The objective of this research is to gain the range of β theoretically then find the optimum tilted angle for application in Indonesia using equation (1) and (2). The optimum β is obtained by choosing maximum radiation from various angles, with the algorithm is as follow

- Input: latitude
- Set: various values of β, monthly average daily total and diffuse radiation on horizontal surface, Klein's numbers of days in a year
- For every value of β do step 4 – 7
- For every month do step 5 – 6
- Calculate: $\delta, \omega_s, \omega'_s$ with equation (3), (4), and (5)

- Calculate R_b and H_T with equation (1) and (2)
- Calculate total radiation in a year
- Find max total radiation and the corresponding angle βopt
- Print βopt

3. Results and discussion

The sky isotropic model by Liu and Jordan usually used to optimize the tilted angle in order to get maximum solar irradiation. However, eq. (4) will limit the choice of β since the equation is in the form of inverse trigonometric function. The domain of inverse cosines function is [-1,1]. Therefore, the inverse cosine in eq. (4), applied in the southern hemisphere, will be bounded into

$$-1 \leq -\tan(\varphi + \beta)\tan\delta \leq 1 \text{ or } -1 \leq \tan(\varphi + \beta)\tan\delta \leq 1 \ldots\ldots\ldots\ldots\ldots(6)$$

Since δ depends on the number of days in a year, which are different constants for every month as shown in Table 1, the boundaries for $\tan(\varphi + \beta)$ satisfies these inequalities

$$-\frac{1}{\tan\delta} \leq \tan(\varphi + \beta) \leq \frac{1}{\tan\delta} \qquad \ldots\ldots\ldots\ldots(7)$$

The boundaries for $\tan(\varphi + \beta)$ each month can be seen in Table 2.

Table 2 The boundaries for $\tan(\boldsymbol{\varphi} + \boldsymbol{\beta})$ each month

Month	**interval of $\tan(\boldsymbol{\varphi} + \boldsymbol{\beta})$**	
	$-\frac{1}{\tan\delta}$	$\frac{1}{\tan\delta}$
Jan	-2,15892	2,158923
Feb	9,437992	-9,43799
Mar	-2,85391	2,853912
Apr	-6,2141	6,214103
May	2,186399	-2,1864
June	-36,2389	36,23887
July	2,63411	-2,63411
Aug	-3,17117	3,171167
Sep	-4,92078	4,920783
Oct	2,245805	-2,2458
Nov	-322,046	322,0464
Dec	4,93099	-4,93099

If the location was already set up, then the boundaries of β for every month of the year can be obtained. As an illustration, Indonesia, the most populous country in the southern hemisphere, is located at -0.789275°S. Put this latitude number into eq. (7) to obtained the boundaries of β each month in Indonesia as seen in table 3.

Table 3 The boundaries for $\boldsymbol{\beta}$ each month in Indonesia

Month	interval of $\boldsymbol{\beta}$	
	Min	**Max**
Jan	-64,357442	65,935992
Feb	-83,162532	84,741082
Mar	-69,900455	71,479005
Apr	-80,068820	81,647370
May	-64,632640	66,211190
June	-87,630067	89,208617
July	-68,422220	70,000770
Aug	-71,708509	73,287059
Sep	-77,723523	79,302073
Oct	-65,208523	66,787073
Nov	-89,032814	90,611364
Dec	-77,746671	79,325221

It can be seen from table 3 that a solar panel located in Indonesia can be tilted from min angle of -89,032814 to max of 90,611364 according to all the mathematical equations used in Liu and Jordan's model. Indonesia is one of the largest archipelago countries, which traversed by the equator. Therefore, some parts of Indonesia are located in the southern hemisphere while the other are in the northern hemisphere, and certain parts of Indonesia are located in the equator. Apply the same procedure to 5 different cities in Indonesia will give not so different results in the boundary of the tilted angle, as seen in Table 4.

Table 4 Mathematical boundary of tilted angle in 5 different cities in Indonesia

City		**Banda Aceh**	**Medan**	**Pontianak**	**Surabaya**	**Kupang**
Latitude		5,54829	3,784303	0	-7,275973	-10,17876
Tilted Angle	Min	-84,273799	-86,03779	-89,82209	-82,54612	-84,273799
	Max	95,370379	93,606392	89,822089	97,098062	95,370379

Those boundaries will fulfil all the equations in the model mathematically. Empirically, the tilted angle never exceeds $0 \leq \beta \leq \frac{\pi}{2}$. The above results will ensure that all the practical angles are in the appropriate interval, mathematically. It also ensures that the optimal tilted angle will be within those intervals. The optimal tilted angle can be obtained by following the algorithm mentioned in methodology. The algorithm run through several simulation with 180 variations of angles within the interval $0 \leq \beta \leq \frac{\pi}{2}$ to find the highest monthly-average daily total radiation. The simulation result for those 5 different cities above can be seen in table 5.

Table 5 Optimal tilted angle for 5 cities in Indonesia

City	**Banda Aceh**	**Medan**	**Pontianak**	**Surabaya**	**Kupang**
Latitude	5,54829	3,784303	0	-7,275973	-10,17876
Optimal tilted angle	3.5^0	4.5^0	9^0	15.5^0	18^0
Highest total radiation (× 10^3)	4.3722	4.3769	4.3990	4.4614	4.4973

4. Conclusion

The calculation result shows that the boundary for the tilted angle empirically satisfies all the mathematical domain of the inverse trigonometric functions. While the optimal tilted angles will be differed for any location. The result in table 5 shows that in Indonesia, the latitude differences are almost the same as the optimal tilted angles differences. The further south the city latitude, the bigger the optimal tilted angle. Thus, if the city located $x°$ north from the equator, which has optimal tilted angle 9°, then the optimal tilted angle for that location is $(9 - x)°$. For cities located in southern hemisphere, the optimal tilted angle can be determined by changing the minus sign into plus. Other result shows that all the optimal tilted angles give almost the same highest total radiation, that is 4421 R per year.

Compliance with ethical standards

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Disclosure of conflict of interest

All authors declare that we have no conflicts of interest.

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