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EVALUATION OF OPTIMUM TILT ANGLES FOR BIPV INSTALLATION IN INDONESIA

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ABSTRACT

Generale rules of thumb for PV-tilt in certain area is equal to the latitude angle of the area. Following the rule, PV system on low-latitude area such as Indonesia should be installed in low PV-tilt angle to receive optimum irradiance. Furthermore, installing PV in low tilt angle has many advantages such as reducing the inter-row spacing requirements, increasing the coverage ratio and power density, increasing more PV numbers in lesser area, generating low-cost PV electricity that resulting in higher economy savings. However, installing PV in low tilt angle has also disadvantages such as dust deposition that resulting in less energy efficiency. Furthermore, for roof integrated photovoltaic in the tropics, pitched roof design in certain angles is preferable to response to high precipitation and to reduce minimum indoor room temperature. Therefore, this study aims to evaluate the performance of several PV-tilt design options and identify the optimum tilt angle of horizontal integrated PV based on annual irradiance received and monthly energy fluctuation, particularly in Indonesia. Simulation method is used to generate the number of annual irradiances for several selected sites in Indonesia. Setting on 10° to 30° PV-tilt angle seems to be a good design option based on annual irradiance and percentages of energy fluctuation.

Keywords: *Energy fluctuation, irradiance, photovoltaic, tilt angle.*

INTRODUCTION

In recent years, Photovoltaic (PV) has been considered as one of potential microgeneration technology. It is proved by the fact that the use of PV worldwide has increased into 500 GWp capacity (Toledo et al. 2020). The growth of PV use can be understood due to its ability to produce energy on-site where the end-users need it (Gholami and Røstvik 2020). When it is supported with energy storage system, it will also provide energy when the users need it.

The increasing use of PV worldwide is also supported by the abundant ability of its source, the solar energy. Indonesia, that is located in tropical area, is one of many countries that has an abundant solar energy potential. The potential is measured by the high solar irradiance amount as well as measured by considering the large potential installation areas (Silalahi et al. 2021).

Regarding the solar irradiance amount, Silalahi and Gunawan (2022) described that global horizontal irradiation (GHI) in Indonesia ranges from 3.6 to 6.4 kW/m2 per day (as illustrated in Figure 1). The Indonesia GHI average that measured in 4.8 kWh/m2 per day is found higher than the daily average GHI in Germany (2.9 kWh/m2), Japan (3.6 kWh/m2), China (4.1 kWh/m2), and Singapore (4.5 kWh/m2). Meanwhile, the solar energy potential that is measured by considering the potential installation area refers to a large land mass and water bodies in Indonesia that can be used for solar panel farms (Silalahi and Gunawan 2022). Furthermore, the potential is also found in forms of direct installation on building envelope, which known as building integrated photovoltaic (BIPV) system (Kumar, Sudhakar, and Samykano 2020).

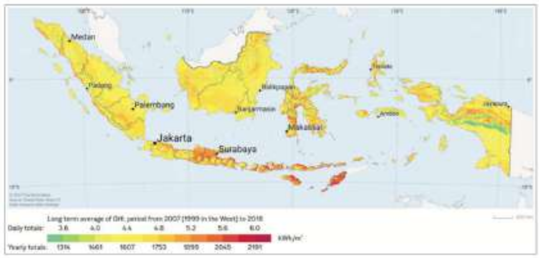

Figure 1. Indonesia Global Horizontal Irradiation Map
Source : (Silalahi and Gunawan 2022).

BIPV is defined as an application of PV where the solar panels become an integrated part of the building facade. The solar panels can be installed on building façade both vertically and horizontally or in sloped position. Hence, the performance of PV is influenced by the position, particularly on the design of PV-tilt and PV-orientation angle. The study found that installing PV in optimum tilt angle can increase power generation up to 10.41% higher than installing PV in horizontal surface (Jing et al. 2023). As the generale rules of thumb, tilt angle in certain area should be equal to the latitude angle of the area and typically installed face the equator (Jing et al. 2023; Martín-Chivelet 2016). Based on this finding, area which is uniquely positioned across the equator such as Indonesia might have certain geographical characteristic that give impact on PV installation. Despite the growing interest in BIPV as a sustainable solution for reducing energy consumption in buildings, research on the optimization of BIPV systems in tropical regions such as Indonesia remains limited, particularly regarding precise tilt angle configurations tailored to local climatic variations.

Most existing studies emphasize fixed or generalized tilt angle recommendations based on temperate or subtropical contexts (Jing et al. 2023; Ghosh, Roy, and Chakraborty 2024; Basak, Chakraborty, and Behura 2025), which may not yield optimal energy performance in equatorial latitudes.

This study fills this gap by providing a location-specific evaluation of optimum tilt angles for BIPV installations across multiple cities in Indonesia, contributing both to practical design guidelines and to the theoretical framework of BIPV performance modeling in tropical climates. From an axiological standpoint, this research aligns with value-driven sustainability science, aiming to inform decisions that balance environmental performance with architectural integration.

Following general rule of thumbs, PV installation in low latitude area such as Indonesia should be installed in low PV-tilt angle to receive optimum solar irradiance. Furthermore, installing PV at low tilt angle has advantages in terms of reducing the inter-row spacing requirements, increasing the coverage ratio and power density, increasing more PV numbers in lesser area, generating low-cost PV electricity which reduces the use of grid electricity, resulting in higher economy savings (Ghosh, Roy, and Chakraborty 2024). However, installing PV in low tilt angle has also some disadvantages.

Particularly in tropical area, dust deposition on low PV-tilt angle is one of the main causes to the decline of PV-efficiency (Ahmed et al. 2023) and the most significant reason of PV power loss (Said et al. 2024). Furthermore, pitched roof in tropical area is preferable to response with high precipitation and reduce the minimum indoor room temperature (Aulia and Veronica 2024).

This study then aimed to evaluate the performance of several PV-tilt design options and identify the optimum tilt angle of horizontal integrated PV based on annual irradiance received and monthly energy fluctuation, particularly in Indonesia. The novelty of this research lies in its aim to deriving tilt angle optimization tailored to Indonesia’s unique solar irradiance patterns, based on those two indicators, thereby enhancing the feasibility and efficiency of BIPV adoption in the region.

In particular, horizontal integrated PV here refers to PV that integrated in 0°< angle of PV surface <80° or <75° from horizontal (Kuhn et al. 2021). Energy fluctuation is calculated from the percentages of differences between highest and lowest irradiance received, captured from the monthly data in a year (Mangkuto et al. 2023).

METHOD

Site Selection

Indonesia consists of numbers of provinces, spread from 11°S to 6°N latitude, and 95°E-141°E longitude. Different latitude and longitude will cause different climate and sequentially provide different solar irradiance, the main energy resource for solar panel (Wijeratne et al. 2019). Hence, to make the study more generalizable, site selected should represent the climate for many provinces in Indonesia. Thus, meteorological stations (BMKG) that are located in 34 provinces in Indonesia are considered as the climate context for this study.

Totally there are 187 technical implementation units of meteorological and climatology departments in Indonesia, classified as *Balai Besar BMKG, kelas 1, kelas 2,* and *kelas 3* of Meteorological, Climatology, and Geophysics Stations ("Penataan Organisasi Dan Tata Kerja BMKG Republik Indonesia No. 6 Tahun 2020" 2020).

One station that classified in highest categories in each province will be selected as the context of the study. Further selection conducted by eliminating stations that located in similar latitude. The list of selected meteorological stations is provided in Table 1.

Table 1. List of Selected Meteorological Stations

No.	Meteorological Stations	Latitude, Longitude
1	Balai besar BMKG Medan, North Sumatra	3.54, 98.64
2	Sta. Geof Kelas I Sultan Iskandar Muda – Banda Aceh	5.52, 95.42
3	Sta. Met. Kelas I Sultan Syarif Kasim II, Pekanbaru, Riau	0.47, 101.45
4	Sta. Geof. Kelas I Radin Inten II – Lampung Selatan, Lampung	-5.19, 105.18
5	Sta. Met. Kelas I Sultan Thaha Jambi	-1.63, 103.64
6	Sta. Klim. Kelas I Central Java	-6.98, 110.38
7	Sta. Geof. Kelas I Sleman, Yogyakarta	-7.81, 110.30
8	Sta. Met. Kelas I Depati Amir, Pangkal Pinang, Bangka Belitung	-2.16, 106.13
9	Balai Besar BMKG Wil III Badung, Bali	-8.74, 115.18
10	Sta. Geof. Kelas I Kupang, NTT	-10.15, 123.61
11	Sta. Met. Kelas I Supadio – Pontianak, West Kalimantan	-0.14, 109.40
12	Sta. Geof. Kelas I Manado, North Sulawesi	1.44, 124.83
13	Sta. Met. Kelas II Tampa Padang Mamuju, West Sulawesi	-2.59, 119.01
14	Sta. Met. Kelas II Maritim Kendari, Sulawesi Tenggara	-3.97, 122.59

Source : (https://www.bmkg.go.id/profil/balai-upt, accessed on February 07th, 2025)

Simulation Method

Web-based simulation tool, HelioScope, is used to generate data of solar radiation received. HelioScope is a cloud-based solar design software developed by Folsom Labs that has been validated through the comparison to other simulated tools (Guittet and Freeman 2018; Zin and Dr. Wunna Swe 2024; Basoglu and Demir 2022). The range of error is similar against the simulated results from other software (SAM, PVsyst, PV*Sol), found within -7% and 4.3% annually and 2.9%-6.6% hourly. The software has also been validated through the comparison on measured results, particularly on vertical installation. The difference between simulated and measured results is 10.57% to 15.16% and considered acceptable according to accuracy percentages determined by ASHRAE which is determined to be less than 30% (Susan 2024). HelioScope software is chosen also due to its ability to generate data of irradiance received, monthly and annually, on an inclined plane, in certain orientation. Based on the understanding of horizontal integrated PV, setting of tilt angle will be examined by systematically adjusting the module in every 10°, from 0° to 80°.

HelioScope simulation setting is conducted in several steps, started with (1) creating new project (where latitude and longitude of the site are inputted into the software), (2) creating new design (where users choose type of PV and set the height, the azimuth, and the tilt), (3) generating data of irradiance (annual and monthly irradiance). Azimuth used is 0° for location placed in south latitude and 180° for location placed in north latitude. Furthermore, the height is set up at 10m above the ground. Figure 2 gives an illustration of HelioScope simulation process and result.

Figure 2. HelioScope Process and Result: (a) Site Selection, (b) Monthly Production, (c) Annual Irradiance
Source: HelioScope, 2025

RESULTS AND DISCUSSION

This section presents the simulation results of the annual solar irradiance received at varying tilt angles for representative cities in both the northern and southern hemispheres of Indonesia including Medan, Aceh, Riau, Lampung, Jambi, Central Java, Yogyakarta, Bangka Belitung, Bali, Kupang, Pontianak, Manado, Padang Mamuju, and Kendari. The data demonstrate that while the optimum tilt angle correlates closely with latitude, the direction of orientation-toward the equator-remains consistent. Table 2 presents data generated for one of the selected sites. Simulation visualizations with angles that provide advantages for this site are presented in Figure 3 and Figure 4. It is noticed from the Figure 3, for every 10° tilt angle differences, tilt angle in 10° produce highest kWh/kWp compared to others. Details of the simulation result for this site in Figure 4 shows the total annual irradiance collected is estimated in 2155.7 kWh/m2, with a relatively uniform monthly production. A complete result for each of area and PV-tilt simulated are presented in Figure 5. Furthermore, Figure 6 presents the energy fluctuation profile for every area and tilt simulated in this study.

Table 2. Simulated Results of Solar Irradiance

Location (lat, long)	Tilt (°)	Energy fluctuation (%)	Annual irradiance (kWh/ m2)
-10.15, 123.61	0	33	2103.5
	10	40	2155.7
	20	53	2143.0
	30	73	2052.1
	40	105	1889.5
	50	154	1658.6
	60	232	1390.1
	70	407	1066.6
	80	686	759.8

Source : Author, 2025

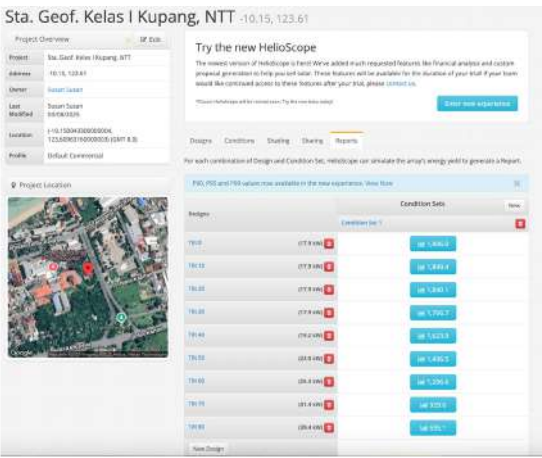

Figure 3. Simulation with Tilt Angles in 10° Differences for Site in -10.15°, 123.61°
Source: HelioScope, 2025

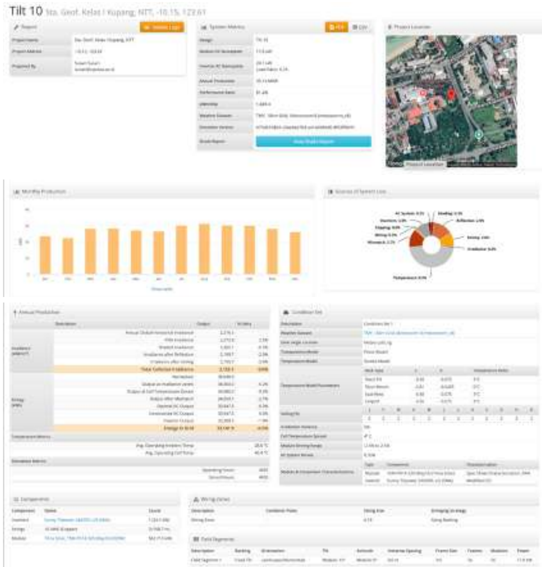

Figure 4. Detail Result of Simulation for Optimum Tilt Angles (10°) in -10.15°, 123.61°
Source : HelioScope, 2025

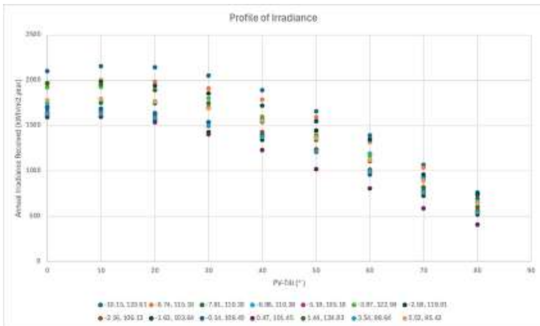

Figure 5. Profile of Annual Irradiance Received
Source: author, 2025

As seen in Figure 5, in any area simulated in this study, annual irradiance received tend to increase from 0° to 10° PV-tilt angle and start to decrease at 20° to 80° PV-tilt. However, annual irradiance received in 20° tilt angle in some of the observed areas are higher than the one received by PV set in horizontal surface (0°). Based on this result, 10° and 20° PV-tilt seems to be a good option for optimum tilt angle for PV installation, particularly in Indonesia.

In general, the annual irradiance of PV in 10° tilt is 0.36% to 2.48% higher than PV in horizontal surface (0°). Meanwhile, the annual irradiance of PV in 20° tilt is 0.97% to 2.21% higher than PV in horizontal surface (0°). Starting in 30° PV-tilt, the annual irradiance received is 0.44% to 13.21% lower than PV in horizontal surface (0°).

The result can be explained by observing the trajectory of the sun on an observed location. Generally known, the Earth is tilted approximately 23.5° on its axis. As the Earth orbits the Sun, different latitudes receive different amounts of sunlight throughout the year. To maximize solar irradiance, a surface should be oriented perpendicular to incoming sunlight, to help capture the most direct radiation. At any given location, the optimal tilt angle for solar panels to receive optimum annual irradiance is approximately equal to the latitude of the location. This is because at solar noon, the sun's position in the sky is directly influenced by the latitude. In Indonesia that placed in 11°S to 6°N, a panel tilted in ranges 0° to 20° will faces the sun more directly throughout the year.

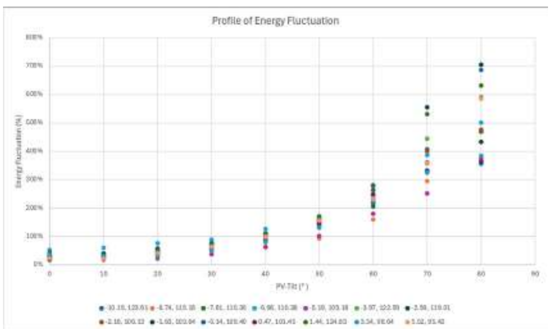

Figure 6. Profile of Energy Fluctuation
Source: author, 2025

Figure 6 presents a profile of energy fluctuation. In general, the irradiance differences increase when a PV system is installed at a larger tilt angle. The four lowest energy fluctuation are presented by design options of 0° to 30° PV-tilt angle, which is calculated less than 100%. Basically, this happens because of how the Sun's position changes throughout the year and how it affects solar panel exposure. The sun's position in the sky varies with the seasons due to the Earth's axial tilt (23.5°). Seasonally, solar angles changes from low solar angles to high solar angles. When a solar panel has a steeper tilt, it becomes more sensitive to these variations. In a steep tilt angle (when the PV-tilt getting closer to vertical surface), panels will receive more irradiance when the solar angle is angle but lose significance irradiance when solar angle is high. In a low PV-tilt angle (closer to horizontal surface) panels receive more uniform irradiance throughout the year because they capture sunlight more evenly. Monthly differences are smaller since the seasonal impact is reduced.

CONCLUSION

Solar irradiance is the main source of energy for PV to generate electricity. To receive optimum irradiance, PV needs to be installed in certain tilt and orientation angle. Related to PV-tilt, generale rule of thumbs described that PV installation in certain area should be equal to the latitude angle of the area. For tropical area located in low latitude angle, option to set roof integrated photovoltaic in low tilt angle against the preference of climate responsive pitched roof design.

This study is conducted to evaluate PV-tilt options in the tropics, particularly in Indonesia, where the solar energy potential presents. Good design options are found when PV is set in 10° to 30° tilt angle. These options are chosen based on its optimum annual irradiance received and minimum energy fluctuation. Setting of PV-tilt in 10° to 20° could make the PV receive irradiance 0.36% to 2.48% higher, compared to the condition when PV set in 0°. Hence, PV in 0° to 30° produce the least energy fluctuation compared to other PV-tilt settings.

This result of this study could be used as an early consideration in PV-tilt setting. It is applicable to various building typologies including low-rise, mid-rise, and high-rise structures under the condition that the selected buildings are unobstructed by surrounding elements such as neighboring structures or dense vegetation. Hence, further study can be conducted with other variables such as dust deposition, rainwater flow, and thermal condition within the buildings that use roof integrated photovoltaic in different tilt angles.

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