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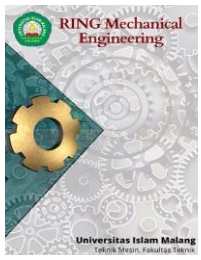

PVWATTS-BASED ASSESSMENT OF SOLAR PHOTOVOLTAIC ENERGY POTENTIAL IN INDONESIAN URBAN AREAS FOR INFRASTRUCTURE PLANNING OPTIMIZATION

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ABSTRACT

The increasing demand for renewable energy in urban areas necessitates comprehensive location-based assessments of solar photovoltaic (PV) system performance. This study presents a simulation-based comparative analysis of solar energy production potential across three representative Indonesian cities: Serang (Banten Province), Yogyakarta (Special Region of Yogyakarta), and Surabaya (East Java Province), representing the western, central, and eastern geographic zones of Java Island. Using the PVWatts simulation tool with standardized system parameters and historical meteorological data, monthly and annual energy yield, solar irradiance, and AC energy output were evaluated for each location. Results indicate that Surabaya recorded the highest annual solar irradiance of 5.54 kWh/m²/day and the greatest annual AC energy production of 1,501 kWh, followed by Yogyakarta (5.27 kWh/m²/day; 1,442 kWh) and Serang (5.02 kWh/m²/day; 1,360 kWh). All three cities exhibited peak performance during the dry season (June September) and minimum production during the wet season (November February). Surabaya demonstrated the most pronounced seasonal variation, with a peak irradiance of 7.18 kWh/m²/day in September and a minimum of 3.91 kWh/m²/day in December. These findings provide a data-driven framework for optimizing solar energy infrastructure planning in Indonesian urban regions and contribute to national renewable energy transition goals aligned with Sustainable Development Goal 7.

Keywords: Photovoltaic, PVWatts, Solar Energy, Urban Infrastructure, Energy Simulation

INTRODUCTION

The global transition toward sustainable energy systems has become a strategic imperative, closely aligned with the United Nations Sustainable Development Goals (SDGs), particularly SDG 7, which targets universal access to affordable, reliable, and clean energy [1]. Solar photovoltaic (PV) technology has emerged as one of the most significant contributors to this transition, with global installed PV capacity surpassing 1 terawatt in 2022 and continuing its rapid expansion trajectory [2]. As urban areas account for more than 70% of global energy consumption, cities are increasingly recognized as critical arenas for deploying distributed renewable energy technologies [3]. Among available options, solar PV systems represent one of the most promising solutions for urban energy generation owing to their modularity, declining installation costs, and minimal operational requirements [4].

Indonesia, situated in the equatorial tropics, possesses an exceptionally high solar energy potential estimated at approximately 4.8 kWh/m²/day on a national average, with some regions receiving in excess of 6.0 kWh/m²/day during dry season months [5]. Despite this abundance, the installed capacity of solar PV in Indonesia remains significantly below its theoretical potential. The government's National Energy Policy (KEN) and the National Energy General Plan (RUEN) set a target of 6.5 GWp of solar PV capacity by 2025, yet actual deployment continues to lag, partly owing to insufficient location-specific, data-driven analysis to guide infrastructure investment decisions [6]. The performance of PV systems is strongly governed by site-specific factors including solar irradiance intensity, ambient temperature, atmospheric conditions, and seasonal variability, all of which differ considerably across Indonesia's vast and geographically diverse landscape [7], [8].

A substantial body of research has established the theoretical and empirical basis for understanding PV system performance under varying climatic conditions. Dubey et al. [7] conducted a systematic investigation of temperature-dependent photovoltaic efficiency, demonstrating that PV module output decreases by approximately 0.45% per degree Celsius rise above the standard test condition temperature of 25°C. This thermal sensitivity is particularly relevant for tropical regions such as Indonesia, where ambient temperatures regularly exceed 30°C. Skoplaki and Palyvos [9] further elaborated on these thermal effects through a comprehensive review of module efficiency models, concluding that accurate temperature correction is essential for reliable energy yield prediction in warm climates.

The influence of climatic variability on PV performance across different geographic contexts has been extensively studied. Tahri et al. [8] evaluated the performance of identical PV systems installed in five countries with markedly different climatic conditions, finding that annual energy yields varied by up to 30% across sites despite identical system specifications, with irradiance availability being the dominant driver. Huld et al. [10] developed a high-resolution solar radiation database for estimating PV performance across Europe and Africa, demonstrating the importance of locally resolved meteorological inputs for accurate simulation. Similarly, Song et al. [11] performed a performance assessment of solar PV systems under varying climatic conditions in India, highlighting that monsoon-driven seasonal irradiance variation creates predictable but significant performance cycles that must be accounted for in system design and grid integration.

PVWatts, the simulation tool employed in this study, has been extensively validated and applied in diverse research contexts. National Renewable Energy Laboratory [12] documented the theoretical basis and validation methodology of PVWatts Version 5, confirming its accuracy for predicting AC energy output with mean absolute errors typically below 5% when compared against measured data from operational systems. Gilman et al. [13] further evaluated PVWatts within the broader System Advisor Model (SAM) framework, demonstrating its utility for comparative performance assessments across multiple geographic locations. The tool has been applied in numerous regional studies; for example, Mondol et al. [14] used hourly simulation data to assess the long-term performance of a grid-connected PV system in Northern Ireland, finding strong agreement between simulated and measured monthly energy yields. In a Southeast Asian context, Wittkopf et al. [15] applied PVWatts-equivalent simulation approaches to evaluate rooftop PV potential in Singapore, demonstrating the tool's suitability for tropical urban environments.

Studies specifically addressing solar PV potential and performance in Indonesia and the broader Southeast Asian region have grown in number over the past decade, though geographic coverage remains uneven. Putri et al. [16] analyzed the energy output of a grid-connected PV system in East Java, Indonesia, reporting annual specific yields consistent with the findings of the present study and noting pronounced seasonal variability linked to the monsoon cycle. Govindarajan et al. [5] conducted a regional review of solar energy potential across Southeast

Asia, identifying Indonesia as possessing among the highest irradiance levels in the region, with eastern Indonesian provinces particularly well-suited for large-scale PV development. Duffie and Beckman [17] provided the foundational analytical framework for solar energy engineering that underpins contemporary simulation tools including PVWatts, establishing the mathematical relationships between irradiance, temperature, and energy conversion that remain central to PV performance modeling.

The role of urban morphology and the built environment in shaping PV performance has received growing attention. Freitas et al. [18] reviewed urban solar energy utilization, emphasizing that rooftop PV potential in dense urban areas is constrained not only by available area but also by shading from adjacent buildings and varying roof orientations. Bódis et al. [19] developed a high-resolution geospatial assessment of solar energy potential across Europe, demonstrating that city-level PV potential varies substantially depending on building stock characteristics, a finding with direct relevance to Indonesian urban planning contexts where rooftop area density varies considerably between cities. Melius et al. [20] applied the National Renewable Energy Laboratory's Geospatial Toolkit to assess rooftop solar PV potential across U.S. cities, providing a methodological precedent for the kind of urban-scale simulation analysis undertaken in the present study.

The degradation and long-term performance characteristics of PV systems also bear on the interpretation of simulation-based assessments. Jordan and Kurtz [21] conducted an extensive analytical review of PV degradation rates, reporting a median annual degradation rate of 0.5% for crystalline silicon modules, which implies that actual long-term energy yields from installed systems will gradually decline below initial simulation estimates. Ayompe et al. [22] measured the actual performance of a 1.72 kW rooftop grid-connected PV system over multiple years, confirming that real-world performance closely tracked simulation outputs when accurate meteorological inputs were used, lending credibility to simulation-based approaches such as the one employed here. Jäger-Waldau [23] provided a comprehensive overview of global PV status and perspectives, contextualizing the rapid cost reductions and deployment growth that have made urban solar PV economically viable in developing country contexts including Indonesia.

Despite this growing body of literature, comprehensive multi-city comparative analyses of PV energy production specifically within the Indonesian urban context, using standardized simulation approaches that allow direct inter-city performance comparisons, remain scarce. Most existing Indonesian studies focus on single installations or specific regions without providing the systematic geographic coverage needed to support national infrastructure planning. The present study addresses this gap by applying PVWatts in a standardized comparative framework across three strategically selected Indonesian cities, thereby contributing novel location-specific evidence to support evidence-based solar energy infrastructure planning.

This study addresses the existing research gap in comparative assessments of urban solar photovoltaic (PV) potential across different regions of Indonesia. Unlike most previous studies that focused on individual locations or specific PV installations, this research applies a standardized PVWatts simulation framework to evaluate and compare PV system performance in three major urban areas of Java Island: Serang (Banten Province), Yogyakarta (Special Region of Yogyakarta), and Surabaya (East Java Province). These cities were selected not only to represent the western, central, and eastern regions of Java but also because they exhibit distinct climatic conditions, urban characteristics, and solar resource profiles that are relevant to urban renewable energy planning. By employing identical system configurations across all locations, this study seeks to quantify and compare monthly and annual solar irradiance as well as AC energy production in the selected cities. Furthermore, the study evaluates the spatial and seasonal variability of PV system performance associated with geographic and climatic differences and provides data-driven technical insights to support solar energy infrastructure planning and development in Indonesian urban environments.

METHOD

1. Flow of research

The research workflow employed in this study is presented in Figure 1. The study began with the identification of the research problem and the selection of representative urban areas in Indonesia. Three cities, namely Serang, Yogyakarta, and Surabaya, were selected based on their geographical distribution across western, central, and eastern Java as well as their distinct climatic and urban characteristics. Subsequently, the geographical coordinates of each city were determined and used as input parameters in the PVWatts simulation platform.

A standardized photovoltaic system configuration was then established to ensure comparability among locations. The simulation parameters included a system capacity of 1 kWp, a fixed tilt angle of 10°, an azimuth angle of 180°, crystalline silicon PV modules, a system loss factor of 14.08%, a DC-to-AC ratio of 1.2, and an inverter efficiency of 96%. These parameters were kept constant for all simulations so that differences in performance could be attributed primarily to local climatic and geographic conditions.

PVWatts simulations were subsequently performed for each study location to obtain monthly and annual solar irradiance and AC energy production data. The simulation outputs were then compiled and analyzed through a comparative approach to evaluate spatial and seasonal variations in photovoltaic performance. Finally, the results were interpreted to identify dominant factors affecting PV energy production and to derive technical insights for supporting solar energy infrastructure planning in Indonesian urban environments.

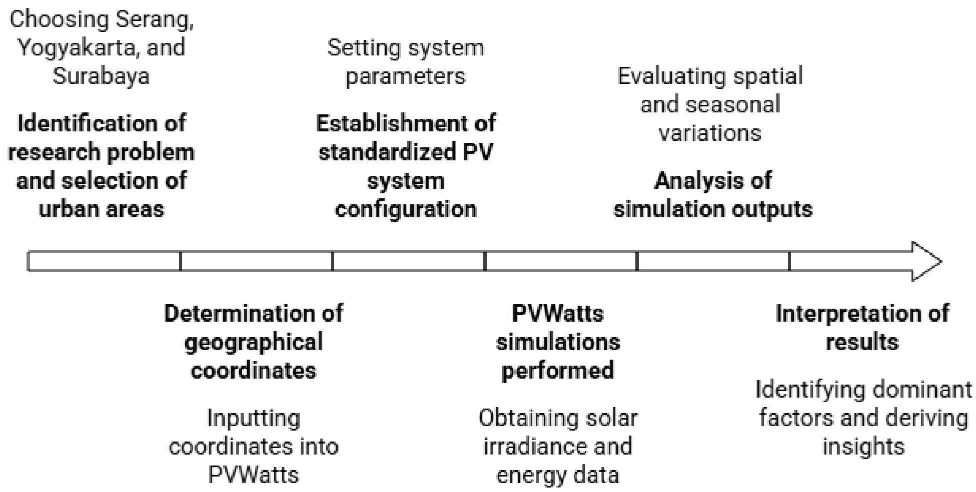

Figure 1. Flowchart of this Research

2. Study Area

Three cities were selected as study locations to represent the geographic and climatic diversity of Java Island, Indonesia. Figure 2 shows the study area. Serang (latitude: 6.12°S, longitude: 106.15°E) is the capital of Banten Province in western Java and is characterized by a tropical monsoon climate with relatively uniform irradiance distribution throughout the year. Yogyakarta (latitude: 7.80°S, longitude: 110.37°E) is situated in the Special Region of Yogyakarta in central Java, featuring a tropical wet and dry climate with more pronounced seasonal irradiance variation. Surabaya (latitude: 7.25°S, longitude: 112.75°E) is the capital of East Java Province and exhibits a tropical savanna climate with the most distinct dry season among the three locations, leading to greater seasonal contrasts in solar energy availability.

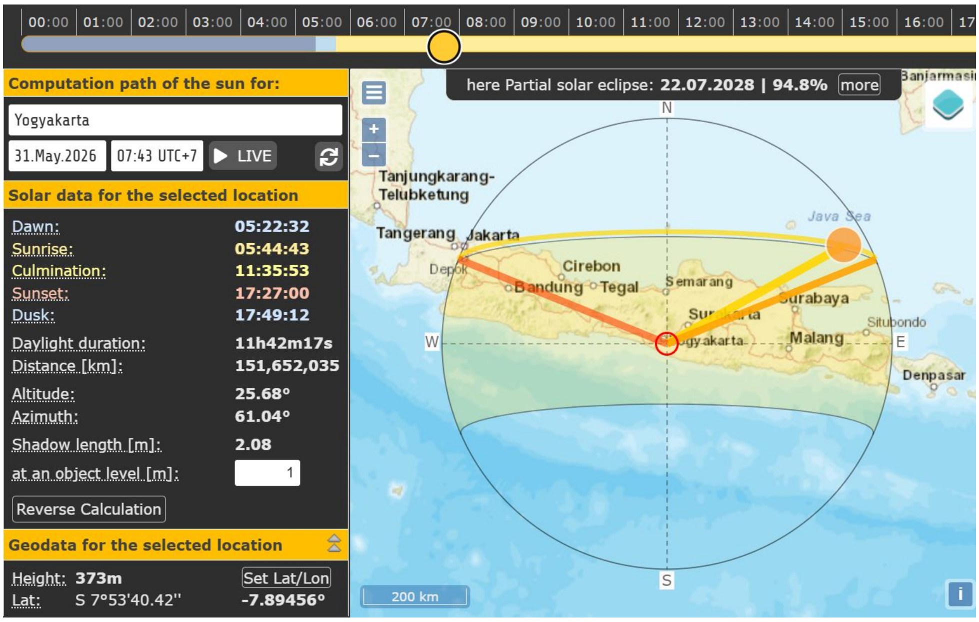

Figure 2. Area of PV Simulation Study

3. Simulation Tool and Parameters

PVWatts Version 5, developed by the National Renewable Energy Laboratory (NREL), was employed as the simulation tool in this study [12]. PVWatts estimates the energy production of grid-connected PV systems using location-specific hourly solar radiation and meteorological data derived from the NASA Surface Meteorology and Solar Energy (SSE) database and the National Solar Radiation Database (NSRDB). The tool computes AC energy output by accounting for system losses including soiling, shading, wiring, connections, and inverter efficiency [13]. Figure 3 shows the display of PV watts used in this study.To ensure comparability across locations, identical system parameters were applied for all three cities. A standard system capacity of 1 kWp was used with a fixed tilt angle of 10° (optimized for equatorial latitudes), south-facing orientation (azimuth 180°), a standard module type (crystalline silicon), and a default system loss of 14.08%. The DC-to-AC ratio was set at 1.2, and the inverter efficiency was maintained at 96%. These standardized parameters allow direct attribution of performance differences to climatic and geographic factors rather than system configuration variables.

Figure 3. Display of PVWatts

4. Data Collection and Analysis

Simulation runs were executed for each city location, generating monthly and annual outputs for two primary variables: (1) solar irradiance (kWh/m²/day), representing the average daily solar radiation received per unit area; and (2) AC energy production (kWh), representing the estimated monthly electrical energy output of the PV system. Annual totals were subsequently derived from the monthly simulation outputs.

Comparative analysis was conducted to identify performance patterns across cities and months, with particular attention to seasonal variations associated with the Indonesian monsoon cycle. The relationship between solar irradiance and energy output was also evaluated to assess the consistency of conversion efficiency across different climatic conditions. All data processing and tabulation were performed using Microsoft Excel.

RESULT AND DISCUSSION

1. Annual Solar Irradiance and Energy Production

Table 1 presents the annual average solar irradiance and total AC energy production for all three study cities. Surabaya recorded the highest annual performance across both indicators, with an average solar irradiance of 5.54 kWh/m²/day and a total annual AC energy output of 1,501 kWh. Yogyakarta ranked second with 5.27 kWh/m²/day and 1,442 kWh annually, while Serang recorded the lowest values at 5.02 kWh/m²/day and 1,360 kWh. The difference in annual energy production between the highest-performing city (Surabaya) and the lowest (Serang) amounts to 141 kWh per kWp installed capacity, representing a 10.4% performance advantage for Surabaya.

Table 1. Annual Solar Irradiance and AC Energy Production by City

City	Solar Rad. (kWh/m²/day)	AC Energy (kWh/year)
Serang, Banten	5.02	1,360
Yogyakarta	5.27	1,442
Surabaya, East Java	5.54	1,501

2. Monthly Solar Irradiance by City

Table 2 presents the monthly solar irradiance values for all three cities. Consistent seasonal patterns are evident across all locations, with irradiance values peaking during the dry season months (June September) and reaching minimum levels during the wet season (November February). September recorded the highest irradiance in both Serang (5.77 kWh/m²/day) and Yogyakarta (6.70 kWh/m²/day), while Surabaya achieved its peak in September as well (7.18 kWh/m²/day). Minimum irradiance was recorded in December for Serang (4.05 kWh/m²/day) and Surabaya (3.91 kWh/m²/day), and in November for Yogyakarta (3.63 kWh/m²/day).

Table 2. Monthly Solar Irradiance (kWh/m²/day) by City

Month	Serang, Banten	Yogyakarta	Surabaya, East Java
January	4.10	4.29	4.53
February	4.70	4.61	4.92
March	4.96	5.17	4.83
April	5.37	5.49	4.97
May	5.30	5.75	6.02
June	5.46	5.70	6.15
July	5.56	5.60	6.44
August	5.75	6.23	7.11
September	5.77*	6.70*	7.18*
October	4.86	5.98	5.69
November	4.30	3.63*	4.78
December	4.05*	4.14	3.91*
Annual Avg.	**5.02**	**5.27**	**5.54**

3. Monthly AC Energy Production by City

Monthly AC energy production data are summarized in Table 3. Surabaya consistently achieved the highest monthly energy output during peak irradiance months, reaching a maximum of 164 kWh in August. An interesting discrepancy was observed in Surabaya, where the highest energy output occurred in August (164 kWh) despite September recording the higher solar irradiance value (7.18 vs. 7.11 kWh/m²/day). This is attributable to the greater number of daylight hours in August relative to September, as well as the influence of ambient temperature on PV conversion efficiency, whereby the slightly lower temperatures in August may have contributed to marginally improved module performance, consistent with findings reported by Dubey et al. [7] and Skoplaki and Palyvos [9]. For Yogyakarta, peak energy output of 150 kWh was recorded in September, coinciding with the peak irradiance month. Serang peaked at 133 kWh in August, reflecting a similar month-length and temperature effect.

Table 3. Monthly AC Energy Production (kWh) by City

Month	Serang, Banten	Yogyakarta	Surabaya, East Java
January	95	100	105
February	98	96	101
March	114	118	110
April	119	122	110
May	122	135	139
June	122	129	139
July	129	132	150
August	133*	146	164*
September	128	150*	159
October	111	138	130
November	95	80*	104
December	94*	96	90*
Annual Total	**1,360**	**1,442**	**1,501**

4. Geographic and Climatic Drivers of Performance Variation

The results demonstrate a clear east-to-west performance gradient across Java Island, with Surabaya outperforming both Yogyakarta and Serang in terms of annual solar irradiance and energy production. This gradient is primarily attributable to the influence of the Australian Monsoon system, which brings stronger and more prolonged dry season conditions to eastern Java compared to the western regions [24]. During the dry season (June September), Surabaya receives significantly higher solar irradiance due to reduced cloud cover, lower atmospheric moisture content, and fewer precipitation events, all of which directly enhance the solar resource available to PV systems. These findings are consistent with those of Govindarajan et al. [5], who identified a similar east west irradiance gradient across the Southeast Asian region.

Serang, located in western Java adjacent to the Sunda Strait, is more strongly influenced by moisture-laden air masses from the Indian Ocean and the Java Sea, resulting in more persistent cloud cover throughout the year and a comparatively lower annual irradiance. The relatively uniform monthly irradiance distribution observed in Serang (range: 4.05 5.77 kWh/m²/day) compared to Surabaya (3.91 7.18 kWh/m²/day) reflects this climatic moderation effect, corroborating observations by Tahri et al. [8] regarding the dominant influence of local climate on inter-site PV performance variation. From a planning perspective, Serang's more stable irradiance profile offers predictability advantages, while Surabaya's higher peak values offer greater energy yield potential but require more robust system sizing and storage considerations to manage seasonal variability.

5. Seasonal Energy Production Patterns

Figure 4 provides a clear comparison of the annual AC energy production achieved by the simulated 1 kWp photovoltaic system in the three study cities. The results indicate a consistent increase in annual energy yield from western to eastern Java, with Surabaya recording the highest annual AC energy production of 1,501 kWh, followed by Yogyakarta at 1,442 kWh and Serang at 1,360 kWh. Compared with Serang, the annual energy output in Surabaya is approximately 10.4% higher, while Yogyakarta demonstrates an intermediate performance level with an increase of approximately 6.0% relative to Serang. These differences are closely associated with variations in annual solar irradiance, where Surabaya exhibits the highest solar resource availability (5.54 kWh/m²/day), followed by Yogyakarta (5.27 kWh/m²/day) and Serang (5.02 kWh/m²/day). The observed trend confirms the strong dependence of photovoltaic energy production on local solar resource conditions and highlights the influence of geographic and climatic factors on system performance. From an infrastructure planning perspective, the higher annual energy yield observed in Surabaya suggests a greater technical potential for photovoltaic deployment, whereas the more moderate performance of Yogyakarta and Serang reflects the need to consider local climatic characteristics when evaluating solar energy development strategies in Indonesian urban areas.

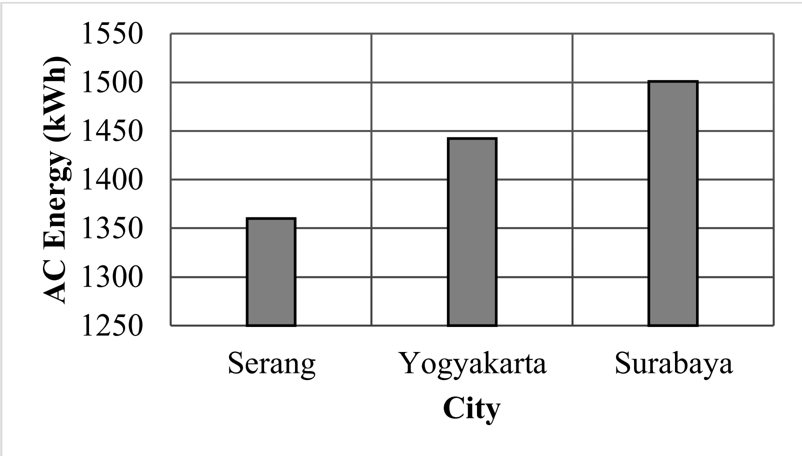

Figure 4. AC Energy Production Comparison for Serang, Yogyakarta, and Surabaya

The pronounced seasonality of solar PV performance across all three cities has significant implications for urban energy planning. The wet season months of November through February consistently recorded the lowest energy outputs, with minimum values of 94 kWh (Serang, December), 80 kWh (Yogyakarta, November), and 90 kWh (Surabaya, December). These reductions represent decreases of approximately 29 47% relative to peak production months, underscoring the importance of incorporating seasonal variability into PV system design and grid integration strategies, as highlighted by Song et al. [11] for comparable monsoon-influenced environments in South Asia.

The dry season months of June through September offer the strongest energy production opportunities across all cities. Energy planners and policymakers should leverage this seasonal window to maximize grid export, charge storage systems, or schedule energy-intensive activities. The correlation between the dry season onset and peak PV performance also aligns with periods of typically high urban cooling loads in Indonesian cities, suggesting a natural demand supply alignment that could be exploited in building-integrated PV applications, as discussed by Freitas et al. [18] in the context of urban solar utilization strategies.

6. Implications for Infrastructure Planning

The simulation results provide several actionable insights for solar energy infrastructure planning in Indonesian urban areas. First, the superior annual energy yields in Surabaya suggest that eastern Java represents a priority zone for large-scale urban PV deployment, particularly for rooftop and building-integrated systems. Second, the relatively stable irradiance profile of Serang, while yielding lower annual totals, may be advantageous for grid stability purposes, as it reduces the magnitude of seasonal fluctuations that planners must accommodate. Third, Yogyakarta's intermediate position and its notably low November irradiance (3.63 kWh/m²/day) highlight the need for carefully sized backup capacity or hybrid energy solutions during the transition months between wet and dry seasons, consistent with recommendations by Bódis et al. [19] for geospatially differentiated solar infrastructure planning.

From a policy standpoint, these findings support differentiated regional incentive structures for solar PV adoption in Indonesia. Regions with higher irradiance and energy yield potential, such as Surabaya and similarly situated eastern Indonesian cities, may justify higher upfront investment in PV capacity, while western cities may benefit more from hybrid solar-storage systems that smooth out inter-seasonal variability. These recommendations align with the Indonesian government's National Energy Policy (KEN) targets, which aim to increase the share of new and renewable energy to 23% of the national energy mix by 2025 [6], and are further supported by Jäger-Waldau's [23] analysis of the economic case for urban PV deployment in developing economy contexts.

7. Limitations and Future Research Directions

This study is subject to several limitations that should be acknowledged. First, the PVWatts simulation relies on historical meteorological data and does not account for future climate change scenarios, which may alter irradiance patterns and temperature conditions over the system's operational lifetime. Second, the analysis was conducted using standardized system parameters and did not account for site-specific factors such as shading from adjacent urban structures, dust accumulation, or local grid infrastructure constraints, factors identified by Freitas et al. [18] as important determinants of real-world urban PV yields. Third, the study is limited to three cities on Java Island and does not represent the full geographic and climatic diversity of Indonesia.

Future research should extend this comparative framework to additional Indonesian cities across Sumatra, Kalimantan, Sulawesi, and eastern Indonesia, where irradiance conditions may differ substantially. Integration of PVWatts results with economic analysis tools such as the System Advisor Model (SAM) [13] or HOMER Pro would enhance the practical applicability of findings for investment planning. Additionally, validation of simulation outputs against measured data from operational PV installations in the study cities, following the approach of Ayompe et al. [22], would strengthen confidence in the simulation-based methodology. Long-term performance projections should also incorporate module degradation rates documented by Jordan and Kurtz [21] to provide realistic lifetime energy yield estimates.

CONCLUSION

This study presented a PVWatts-based comparative assessment of solar photovoltaic energy production potential across three Indonesian urban areas: Serang, Yogyakarta, and Surabaya. The simulation results demonstrated consistent east-to-west performance gradients, with Surabaya achieving the highest annual AC energy output of 1,501 kWh/kWp, followed by Yogyakarta (1,442 kWh/kWp) and Serang (1,360 kWh/kWp). All cities exhibited pronounced seasonal performance variation driven by the Indonesian monsoon cycle, with peak production during the dry season (June September) and minimum production during the wet season (November February). The temperature-induced discrepancy between peak irradiance months and peak energy production months, observed in both Serang and Surabaya, is consistent with established findings on thermal efficiency losses in crystalline silicon modules.

The findings provide a data-driven foundation for regionally differentiated solar energy infrastructure planning in Indonesia. Surabaya and similarly situated eastern Indonesian cities

represent high-priority zones for large-scale PV deployment, while western cities such as Serang may benefit from hybrid solar-storage configurations to manage lower but more stable irradiance conditions. These results contribute to the evidence base supporting Indonesia's national renewable energy transition objectives and demonstrate the utility of standardized simulation approaches for multi-city PV performance assessment.
The methodology employed in this study combining standardized PVWatts simulation parameters with comparative spatial analysis offers a scalable and replicable framework for extending similar assessments to other Indonesian cities and to tropical developing nations with comparable climatic conditions and renewable energy planning needs.

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