International Journal of Electrical and Computer Engineering (IJECE)
Vol. 15, No. 4, August 2025, pp. 3603~3612
ISSN: 2088-8708, DOI: 10.11591/ijece.v15i4.pp3603-3612

Design strategies for solar photovoltaic integration in rural areas

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Article Info

Article history:

Received Sep 4, 2024
Revised Mar 5, 2025
Accepted Mar 20, 2025

Keywords:

Rural electrification
Solar energy
Solar irradiance
Solar system sizing
Tilt angle variation

ABSTRACT

This study explores the optimization of photovoltaic (PV) systems in the Sungai Tiang Camp region, Malaysia, with a focus on determining the ideal tilt angles to maximize energy generation in a tropical environment while incorporating a cost analysis. While existing studies optimize tilt angles for energy maximization in temperate regions, this study addresses the unique climatic and socio-economic conditions of rural Malaysia. Unlike fixed-tilt assumptions common in prior work, this research explores cost-effective, manually adjustable systems tailored for local weather patterns and rural affordability. To address this, the study examines the relationship between tilt angle, solar irradiance, temperature and output power. The results are analyzed to identify optimal configurations. Results reveal that tilt angles between 5° and 10° deliver the highest energy output, with slight seasonal adjustments for efficiency improvement. These findings align with Malaysia's tropical solar profile, offering practical insights for micro-scale solar deployments in similar climates. By addressing the unique needs of remote areas, this research contributes to bridging the gap in localized PV studies. Its outcomes not only enhance the understanding of solar PV performance in tropical conditions but also provide valuable guidelines for rural electrification and sustainable energy solutions in equatorial regions worldwide.

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1. INTRODUCTION

According to Malaysia Energy Information Hub [1], the essential for energy in Malaysia is rising drastically in every sector including industrial, transport, agriculture, and residential. Figure 1 illustrates how Malaysia's energy demand is rising annually. It is apparent that the transportation sector's increasing demand is responsible for the largest overall increase in energy consumption, even in the face of a significant decline in manufacturing production. The issue with the increase in energy use is that energy resources, particularly fossil fuels, are running out [2] and this limitation has an effect on the rural area's energy division. Given that rural locations typically have ample space and an abundance of energy resources, particularly solar energy resource obtained through sunlight, there are increasing numbers of solar energy intervention being focused especially in rural area in Malaysia in order to reduce the overall annual cost of electricity and also carbon emissions [3]. Solar intervention programs, which target at areas that are poorer and endowed with greater solar radiation, can potentially make an unprecedented contribution to poverty reduction [4]. Amidst the numerous challenges related to economic and infrastructure development, solar photovoltaic (PV) technology stands out as a clean and efficient means of generating energy. This technology has the potential to alleviate the nation's chronic lack of electricity, and standalone PV systems can serve as a practical and quick substitute for electricity in households [5], [6].

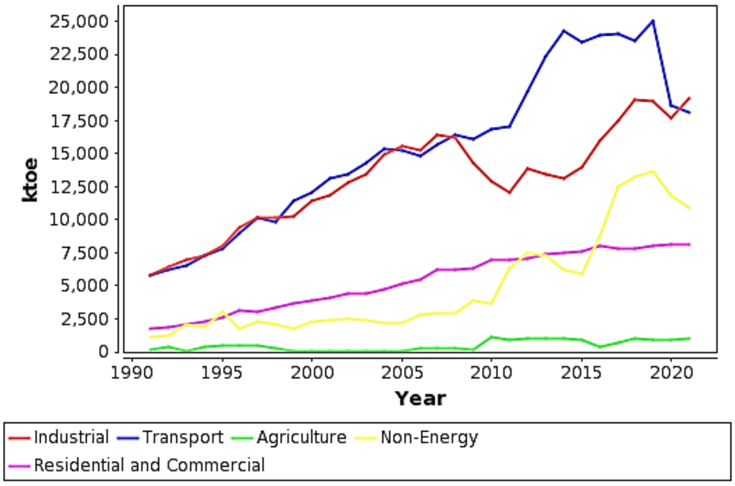

Figure 1. Energy demand in Malaysia by sector

Malaysia still has some ways to go before reaching its 2025 target of 20% renewable energy penetration. Just 2% of the nation's electricity is now produced by renewable energy sources, such as solar energy [7]. Since solar mini- and micro-grids can meet larger levels of demand, they have also experienced significant expansion. Nonetheless, they exhibit characteristics of both off-grid and on-grid solutions, especially when considering the economic strategy [8]. Rural Malaysia faces energy scarcity, driven by limited access to reliable electricity and a dependence on costly and unsustainable fossil fuel-based systems. While government initiatives have focused on promoting renewable energy, there remains a gap in region-specific research for rural solar PV system design. Most studies have emphasized large-scale solar farms or urban electrification, leaving rural off-grid areas with minimal attention. This creates inefficiencies in solar PV implementation and limits its potential as a cost-effective energy solution for rural communities.

In South East Asia, Malaysia has been competitive along with Vietnam and Thailand since 2011 in term of solar PV intervention with numerous governmental interventions for solar PV development are being initiated across the country due to its solar irradiation advantage and plummeting solar system cost [9]. To avoid the problem of growing electricity prices in the near future, numerous stakeholders must launch a variety of initiatives and strategies to promote this green energy. One way to help in this endeavor as well as reduce rural poverty would be to introduce community programs that may finance the rural villages' construction of solar power systems [10]. Among all, Safari *et al.* [11] investigates the rural populace's acceptability of renewable energy in Mersing, Johor, should it be delivered there. With PV module orientation estimation, the ideal tilt angle of the solar system to be placed in an ecotourism center in Sabah is depicted in [1]. Studies [12], [13] suggest using picture segmentation to determine the best places to build renewable energy in isolated areas without access to electricity in Sabah and Sarawak.

Despite the numerous solar interventions in Malaysia, particularly in Perak, rural applications remain limited, especially in smaller, remote settlements like Sungai Tiang Dua. Perak, with its undeveloped areas still facing issues of rural isolation and poverty, has made significant efforts to implement solar energy solutions. For instance, study [14] focuses on hybrid renewable systems incorporating rainfall energy, offering insights into diversifying energy sources for rural areas, while study [15] emphasizes localized system sizing for Malaysian rural homes, laying a foundation for effective energy solutions. While these studies focus on hybrid and rural systems, they do not address the specific needs of more remote locations like Sungai Tiang Dua.

Other studies, such as those in Kampar, Perak [16], focus on solar PV systems for residential areas, while large-scale solar farm projects in more urbanized regions like Perak Tengah [17], Tahfiz institutions

[18], Universiti Utara Malaysia [19] and charity home [20] have been explored. Additionally, studies such as studies [21] and [22] highlight community-based solar lighting projects aimed at enhancing energy security in urbanized regions, while study [23] addresses solar aid relief for flood-affected areas in Malaysia's Felda regions. Another intervention, explored in [24], applies solar PV lighting for safety measures in Puncak Iskandar, Perak.

However, none of these studies comprehensively cover the challenges faced by smaller, more remote rural settlements like Sungai Tiang Dua, where energy access remains a significant issue. Unlike the larger urban-based or hybrid systems presented in previous research, Sungai Tiang Dua's unique environmental conditions—including high rainfall, frequent cloud cover, and the need for off-grid energy solutions—require a more tailored approach to solar PV design. Some studies including [14] depicts tilt angle considerations as part of overall system sizing, but did not delve deeply into how seasonal and climatic variations impact optimal tilt configurations. This limitation is particularly significant in regions like Sungai Tiang Camp, where high rainfall, frequent cloud cover, and the need for maximum energy generation in off-grid areas present unique challenges. Tilt angle variation is a critical aspect not fully explored in previous studies, especially in such a challenging environment. This study aims to fill this gap by focusing on the tailored solar PV solutions necessary for such locations, ensuring sustainable, cost-effective, and efficient energy generation that meets the unique demands of remote areas to contribute to Malaysia's renewable energy targets by 2025 [25].

2. RESEARCH METHOD

2.1. Site selection for micro scale PV deployment

Sungai Tiang Camp, a rural recreational area in Perak, Malaysia, was chosen as the study site due to its isolated location and potential for solar energy generation. Reached exclusively by boat, the settlement is completely off the national electricity grid and relies on diesel and gasoline generators for its energy needs. This conservation park, located in the Hulu Perak District at coordinates 5°40' N, 101°23' E, receives an average daily solar irradiance of 4.7 kWh/m² and an average daily temperature of 24.75 °C [26]. Similar studies, such as those in remote areas of Sabah, have highlighted the viability of solar PV systems in isolated off-grid locations with comparable solar irradiance levels, demonstrating the potential for solar solutions in such areas. However, Sungai Tiang Camp presents a unique case due to its specific environmental conditions, including its reliance on non-renewable generators and remote accessibility, making it an ideal site for exploring solar energy optimization strategies.

2.2. Micro solar PV system sizing and specifications

The technical approach to micro-grid sizing in this study is based on estimated consumption for capacity and forecast demand techniques tailored to Sungai Tiang Hamlet. The sizing methodology, modeled using simulation software PVsyst, simulates energy output from the solar PV system under varying tilt angles, similar to the methodology applied in [27]. This approach is aligned with studies that suggest solar PVs can supply rural households with electricity for 2 to 6 hours a day [28]. For this project, monocrystalline solar panels are selected for their higher efficiency (up to 20%), making them ideal for the limited area available. The sizing process involves determining the correct solar panels, batteries, inverters, and other components based on specific energy needs.

The average solar peak hours at Sungai Tiang are 4 hours/day, a crucial factor in determining the system size. This corresponds to the duration of time when sunlight is strong enough to produce the panel's maximum rated output. To calculate the system size, the theoretical formula in (1) is used.

$$System\ Size\ (Wp) = \ (Wh\ \times\ n)\ /\ Peak\ sun\ hours \tag{1}$$

The solar PV correction factor (n) adjusts for temperature-induced efficiency losses in photovoltaic systems. As temperatures rise, the efficiency of PV modules typically decreases, with a common temperature coefficient of around -0.5% per degree Celsius for crystalline silicon modules. In Malaysia, where average temperatures can reach 34 °C, this loss is particularly significant, and studies, such as one conducted in Perlis, highlight the decrease in output with higher operating temperatures [29]. Therefore, a correction factor of 0.8 is applied to account for these temperature effects, ensuring more accurate energy output calculations for systems in high-temperature environments like Sungai Tiang.

$$Solar\ PV\ Array = \ System\ size\ (Wp)\ /\ Solar\ panel\ rated\ power\ peak \tag{2}$$

Study in [30] have highlighted the importance of maximizing both the solar PV array and the battery bank size to meet energy requirements, particularly in rural settings. The current study follows a similar approach by accounting for both solar radiation and daily energy needs to calculate the required components. A key part of this design is the battery capacity, which is determined using (3).

$$Battery\ Capacity\ (Ah) = Wh\ /\ (nominal\ voltage\ battery) \quad (3)$$

By integrating a maximum power point tracking solar charge controller for efficient energy storage, this design ensures that the battery storage and solar panels are optimized for the daily energy needs of the camp.

2.3. Measurements and data collections

A solar irradiance meter was employed to directly measure the solar irradiance at the study site, recording the intensity of solar radiation in watts per square meter (W/m²) at various intervals throughout the day, with a particular focus on peak sunlight hours between 11 AM and 3 PM. In addition, energy production data from existing solar photovoltaic (PV) installations in nearby rural areas were sourced from local utility providers and academic studies, providing a comprehensive baseline for validating the simulation results for Sungai Tiang Camp. This comparison ensured that the data-driven models accurately reflected real-world performance. Furthermore, the collected data encompassed a range of tilt angles (0° to 45°) to optimize energy production, thereby enabling a thorough investigation of the impact of tilt angle variations on the overall efficiency of the system [31].

Data for this study were collected by positioning photovoltaic (PV) panels at four distinct tilt angles—0°, 15°, 30°, and 45°—at a location with optimal exposure to solar irradiance to assess the impact of tilt angle variations on energy production. Measurements were recorded from 09:00 to 17:00 at 30-minute intervals. The relationship between the tilt angle and the power output of the solar panels, particularly at the maximum power point (MPP), is critical for optimizing solar energy production. The MPP represents the point on the current-voltage curve where the product of current (I) and voltage (V) reaches its maximum, thereby maximizing the power output of the panel. The tilt angle plays a significant role in determining the amount of sunlight that the panel receives throughout the day and across different seasons. Empirical data typically shows a peak in power output as a function of the tilt angle, corresponding to the optimal angle that maximizes irradiance capture and thus power output. If the tilt angle deviates from this optimal configuration, whether too steep or too shallow, the effective irradiance decreases, leading to a reduction in power generation. This phenomenon is governed by the fact that the power output is highest when sunlight strikes the panel perpendicularly. This methodology mirrors approaches used in prior studies such as [32], which investigated the influence of tilt angle variations on solar panel efficiency and energy output.

3. RESULTS AND DISCUSSION

3.1. Solar PV system sizing and cost computations

The hourly energy consumption is determined by summing the total energy usage of all appliances and devices to be powered by the solar PV system throughout the day, as detailed in Table 1. Given the average solar peak hours of 4 hours/day and a correction factor of $n = 0.8$, the required size of the solar PV system is calculated in terms of Watt-peak (Wp), based on its energy consumption in Watt-hour (Wh) as per (4). Once the Watt-peak value is established, the appropriate solar PV array size is determined. This calculation incorporates the energy requirements of essential electrical equipment for a single camp. Using (5), the total number of units required for the system is then calculated. Additionally, the battery capacity in Ampere-hour (Ah) and the associated charging rate are determined through (6) and (7), respectively, as outlined below.

Table 1. Hourly energy consumption in 1 unit camp

No.	Equipment	Quantity	Watt (W)	Usage per day (Quantity×Watt×Hours/day)	Total Watt per hour in a day
1	T8 LED Light	3	18	3×18W×6h	324 Wh
2	Stand Fan	1	58	1×58W×6h	348 Wh
3	Phone charger	1	15	1×15W×2h	30 Wh
		Total usage for single camp (Wh)			702

$$\begin{aligned} System\ Size\ (Wp) &= (Wh \times n)/Peak\ sun\ hours \\ &= (702\ Wh \times 0.8)/4\ hours = 140.4\ Watt\ peak \end{aligned} \quad (4)$$

$$\begin{aligned} Solar\ PV\ Array &= System\ size\ (Wp)\ /\ Solar\ panel\ rated\ power\ peak \\ &= 140.4\ Wp\ /100\ Wp = 1.404\ units \\ &\approx 2\ units\ of\ solar\ panel\ rated\ 100\ W \end{aligned} \quad (5)$$

$$Battery\ Capacity\ (Ah) = Wh\ /\ (nominal\ voltage\ battery)$$
$$= (702\ Wh)\ /\ (24\ V) =\ 29.25\ Ah\ per\ day \quad (6)$$

$$Charging\ Time\ (hours) = Battery\ Capacity(Wh)/(Solar\ Panel\ Power)$$
$$= (30\ Ah \times 24\ V)\ /\ (100\ W) = 7.2\ hours \quad (7)$$

The nominal voltage of the battery is 24 V whereas the solar panel's output ranges from 12 to 24 V. The solar charge controller will maximize the parameter that the battery can get in order to shield it from harm. A 24 V, 30 Ah battery would provide adequate storage for the load. The charging time required to fill the battery from 0% to 100% is 7.2 hours. Given that the single camp, estimated total energy consumption is 140.4 Watts, the inverter size ought to be 25% to 30% larger than the load. For this reason, the inverter needs to be 200 watts or larger. The project's cost breakdown is shown as follows. This project can save RM988.00 per unit and reserve the consumption of fossil fuels for a single diesel generator that costs RM 2000.00 and uses fossil fuels.

a. 2×Monocrystalline Solar panel 100 Wp	: RM 350.00
b. Battery 30 Ah	: RM 220.00
c. Inverter 1000 w	: RM 140.00
d. MPPT solar charge controller	: RM 102.00
e. System mounting structure	: RM 100.00
f. Balance of system (BOS)	: RM 100.00
Total	: RM 1012.00

3.2. Optimal tilt angle

Based on the data presented in Figure 2, which shows the average power output (W) for different tilt angles (0°, 15°, 30°, and 45°) throughout the day, the optimal tilt angle varies depending on the time of day. In the morning (9:00 AM to 11:00 AM), panels with a tilt angle of 45° generate the highest power output. This is likely due to the steeper angle optimizing solar capture as the sun is lower in the sky during these early hours. As the day progresses and the sun rises higher, the 45° tilt angle becomes less effective. During midday (11:30 AM to 2:00 PM), panels with a tilt angle of 30° consistently achieve the highest power output. This reflects an optimal alignment with the sun’s position at its zenith, making 30° the most efficient tilt angle during peak sunlight hours. This midday performance is critical for maximizing daily energy generation. In the afternoon (2:30 PM to 5:00 PM), the tilt angles of 15° and 0° perform better than steeper angles. Among these, the 15° tilt angle provides more consistent power generation, especially as the sun lowers in the sky, making it an effective choice for late-day energy capture.

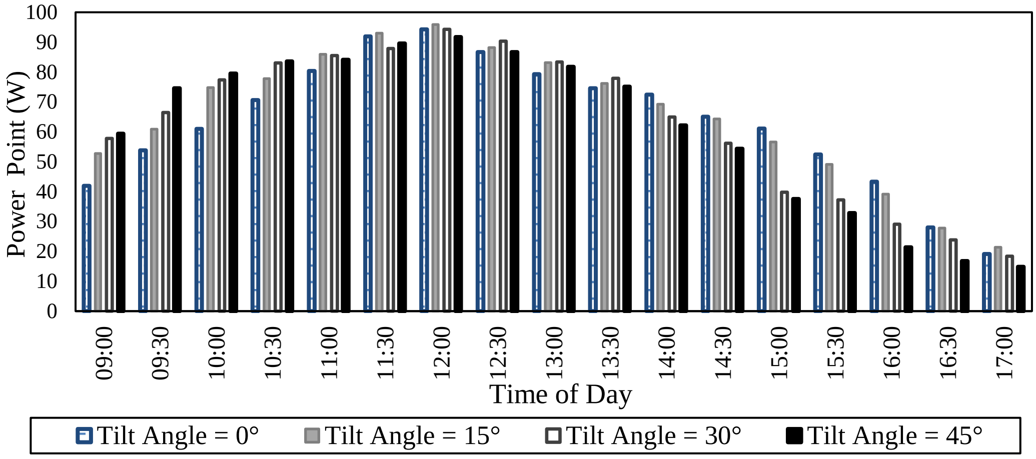

Figure 2. Average power point for variations in solar PV tilt angle

Based on these observations, a 30° tilt angle is recommended for fixed-tilt installations, as it provides the highest overall power output throughout the day. For systems with manually adjustable or seasonal tilts, a combination of 45° for early mornings and 15° for late afternoons could further optimize energy output, particularly in tropical climates with variable solar paths. Fixed solar panels, which typically rely on a compromise tilt angle to optimize annual energy output, are less effective compared to adjustable panels that can be repositioned to follow optimal angles throughout the year. As highlighted in [33], mid-range tilt angles like 15° and 30° have proven to be effective for tropical regions. This study builds on such findings by analyzing the interplay of tilt configurations at Sungai Tiang Camp. The data show that while 45° and 30° tilt angles are advantageous at sunrise, their effectiveness diminishes after midday, whereas the 0° and 15° configurations maintain higher efficiency throughout the afternoon.

By comparing fixed and adjustable tilt configurations, this research emphasizes the importance of dynamic optimization for PV systems in rural areas like Sungai Tiang Camp. These findings underscore the potential of tilt-angle adjustments to maximize solar power generation and meet local energy demands more effectively. This tilt angle variation can be effectively applied in Sungai Tiang Camp and also as a guideline to similar tropical climates to enhance photovoltaic system efficiency.

3.3. Irradiance effect on maximum power point voltage

The relationship between irradiance and the maximum power point voltage (Vmp) is crucial for optimizing solar panel performance under varying sunlight conditions. Irradiance, measured in W/m², directly affects Vmp, which determines the panel's maximum power output. As shown in Figure 3, Vmp increases gradually with irradiance from early morning (9:00 AM) to peak hours (around 3:00 PM), driven by enhanced charge carrier generation. However, thermal effects beyond this point temper further increases in Vmp despite higher irradiance. These findings underscore the intricate balance between irradiance and Vmp in maintaining high efficiency under real-world conditions.

Previous studies, such as [33], have highlighted the nonlinear relationship between Vmp and irradiance, particularly the temperature-induced losses at higher irradiance levels. This work addresses gaps in earlier research by providing a detailed hourly analysis, capturing the influence of tropical sunlight cycles on Vmp. Unlike past studies focusing solely on peak sunlight hours, this study identifies the distinct impact of morning irradiance increases on Vmp due to cooler temperatures. A key challenge resolved here is incorporating real-time temperature effects, offering a more practical approach to optimizing solar PV systems under dynamic. conditions. This research builds on prior work while tackling the challenge of understanding Vmp behavior under varying irradiance and temperature conditions in a tropical environment. The insights provided are essential for improving solar PV system design and efficiency, especially through better thermal management strategies.

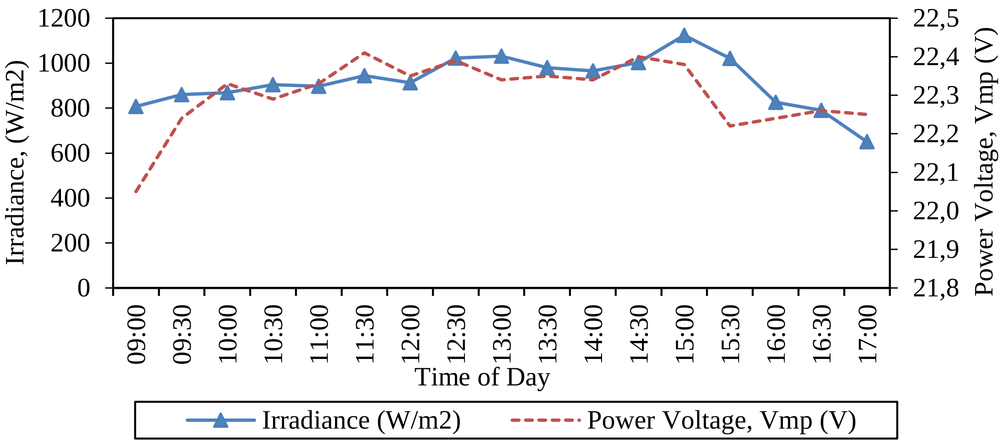

Figure 3. Irradiance effect on maximum power point voltage

3.4. Temperature effect on maximum power point voltage

This study highlights the interplay between temperature and irradiance on the maximum power point voltage (Vmp) of photovoltaic (PV) systems. As depicted in Figure 4, Vmp initially rises with increasing temperature and irradiance from 9:00 am to 3:00 pm. However, after 3:00 pm, the Vmp stabilizes or slightly declines, suggesting that thermal effects at higher temperatures begin to dominate, counteracting the benefits of irradiance. This indicates that elevated temperatures can lead to efficiency losses in PV systems.

The observed trends align with findings by [34], who reported a stronger negative impact of temperature compared to the positive influence of irradiance on Vmp. A notable strength of this study is its comprehensive real-time data collection, which provides detailed insights into diurnal variations. However, the lack of data during the evening limits a full understanding of PV system performance. Additionally, the stabilization of Vmp after 3:00 pm suggests the presence of counteracting factors that require further investigation.

This study underscores the critical balance between irradiance and temperature in determining PV efficiency. While irradiance positively affects Vmp, excessive heat significantly diminishes performance, as seen after 3:00 pm. These findings are particularly relevant for optimizing PV systems in high-temperature environments. Future studies should explore innovative cooling strategies and materials to mitigate thermal effects and investigate the specific thresholds at which temperature effects outweigh irradiance gains.

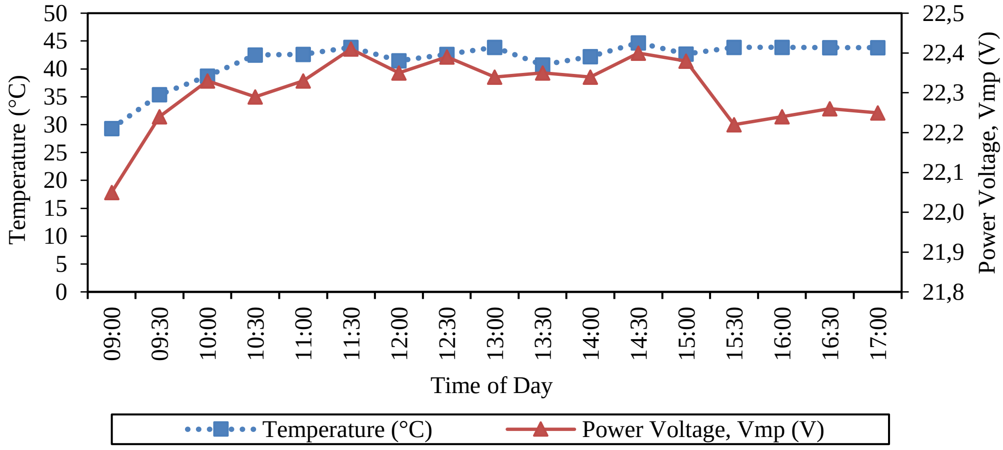

Figure 4. Temperature effect on maximum power point voltage

3.5. Battery charging time

The battery charging profile in Figure 5 demonstrates a consistent increase in the state of charge (SoC) over time, reaching 100% at approximately 480 minutes. The charging process shows a near-linear increase during the early and middle stages, indicating steady energy input. However, a slight tapering is observed as the SoC approaches full capacity, suggesting a controlled charge saturation phase to prevent overcharging.

This finding is consistent with prior studies, such as those by [34], which emphasize the importance of a controlled tapering phase during battery charging to extend lifespan and ensure safety. The strength of this study lies in the clear depiction of charging dynamics over an extended period. However, it lacks insights into potential thermal effects during charging, which could impact efficiency and safety. The linearity of the early-stage charging also warrants further exploration to identify any system-specific optimizations. This study provides a comprehensive analysis of the battery charging rate, showcasing a smooth progression towards full capacity. The results are significant for optimizing charging protocols in renewable energy systems.

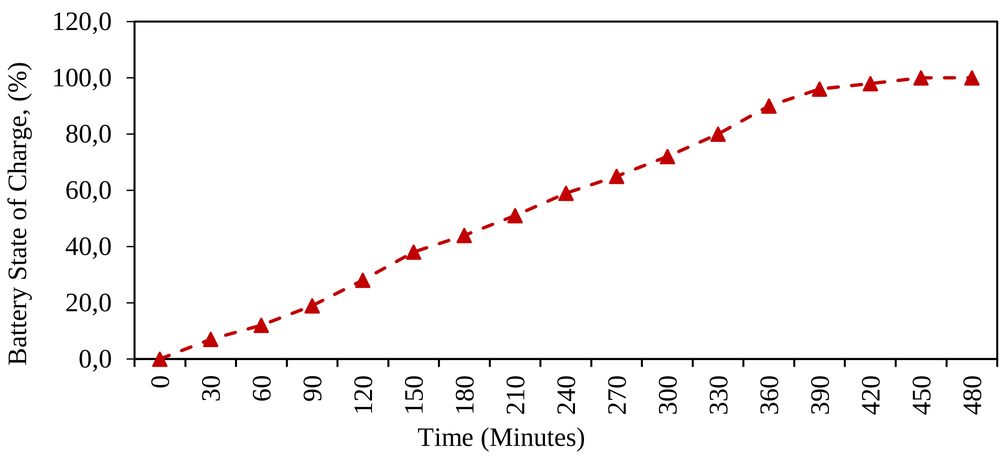

Figure 5. Battery charging rate

4. CONCLUSION

This study advances the understanding of photovoltaic (PV) system optimization in tropical environments, specifically for rural applications like Sungai Tiang Camp in Malaysia. Unlike previous studies that predominantly address urban areas temperate regions or rely on fixed-tilt configurations, this research explores cost-effective, adjustable systems tailored to local climatic and socio-economic conditions. By evaluating the relationships between tilt angle, solar irradiance, temperature, and energy output, the study identifies optimal configurations, with tilt angles of 5° to 10° proving most effective for maximizing energy generation under Malaysia’s tropical solar profile.

The novelty of this study lies in integrating localized cost analysis, detailed performance modeling, and seasonal tilt angle adjustments for micro-scale solar deployments. It also provides actionable insights for rural electrification by demonstrating how simple, manually adjustable systems can balance energy efficiency with affordability. Additionally, the research contributes to bridging the gap in PV system studies for equatorial regions, offering scalable solutions for other tropical areas.

The findings emphasize the importance of dynamic optimization, including seasonal tilt angle adjustments and the incorporation of real-time thermal effects, to improve PV performance. Recommendations for future work include investigating advanced cooling mechanisms, exploring automated tracking systems to optimize tilt angles, and integrating long-term environmental data to enhance predictive modeling. By addressing these areas, future studies can further enhance solar PV efficiency and sustainability, providing robust energy solutions for rural and remote communities worldwide. This study thus not only strengthens PV system design for tropical climates but also lays a foundation for more sustainable energy practices in underrepresented regions.

FUNDING INFORMATION

The authors declare that no financial support or funding was received from any government, private, or institutional body for the planning, execution, analysis, or publication of this research. All resources utilized in the completion of this study were provided independently by the authors and their respective institutions. This work was carried out without the influence of any external financial interest or sponsorship.

AUTHOR CONTRIBUTIONS STATEMENT

This section outlines the specific roles of each author based on the Contributor Roles Taxonomy (CRediT), which helps to provide transparency and accountability in collaborative research. The table below identifies the contributions of each author across various stages of the research and publication process. A checkmark (✓) denotes the responsibility undertaken by the respective author.

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The authors declare that they have no known financial, personal, or professional conflicts of interest that could have influenced the work reported in this manuscript. This includes, but is not limited to, affiliations, funding sources, or personal beliefs that may be perceived to affect the objectivity, integrity, or impartiality of the research and its findings.

DATA AVAILABILITY

The authors confirm that the data supporting the findings of this study are available within the article. All key results, calculations, and supporting evidence are presented in the main text. Additional data related to tilt angle testing, system sizing, and irradiance measurements can be made available upon reasonable request from the corresponding author.

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