# Evaluating solar photovoltaic panel orientations for an open-field internet of things framework

**Khairul Anuar Mohamad[1], Mohamad Syahmi Nordin[2], Hairul Hafizi Hasnan[3], Ahmad Fateh Mohamad Nor[1], Rohaiza Hamdan[1], Nazirah Mohamad Abdullah[4], Nor Anija Jalaludin[5]**

[1]Department of Electrical Engineering, Faculty of Electrical and Electronic Engineering, Universiti Tun Hussein Onn Malaysia, Parit Raja, Malaysia
[2]MT Data Driven Sendirian Berhad, Cyberjaya, Malaysia
[3]Department of Music, Faculty of Creative Arts, Universiti Malaya, Kuala Lumpur, Malaysia
[4]Department of Technology and Natural Resources, Faculty of Applied Science and Technology, Universiti Tun Hussein Onn Malaysia, Parit Raja, Malaysia
[5]Department of Electrical Engineering Technology, Faculty of Engineering Technology, Universiti Tun Hussein Onn Malaysia, Parit Raja, Malaysia

**Article Info**

***Article history:***

Received Apr 29, 2025
Revised Oct 9, 2025
Accepted Dec 6, 2025

***Keywords:***

Horizontal
Open-field internet of things
Photovoltaic orientation
Tilt
Vertical

**ABSTRACT**

This paper presents a comparative experimental analysis of horizontal, vertical, and 45° tilt photovoltaic (PV) panel orientations, evaluated with and without load conditions in a tropical environment. Simultaneous measurements of open-circuit voltage ($V_{oc}$), short-circuit current ($I_{sc}$), and average power were conducted over three consecutive days to facilitate orientation-specific performance comparisons. Results show that the horizontal orientation demonstrated robust midday performance, achieving 3.65 W with load on one of the test day, but declined sharply in post-noon periods. The vertical orientation consistently produced lower average power outputs, approximately 3.1 W with load. As a reference, the 45° tilt consistently produced the highest output, with average load powers of 3.77 W, 3.41 W, and 3.64 W over the three days. This performance exceeded horizontal orientations by 2–5% and vertical orientations by 15–20%. Both horizontal and tilt orientations consistently surpassed internet of things (IoT) operational thresholds of 3.3–5.0 V and 100–200 mA required for low-power sensor nodes, ensuring excess energy for storage. In contrast, the vertical orientation posed a risk of inadequate current in late afternoon periods. Thus, the results indicate that the orientation selection should be environment-driven. Horizontal or tilted orientations are suitable for rural and open-field IoT settings, while vertical orientations are advantageous for space-constrained or dust-prone environments.



***Corresponding Author:***

Khairul Anuar Mohamad
Department of Electrical Engineering, Faculty of Electrical and Electronic Engineering
Universiti Tun Hussein Onn Malaysia
Parit Raja 86400 Batu Pahat, Johor, Malaysia
Email: khairulam@uthm.edu.my

## 1. INTRODUCTION

The integration of solar photovoltaic (PV) technology with internet of things (IoT) systems is transforming the potential for autonomous, efficient, and sustainable operations across various sectors by enabling real-time monitoring, intelligent control, and autonomous operation [1]-[3]. This synergy is especially beneficial in off-grid and energy-insecure areas, where dependable power sources are limited and operational continuity is crucial. IoT frameworks facilitate the deployment of intelligent, interconnected devices that can monitor, control, and optimise processes in real time, but their effectiveness is significantly dependent on a continuous power supply. Solar PV systems offer a clean, renewable, and modular energy source that satisfies these requirements, rendering them ideally suited for IoT-enabled applications. Recently, various applications of solar-powered IoT frameworks in agriculture, security, environmental monitoring, wildlife conservation, automation, and other domains have increasingly relied on renewable energy sources to ensure continuous operation in off-grid environments. Solar-integrated IoT devices are revolutionising resource monitoring and management across various areas. In precision agriculture, PV-powered IoT networks manage irrigation, monitor soil moisture and nutrient levels, and optimise water usage, thereby enhancing yields in areas with restricted electrical availability [4], [5]. In environmental monitoring, solar energy powers IoT sensor networks that monitor air quality, weather conditions, and water levels, producing vital datasets for disaster preparedness, climate modelling, and resource conservation [6], [7]. Wildlife conservation efforts utilise solar-powered IoT camera traps, global positioning system (GPS) tracking collars, and sound sensors to gather data in distant or environmentally sensitive environments without the need for intrusive infrastructure [8], [9].

Solar-powered IoT installations diminish reliance on fossil fuels, decrease greenhouse gas emissions, and facilitate the implementation of intelligent microgrids in underprivileged regions. The efficacy of these systems is closely correlated with the PV array's capacity to provide adequate electricity under diverse environmental conditions, in addition to being influenced by factors such as solar irradiance, temperature, and shading. Panel orientation, defined by tilt and azimuth relative to the sun's trajectory, is a critical technical factor influencing PV power generation. Orientation influences the amount of incident solar irradiance collected over time, thus impacting both daily energy output and the system's reliability and long-term efficiency. Fixed systems may benefit from periodic adjustments to the tilt angle to account for seasonal variations in solar irradiance [10]. However, optimising the orientation and tilt angle for rural installations with space constraints is crucial for maximising energy output and ensuring system reliability [11]. In open-field IoT frameworks, where continuous power is essential and maintenance resources are frequently constrained, optimising panel orientation emerges as a critical technical challenge that directly influences sustainability, scalability, and cost-efficiency.

The physical orientation of the solar panels, which controls the quantity of solar irradiance gathered over time, significantly impacts the efficiency of PV-powered IoT devices. To optimise the annual energy generation in fixed systems, conventional installation standards recommend orienting PV modules toward the equator with a tilt angle equal to the site's latitude [12]. Although this method performs satisfactorily in many areas, it is not always the best option for all operational or environmental circumstances. To overcome orientation-related performance limitations, researchers have thus looked into alternate designs, both fixed and adaptive. Fixed horizontal systems with optimal tilt angles have been extensively researched owing to their mechanical simplicity, cost-effectiveness, and reliable performance under stable solar exposure conditions [13], [14]. Nevertheless, these systems may exhibit reduced efficiency during low solar angles or considerable seasonal variation in solar position. Adaptive tracking systems, comprising single-axis and dual-axis trackers, dynamically modify the tilt and azimuth of PV modules to align with the sun's path. Field studies indicate that adaptive tracking can enhance energy yield by as much as 45% relative to fixed installations, particularly in rural and open-field settings where space is abundant [15]. Meanwhile, vertical PV systems have gained attention due to their operational advantages in particular settings. In contrast to horizontal arrays, vertical systems exhibit less vulnerability to dust deposition and shadowing from adjacent structures, hence decreasing maintenance frequency and maintaining performance in dusty or polluted conditions [16]. They also provide enhanced integration capabilities in space-limited environments, such as urban facades, fences, or sound barriers, where ground-mounted systems are unfeasible. In agrivoltaic systems, vertical PV arrays facilitate concurrent agricultural production and energy generation by reducing shading on crops, which helps to produce up to three times more electricity per unit of farmland lost compared to traditional ground-mounted systems [17]. Their versatility in various terrains makes them appealing for ecologically sensitive areas, where the preservation of natural landscapes is crucial [18].

Beyond these technical benefits, PV orientation strategies serve as a critical design factor for urban energy requirements, where integration into building façades or constrained-space installations is essential [16], as well as for sustainable development in rural and conservation-orientated regions [18]. Vertical or suitably inclined horizontal PV systems can deliver dependable, low-maintenance energy for IoT-based remote monitoring systems used in agriculture, forestry, and environmental conservation [5], [19]. The compatibility is crucial given the minimal but ongoing power demands of IoT setups. A conventional remote sensing IoT node, equipped with temperature, humidity, or soil moisture sensors, a microcontroller unit (MCU) (such as an ESP32 or Arduino), and a low-power communication module (such as long range (LoRa), narrowband (NB-IoT), or Zigbee), typically requires between 0.5 and 2 W for uninterrupted operation. The overall daily energy usage typically ranges from 5 to 20 Wh when integrated with intermittent operations like wireless data transfer or image capturing, contingent upon the duty cycle and communication range.

Consistently meeting this demand in remote locations depends mainly on panel orientation, as inadequate alignment may result in extended battery charging durations and subsequent service disruptions. These challenges are particularly critical in off-grid IoT implementations, where maintenance visits are both expensive and infrequent.

Although prior research has examined the energy performance of horizontal and vertical PV panels separately, it has not directly compared both orientations under uniform environmental circumstances for IoT-enabled systems [6], [12], [20]. Current orientation research predominantly focuses on general PV applications, such as residential rooftop systems, grid-connected commercial arrays, or extensive solar farms, while neglecting the operational requirements specific to IoT deployments, where power continuity, spatial limitations, and maintenance accessibility are paramount. Moreover, limited research has investigated the impact of PV orientation on system performance in both loaded and unloaded states, despite the variable duty cycles, intermittent communications, and battery-buffered energy supply typical of IoT devices. In addition, existing literature rarely combines environmental, spatial, and economic factors within a unified comparative framework. Horizontal PV orientations are known for their high energy yields in unobstructed environments, but they may experience issues related to dust accumulation or shading in urban and desert settings [21]. In contrast, vertical PV systems offer benefits such as land preservation, integration into building façades, and decreased soiling losses [22]. However, their performance relative to horizontal designs in rural IoT settings has not been systematically evaluated under the same conditions. Without context-specific comparative analysis, there is a lack of empirical evidence to determine the optimal PV orientation for IoT-based remote monitoring, environmental sensing, and other autonomous applications, particularly in off-grid deployments where performance reliability is critical and maintenance resources are limited.

This study presents a comprehensive experimental comparison of horizontal and vertical PV panel orientations for IoT-based applications under consistent environmental conditions. Moreover, this study conducts side-by-side performance measurements to ensure a controlled and unbiased comparison of energy yields, in contrast to previous studies that analysed each orientation in isolation. The analysis includes both with and without load conditions, highlighting the impact of orientation on the operational performance of IoT devices and the potential for open-circuit energy generation.

## 2. METHOD

The experimental setup aimed to assess and compare the performance of solar PV panels oriented horizontally, vertically, and at a 45° inclination for powering IoT-based systems in real-world situations. This methodology directly tackles the knowledge deficiencies highlighted in the Introduction section, specifically the absence of side-by-side comparisons between orientations under uniform environmental circumstances and the lack of performance assessments with and without load conditions. The chosen orientations represent a horizontal (0° tilt), which is frequently utilized when the installation surface is aligned with the ground, a vertical (90° tilt), which is appropriate for installations constrained by space, characterized by high dust levels, or installed on façades, and a 45° angle, which is the estimated ideal fixed tilt for the latitude of the test location at the Parit Raja test site in Batu Pahat, Johor (1.852493° N, 103.084092° E), functions as the reference orientation [1], [3]. Testing was performed outdoors at a consistent location to guarantee uniform irradiance exposure across all orientations over the three consecutive measurement days (19/12/2025 until 21/12/2025). Solar irradiance was monitored at 60-minute intervals using a calibrated solar power meter (model: SM206-solar) positioned adjacent to the PV modules to ensure accurate site-level readings. Peak irradiance on Day 1 was 850–950 W/m² under clear-sky conditions, Day 2 was 500–700 W/m² affected by intermittent cloud cover, and Day 3 was 880–950 W/m² under clear-sky conditions. During the measurement period, ambient air temperatures ranged from 28 to 33 °C, with PV module surface temperatures estimated at 40 to 50 °C around midday due to solar heating. The experimental procedure follows established PV performance evaluation standards [23], modified for IoT system integration.

### 2.1. Hardware system architecture

The experimental hardware system was developed to assess the energy generation performance of solar PV modules across three orientations and their capacity to provide continuous power to an IoT-based monitoring system. The configuration incorporates solar energy generation, charge regulation, energy storage, and real-time load operation within a modular and replicable framework. Figure 1 shows the block diagram of the experimental hardware system. The hardware architecture comprises five main components: the solar PV panel, a solar charge controller (DC–DC converter), an energy storage unit (12 V lead-acid battery), an IoT load, and measurement instruments. The solar PV panel (SWOM-03 mono-crystalline module) is the main energy source, transforming incident solar irradiance into direct current (DC) electrical power. Three orientations were tested: horizontal (0° tilt, facing the equator), vertical (90° tilt), and tilted at

45°. The 45° orientation was chosen as a reference orientation due to its appropriateness for the latitude of the test location, aligning with established optimal-tilt guidelines [6], [12]. The specifications of the solar PV panel are provided in Table 1. The generated DC power is fed into a charge controller (DC–DC converter), which manages voltage and current to ensure safe charging of the energy storage unit (12 V lead-acid battery) while providing a regulated output to the IoT load. The charge controller regulates battery charging and discharging, thereby maintaining stable operation in off-grid settings. The IoT load consists of a standard low-power monitoring node, which includes a MCU, environmental sensors, and a wireless communication module. This load replicates practical IoT implementations in areas such as environmental sensing, agricultural monitoring, and wildlife monitoring. The measurement instruments, specifically a calibrated digital multimeter, are connected at critical points in the circuit to record electrical parameters such as open-circuit voltage ($V_{oc}$), short-circuit current ($I_{sc}$), and load voltage/current (for power output) during operation.

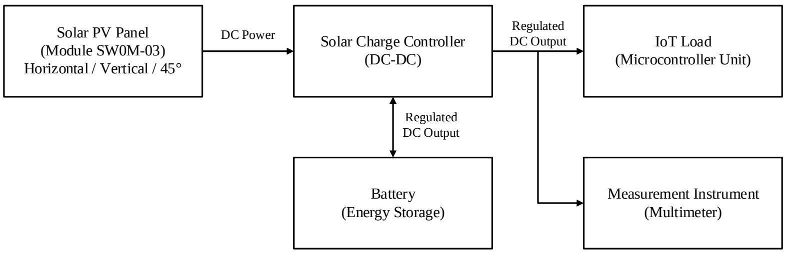



Figure 1. Block diagram of the experimental hardware system

Table 1. Specification of the solar PV panel

| Specification | Value |
|---|---|
| Model type | SW0M-3 |
| Solar cell type | Mono-crystalline |
| Peak power ($p_m$) | 10 W |
| Maximum power voltage ($v_{mp}$) | 17.9 V |
| Maximum power current ($i_{mp}$) | 0.55 A |
| Open circuit voltage ($v_{oc}$) | 21.2 V |
| Short circuit current ($i_{sc}$) | 0.61 A |

Figure 2 shows the configuration used to measure electrical parameters for assessing the performance of solar PV modules in three orientations under two operational conditions. In the without-load condition, as shown in Figure 2(a), the IoT load is severed by disconnecting the breaker between the charge controller and the load, resulting in a no-load or open-circuit condition. This configuration allows for the assessment of the PV module's $V_{oc}$ and $I_{sc}$ independent of load consumption, thereby reflecting the module's maximum generation potential under specified orientation and irradiance conditions. Meanwhile, in the with-load condition, as shown in Figure 2(b), the breaker to the IoT load is closed, allowing the PV module to deliver regulated DC power to both the IoT load and the battery through the charge controller. This with-load setup replicates field operations, wherein the PV system must support uninterrupted IoT device functionality while preserving battery charge. In both arrangements, the PV panel assessed in horizontal, vertical, and 45° tilt orientations serves as the principal energy source, transforming solar irradiance into DC electrical power.

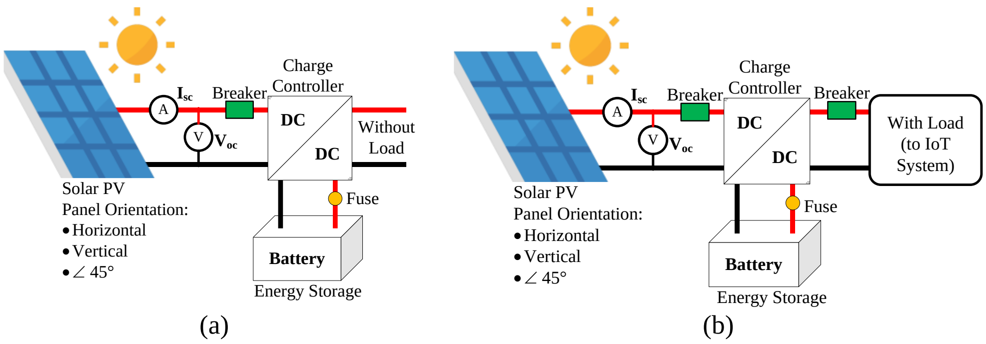



Figure 2. Schematic diagram of the experimental solar PV system measurement setup under two operational conditions; (a) without a load (open-circuit condition) and (b) with a load powering the IoT system

### 2.2. System flow and test scenarios

The experimental procedure enabled a systematic and reproducible evaluation of solar PV performance across horizontal, vertical, and 45° tilt orientations under both loaded and unloaded conditions. Upon mounting the PV module to an adjustable frame, the tilt was calibrated using a digital inclinometer, and the azimuth was established at true south (180°) for all experiments. The hardware connections followed the configurations shown in Figures 1 and 2, and all breakers, fuses, and measurement points were verified prior to the measurement of each test session.

Each orientation was subjected to two test settings. In the no-load condition, the IoT load was detached, and the module's $V_{oc}$ and $I_{sc}$ were measured to evaluate maximum potential generation. In the with-load condition, the IoT system was linked via the charge controller, enabling the PV panel to concurrently supply electricity to the load and charge the battery, thereby replicating field operation conditions.

Concurrent measurements of $V_{oc}$ and $I_{sc}$ for all three orientations were conducted every 60 minutes from 09:00 to 17:00 local time. This method ensured that the measurements for each orientation were obtained under identical solar and environmental conditions. Instantaneous power (P) was calculated for each timestamp using the equation $P=V\times I$. The average daily power output ($P_{avg}$) for each orientation and condition was then determined from all measurements obtained throughout the day.

Figure 3 shows the flowchart of the experimental procedure for the comparison of solar PV orientations. Readings for all three orientations and both settings were conducted at each 60-minute interval prior to advancing to the subsequent scheduled time point. After all measurements for the day were collected, the data were analysed to compare the performance of horizontal, vertical, and 45° tilt orientations with and without load conditions. Performance analysis involved a comparison of $V_{oc}$, $I_{sc}$, and $P_{avg}$ across three orientations and two operational settings. This analysis offers a quantitative framework for assessing the appropriateness of various PV orientations for powering IoT systems in off-grid settings, where reliability and efficiency are critical.

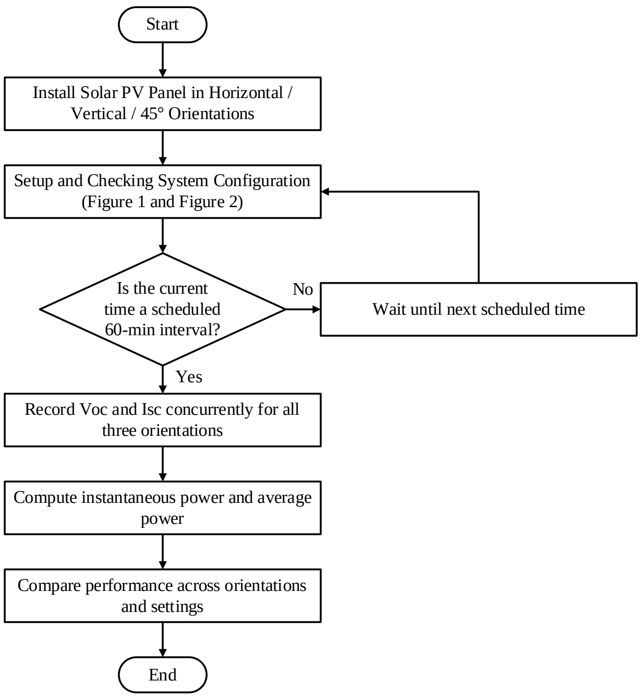



Figure 3. Flowchart of the experimental procedures for different orientations of the PV panels

## 3. RESULTS AND DISCUSSION

This section presents the experimental results and their interpretation, focusing on the comparative performance of solar PV panels positioned in horizontal, vertical, and 45° tilt orientations. The evaluation is based on the electrical characteristics of the panels, specifically $V_{oc}$ and $I_{sc}$, in addition to the average power outputs recorded under both with and without load conditions. The analysis of these parameters over three consecutive days reveals orientation-dependent variations in generation capacity. It provides insights into their implications for powering open-field IoT systems in off-grid environments.

### 3.1. Electrical parameters under three orientations

Figure 4 shows the variation of $V_{oc}$ and $I_{sc}$ over Day 1 for horizontal, vertical, and 45° tilt orientations. Across all orientations, $V_{oc}$ and $I_{sc}$ followed a diurnal profile consistent with solar irradiance patterns, as they increased progressively after 09:00, peaked close to solar noon (12:00–13:00), and then decreased in the evening. The $V_{oc}$ peaked at about 20.7 V at midday for the horizontal orientation, as shown in Figure 4(a), whereas $I_{sc}$ increased to 0.52 A before progressively declining. In the afternoon, the vertical orientation, as shown in Figure 4(b), yielded much lower $I_{sc}$ values, dropping below 0.36 A around 14:00, but a similar peak $V_{oc}$ (approximately 19.2 V). As the solar altitude rose, the effective irradiance on the vertically installed module decreased, which is consistent with the findings reports in [24]. The performance was stable with the 45° tilt orientation, as shown in Figure 4(c), with $I_{sc}$ maintaining values above 0.35 A for most of the afternoon and $V_{oc}$ peaking near to 20.8 V. These results indicate that aligning the tilt orientation with site latitude maximises current generation and voltage stability [25].

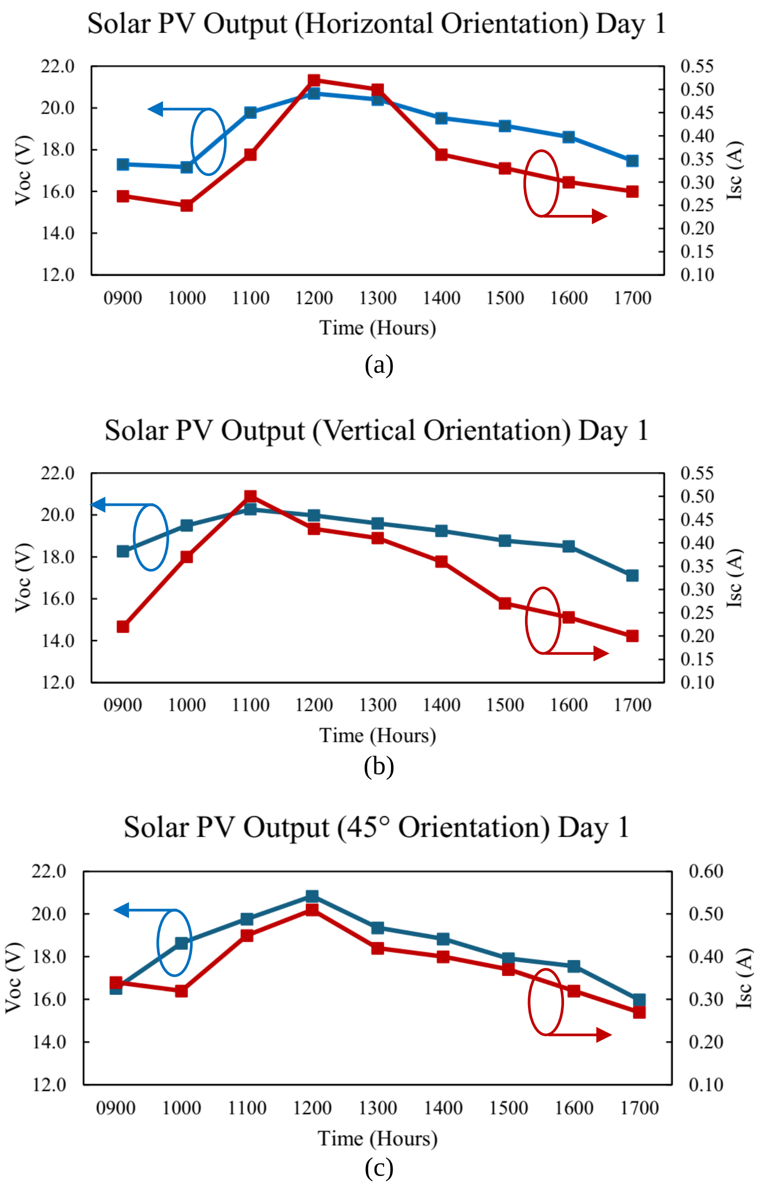
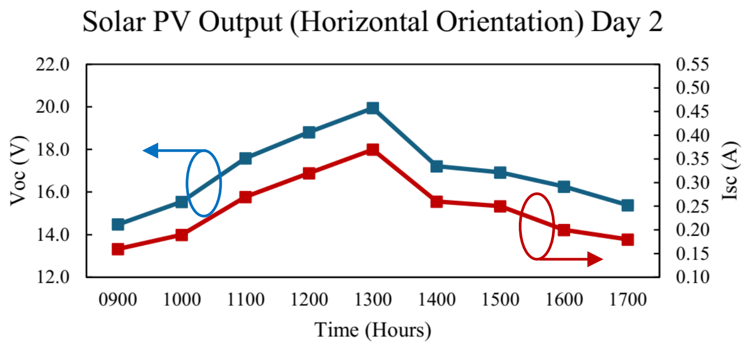
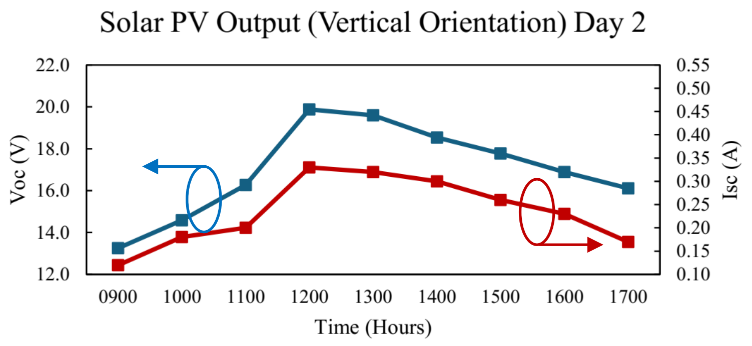



Figure 4. Variation of $V_{oc}$ and $I_{sc}$ for; (a) horizontal, (b) vertical, and (c) 45° tilt orientations over Day 1

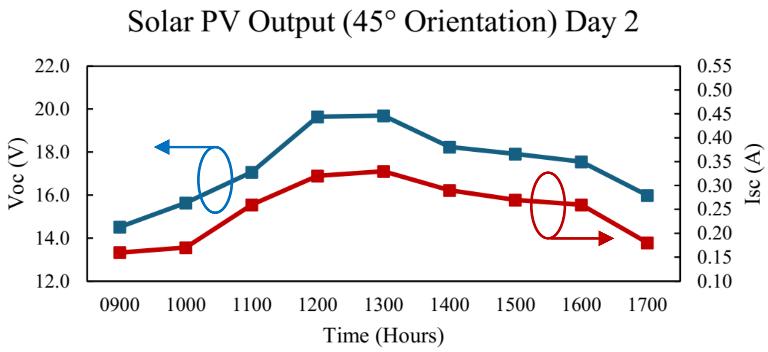
Meanwhile, Figure 5 shows the variation of $V_{oc}$ and $I_{sc}$ for horizontal, vertical, and 45° tilt orientations during Day 2. As on Day 1, both parameters followed a diurnal profile consistent with solar irradiance patterns, as they increased progressively after 09:00, peaked close to solar noon (12:00–13:00), and then decreased in the evening. In the horizontal orientation, as shown in Figure 5(a), $V_{oc}$ peaked at just under 19.9 V about midday, marginally lower than on Day 1. At the same time, $I_{sc}$ attained roughly 0.37 A before experiencing a gradual decline in the afternoon. The current curve exhibited a wider plateau between 11:00 and 13:00, indicating more diffuse irradiance conditions that marginally diminished the peak while extending the duration of elevated energy production. In the vertical orientation, as shown in Figure 5(b), the voltage attained values similar to other orientations (approximately 19.8 V), although the current output remained the lowest among the three orientations. $I_{sc}$ reached a maximum of approximately 0.33 A at noon and subsequently decreased to 0.26 A after 14:00. This trend indicates the reduced effectiveness of vertically oriented modules in capturing noon irradiance due to adverse incidence angles, a limitation consistently emphasised in previous research [26]. The 45° tilt orientation, as shown in Figure 5(c), exhibited the most balanced performance. The $V_{oc}$ reached a maximum of approximately 19.7 V, similar to the horizontal condition. At the same time, $I_{sc}$ surpassed 0.33 A and sustained this level until after 15:00. In comparison to the horizontal orientation, the inclined setup produced a more consistent afternoon current profile, highlighting its robustness under fluctuating irradiance. The results are consistent with theoretical expectations, which indicate that a latitude-matched tilt maximises current stability and ensures sustained energy yield [27].



(a)



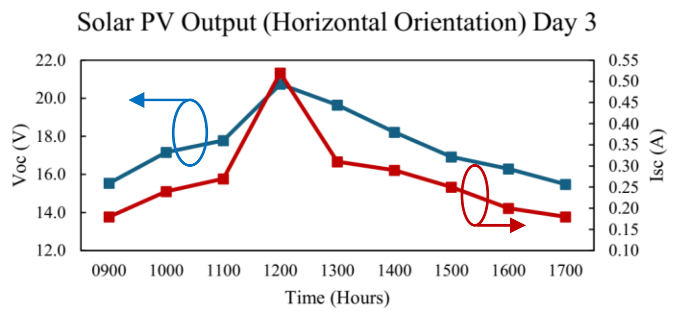
(b)



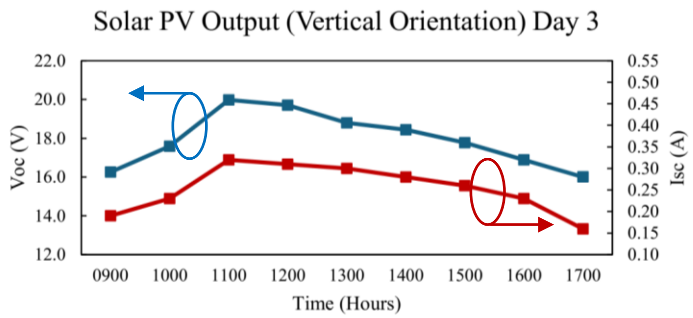
(c)

Figure 5. Variation of $V_{oc}$ and $I_{sc}$ for; (a) horizontal, (b) vertical, and (c) 45° tilt orientations during Day 2

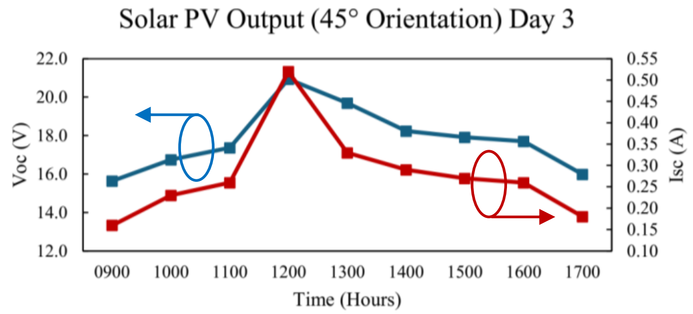
Finally, Figure 6 shows the variation of $V_{oc}$ and $I_{sc}$ profiles for horizontal, vertical, and 45° tilt orientations on Day 3. Similar to the previous days, both voltage and current increased in the morning, peaked near solar noon, and then decreased in the evening as they followed the diurnal solar irradiance cycle. However, Day 3 displayed more variability around midday, which was expected due to intermittent cloud cover. In the horizontal orientation, as shown in Figure 6(a), $V_{oc}$ exceeded 20.8 V, comparable to Day 1, while $I_{sc}$ peaked at approximately 0.52 A at 12:00 before a sharp decline. The abrupt midday peak and subsequent sharp decline indicate transient shading or fluctuations in irradiance, resulting in increased variability relative to the more consistent profiles observed on Day 2. The horizontally oriented panels indicate the sensitivity to fluctuations in short-term irradiance. In the vertical orientation, as shown in Figure 6(b), the voltage performance was similar to that of the other orientations (approximately 18–19 V), although the current output remained the lowest. Peak $I_{sc}$ was observed at approximately 0.31 A around noon, subsequently decreasing gradually to below 0.16 A by late afternoon. Although the current output of the vertically oriented panel is lower, it demonstrated greater stability, exhibiting reduced midday fluctuations compared to the horizontal orientation. This trend is consistent with previous findings, which indicates that vertical modules, while not optimal for energy yield, display reduced sensitivity to transient irradiance variations [28]. The 45° tilt orientation, as shown in Figure 6(c), exhibited performance characteristics that integrated the benefits of the other two orientations. The $V_{oc}$ reached a maximum of approximately 20.9 V, with the $I_{sc}$ peaked at 0.52 A and remained above 0.30 A until after 15:00. Although Day 3 demonstrated midday variability, the tilted orientation exhibited smoother transitions, mitigating the significant spikes and declines observed in the horizontal orientation. This observation supports previous theoretical and experimental findings, which indicate that tilt alignment with site latitude improves stability under varying sky conditions [29].




(a)




(b)




(c)

Figure 6. Variation of $V_{oc}$ and $I_{sc}$ for; (a) horizontal, (b) vertical, and (c) 45° tilt orientations on Day 3

Table 2 summarises orientation-dependent performance peak $V_{oc}$, peak $I_{sc}$, and post-noon $I_{sc}$ values (after 14:00) for horizontal, vertical, and 45° tilt orientations over three consecutive measurement days. The horizontal orientation yielded the highest peak currents ($I_{sc}$=0.45–0.52 A), which confirmed its capability for maximum instantaneous output, but exhibited a sharp decline in the post-noon. The vertical orientation, while maintaining voltages similar to the other orientations (approximately 19.9–20.3 V), consistently produced the lowest currents ($I_{sc}$≤0.34 A), frequently dropping below 0.25 A after post-noon (14:00). In contrast, the 45° tilt orientation demonstrated a balanced performance with high peak currents ($I_{sc}$=0.38–0.48 A) and sustained post-noon current (>0.29 A) across all test days, thereby confirming its robustness under varying environmental conditions. From the perspective of IoT systems, these performance differences are critical. Low-power wireless sensor nodes typically require supply voltages between 3.3 and 5.0 V and continuous currents of 100 to 200 mA for reliable operation. Both the horizontal and 45° tilt orientations consistently exceeded these thresholds during daytime operation, thus ensuring surplus energy for storage. In contrast, the vertical orientation presented a risk of inadequate current during late-afternoon hours, which could compromise continuous operation in off-grid IoT applications unless supported by larger storage capacity or hybrid energy sources. The findings support previous studies indicating that tilt-optimised orientations typically achieve greater and more consistent energy capture. In contrast to exhibiting inferior electrical performance, vertical orientations are beneficial in particular deployment scenarios, including environments with high dust exposure, spatial constraints, or applications integrated with agricultural and wildlife conservation systems.

Table 2. Electrical parameters across three days for different panel orientations

| Orientation | Day | Peak $V_{oc}$ (V) | Peak $I_{sc}$ (A) | Post-noon $I_{sc}$ (A) | Key observations |
|---|---|---|---|---|---|
| Horizontal | 1 | 20.7 | 0.52 | 0.36 | Consistently highest peaks, but sharper post-noon decline; sensitive to variability |
| | 2 | 20.0 | 0.37 | 0.26 | |
| | 3 | 20.7 | 0.52 | 0.29 | |
| Vertical | 1 | 20.3 | 0.50 | 0.36 | Stable voltage, but lowest current across all days |
| | 2 | 19.9 | 0.33 | 0.30 | |
| | 3 | 20.0 | 0.32 | 0.28 | |
| 45° tilt | 1 | 20.8 | 0.51 | 0.40 | Balanced output; sustained post-noon current; most robust orientation |
| | 2 | 19.7 | 0.33 | 0.29 | |
| | 3 | 20.9 | 0.52 | 0.29 | |

### 3.2. Average power output with and without load

Figures 7-9 show the average power output of the solar PV panels for three orientations (horizontal, vertical, and 45° tilt) under both without-load (open-circuit, connected only to the controller and battery) and with-load (IoT system powered) conditions for Days 1-3, respectively. The measured power consistently exceeded that of without-load conditions when compared to with-load conditions, indicating the anticipated voltage drop and current draw linked to powering an actual IoT load.

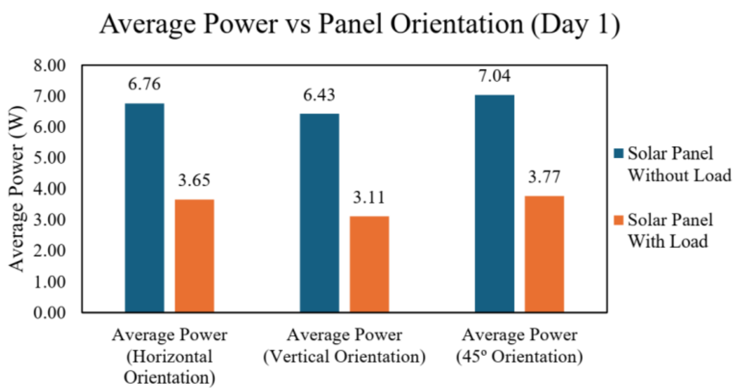



Figure 7. The average power output for three panel orientations with and without load on Day 1

On Day 1, as shown in Figure 7, the horizontal and 45° tilt orientations produced the highest without-load power outputs of 6.76 W and 7.04 W, respectively. Under load conditions, these outputs decreased to 3.65 W and 3.77 W. The vertical orientation generated 6.43 W without load and decreased to

3.11 W when powering the IoT system. However, on Day 2, as shown in Figure 8, variations in weather affected overall performance across all orientations. The average without-load power decreased to 4.24 W for the horizontal orientation, 4.12 W for the vertical orientation, and 4.42 W for the 45° tilt orientation. The power values with-load were consistently lower, ranging from 3.15 W (vertical) to 3.41 W (45° tilt). As shown in Figure 9, by Day 3, there was partial performance recovery. The 45° tilt orientation produced the highest average power (5.10 W without-load and 3.64 W with-load), while the horizontal orientation yielded 4.91 W and 3.58 W, respectively. The vertical orientation exhibited the lowest power values with 4.61 W without-load and 3.15 W with-load.

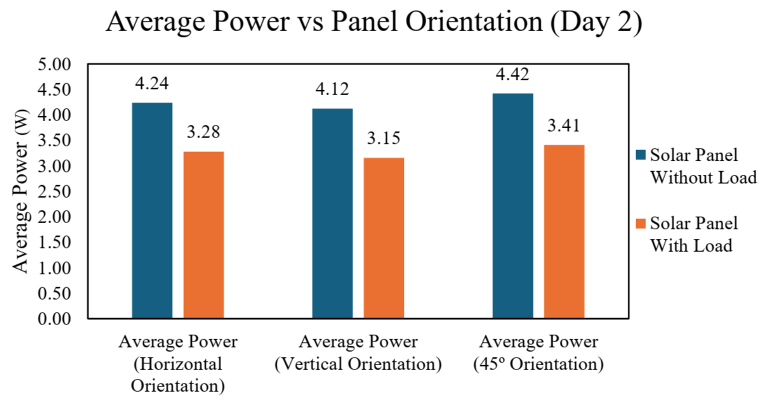



Figure 8. The average power output for three panel orientations with and without load on Day 2

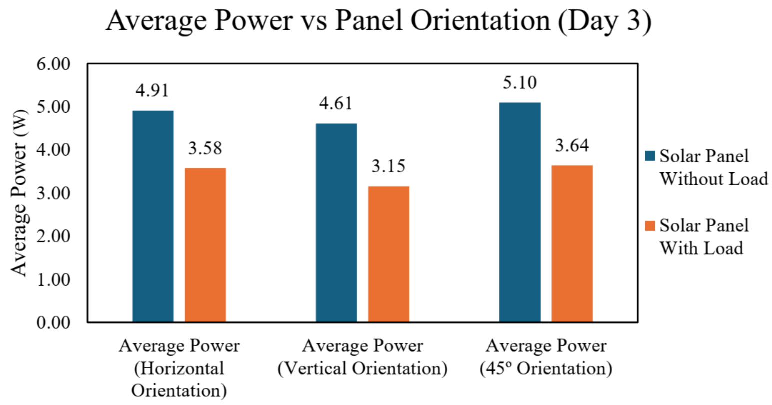



Figure 9. The average power output for three panel orientations with and without load on Day 3

Table 3 presents the key observations of average power output for the panel orientations over three days, under both without- and with-load conditions. It confirms that load conditions significantly diminish overall power availability, as expected due to current draw and related system losses. The power delivery outcomes presented in Table 3 reflect the comparative patterns for $V_{oc}$ and $I_{sc}$ shown in Table 2. The results confirm that aligning the panel tilt with site latitude enhances irradiance capture efficiency during the day. The horizontal orientation exhibited average power values that were only slightly lower than the tilt orientation, particularly under load conditions, where the difference was less than 0.2 W on most days. The vertical orientation exhibited consistent underperformance, with load averages stabilising at approximately 3.1 W across all days, indicating a 10–15% deficit relative to the tilt orientation. All orientations provided adequate voltage for IoT operation, but variations in current generation primarily influenced overall power availability.

The horizontal orientation generated the highest peak currents, but it experienced more pronounced declines after noon, resulting in diminished load power in the later part of the day. While maintaining a stable voltage output, the vertical orientation consistently yielded the lowest current and, as a result, the lowest average power, with load values stabilising at approximately 3.1 W over several days. The 45° tilt orientation demonstrated a balanced profile, sustaining strong post-noon currents exceeding 0.30 A and achieving optimal and consistent power delivery in both with and without load conditions. The correlation between electrical parameters and power outcomes highlights that current sustainability, rather than voltage level, is essential for ensuring a reliable energy supply in IoT applications. The findings are consistent with previous research that points out the importance of sustainable current output and stable diurnal profiles in off-grid solar applications [30]. Further long-term monitoring across various seasonal and weather conditions would enhance the validation of these trends and offer more comprehensive insights into year-round reliability.

Table 3. Key observations on average power output for different panel orientations with and without load

| Orientation | Day | Average power output |
|---|---|---|
| Horizontal | 1 | High no-load power, but load reduces the output by nearly 46% |
| | 2 | Moderate; remains above the IoT thresholds |
| | 3 | Consistent recovery; relatively stable load performance |
| Vertical | 1 | Weakest load delivery; <50% of no-load |
| | 2 | Narrow load/no-load margin, indicating inefficiency |
| | 3 | Similar pattern; lowest with-load reliability |
| 45° tilt | 1 | Highest overall, load output close to horizontal |
| | 2 | Best resilience under cloudier conditions |
| | 3 | Sustained superiority; consistently above the IoT thresholds |

### 3.3. Comparative analysis between horizontal and vertical panel orientations

Depending on the environmental and infrastructural context, we can strategically leverage the specific benefits of integrating vertical and horizontal orientations in IoT systems. The horizontal orientation consistently produced higher current and power outputs than the vertical orientation over the three days. Horizontal orientation exhibited an average increase of 30–40% in $I_{sc}$ compared to vertical orientation, as indicated in Table 2. This difference corresponded to a 15–20% increase in load power, as presented in Table 3. On Day 1, horizontal orientation produced 3.65 W under load, while vertical orientation generated only 3.11 W, resulting in a 17% advantage. Despite less favourable irradiance conditions on Day 2, the horizontal orientation maintained a 4–6% higher output, which indicates that horizontal orientation, when not limited by spatial constraints, are better suited for rural IoT applications such as wildlife monitoring or deterrent systems and agricultural monitoring, where stable diurnal power availability is essential. The pronounced decline in performance observed in horizontal orientations post-noon suggests a sensitivity to the angle of irradiance, necessitating adequate energy storage to maintain reliability overnight.

In contrast, despite generating considerably lower current and power, the vertical orientation maintained similar voltage stability and provided distinct practical advantages. Throughout the three days, vertical load power stabilized at approximately 3.1 W, indicating a deficit of 10–15% relative to horizontal orientation and a 15–20% deficit compared to the 45° tilt orientation. Vertical panels mitigate land-use conflicts, exhibit reduced susceptibility to dust accumulation, and facilitate seamless integration into building facades or fences, thereby rendering them particularly suitable for urban IoT applications. Facade-mounted vertical panels can support smart city devices, including air quality sensors, traffic monitors, and street-light communication modules, while preserving valuable ground space. In rural or conservation contexts, vertically mounted panels installed along perimeter fences can fulfil dual functions: powering electric fencing systems for wildlife deterrence and supplying energy to IoT-based monitoring devices, including motion sensors and camera traps. This integrated approach reduces land use, utilizes existing fencing, and improves sustainability in environmentally sensitive regions. Nonetheless, their 15–20% lower electrical yield indicates that larger-capacity batteries or supplementary energy sources are necessary to offset decreased current generation, particularly in the late afternoon.

The results highlight the potential of hybrid PV systems that integrate multiple panel orientations. Horizontal panels optimize daytime energy yields, whereas vertical panels enhance early-morning or facade-based generation, providing resilience to shading, orientation constraints, and spatial limitations. Dual-orientation systems may decrease variability and provide a more continuous power profile, which is critical for IoT applications requiring uninterrupted operation. Recent studies on PV systems indicate that similar hybrid approaches enhance overall energy capture and system resilience [31]. The comparative analysis indicates that horizontal orientation exceeds vertical by 15–20% in electrical yield, but vertical systems maintain structural and contextual benefits in constrained environments. The 45° tilt orientation represents the optimal balance, offering stability and efficiency. Consequently, the orientation selection should be environment-driven, with hybrid orientations representing viable strategy for developing resilient and sustainable IoT energy solutions.

## 4. CONCLUSION

This work performed a systematic comparative analysis of solar PV orientations in horizontal, vertical, and 45° tilts, in the context of powering IoT systems. The findings indicate that panel orientation affects electrical performance and long-term viability for IoT applications, especially in off-grid situations where a continuous power supply is essential. The 45° tilt consistently demonstrated the highest performance, yielding average with-load power outputs over three testing days. The values were 2–5% higher than horizontal orientations and 15–20% higher than vertical setups. Horizontal orientation exhibited comparable peak values but demonstrated increased variability in the post-noon period, indicating their reliance on solar altitude. Vertical orientation exhibited noticeably lower average with-load power. The consistency of these trends observed over three independent days indicates that the orientation effect is systematic, with tilt orientation identified as the most balanced solution for continuous IoT powering. Despite these findings, certain limitations remain. The dataset was limited to a span of three consecutive days within tropical conditions at a single geographic location. Extended monitoring across different seasons and latitudes is necessary for generalizing these findings, especially under varying solar angles and climatic conditions.


## ACKNOWLEDGMENTS

This research was supported by Universiti Tun Hussein Onn Malaysia (UTHM) through Multi-Disciplinary Research (MDR) grant (Vot Q772).

## FUNDING INFORMATION

This research was funded by Universiti Tun Hussein Onn Malaysia (UTHM) under the Multi-Disciplinary Research (MDR) grant scheme. The specific grant awarded for this project is identified as Vot Q772. The MDR grant is a funding scheme to support multidisciplinary research that integrates expertise from various fields, including engineering, science, social sciences, information technology, and related disciplines.


## AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

| Name of Author | C | M | So | Va | Fo | I | R | D | O | E | Vi | Su | P | Fu |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Khairul Anuar Mohamad | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | | ✓ | ✓ | | ✓ | ✓ | ✓ |
| Mohamad Syahmi Nordin | ✓ | ✓ | ✓ | | | ✓ | | | ✓ | | ✓ | | | |
| Hairul Hafizi Hasnan | ✓ | | ✓ | | ✓ | | | | ✓ | ✓ | | | | |
| Ahmad Fateh Mohamad Nor | | ✓ | | | ✓ | ✓ | | | | ✓ | ✓ | | | |
| Rohaiza Hamdan | | ✓ | | | ✓ | ✓ | | ✓ | | ✓ | ✓ | | | |
| Nazirah Mohamad Abdullah | ✓ | | | ✓ | | | ✓ | | | ✓ | | | | ✓ |
| Nor Anija Jalaludin | | ✓ | | ✓ | | | ✓ | | | ✓ | | | | ✓ |

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 competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. Authors state no conflict of interest.

## DATA AVAILABILITY

The authors confirm that the data supporting the findings of this study are available within the article [and/or its supplementary materials].

## REFERENCES


[1] D. Benavides, P. Arévalo, A. C. Ortega, F. Sánchez-Sutil, and E. Villa-Ávila, "Energy management model for a remote microgrid based on Demand-Side energy control," *Energies*, vol. 17, no. 1, pp. 170, Dec. 2023, doi: 10.3390/en17010170.

[2] R. Jain and M. T. Shah, "Design and development of IoT-based solar photo-voltaic system," *2023 IEEE 11th Region 10 Humanitarian Technology Conference (R10-HTC)*, Rajkot, India, 2023, pp. 213-218, doi: 10.1109/R10-HTC57504.2023.10461860.

[3] H. Ghasemnejad, S. Dorahaki, M. Rashidinejad, and S. M. Muyeen, "An IGDT optimization model for a prosumer-oriented citizen energy community considering hydrogen parking lots, energy sharing and thermal comfort," *International Journal of Hydrogen Energy*, vol. 101, pp. 972–982, Jan. 2025, doi: 10.1016/j.ijhydene.2024.12.500.

[4] S. Kaunkid and A. Aurasopon, "Efficient Solar-Powered IoT Drip Irrigation for tomato yield and quality: An evaluation of the effects of irrigation and fertilizer frequency," *Journal of Experimental Biology and Agricultural Sciences*, vol. 11, no. 5, pp. 845–853, Nov. 2023, doi: 10.18006/2023.11(5).845.853.

[5] G. Xu, Y. Shi, X. Sun, and W. Shen, "Internet of things in marine environment monitoring: A review," *Sensors*, vol. 19, no. 7, pp. 1711, Apr. 2019, doi: 10.3390/s19071711.

[6] L.-M. Ang, K. P. Seng, G. K. Ijemaru, and A. M. Zungeru, "Deployment of IoV for smart cities: Applications, architecture, and challenges," *IEEE Access*, vol. 7, pp. 6473–6492, Dec. 2018, doi: 10.1109/access.2018.2887076.

[7] H. Ghasemnejad, M. Rashidinejad, A. Abdollahi, S. Dorahaki, and M. Shafie-Khah, "An integrated three-stage framework for the formation and operation of citizen energy sub-communities based on prosumer attitudes," *Energy*, vol. 322, pp. 135649, Mar. 2025, doi: 10.1016/j.energy.2025.135649.

[8] A. L. Barros, S. Alcobia, P. Gonçalves, D. I. MacKenzie, and M. Santos-Reis, "Assessment of technological developments for camera-traps: a wireless transmission system and solar panels," *Wildlife Society Bulletin*, vol. 48, no. 1, pp. 1506, Jan. 2024, doi: 10.1002/wsb.1506.

[9] G. Kalmár, G. Wittemyer, P. Völgyesi, H. B. Rasmussen, M. Maróti, and Á. Lédeczi, "Animal-borne anti-poaching system," *MobiSys 2019 - Proceedings of the 17th Annual International Conference on Mobile Systems, Applications, and Services*, vol. 6562, pp. 91–102, Jun. 2019, doi: 10.1145/3307334.3326080.

[10] H. Ennaceri and K. Loudiyi, "Modeling the variation of optimum tilt angles for flat-plate solar collectors in Ifrane, Morocco," *2013 International Renewable and Sustainable Energy Conference (IRSEC)*, Ouarzazate, Morocco, 2013, pp. 106-111, doi: 10.1109/IRSEC.2013.6529661.

[11] A. Kies, J. Jurasz, and P. B. Dąbek, "Market value of PV battery systems for autonomous rural energy supply," *Energy Procedia*, vol. 158, pp. 1188–1193, Feb. 2019, doi: 10.1016/j.egypro.2019.01.305.

[12] A. Gedifew and A. Benor, "Evaluating the impact of tilt angles and tracking mechanisms on photovoltaic modules in Ethiopia," *Frontiers in Energy Research*, vol. 12, pp. 1519725, Jan. 2025, doi: 10.3389/fenrg.2024.1519725.

[13] T. A. Dabbousa, I. Al-Reqeb, S. Mansour, and M. A. A. M. Zainuri, "The effect of tilting a PV array by monthly or seasonal optimal tilt angles on energy yield of a solar PV system," *2021 International Conference on Electric Power Engineering – Palestine (ICEPE- P)*, Gaza, Palestine, 2021, pp. 1-5, doi: 10.1109/ICEPE-P51568.2021.9423475.

[14] B. Babes *et al.*, "New optimal control of permanent magnet DC motor for photovoltaic wire feeder systems," *Journal Européen Des Systèmes Automatisés*, vol. 53, no. 6, pp. 811–823, Dec. 2020, doi: 10.18280/jesa.530607.

[15] B. Talbi, F. Krim, A. Laib, A. Sahli, and B. Babes, "A Sugeno-Fuzzy Tuning Approach of Weighting Factor in Model Predictive Control for PV Grid-Tied PUC7 Multi-Level Inverter," *2022 3rd International Conference on Smart Grid and Renewable Energy (SGRE)*, Doha, Qatar, 2022, pp. 1-6, doi: 10.1109/SGRE53517.2022.9774159.

[16] S. Kahla, B. Babes, N. Hamouda, A. Boutaghane, and A. Bouafassa, "Developing an improved ANN algorithm assisted by a colony of foraging ants for MPP tracking of grid interactive solar powered arc welding machine," *Lecture Notes in Networks and Systems*, pp. 512–520, Dec. 2020, doi: 10.1007/978-3-030-63846-7_48.

[17] M. H. Riaz, H. Imran, R. Younas, and N. Z. Butt, "The optimization of vertical bifacial photovoltaic farms for efficient agrivoltaic systems," *Solar Energy*, vol. 230, pp. 1004–1012, Nov. 2021, doi: 10.1016/j.solener.2021.10.051.

[18] A. Zorig, M. Souilah, N. Hamouda, B. Babes, and H. Amar, "Improving the power quality of the grid-connected PV system using a high selective self tuning filter," *2024 2nd International Conference on Electrical Engineering and Automatic Control (ICEEAC)*, Setif, Algeria, 2024, pp. 1-6, doi: 10.1109/ICEEAC61226.2024.10576434.

[19] J. Zhang, T. Wang, Y. Chang, and B. Liu, "A sustainable development pattern integrating data centers and pasture-based agrivoltaic systems for ecologically fragile areas," *Resources Conservation and Recycling*, vol. 188, pp. 106684, Sep. 2022, doi: 10.1016/j.resconrec.2022.106684.

[20] H. Jang *et al.*, "Comparative study on energy yield of tunnel oxide passivated contact (TOPCON) and passivated emitter and rear contact (PERC) solar cells and analysis of optimal installation method for vertical photovoltaics," *Process Integration and Optimization for Sustainability*, vol. 8, no. 4, pp. 993–1001, Apr. 2024, doi: 10.1007/s41660-024-00408-4.

[21] C. Carbajosa, S. Marín-Coca, M. Gavira-Aladro, and A. Martínez-Cava, "Optimizing energy production in PV systems: Comprehensive review of radiation models and key factors influencing power generation," *Renewable Energy*, vol. 2449, p. 123085, Aug. 2025, doi: 10.1016/j.renene.2025.123085.

[22] Y. Zhang, T. Chen, E. Gasparri, and E. Lucchi, "A modular agrivoltaics building envelope integrating thin-film photovoltaics and hydroponic urban farming systems: A circular design approach with the multi-objective optimization of energy, light, water and structure," *Sustainability*, vol. 17, no. 2, pp. 666, Jan. 2025, doi: 10.3390/su17020666.

[23] M. G. Vemula, J. J. John, J. Kuitche, and G. Tamizhmani, "Power rating of photovoltaic modules per IEC 61853-1 standard using a new outdoor test method," *2013 IEEE 39th Photovoltaic Specialists Conference (PVSC)*, Tampa, FL, USA, 2013, pp. 0724-0728, doi: 10.1109/PVSC.2013.6744253.

[24] W. O. A. Al-Rashidy and A. A. Azooz, "Efficiency of vertically installed solar PV panels," *Applied Solar Energy*, vol. 60, no. 3, pp. 400–410, Jun. 2024, doi: 10.3103/s0003701x24600164.

[25] A. George and R. Anto, "Analytical and experimental analysis of optimal tilt angle of solar photovoltaic systems," *2012 International Conference on Green Technologies (ICGT)*, Trivandrum, India, 2012, pp. 234-239, doi:

10.1109/ICGT.2012.6477978.
[26] K. Gairaa, A. Khellaf, F. Chellali, S. Benkaciali, Y. Bakelli, and S. Bezari, "Maximisation and optimisation of the total solar radiation reaching the solar collector surfaces," in *Springer eBooks*, Jan. 2015, pp. 873–886, doi: 10.1007/978-3-319-17031-2_57.
[27] P. Manjunath, D. Devaprakasam, and D. Paul, "Estimation of global solar radiation and optimal tilt angles of solar panels for Pune, India," *International Journal of Design & Nature and Ecodynamics*, vol. 16, no. 1, pp. 85–90, Feb. 2021, doi: 10.18280/ijdne.160111.
[28] M. Kivambe, A. Abdallah, B. Figgis, G. Scabbia, M. Abdelrahim, and J. Lopez-Garcia, "Assessing vertical east-west bifacial photovoltaic systems in desert environments: Energy yield and soiling mitigation," *Solar Energy*, vol. 279, pp. 112835, Aug. 2024, doi: 10.1016/j.solener.2024.112835.
[29] W. M. Grady and H. Thomas, "Predicting the impact of panel orientation and tracking on PV daily energy harvest," *IEEE Energytech*, pp. 1–3, Jul. 2013, doi: 10.1109/energytech.2013.6645344.
[30] T. Dewi, P. Risma, and Y. Oktarina, "A review of factors affecting the efficiency and output of a PV system applied in tropical climate," *IOP Conference Series Earth and Environmental Science*, vol. 258, no. 1, p. 012039, May 2019, doi: 10.1088/1755-1315/258/1/012039.
[31] A. S. Khan, M. Ikram, and M. F. Jalil, "A Review on bifacial PV modules operating in partial shading conditions," *2024 3rd International Conference on Power Electronics and IoT Applications in Renewable Energy and its Control (PARC)*, Mathura, India, 2024, pp. 297-302, doi: 10.1109/PARC59193.2024.10486461.

## BIOGRAPHIES OF AUTHORS

**Khairul Anuar Mohamad** is an Associate Professor at the Department of Electrical Engineering, Universiti Tun Hussein Onn Malaysia (UTHM). He received his Bachelor of Engineering from the University of Electro-Communications, Japan, his Master of Science from the University of Newcastle, U.K., and his Ph.D. from Muroran Institute of Technology, Japan. His research focuses on data-driven solutions, sensor development, and system integration, particularly in corrosion control and cathodic protection. He also leads the project development of an integrated bee frequencies sound system for sustainable elephant intrusion mitigation. He can be contacted at email: khairulam@uthm.edu.my.

**Mohamad Syahmi Nordin** is the Chief Executive Officer (CEO) of MTData Driven Sdn Bhd, which he founded in 2023. He received his Bachelor of Science (Hons) in Physics with Electronics and Master of Science (Physics) from Universiti Malaysia Sabah and his Ph.D. in Applied Physics from the University of Essex, U.K. He served as Senior Research Officer and has expertise in electronics, semiconductor materials, optoelectronics, photonics, nanotechnology, and terahertz spectroscopy. His company focuses on data-driven solutions for industrial IoT and big data analytics in remote corrosion monitoring. He can be contacted at email: imhays179@gmail.com.

**Hairul Hafizi Hasnan** is a Senior Lecturer at the University of Malaya, specializing in audio engineering and music production. He holds a doctorate and a master's degree in music production from the University of York, U.K., as well as bachelor's degrees in physics with electronics and music, reflecting his interdisciplinary expertise. His research spans acoustics, audio technology, and applied sound studies. Currently, he focuses on identifying sounds and tones to help keep elephants away, using sound analysis to create eco-friendly solutions for reducing conflicts between humans and elephants. He can be contacted at email: hairulhasnan@um.edu.my.

**Ahmad Fateh Mohamad Nor** received his Ph.D. in Electrical Engineering from Universiti Tun Hussein Onn Malaysia (UTHM), where he is a Senior Lecturer in the Faculty of Electrical and Electronic Engineering. He is a registered Professional Technologist (Ts.) with the Malaysia Board of Technologists. His research interests include renewable energy systems, power electronics, the internet of things (IoT), and smart energy management. He has led several funded projects and is a member of the MDR grant. He has published extensively in journals and conferences. He can be contacted at email: afateh@uthm.edu.my.

**Rohaiza Hamdan** received her Ph.D. in Electrical Engineering from Universiti Teknologi Malaysia and is currently a Senior Lecturer at the Faculty of Electrical and Electronic Engineering, Universiti Tun Hussein Onn Malaysia (UTHM). Her research interests include renewable energy systems, photovoltaic (PV) integration, smart grids, and internet of things (IoT)-based applications. She has been actively involved in funded projects on PV-powered systems, including the MDR grant project. She also actively contributes to the advancement of sustainable energy solutions for rural and off-grid communities. She can be contacted at email: rohaiza@uthm.edu.my.

**Nazirah Mohamad Abdullah** is an Associate Professor at Universiti Tun Hussein Onn Malaysia (UTHM) with research interests spanning wireless communication, the internet of things (IoT), and sustainable energy systems. Her work focuses on integrating IoT for environmental monitoring, agriculture, and rural applications. She has contributed to projects involving navigation solutions for human–elephant coexistence, applying IoT-based sensing and tracking technologies to mitigate human–wildlife conflicts. She has published in international journals and conferences and is actively engaged in interdisciplinary research on smart systems for societal and environmental sustainability. She can be contacted at email: nazirah@uthm.edu.my.

**Nor Anija Jalaludin** is a Senior Lecturer at the Faculty of Engineering Technology, Universiti Tun Hussein Onn Malaysia (UTHM). She received her Ph.D. in Electrical Engineering from Universiti Teknologi Malaysia. Her research interests include renewable energy systems, power electronics, and internet of things (IoT) applications for smart and sustainable solutions. She has contributed to various projects integrating solar photovoltaic technologies with embedded systems and is actively involved in integrating technology to safeguard villages from elephant intrusions, a community-driven initiative applying IoT-based monitoring to mitigate human–wildlife conflicts. She can be contacted at email: noranija@uthm.edu.my.