Evaluation of Solar Energy Potential in Bojakan Village, Mentawai Islands Using PVGIS Simulation

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ABSTRACT

Electricity access remains highly uneven in Indonesia, especially in remote and underserved island regions such as the Mentawai Islands in West Sumatra. Bojakan Village, located in North Siberut District, is one of several communities still lacking electricity from the national utility grid (PLN). In response to this challenge, this study explores the technical feasibility of deploying solar photovoltaic (PV) systems as a renewable energy solution. Using hourly simulation data for a standard 1 kWp PV system from the Photovoltaic Geographical Information System (PVGIS), developed by the Joint Research Centre (JRC), energy production was analyzed over a three-year period (2021–2023). The data were processed in MATLAB to assess daily output, seasonal fluctuations, and average performance. Findings show that the PV system produces an average of 3.64 kWh/day. To meet the village's projected electricity demand by 2031, a system with a capacity of approximately 49.7 kWp would be required, occupying a ground area of around 1,093.4 m². The results indicate that Bojakan holds sufficient solar potential for a sustainable off-grid energy system, subject to further technical and socio-economic considerations.

KEYWORDS: *Solar energy, PVGIS, PLTS system, Rural electrification, Mentawai.*

NOMENCLATURE

A	Required land area for PV installation (m²)
E_{daily}	Total daily energy produced (Wh)
$\bar{E}_{PV}$	Average daily energy per 1 kWp system (kWh/kWp/day)
E_{load}	Estimated daily electricity demand (kWh/day)
fd	Derating factor (unitless)
Pi	Hourly PV system power output (W)
P_{PLTS}	Required PV system capacity (kWp)
r	Area-to-capacity ratio (m²/kWp)

1.0 INTRODUCTION

Equitable access to electricity is a fundamental pillar in supporting inclusive and sustainable socio-economic development. In Indonesia, the government has succeeded in increasing the national electrification ratio to over 99% by 2023. However, this achievement does not fully reflect the actual conditions on the ground, especially in remote, outermost, and underdeveloped regions commonly known as 3T areas where disparities in electricity distribution remain significant. One such region still facing considerable challenges in electrification is the Mentawai Islands Regency, located in West Sumatra Province. This archipelagic area consists of scattered islands with a humid tropical climate and limited basic infrastructure, which complicates conventional energy development.

As of 2023, at least seven villages in the Mentawai Islands namely Betumonga, Sagulubbek, Sirilogui, Sotboyak, Simatalu, Sigapokna, and Bojakan remain unconnected to the national grid operated by the state-owned utility PLN [1]. Among them, Bojakan Village in North Siberut District represents a critical case study for assessing both the challenges and opportunities of renewable energy-based electrification. Spanning an area of 263.04 km² and inhabited by 1,168 residents, the village comprises three main hamlets: Bojakan, Lubaga, and Baik. According to data from the Central Bureau of Statistics, out of 301 households, 296 do not have access to electricity, while the remaining five rely on limited and individually managed off-grid sources [2].

At the regional level, the Mentawai power system is currently supported by a 20 kV distribution network with an installed capacity of 9.5 MW and a net available capacity of approximately 5.5 MW. However, this capacity only meets a peak load of around 3.3 MW and is insufficient to serve isolated areas where infrastructure development costs are prohibitively high. Therefore, a decentralized electrification strategy based on renewable energy sources has become highly relevant. This aligns with national policy as outlined in the Electricity Supply Business Plan (RUPTL) 2025–2034, which emphasizes diesel displacement and the promotion of renewable energy in island and rural regions [3].

Among renewable energy options, solar energy is considered one of the most promising for tropical regions such as the Mentawai Islands. With abundant and relatively stable solar radiation throughout the year and the modular nature of photovoltaic (PV) systems, solar energy offers a flexible, cost-effective, and scalable solution suitable for off-grid applications. However, to date, no quantitative technical assessment has been conducted to evaluate the solar energy potential in Bojakan Village, despite its critical role in informing site-specific solar power plant (PLTS) planning.

The projected daily electricity demand in Bojakan by 2031 is estimated at 134.37 kWh/day [4], which includes energy needs from 428 households and 25 public facilities such as schools, health centers, village offices, and places of worship. To address this challenge, this study aims to evaluate the technical potential of solar energy in Bojakan Village using hourly simulation data of a 1 kWp PV system obtained from the Photovoltaic Geographical Information System (PVGIS), developed by the Joint Research Centre (JRC) of the European Commission. The analysis period spans from 2021 to 2023, and includes estimations of average daily electricity production, seasonal fluctuation patterns, required minimum PLTS capacity, and land area requirements for ground-mounted PV installations.

By employing open-source data and a comprehensive technical approach, this study is expected to contribute meaningfully to renewable energy-based electrification planning in underserved areas and serve as an initial reference for developing off-grid community-scale solar power systems in Indonesia.

2.0 METHOD

2.1 Research Location

This research adopted a quantitative-descriptive methodology to assess the technical potential of solar energy deployment in Bojakan Village, located in the North Siberut Subdistrict, Mentawai Islands Regency, West Sumatra Province, Indonesia. Bojakan is officially categorized as a 3T (underdeveloped, frontier, and outermost) area—a classification used by the Government of Indonesia to identify regions with significant infrastructure and development deficits. As of 2023, the village remains without access to electricity from the national utility provider (PLN), making it a relevant case study for decentralized renewable energy applications.

Geospatially, the study site lies at 98.83° East longitude and −1.27° South latitude, placing it within the humid tropical climatic zone that dominates much of the Indonesian archipelago. The geographical location of Bojakan Village is visualized in Figure 1, where the starred marker indicates its relative remoteness from major urban or grid-connected settlements. The village is isolated by challenging terrain and lacks reliable overland transport infrastructure, factors which substantially hinder the development of centralized power grid extensions.

Furthermore, the persistent high humidity, dense vegetation, and frequent rainfall common attributes of the region's equatorial rainforest climate pose additional considerations in the design and operation of photovoltaic (PV) systems, especially in terms of panel soiling, material degradation, and reduced solar insolation during extended wet seasons. These constraints emphasize the necessity for tailored system designs that account for environmental stressors. Given these characteristics, Bojakan Village provides a critical microcosm for examining the feasibility of off-grid solar PV systems in remote, underserved island communities.

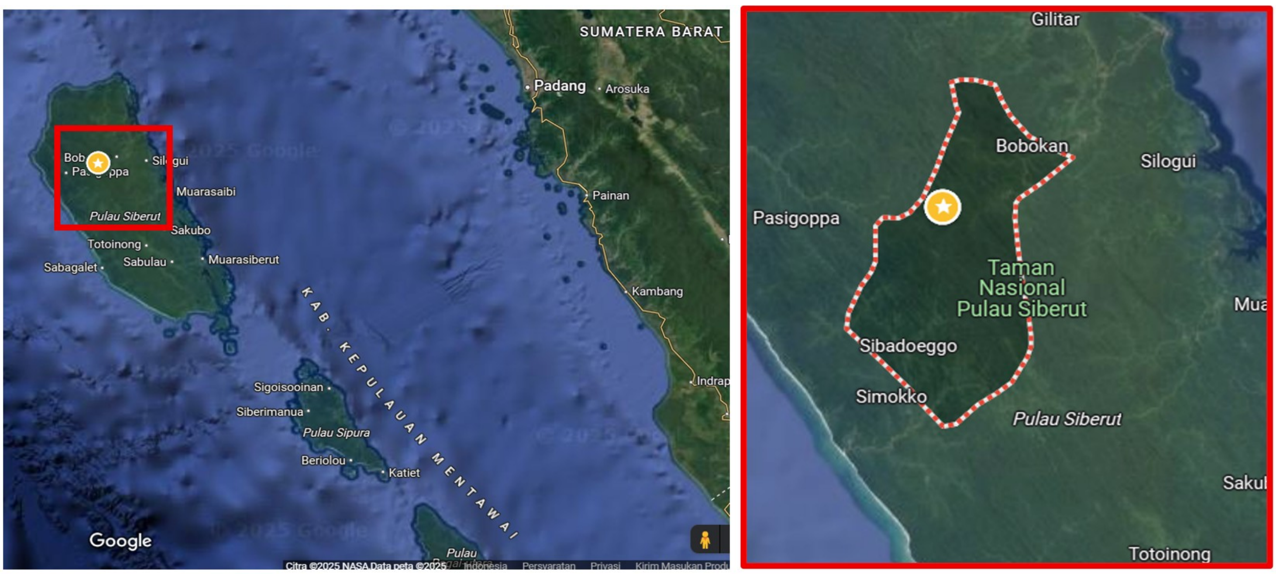

Figure 1: Data collection location map

The outcomes of such assessments are increasingly important to national policy frameworks, such as the *Rencana Usaha Penyediaan Tenaga Listrik (RUPTL)* 2025–2034, which prioritize renewable-based electrification for isolated areas. This methodological approach, grounded in empirical data and geographic specificity, enables a realistic evaluation of solar energy potential and contributes to evidence-based planning for sustainable rural electrification strategies.

2.2 Data Source And Characteristics

This study utilizes secondary data derived from the Photovoltaic Geographical Information System (PVGIS), a solar energy modeling platform developed by the Joint Research Centre (JRC) of the European Commission [5]. PVGIS provides hourly estimates of photovoltaic system output based on technical system parameters, geographic location, and historical climate data collected from both satellite observations and ground-based measurements. Due to its adequate spatial and temporal resolution, PVGIS is widely adopted in technical studies and solar energy planning, especially in tropical and subtropical regions [6].

The analysis in this study was conducted using the geographic coordinates of Bojakan Village, namely 98.83° E and −1.27° S. The dataset comprises hourly power output (P) in watts from a simulated 1 kWp photovoltaic (PV) system for three consecutive years: 2021, 2022, and 2023. The P values represent direct estimates of energy generated by a standard PV system at the specified location, accounting for daily atmospheric variability and solar radiation intensity during the simulation period.

The PVGIS configuration was adjusted to represent a crystalline silicon PV system, which is the most commonly used and technically reliable photovoltaic technology in tropical regions [7]. Technical parameters included an automatically optimized panel tilt angle of 11° to maximize energy production at low latitudes. The azimuth orientation was set to 0°, meaning the panels face true south (in the Northern Hemisphere) or true north (in the Southern Hemisphere), which is optimal for equatorial locations such as Mentawai. A system loss assumption of 14% was used, incorporating losses from inverter inefficiency, wiring, partial shading, dust accumulation, and module degradation. This loss estimate follows PVGIS recommendations for remote and humid tropical environments, where operational challenges are generally more pronounced.

All simulation settings were configured using the online PVGIS interface, with the input parameters illustrated in Figure 2. The simulation results were exported in .csv format and processed using MATLAB software for energy conversion, daily aggregation, statistical analysis, and visualization. These results form the basis for evaluating system capacity and land requirements in subsequent sections.

2.3 Energy Conversion

Hourly power output data from the PVGIS simulation were converted into daily energy values (Wh), denoted as E_{daily}, by summing the power across 24 hours. This process is expressed in Equation (1):

$$E_{\text{daily}} = \sum_{i=1}^{24} P_i \tag{1}$$

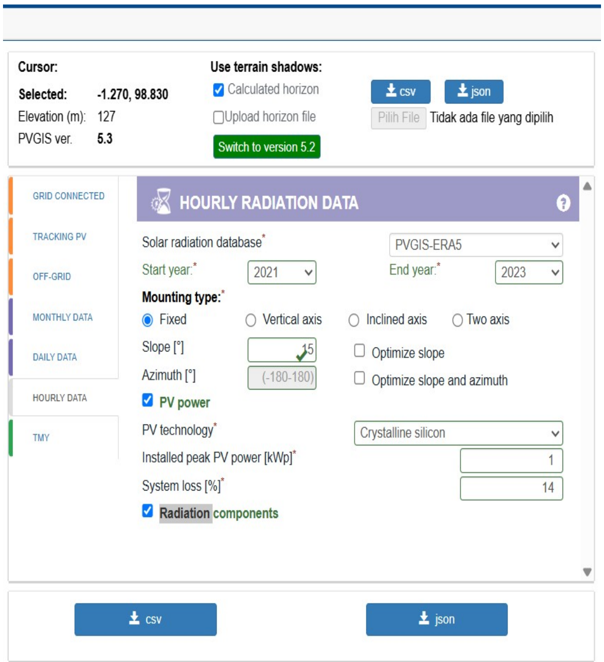

Figure 2: The PVGIS simulation settings

To evaluate long-term performance, the average daily energy over one year was calculated using Equation (2):

$$\bar{E}_{\text{daily}} = \frac{1}{N} \sum_{j=1}^{N} E_{\text{daily},j} \tag{2}$$

Both equations are adapted from standard methods in solar energy performance assessment, and widely referenced in PV output estimation practices [8][9].

2.4 Estimating Required PV System Capacity

To estimate the total installed PV capacity P_{PLTS} required to meet the daily energy demand of the village, Equation (3) was used:

$$P_{\text{PLTS}} = \frac{E_{\text{load}}}{\bar{E}_{\text{PV}} \times f_d} \tag{3}$$

In this equation, E_{load} is the projected daily energy demand, E_{PV} is the average daily output from a 1 kWp PV system, and f_d is the derating factor. A derating factor of 0.743 was used in this study, based on empirical results from off-grid PV–battery systems in remote communities [10]. This value accounts for real-world performance losses such as inverter inefficiency, cable losses, panel soiling, shading, and module degradation. According to NREL and SEI guidelines, derating factors typically range from 0.75 to 0.85 depending on environmental and operational conditions [8][9]. Thus, using a value of 0.743 is considered conservative yet realistic, especially for remote, high-humidity regions like Bojakan.

2.5 Estimating Land Area Requirement

For ground-mounted systems, the required land area is calculated as [11]:

$$A = P_{\text{PLTS}} \times r \tag{2}$$

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Here, r denotes the land-use ratio (m² per kWp). A value of 22 m²/kWp was used, representing a conservative estimate suitable for ground-mounted systems in rural or topographically challenging locations [12]. This land-use ratio accounts for space required not only by the PV panels, but also for inter-row distances to avoid shading, access paths for maintenance, and buffer zones to accommodate uneven terrain. This is in accordance with recommendations from Solar Energy International (SEI), which emphasize spatial allowances for systems without pre-existing rooftop infrastructure [8][9]. The application of this ratio reflects common off-grid design practices, particularly in regions where land is available but access and environmental constraints demand flexible layout planning. Therefore, 22 m²/kWp is considered a practical estimate for Bojakan's context.

3.0 RESULTS AND DISCUSSION

3.1 Daily Solar Energy Fluctuation

Solar energy production in 2021 exhibited a distinct seasonal pattern, as illustrated in Figure 3. The average daily energy output of the 1 kWp PV system was recorded at 3.60 kWh, with a standard deviation of 1.04 kWh. The maximum output occurred on November 29, reaching 5.46 kWh, while the lowest value was recorded on August 17 at only 0.51 kWh. This reduction in output generally coincided with the rainy season in West Sumatra, which typically spans from May to August, potentially affecting solar radiation intensity and photovoltaic system efficiency.

Overall, the average daily production falls within a reasonable range for PV systems operating in tropical regions. This outcome aligns with findings from experimental studies on household PV systems in Indonesia, which report that a 1 kWp system can produce between 3.5 and 4.0 kWh per day under optimal conditions [13]. Additionally, other research suggests that the western region of Sumatra possesses relatively stable solar radiation characteristics, making it suitable for the development of community-based solar energy systems [14].

Considering the seasonal variability and performance outcomes throughout 2021, the results offer an initial indication that Bojakan Village holds sufficient technical potential for off-grid PV system development. However, further investigation into non-technical aspects such as humidity effects, system maintenance, and long-term operational sustainability is recommended.

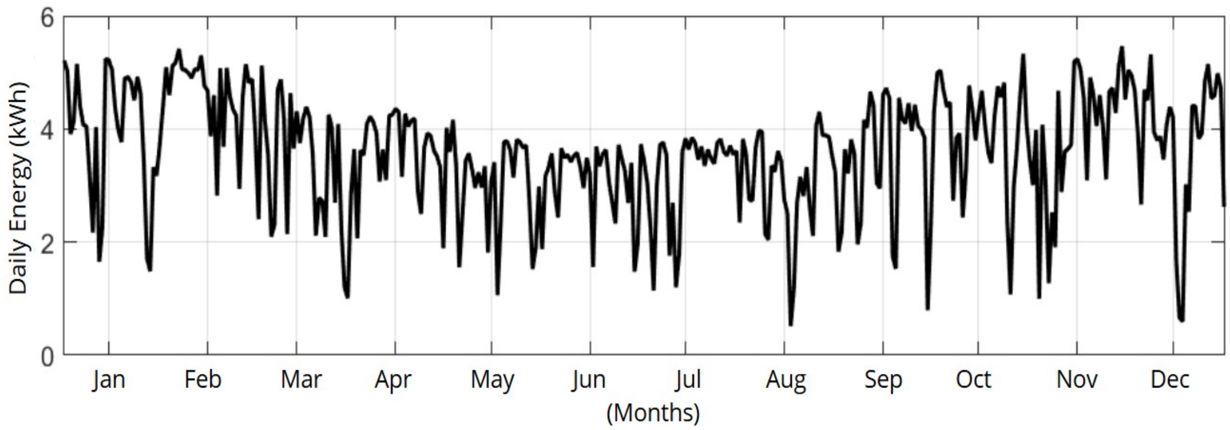

Figure 3: Daily energy profile in 2021

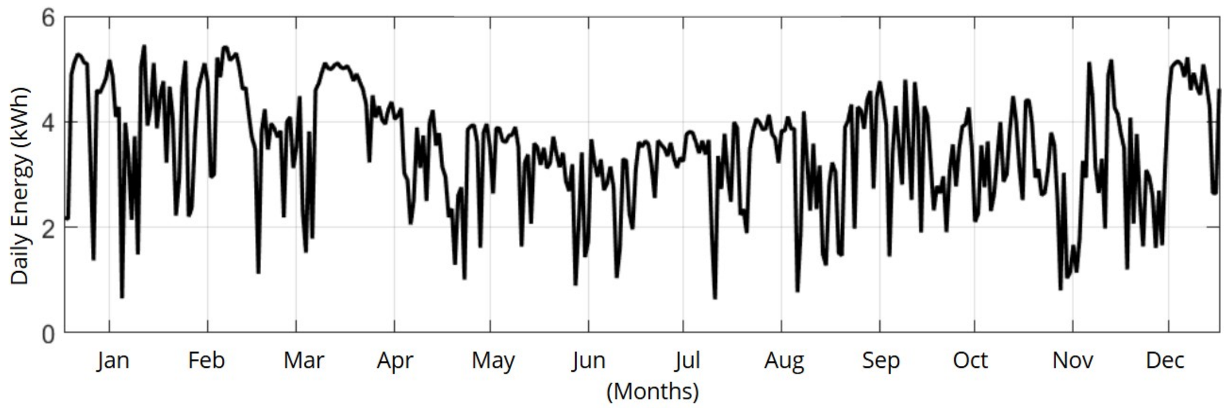

Figure 4: Daily energy profile in 2022

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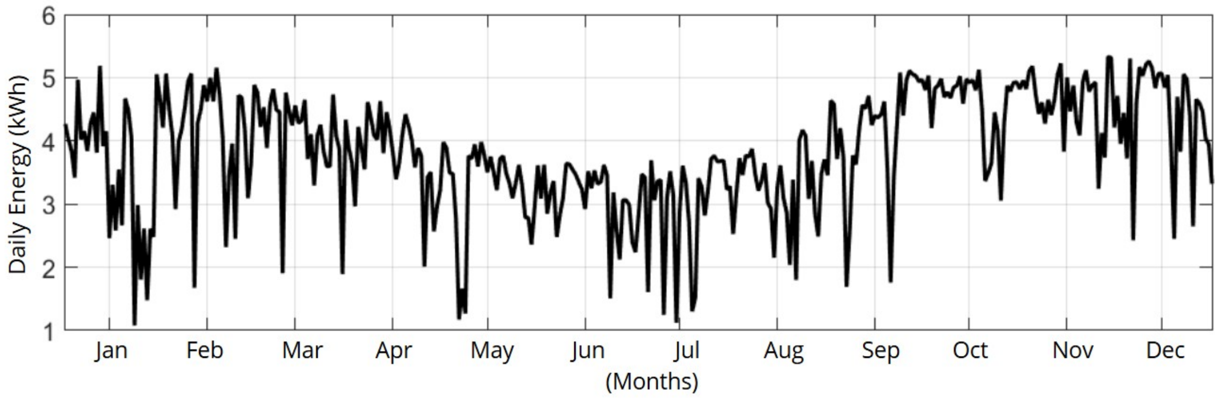

Figure 5: Daily energy profile in 2023

The year 2022 demonstrated a decline in PV system performance compared to the previous year, as illustrated in Figure 4. The average daily energy production was recorded at 3.49 kWh, accompanied by the highest standard deviation over the three-year period at 1.08 kWh. The peak output occurred on January 26 at 5.45 kWh, while the lowest value was observed on July 25 at 0.64 kWh. This considerable fluctuation reflects the system's sensitivity to weather variations, particularly during the rainy season.

Mid-year climatic instability, including high rainfall and increased cloud cover, contributed to the reduction in solar irradiance received by the PV modules. Nevertheless, the average daily output of 3.49 kWh remains within an acceptable range and is relatively close to the reference values reported for household-scale PV systems in Indonesia, which can typically generate around 4–5 kWh/day for a 1 kWp system depending on local weather conditions and site characteristics [14]. These findings indicate that the PV system performance in Bojakan Village remains competitive and technically viable for further development, despite being situated in a humid tropical climate with environmental challenges.

The year 2023 recorded the most optimal performance among the three years analyzed, as illustrated in Figure 5. The average daily energy output of the 1 kWp PV system reached 3.83 kWh, higher than in the previous years. The standard deviation was the lowest, at 0.92 kWh, indicating a relatively stable energy production throughout the year. The highest daily output was recorded on November 28 at 5.33 kWh, while the lowest was on January 23 at 1.08 kWh. Notably, there were no days with production below 1 kWh, which suggests that the system remained operational even under suboptimal weather conditions.

This result indicates that the climatic conditions in 2023 were generally more favorable for photovoltaic systems, in terms of both irradiance intensity and consistency. Such operational stability is an important indicator of PV system reliability, especially in remote island regions where logistical constraints and maintenance challenges are more prominent.

As a comparison, a 3 kWp rooftop PV system in Surabaya has been reported to produce an average of 10.7 kWh/day, equivalent to approximately 3.6 kWh/kWp/day [15]. With the Bojakan system reaching an average of 3.83 kWh/day from a 1 kWp installation, its performance can be considered highly feasible, and even comparable to PV systems in urban tropical settings, despite being installed under more basic conditions in a remote location.

3.2 Monthly Energy Distribution

The monthly energy distribution in 2021, as illustrated in Figure 6, exhibits a distinct seasonal pattern. Significant variability was observed between May and August, characterized by a wide range of values and the presence of several low outliers. This condition is strongly presumed to be influenced by high rainfall during this period, which likely reduced solar irradiance levels and directly impacted the performance of the PV system.

In contrast, from October to December, the distribution appears narrower, with a relatively high and stable median output. This suggests more favorable weather conditions clearer skies and more consistent solar exposure resulting in optimal energy production and minimal disruption. This seasonal trend aligns with the typical humid tropical climate pattern of the Mentawai Islands, where the wet season generally occurs mid-year and the dry season toward the end of the year.

Overall, the 2021 boxplot indicates that the PV system in Bojakan maintained a reliable level of performance throughout the year, despite experiencing pronounced fluctuations during the rainy season. These findings underscore the importance of incorporating adaptive design strategies in solar energy systems to effectively address seasonal variability, particularly in tropical island regions [16]. The distribution of solar energy production in 2022, as presented in Figure 7, exhibits the lowest stability among the three years analyzed. This is evidenced by the consistent appearance of low outliers during the months of June through September. The inter-quartile range is also relatively wide, indicating high variability in daily energy output throughout this period. Such fluctuations are most likely associated with less favorable atmospheric conditions, such as increased cloud cover and heavy rainfall during the easterly monsoon season, which is known to bring intense precipitation to the western part of Indonesia, including the Mentawai Islands. As solar energy generation is highly dependent on solar irradiance, this resulted in significantly reduced output over an extended duration.

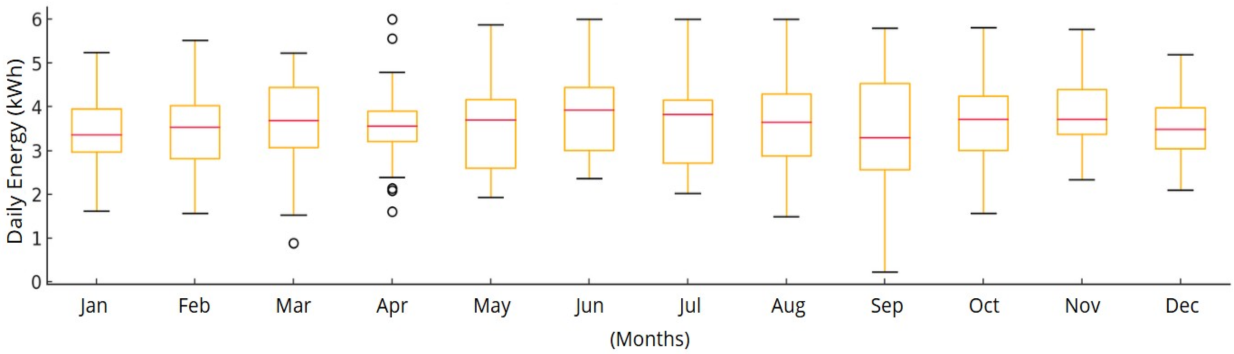

Figure 6: Monthly distribution in 2021

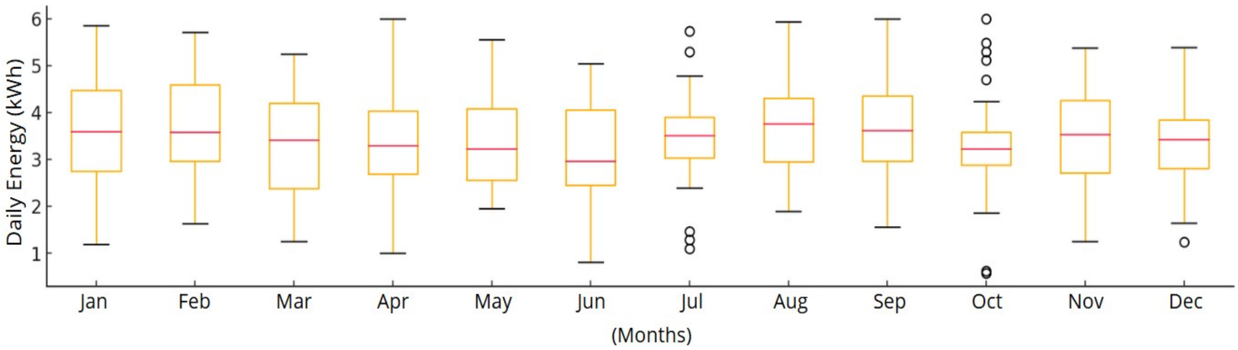

Figure 7: Monthly distribution in 2022

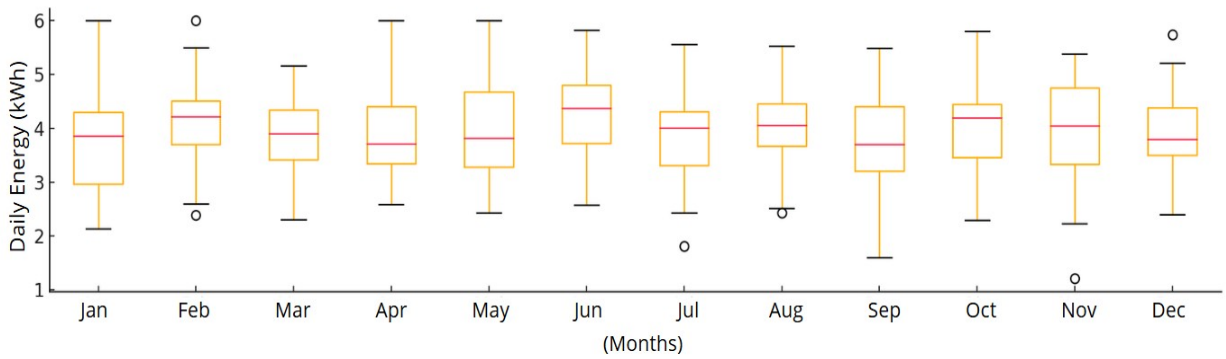

Figure 8: Monthly distribution in 2023

These findings highlight the operational challenges that must be addressed in deploying PV systems in humid tropical regions. Accordingly, PV systems in areas like Bojakan should be designed with seasonal variability in mind potentially through the integration of energy storage (batteries), system overdesign, or weather-adaptive control mechanisms. Similar recommendations have been emphasized by IRENA, which noted that the successful implementation of solar energy systems in tropical regions depends on their ability to adapt to local climatic conditions [17].

The distribution of solar energy production in 2023, as illustrated in Figure 8, indicates a relatively higher level of stability compared to the previous two years. Most months exhibit a narrow spread of values, with daily production medians consistently exceeding 3.5 kWh. This pattern suggests lower day-to-day variability in energy output during the year. No significant extreme outliers are observed, implying that daily fluctuations remained moderate and were not heavily impacted by abrupt weather disturbances. While some degree of variability remains inherent to tropical climates, this trend reflects that the photovoltaic (PV) system operated under relatively stable climatic conditions throughout 2023.

Considering this pattern, it can be inferred that 2023

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represents a more consistent period of solar energy availability in Bojakan Village. Nevertheless, further studies and continuous monitoring are still necessary to assess the long-term technical viability of developing a community-based off-grid PV system in the region.

3.3 Integrated Analysis of Solar Energy Potential

An integrative analysis of the 1 kWp photovoltaic (PV) system energy production in Bojakan Village over the period of 2021–2023 reveals a moderate level of inter-annual variability, while remaining within a technically feasible productivity range. As presented in Table 1, the highest average daily output was recorded in 2023 at 3.828 kWh/day, whereas the lowest was observed in 2022, with an average of 3.488 kWh/day. Overall, the annual averages across the three years ranged from 3.49 to 3.83 kWh/day, with a cumulative mean value of 3.637 kWh/day.

Table 1: Daily energy statistics of 1 kWp PV system

Year	Average (kWh/day)	Maximum (kWh/day)	Minimum (kWh/day)	Standard Deviation (kWh)
2021	3.597	5.463	0.515	1.039
2022	3.488	5.453	0.637	1.080
2023	3.828	5.331	1.079	0.923

The daily maximum energy output ranged from 5.331 to 5.463 kWh/day, indicating that the system was able to approach the theoretical peak output of a 1 kWp PV system under optimal conditions on certain days. Meanwhile, the minimum daily values remained above 0.5 kWh, with the lowest recorded value in 2021 at 0.515 kWh. This suggests that the system continued to produce energy even during the lowest irradiation periods, typically occurring at the peak of the rainy season. The annual standard deviations ranged from 0.923 to 1.080 kWh, with the highest variation observed in 2022. This fluctuation reflects the seasonal weather patterns that influence the stability of energy production. The high variability in 2022 also corresponds to earlier findings in the monthly distribution analysis, which indicated several outliers during mid-year.

Overall, the inter-annual stability of energy production suggests that a 1 kWp PV system demonstrates reasonably reliable performance in Bojakan Village. Moreover, the PVGIS simulation results support the assumption that tropical coastal areas such as Mentawai have adequate solar energy potential. These findings align with national reports on solar energy potential, which cite a technical installed capacity of 207 GWp [18], as well as studies in other tropical regions like Bali, where similar outputs in the range of 3.5–4.0 kWh/kWp/day have been reported.

Given the relatively stable average production and the absence of days with energy output below 0.5 kWh, Bojakan Village exhibits a promising solar energy profile for off-grid photovoltaic system development. Nevertheless, practical implementation would require well-designed storage systems and load management strategies to ensure optimal performance under seasonal variability.

3.4 Estimated PV System Capacity

To meet the projected daily electricity demand of Bojakan Village, estimated at 134.37 kWh/day by 2031 as stated by Fathurahman [4], a solar photovoltaic power system (PLTS) must be designed with a capacity that aligns with the site-specific solar energy potential. The system capacity estimation considers both the average daily energy yield of a 1 kWp photovoltaic (PV) system and the overall system efficiency, which is accounted for using a derating factor. Based on the simulated output data of a 1 kWp PV system over a three-year period (2021–2023), the following average daily energy production values were obtained:

$$\bar{E}_{\mathrm{PV}} = \frac{3.597 + 3.488 + 3.828}{3} = 3.637\ \mathrm{kWh/day}$$

By applying a derating factor of 0.743 which reflects the actual system efficiency of PV installations in remote areas the required capacity of the solar PV system (PLTS) can be calculated using the following equation:

$$P_{\mathrm{PLTS}} = \frac{E_{\mathrm{load}}}{\bar{E}_{\mathrm{PV}} \times f_d}$$

$$P_{\mathrm{PLTS}} = \frac{134{,}37\ \mathrm{kWh/hari}}{3{,}637\ \mathrm{kWh/kWp/hari} \times 0{,}743} \approx 49{,}7\ \mathrm{kWp}$$

Thus, to meet the projected daily electricity demand of 134.37 kWh while accounting for realistic system efficiency under field conditions a minimum PV system capacity of 49.7 kWp is required. This estimation serves as a foundational reference for planning a technically viable and sustainable off-grid solar power system tailored to the specific conditions of Bojakan Village.

3.5 Estimated Land Requirement

Land requirement estimation is a critical component in the planning of photovoltaic power systems, particularly for ground-mounted configurations commonly implemented in remote areas. Based on technical assessments and the study by Martín-Chivelet [8][9], the required land area for each kilowatt-peak (kWp) of installed PV capacity is estimated to be approximately 22 m^2/kWp. This value accounts not only for the physical dimensions of the panels but also includes spacing between panel strings, access pathways for maintenance, and additional tolerance for uneven terrain and suboptimal layout due to site constraints.

Given the previously calculated system capacity of 49.7 kWp, the total minimum land area requirement can be estimated using the following equation:

$$A = P_{\mathrm{PLTS}} \times r$$

$$A = 49{,}7\ \mathrm{kWp} \times 22\ \mathrm{m}^2/\mathrm{kWp} = 1.093{,}4\ \mathrm{m}^2$$

Therefore, an estimated land area of approximately 1,093.4 m^2 is required for the installation of a 49.7 kWp photovoltaic system in Bojakan Village. It is important to note that this estimate does not include additional space that may be necessary for supporting components such as inverters, maintenance pathways, and safety buffer zones, which may be required depending on the specific geographical and technical site conditions.

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4.0 CONCLUSION

This study has evaluated the technical potential of solar photovoltaic (PV) energy as an off-grid electrification solution for Bojakan Village, located in the remote Siberut Utara District of the Mentawai Islands, Indonesia. The evaluation was based on simulated hourly output data from a 1 kWp PV system using the PVGIS platform developed by the Joint Research Centre (JRC) of the European Commission for the period 2021 to 2023. The findings of this research provide a comprehensive technical assessment that includes average daily energy production, seasonal fluctuation patterns, estimated system capacity, and projected land requirements. The analysis revealed that the average daily energy production of a 1 kWp PV system ranged from 3.488 to 3.828 kWh/day, with a cumulative mean of 3.637 kWh/day. These values, accompanied by annual standard deviations ranging between 0.922 and 1.080 kWh, suggest a moderate seasonal variability typically influenced by the region's tropical monsoon climate. Solar energy production generally declined during the mid-year rainy season (May to August) and increased in the latter part of the year, particularly from October to December, when solar irradiance was more stable. In order to meet the projected daily electricity demand of 134.37 kWh/day in Bojakan by 2031, the minimum required PV system capacity was estimated at 49.7 kWp. This calculation was based on the averaged energy yield and a conservative derating factor of 0.743, which accounts for system losses due to inverter inefficiencies, cable resistance, shading, dust accumulation, and module degradation factors that are particularly relevant in remote, humid tropical settings such as Bojakan. To accommodate a PV system of this scale using a ground-mounted configuration, a land area of approximately 1,093.4 m² would be required, assuming a land-use ratio of 22 m²/kWp. This estimation excludes additional space for inverters, maintenance pathways, and safety buffers, which may increase the overall spatial requirements depending on site-specific topographical and infrastructural conditions. Overall, the results indicate that Bojakan Village possesses a technically viable solar resource that could support the development of a community-based off-grid PV system. However, the findings also underscore the importance of addressing non-technical dimensions in future research, including economic feasibility studies, socio-institutional readiness, supply chain logistics, and maintenance frameworks. Furthermore, given the variability in weather and the challenges posed by tropical climates, integration of storage systems and adaptive control strategies should be considered to enhance system resilience. This study contributes valuable baseline data for planning decentralized electrification in Indonesia's underserved regions and can serve as a reference model for similar remote communities across the archipelago. Future work should focus on hybrid system simulations, cost–benefit analysis, and pilot implementation studies to validate the technical assumptions made in this research and to inform policy-level decisions.

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