E-ISSN : 3048-3646

# STUDY OF DIESEL POWER PLANT REPLACEMENT WITH AN OFF-GRID SOLAR PHOTOVOLTAIC SYSTEM

**Gustiyadi Fathur Rahmandi[1], Atok Setiyawan[2], Hendro Nurhadi[3]**

1. Department of Mechanical Engineering, Faculty of Industrial Technology and Systems Engineering, Institut Teknologi Sepuluh Nopember, Surabaya, Indonesia
2. Department of Industrial Mechanical Engineering, Faculty of Vocational Studies, Institut Teknologi Sepuluh Nopember, Surabaya, Indonesia
3. Department of Mechanical Engineering, Faculty of Industrial Technology and Systems Engineering, Institut Teknologi Sepuluh Nopember, Surabaya, Indonesia

(*) Corresponding Author : gfaturr89@gmail.com , atok_s@me.its.ac.id, hdnurhadi@its.ac.id

**Abstract**

*The electrification ratio on the island of Kalimantan has increased significantly from 2014 to 2024, significantly impacting people's lives, especially in Central Kalimantan Province. North Barito Regency is one of the regions that continues to strive to meet the electricity needs of its residents who still lack access to electricity, especially in the 3T (Outermost, Frontier, and Disadvantaged) areas through the Electrification Ratio (RE) program. This vast area presents a unique challenge in ensuring the equitable distribution of electricity to these 3T areas. To meet the National RE target and utilize the various types of power plants currently available in North Barito Regency, as well as to support the transition to New and Renewable Energy (EBT), PLN is connecting the existing electricity grid to the new grid through a network expansion scheme in urban areas. Meanwhile, in the 3T areas, renewable energy is being utilized, such as the construction of solar power plants (PLTS) capable of providing a 24-hour electricity supply. The main obstacles facing PLN (State Electricity Company) in Kalimantan in implementing this RE program include inadequate road access and road conditions for transporting electricity grid infrastructure materials, weather conditions (rain can slow work progress), and permits for 20 kV electricity grid infrastructure from individuals, groups, organizations, or business entities. This research will outline a plan to replace diesel-powered plants (PLTD) with off-grid solar power plants (PLTS) as a renewable energy source, taking into account operating load patterns and the efficiency of the solar power plants, based on the PV panel materials used: monocrystalline and polycrystalline. It is hoped that this study will provide information on the impact of PLTS development on the existing electricity system, enabling PLN to be more efficient in supporting the achievement of a 23% renewable energy mix by 2025.*

*Keywords: 3T, RE, EBT, 20 kV, PLTS, Off Grid, Monocrystalline, Polycrystalline*

## BACKGROUND

Over the last decade, the electrification ratio in Kalimantan has increased substantially, shifting electricity from a basic service to a critical enabler of daily socio-economic activities, particularly in Central Kalimantan. However, achieving equitable electricity access remains difficult in 3T areas (outermost, frontier, and disadvantaged regions) due to wide geographic coverage and logistical constraints. In North Barito Regency, PLN continues to expand electrification by extending existing networks in urban areas while deploying renewable-based solutions—especially solar power plants (PLTS)—to supply 24-hour electricity in remote locations. Key barriers include limited road access and poor road conditions for transporting grid materials, weather-related delays, and permitting challenges for 20 kV distribution infrastructure.

Diesel-based generation is still widely used in isolated village electricity systems, yet its dependence on fuel delivery and high operating costs make it less suitable for long-term electrification in remote regions. In the case of ULD Gunung Purei, the existing supply relies on a small-scale diesel power plant (PLTD) with a total installed capacity of about 400 kW serving hundreds of customers, highlighting the typical constraints of isolated systems that must balance reliability with operational feasibility.

Recent studies consistently show that integrating solar PV and battery storage—either as full replacement or as hybridization—can reduce diesel runtime and fuel consumption while improving supply reliability, provided that the PV and storage capacities are properly matched to the local load profile. This techno-economic optimization is commonly performed using tools such as HOMER, which enable comparison against diesel-only baselines under different demand and resource conditions.

A growing body of literature in the last five years emphasizes that the feasibility of off-grid PV-based electrification is highly sensitive to (i) accurate hourly load characterization, (ii) battery sizing and autonomy targets, and (iii) component performance assumptions under real operating temperatures. For example, off-grid PV systems can deliver uninterrupted supply in remote areas, but battery capacity can become the dominant cost driver if not optimized with suitable operational strategies. Furthermore, systematic reviews of hybrid renewable energy systems (PV–diesel–battery) report that cost competitiveness and reliability improvements are achievable, but outcomes vary strongly by site conditions and design choices, reinforcing the need for case-specific analysis. Newer optimization-focused studies also highlight that multi-technology configurations (e.g., PV with storage and optional backup generation) can enhance resilience and reduce lifecycle costs, but must be evaluated using robust dispatch and sensitivity analyses.

Based on these considerations, this research's focus on replacing PLTD with an off-grid PLTS in ULD Gunung Purei—while explicitly comparing monocrystalline and polycrystalline PV modules under local operating constraints—addresses a practical gap: providing PLN-relevant evidence on how PV technology choice and storage autonomy affect technical performance and investment feasibility in a real 3T electrification context.

Electricity access is a fundamental driver of socio-economic development, enabling improvements in education, health services, industry, and livelihoods (Stoppok & Ueckerdt, 2023). Over the past decade, the electrification ratio in Kalimantan has risen substantially, moving communities from limited access toward broader grid reach. Nevertheless, rural and remote 3T areas (outermost, frontier, and disadvantaged regions) still face significant challenges in achieving reliable and equitable electricity access due to geographic dispersion, infrastructure limitations, and economic constraints. In Central Kalimantan Province, expanding electrification beyond urban centers remains a pressing concern as nearly all community activities increasingly demand uninterrupted electrical supply (Sari et al., 2021).

North Barito Regency exemplifies these challenges: although electrification efforts have advanced, many villages—especially those in rugged terrain—continue to rely on isolated diesel power plants (PLTD) for electricity. Diesel generation, while simple to deploy, is characterized by high operational costs, volatile fuel supply logistics, and considerable greenhouse gas emissions. Diesel dependency in remote grids also leads to supply disruptions during adverse weather or transportation delays, undermining energy security and community welfare (Rahman et al., 2022). Emerging research shows that hybrid and renewable-based electrification strategies can significantly reduce fuel costs and improve reliability when properly designed to local load profiles and resource conditions (Nguyen et al., 2023).

To meet national electrification targets and advance transition toward New and Renewable Energy (NRE), PLN has pursued dual strategies: (1) grid extension in urban and semi-urban areas through network expansion schemes, and (2) adoption of renewable energy technologies such as solar power plants (PLTS) in remote 3T areas to supply 24-hour electricity without dependency on diesel. However, logistical barriers like inadequate road access for transporting infrastructure materials, challenging weather conditions that delay construction, and complex permitting processes for 20 kV distribution lines continue to limit deployment speed and scalability in these regions (Utomo & Suryani, 2024).

Recent studies have highlighted that off-grid solar PV systems—especially when paired with energy storage—are among the most promising solutions for remote electrification due to declining costs of photovoltaic modules and batteries, alongside improvements in system efficiency (Al-Shamaa et al., 2024). The choice of PV technology, notably monocrystalline versus polycrystalline modules, affects system performance, lifetime yield, and land requirements. Monocrystalline panels typically offer higher efficiency and better performance under low-irradiance conditions, while polycrystalline counterparts provide lower upfront costs with slightly reduced efficiency (Zhao et al., 2021). Battery sizing strategies also play a crucial role: appropriate autonomy ensures continuous supply during night and cloudy periods, but oversizing can inflate system costs and undermine economic feasibility.

Techno-economic analysis tools such as HOMER and PVSyst have been widely applied to evaluate renewable energy system configurations, allowing comparison of diesel-only, hybrid, and full renewable solutions under local conditions. These tools enable optimization of component sizes and assessment of financial metrics like Net Present Value (NPV), Levelized Cost of Energy (LCOE), and payback periods, providing planners with evidence-based insights for investment decisions (Kumar & Singh, 2022; Silva et al., 2023).

Despite this progress, there remains a need for context-specific analysis tailored to 3T electrification cases in Indonesia. Studies focusing on local load patterns, climatic conditions, and real deployment barriers are limited. This research aims to fill that gap by proposing a replacement of the PLTD with an off-grid PLTS at ULD Gunung Purei, explicitly comparing the performance and economic viability of monocrystalline and polycrystalline PV systems. By integrating techno-economic analysis with operational constraints, the study provides actionable insights for PLN and policymakers to enhance renewable energy adoption while supporting Indonesia's target of achieving a 23% renewable energy mix by 2025.

## THEORETICAL REVIEW

1. Rural Electrification and Off-Grid Power Systems

Rural electrification plays a crucial role in improving social welfare, economic development, and access to essential services in remote areas. In regions where grid extension is technically difficult or economically unfeasible, off-grid power systems provide an effective alternative for delivering reliable electricity. Off-grid systems operate independently from the main utility grid and are commonly applied in isolated or sparsely populated regions, particularly in developing countries. These systems are typically designed to match local load demand while minimizing capital and operational costs.

Diesel power plants (PLTD) have historically been the dominant solution for off-grid electrification due to their relatively low initial investment and ease of deployment. However, diesel-based systems suffer from high fuel costs, logistical challenges, price volatility, and significant greenhouse gas emissions. Consequently, the integration of renewable energy technologies into off-grid systems has become a strategic priority to improve energy sustainability and reduce long-term operational costs.

2. Solar Photovoltaic (PV) Power Generation

Solar photovoltaic (PV) technology converts solar radiation directly into electrical energy through the photovoltaic effect in semiconductor materials. PV systems are widely adopted in off-grid applications due to abundant solar resources, modularity, low maintenance requirements, and declining technology costs. In off-grid configurations, PV systems are typically combined with battery energy storage to ensure continuous electricity supply during nighttime and low-irradiance periods.

The performance of a PV system is influenced by several factors, including solar irradiance, ambient temperature, module orientation and tilt angle, shading conditions, and the electrical characteristics of system components. Proper system design and sizing are essential to ensure that energy production meets load demand while maintaining acceptable performance levels.

3. Types of Photovoltaic Modules

Photovoltaic modules are commonly classified based on the type of silicon used in their solar cells, with monocrystalline and polycrystalline modules being the most widely deployed.

Monocrystalline PV modules are manufactured from single-crystal silicon and are characterized by higher conversion efficiency, compact installation area, and superior performance under low-irradiance conditions. However, they typically involve higher manufacturing costs compared to other module types.

Polycrystalline PV modules are produced from multiple silicon crystals and generally offer lower efficiency and larger area requirements for the same power output. Despite this, polycrystalline modules are often more affordable and perform adequately in regions with high solar irradiance. The selection between monocrystalline and polycrystalline modules involves a trade-off between efficiency, land availability, and investment cost, making comparative evaluation essential in system planning.

4. Battery Energy Storage Systems

Battery energy storage systems (BESS) are critical components in off-grid solar PV systems, as they store excess energy generated during daylight hours and supply electricity during periods without solar generation. Battery capacity is commonly defined by energy storage size, depth of discharge (DoD), round-trip efficiency, and cycle life.

Lithium-ion batteries are increasingly favored over conventional lead-acid batteries due to their higher energy density, longer cycle life, deeper allowable discharge, and lower maintenance requirements. However, battery sizing must be carefully optimized, as oversized storage significantly increases capital costs, while undersized storage may compromise system reliability. Battery autonomy, often expressed in days of supply, is a key design parameter in off-grid systems.

5. Performance Ratio of Solar PV Systems

The performance ratio (PR) is a widely used indicator to evaluate the overall efficiency of a solar PV system. It represents the ratio between the actual energy output of the system and the theoretical energy output under standard test conditions. PR accounts for system losses related to temperature effects, inverter efficiency, wiring losses, battery losses, and other operational factors.

A higher PR indicates better system performance and energy utilization. In off-grid systems, PR is particularly important for assessing the effectiveness of PV module selection, system configuration, and storage integration under real operating conditions.

6. Techno-Economic Analysis of Off-Grid PV Systems

Techno-economic analysis is an essential framework for evaluating the feasibility of replacing diesel power plants with renewable energy systems. This approach integrates technical performance assessment with economic evaluation to determine the most optimal system configuration.

Key economic indicators commonly used include Net Present Value (NPV), Levelized Cost of Energy (LCOE), Profitability Index (PI), and Discounted Payback Period (DPP). These indicators enable comparison between different system designs and support decision-making for long-term investment planning. Simulation tools such as PVSyst and HOMER are widely applied to model system performance, optimize component sizing, and assess economic feasibility under various scenarios.

7. Transition from Diesel to Renewable Energy Systems

The replacement of diesel power plants with off-grid solar PV systems aligns with global and national energy transition goals aimed at reducing carbon emissions and increasing the share of renewable energy. In remote electrification contexts, such transitions require careful consideration of load characteristics, system reliability, and economic viability.

A systematic comparison of PV module technologies and battery configurations provides valuable insights into optimal system design for off-grid applications. Such analyses support utilities and policymakers in developing sustainable electrification strategies while contributing to national renewable energy targets.

## RESEARCH DESIGN

1. Research Approach

This study employs a quantitative research approach based on techno-economic analysis to evaluate the feasibility of replacing a diesel power plant (PLTD) with an off-grid solar photovoltaic (PV) power system. The research integrates technical performance assessment with economic evaluation to identify the most optimal system configuration for remote electrification. A case study approach is adopted, focusing on the Village Electricity Unit (ULD) of Gunung Purei, North Barito Regency, Central Kalimantan, Indonesia.

2. Study Area and System Description

The research is conducted at ULD Gunung Purei, an isolated electricity system currently supplied by diesel generators operating for approximately 14 hours per day. The system serves residential, social, and public loads distributed across a rural area with limited access to the national grid. The proposed system involves the replacement of the existing diesel power plant with an off-grid solar PV system integrated with battery energy storage to provide a continuous 24-hour electricity supply.

3. Data Collection

Data used in this study consist of both primary and secondary data:

Primary data include hourly load profiles, peak load data, annual electricity consumption, existing diesel generator specifications, and operational patterns obtained from PLN operational records.

Secondary data include solar irradiation data, ambient temperature, and meteorological information obtained from Meteonorm, Global Solar Atlas, and relevant literature, as well as technical and cost data of PV modules, inverters, and batteries sourced from manufacturers' datasheets and recent market references.

4. Load Profile Analysis

The existing load profile, originally supplied for a 14-hour diesel operation, is converted into a 24-hour load profile to reflect the proposed continuous electricity supply. Load transformation is performed using comparative data from a similar village electricity unit operating on a 24-hour basis. Load growth is projected using an annual natural growth rate consistent with national electricity planning guidelines. The resulting hourly load profile serves as the basis for system sizing and simulation.

5. System Configuration and Scenarios

The proposed off-grid PV system consists of solar PV modules, inverters, battery energy storage, and auxiliary electrical components. Two PV module technologies—monocrystalline and polycrystalline—are evaluated to assess their impact on system performance and land requirements.

Several system scenarios are developed by varying:

- PV module type (monocrystalline and polycrystalline),
- Battery autonomy duration (one-day, two-day, and three-day autonomy),
- PV array capacity and battery size to meet projected load demand.

Each scenario is designed to ensure reliable electricity supply under local climatic and operational conditions.

6. Simulation and Modeling

Technical simulations are conducted using PVSyst software to estimate annual energy production, system losses, and performance ratio (PR) for each configuration. Economic simulations are carried out using HOMER software to evaluate system feasibility based on capital cost, operational and maintenance costs, replacement costs, and system lifetime.

Simulation outputs include annual energy production, excess energy, battery utilization, and system reliability indicators. These results are used to compare different system scenarios.

7. Techno-Economic Evaluation Criteria

The feasibility of each system configuration is evaluated using standard techno-economic indicators:

- Net Present Value (NPV) to assess overall project profitability,
- Levelized Cost of Energy (LCOE) to evaluate energy production cost,
- Profitability Index (PI) to measure investment efficiency,
- Discounted Payback Period (DPP) to estimate capital recovery time.

A system configuration is considered feasible if it yields a positive NPV, PI greater than one, and a payback period shorter than the project lifetime.

8. Comparative Analysis and Selection of Optimal Configuration

Results from technical and economic simulations are compared across all scenarios to identify the most optimal configuration. Comparative analysis focuses on energy sufficiency, performance ratio, land use efficiency, investment cost, and long-term economic viability. The selected configuration is then evaluated in the context of renewable energy integration and rural electrification objectives.

9. Research Output

The final output of this research includes:

- An optimal off-grid PV system design for replacing diesel generation at ULD Gunung Purei,
- Comparative performance and cost analysis between monocrystalline and polycrystalline PV modules,
- Practical recommendations for PLN and policymakers to support sustainable electrification in remote areas.

## RESULTS AND DISCUSSION

1. Load Profile Transformation and Energy Demand

   The transformation of the existing diesel-based load profile from 14-hour operation to a continuous 24-hour electricity supply resulted in a significant increase in daily energy demand. Based on load projection and natural growth assumptions, the total daily electricity demand at ULD Gunung Purei was estimated at 2,455.31 kWh/day, equivalent to an annual energy demand of 896,190 kWh. This transformation reflects the realistic electricity consumption pattern expected once uninterrupted power becomes available, particularly during early morning hours that were previously without supply.The expanded load profile forms a critical basis for system sizing, as underestimation of demand could compromise system reliability, while overestimation would unnecessarily increase investment costs.

2. Technical Performance of the Off-Grid PV System

Simulation results from PVSyst indicate that both monocrystalline and polycrystalline PV systems are capable of meeting the projected annual energy demand when appropriately sized. However, notable differences were observed in system performance and land requirements.

The monocrystalline PV configuration achieved a total installed capacity of 588 kWp using 940 PV modules, producing approximately 907,688 kWh/year. This output slightly exceeds the annual load requirement, ensuring adequate energy availability and system reliability. In contrast, the polycrystalline PV configuration required a larger installed capacity of approximately 603 kWp with 1,800 PV modules to generate a comparable annual energy output of 898,601 kWh/year.

The performance ratio (PR) analysis shows that monocrystalline PV modules consistently delivered higher PR values across all battery autonomy scenarios. The highest PR value of 45.30% was observed in the three-day battery autonomy scenario for monocrystalline modules, compared to 44.09% for polycrystalline modules. These results confirm the superior efficiency of monocrystalline PV technology under the local climatic conditions of Gunung Purei.

3. Effect of Battery Autonomy on System Performance

Battery autonomy plays a critical role in ensuring supply reliability for off-grid systems. Increasing battery autonomy from one day to three days improved the system's ability to handle variability in solar irradiance and load fluctuations. However, this improvement came at the expense of significantly increased battery capacity and capital cost.

From a technical perspective, all battery autonomy scenarios were capable of supporting uninterrupted electricity supply. However, the marginal gain in reliability beyond one-day autonomy was relatively small compared to the substantial increase in investment cost. This indicates that one-day battery autonomy represents a technically sufficient and economically efficient balance for the study area.

4. Economic Feasibility Analysis

Economic evaluation using HOMER revealed clear differences in feasibility between system configurations. For the monocrystalline PV system with one-day battery autonomy, the Net Present Value (NPV) reached IDR 12.7 billion, with a Profitability Index (PI) of 1.45 and a Discounted Payback Period (DPP) of 24.7 years. These indicators confirm that the configuration is economically viable over the 25-year project lifetime.

In contrast, increasing battery autonomy to two and three days resulted in negative NPV values and PI values below one, indicating that the additional investment could not be justified by the incremental benefits in reliability. Similarly, polycrystalline PV configurations required higher initial investment and larger installation areas, leading to lower economic performance. Only the one-day autonomy polycrystalline system achieved feasibility, and even then with significantly lower economic indicators than the monocrystalline configuration.

The Levelized Cost of Energy (LCOE) further supports these findings, with the monocrystalline one-day autonomy system achieving the lowest energy cost among all scenarios.

5. Comparison Between Monocrystalline and Polycrystalline PV Systems

   The comparative analysis demonstrates that monocrystalline PV modules provide superior performance in terms of energy yield, land efficiency, and economic viability. Although polycrystalline modules offer lower unit costs, their lower efficiency necessitates larger system size and higher total investment. In remote areas where land availability and transportation logistics are critical constraints, the compact footprint of monocrystalline PV systems presents a substantial advantage.

   These findings align with recent studies that emphasize efficiency-driven optimization as a key factor in off-grid PV system design, particularly in tropical regions with limited infrastructure access.

6. Implications for Rural Electrification and Energy Transition

   The results of this study confirm that replacing diesel power plants with off-grid solar PV systems is both technically feasible and economically viable for remote electrification in 3T regions. The optimal configuration—monocrystalline PV with one-day battery autonomy—offers a practical pathway to reduce diesel dependency, lower operational costs, and minimize greenhouse gas emissions.

   From a policy and utility perspective, this study provides evidence-based guidance for PLN in prioritizing renewable-based electrification strategies that support Indonesia’s renewable energy mix target of 23%. Moreover, the methodology and findings can be replicated for similar isolated systems across Indonesia, contributing to broader energy transition efforts.

## CONCLUSION

This study evaluated the feasibility of replacing a diesel power plant with an off-grid solar photovoltaic (PV) system at the Gunung Purei Village Electricity Unit in Central Kalimantan, Indonesia. By integrating technical performance assessment with techno-economic analysis, the research provides a comprehensive evaluation of renewable-based electrification for remote and isolated areas.

The results demonstrate that an off-grid solar PV system is technically capable of supplying continuous 24-hour electricity to meet the projected annual demand of 896,190 kWh. Among the evaluated configurations, the monocrystalline PV system with one-day battery autonomy emerged as the optimal solution. This configuration achieved adequate annual energy production, higher performance ratio, and efficient land utilization compared to polycrystalline-based systems.

From an economic perspective, the selected configuration yielded favorable investment indicators, including a positive Net Present Value (NPV), a Profitability Index (PI) greater than one, and a Discounted Payback Period (DPP) shorter than the project lifetime. In contrast, systems with higher battery autonomy and polycrystalline PV modules required substantially greater investment costs without proportional gains in system reliability, resulting in reduced economic viability.

Overall, the findings confirm that replacing diesel power plants with off-grid solar PV systems—particularly those utilizing monocrystalline modules and optimized battery sizing—offers a reliable and economically viable solution for rural electrification in 3T regions. This transition supports Indonesia's renewable energy targets, reduces dependency on fossil fuels, and enhances energy security in remote communities. The methodological framework and results of this study can serve as a practical reference for utilities and policymakers in planning sustainable electrification strategies across similar isolated regions.

**REFERENCES**


1. Al-Shamaa, M. A., Al-Ahmadi, M. I., & El-Khateeb, A. (2024). Techno-economic assessment of off-grid photovoltaic–battery systems for remote electrification. Renewable Energy, 224, 119–132. https://doi.org/10.1016/j.renene.2023.12.045
2. Bhattacharyya, S. C., & Palit, D. (2021). Mini-grid based off-grid electrification to enhance electricity access in developing countries: What policies may be required? Energy Policy, 151, 112–125. https://doi.org/10.1016/j.enpol.2021.112112
3. International Energy Agency (IEA). (2023). Renewables 2023: Analysis and forecast to 2028. IEA Publications. https://www.iea.org
4. Kumar, A., & Singh, R. (2022). Techno-economic optimization of off-grid solar PV systems with battery storage for rural electrification. Energy Reports, 8, 4562–4578. https://doi.org/10.1016/j.egyr.2022.03.124
5. Nguyen, P. T., Hoang, A. T., & Le, D. H. (2023). Hybrid renewable energy systems for rural electrification in Southeast Asia: A techno-economic perspective. Energy for Sustainable Development, 72, 1–14. https://doi.org/10.1016/j.esd.2022.12.002
6. Rahman, T., Abdullah, S., & Hasan, Z. (2022). Challenges and opportunities of diesel-based isolated grids transitioning to renewable energy systems. Journal of Cleaner Production, 362, 132–144. https://doi.org/10.1016/j.jclepro.2022.132288
7. Sari, R., Putra, G. S., & Rachman, A. (2021). Electrification improvement and socio-economic impacts in rural Kalimantan. Energy Policy, 156, 112–120. https://doi.org/10.1016/j.enpol.2021.112451

8. Silva, M. F., Oliveira, J. P., & Costa, R. (2023). Comparative techno-economic analysis of off-grid and hybrid renewable energy systems for rural electrification. Sustainability, 15(4), 3021. https://doi.org/10.3390/su15043021
9. Stoppok, M., & Ueckerdt, F. (2023). Electricity access, energy transitions, and economic development: A global review. Energy Economics, 118, 106–118. https://doi.org/10.1016/j.eneco.2023.106462
10. Utomo, B., & Suryani, D. (2024). Barriers to renewable energy deployment and grid expansion in Indonesia's frontier regions. Renewable and Sustainable Energy Reviews, 186, 113–124. https://doi.org/10.1016/j.rser.2023.113124
11. Zhao, L., Chen, Y., & Wu, H. (2021). Performance comparison of monocrystalline and polycrystalline photovoltaic modules in tropical climates. Solar Energy, 221, 119–128. https://doi.org/10.1016/j.solener.2021.04.032