Bulletin of Electrical Engineering and Informatics
Vol. 15, No. 6, December 2026, pp. 4766~4773
ISSN: 2302-9285, DOI: 10.11591/eei.v15i6.12759

Optimization and integration of solar PV systems for sustainable energy transition in Indonesia

Suwarno[1], Catra Indra Cahyadi[2]
[1]Electrical Engineering Study Program, Faculty of Engineering, Universitas Muhammadiyah Sumatera Utara, Medan, Indonesia
[2]Department of Electrical and Electronic Engineering, Politeknik Pelayaran Malahayati, Banda Aceh, Indonesia

Article Info

Article history:

Received Mar 8, 2026
Revised Sep 15, 2026
Accepted Oct 4, 2026

Keywords:

Energy transition
Indonesia
Optimization
Renewable energy
Solar photovoltaic
Techno-economic analysis

ABSTRACT

Indonesia's growing demand for clean and reliable electricity requires effective renewable energy integration. Solar photovoltaic (PV) technology offers substantial potential due to the country's abundant solar resources, although variations in solar irradiance, system performance, and investment costs remain significant challenges. This study aims to optimize and evaluate solar PV integration based on technical performance and economic feasibility to support Indonesia's sustainable energy transition. A quantitative approach is applied to analyze solar irradiance, PV energy production, system efficiency, capacity factor, investment and operational costs, levelized cost of energy (LCOE), and net present cost (NPC). Various system configurations and operating scenarios are assessed to identify the most effective combination of PV capacity and components. The results are expected to determine an optimal configuration that ensures reliable energy production, improved technical performance, and competitive energy costs. Furthermore, the study examines the relationship between technical performance and economic indicators to support researchers, policymakers, and energy planners in developing sustainable and economically viable solar PV systems in Indonesia.

This is an open access article under the CC BY-SA license.

Corresponding Author:

Suwarno
Electrical Engineering Study Program, Faculty of Engineering, Universitas Muhammadiyah Sumatera Utara
St. Capt. Muchtar Basri No. 3, Medan, Indonesia
Email: suwarno@msu.ac.id

1. INTRODUCTION

Indonesia is experiencing increasing electricity demand due to population growth, economic development, urbanization, and industrial activity. At the same time, the electricity sector remains heavily reliant on conventional fossil fuel-based power plants, particularly coal and natural gas [1]. This situation creates challenges related to greenhouse gas emissions, energy security, and long-term sustainability. Therefore, a transition to renewable energy is crucial for reducing environmental impacts and building a more resilient and sustainable electricity system. The global energy sector is undergoing a significant transformation towards a sustainable and low-carbon energy system [2], [3]. Growing concerns about climate change, environmental degradation, and fossil fuel depletion have prompted many countries to accelerate the development of renewable energy technologies [4], [5]. Solar photovoltaic (PV) technology has emerged as one of the most promising renewable energy sources due to its scalability, decreasing costs, and environmental benefits [6], [7]. Indonesia, as a tropical country near the equator, has abundant solar energy potential, with average solar radiation ranging from 4–5.5 kWh/m²/day [8]. Despite its high potential, solar energy's contribution to the national energy mix is still relatively small compared to fossil-based power plants

[9], [10]. The national energy policy targets a significant increase in the share of renewable energy to support energy security and reduce greenhouse gas emissions [11], [12].

Indonesia has significant solar energy potential due to its year-round sunshine and vast territory. However, PV electricity production is affected by solar radiation, temperature, weather, and location. PV grid integration also requires proper capacity management, inverters, and energy management to maintain voltage, power quality, and reliability. Therefore, optimization is necessary to determine the appropriate PV capacity and configuration [13]. In addition to technical aspects, economic feasibility is also crucial. Analysis such as levelized cost of energy (LCOE), net present cost (NPC), investment costs, and operating costs are used to assess system profitability. This study aims to develop an efficient, reliable, and economical PV system to support Indonesia's sustainable energy transition.

However, the implementation of solar PV systems requires proper planning, especially in terms of system optimization, grid integration, and economic feasibility [14], [15]. Without proper optimization, PV systems can experience low performance, high operating costs, and inefficient energy production [16], [17]. Therefore, a comprehensive technical-economic evaluation is necessary to ensure optimal PV system design and integration. Previous studies have examined the performance of solar PV, hybrid energy systems, and grid integration techniques [18], [19]. However, many studies still focus primarily on technical performance or economic feasibility separately [20], [21]. In practice, these two aspects must be analyzed simultaneously to obtain optimal solutions that support long-term energy sustainability [22], [23].

Solar energy potential in Indonesia, Indonesia has significant solar energy potential due to its location near the equator and year-round sunshine. Solar intensity varies by region due to location, cloud cover, season, and weather. Average solar radiation in many areas is around 4–5.5 kWh/m²/day, making PV suitable for electricity generation. PV systems can be implemented in homes, large-scale power plants, remote areas, and battery-powered systems [24]. However, PV electricity production is affected by weather conditions, requiring careful planning. Factors such as solar radiation, temperature, land use, electricity demand, and cost must be considered to achieve an efficient, reliable, and economical PV system. Indonesia has significant solar energy resources due to its geographical location on the equator. Average solar radiation varies from 4.5 to 5.5 kWh/m²/day in different regions [25]. The integration of these systems can make a significant contribution to reducing dependence on fossil fuel-based power generation.

2. METHOD

This study uses a quantitative simulation-based method to optimize solar PV systems in Indonesia from technical and economic aspects. The data used include solar radiation, temperature, electricity demand, and meteorological data. These data are used to estimate the potential and production of PV energy. Next, several configurations are created with varying PV capacities, inverters, batteries, and operating strategies. Each configuration is analyzed based on energy production, efficiency, capacity factor, renewable energy, system losses, and reliability. The economic analysis includes capital expenditure (CAPEX), operation and maintenance costs, LCOE, and NPC. Several scenarios, namely conservative, realistic, and optimistic, are used to examine the effects of changing conditions and costs. Technical and economic results are compared to determine the most optimal, efficient, reliable, and economical PV configuration.

2.1. System modeling

A solar PV system model was developed to evaluate the technical performance and economic feasibility of PV integration in Indonesia. Its main components consist of a PV array, a maximum power point tracking (MPPT) controller, a battery, an inverter, an electrical load, a power grid, and a monitoring system. The PV array converts solar radiation into DC electricity. Solar irradiance and temperature are used as the main input parameters to estimate PV power production [26]. The MPPT controller regulates the PV output so that the system can operate near its maximum power point. The battery stores excess electricity (EE) generated by the PV system and supplies energy when PV production is insufficient. The inverter converts DC electricity to AC electricity to supply the electrical load. In a grid-connected configuration, the power grid provides additional electricity when PV generation and batteries cannot meet the load. The basic energy balance is expressed as (1):

$$P_{PV} + P_{Grid} + P_{Batt} = P_{Load} + P_{Loss} \quad (1)$$

where: P_{PV} is PV power, P_{Batt} is battery power, P_{Grid} is grid power, P_{Load} is load demand, and P_{Loss} is system losses.

This model evaluates PV energy production, efficiency, capacity factor, renewable energy contribution, and system losses. Economic parameters include investment cost, operation and maintenance cost, replacement cost, project life, LCOE, and NPC. Different PV capacities and operating conditions are compared to determine the most suitable configuration. The optimal system is selected based on good energy production, reliable operation, and low energy costs. This simple model provides a practical basis for

analyzing solar PV integration and supporting Indonesia's sustainable energy transition. A PV system consists of several main components. Solar PV modules convert sunlight into DC electricity and serve as the primary source of energy generation. A charge controller regulates the flow of electricity from the PV modules to the battery to ensure safe operation and prevent overcharging. The battery stores energy for use when the sun is unavailable, such as at night or during cloudy weather. An inverter converts DC electricity from the PV or battery into AC electricity that can be used by electrical appliances. The electrical load or grid uses the energy generated by the PV system to meet its electricity needs. System performance is affected by solar intensity, component capacity, and environmental conditions. With proper component selection and arrangement, a PV system can produce energy efficiently, stably, and reliably.

2.2. Optimization parameters

Optimization parameters are used to find the best solar PV system for Indonesia. The main parameters include PV capacity, battery capacity, inverter capacity, energy production, renewable energy fraction, unmet load (UL), EE, LCOE, and NPC. PV and battery capacities determine how much electricity can be produced and stored. Energy production indicates the amount of electricity generated by the PV system, while the renewable energy fraction indicates the contribution of solar energy to total electricity demand. UL indicates electricity demand that cannot be met, while EE represents unused PV energy. LCOE and NPC are used to evaluate the economic performance of the system. The optimal configuration is selected based on high energy production, high renewable energy contribution, low UL, and low energy costs. This approach ensures that the selected PV system is technically effective, reliable, and economically feasible. The optimization process considers several key parameters, namely PV capacity (kWp) to determine the solar power plant's ability to generate electricity, battery capacity (Ah) to determine energy storage capacity, and inverter power (kW) to convert DC electricity to AC. Furthermore, the optimization takes into account load demand, solar radiation, and system efficiency. These parameters are used to determine the appropriate system size for energy needs. The simulation aims to obtain a PV system with low investment costs, optimal energy production, and good reliability.

2.3. Economic analysis

An economic analysis is conducted to determine whether a solar PV system is financially viable. This analysis considers the initial investment cost, operation and maintenance costs, replacement costs, system lifespan, and electricity savings. These costs are compared to the amount of electricity generated by the PV system. Two primary economic indicators are used: the LCOE and the NPC. LCOE represents the average cost of electricity generated by the PV system over its lifetime, while NPC represents the total system cost over the project period. This analysis compares several PV configurations to determine which system provides the lowest energy cost with adequate electricity production. A system is considered economically attractive when it has a relatively low LCOE and NPC while maintaining good technical performance. Therefore, economic analysis supports the optimization process by identifying PV configurations that provide a balance between investment costs, energy production, system reliability, and long-term economic benefits.

$$LCOE = \frac{\sum C_t}{\sum E_t} \tag{2}$$

Where: C_t is the total cost over the lifetime and E_t is the total energy generated.

$$NPC = \sum \frac{C_t}{(1+i)^t} \tag{3}$$

Where: i is the discount rate and T is the project period.

2.4. HOMER pro-based techno-economic optimization simulation

HOMER pro is used to simulate and optimize solar PV systems based on technical performance and economic costs. The software compares multiple system configurations to determine the most suitable PV system to meet electricity needs. Input parameters: the main parameters entered into HOMER pro are solar radiation (kWh/m²/day), temperature (°C), electrical load (kWh/day), PV capacity (kWp), battery capacity (kWh), inverter capacity (kW), PV, and battery costs, operation and maintenance costs, project lifetime (in years), discount rate (%), electricity tariff, for grid-connected systems.

Simulation process: HOMER pro calculates the electricity generated by a PV system and compares it to electricity demand. Excess PV energy can be stored in batteries, while batteries or the grid supply electricity when PV production is insufficient. Different sizes of PV, batteries, and inverters are then compared to find the best configuration.

Main output: this simulation provides optimal PV system configuration, annual PV energy production, renewable fraction (RF), EE, UL, initial investment cost, annual operating cost, NPC, and LCOE [27]. The optimal system is selected based on high energy production, low UL, high renewable energy contribution, and low NPC and LCOE. Thus, HOMER pro helps identify PV systems that are technically reliable and economically feasible for sustainable energy development in Indonesia. PV system optimization was performed using HOMER pro simulation software to evaluate system performance, reliability, and economic feasibility [28].

2.5. System configuration

The proposed system consists of solar PV panels, an MPPT controller, battery storage, an inverter, an electrical load, and the public electricity grid. The PV panels convert solar radiation into direct current (DC) electricity. The MPPT controller regulates the PV output and ensures that the panels operate near their maximum power point. The generated DC electricity is fed to the battery and inverter. The battery stores excess solar energy and supplies electricity when PV generation is insufficient. The inverter converts DC electricity to AC electricity for the electrical load. The public electricity grid is used as a backup source when the PV system and battery cannot meet the load demand. If permitted, EE from the PV system can also be fed to the public electricity grid. Key system parameters include PV capacity (kWp), battery capacity (kWh), inverter capacity (kW), solar radiation, electrical load, and grid electricity price [29]. Different component sizes are simulated using HOMER Pro to determine the optimal configuration. The system is evaluated based on PV energy production, renewable energy fraction, system efficiency, UL, EE, NPC, and LCOE. The chosen configuration is a system that provides sufficient electricity, reliable operation, high renewable energy utilization, and the lowest reasonable energy costs.

Table 1 shows the parameters and symbols used in the PV system simulation. These parameters include module capacity, battery capacity, inverter power, solar radiation, and load demand, which are used as the basis for performance analysis and system optimization.

Table 1. Simulation parameters and signs

Parameter	Sign
PV capacity	1.1 kWp
Battery capacity	24 V–400 Ah
Inverter capacity	1.5 kW
Average solar radiation	5.1 kWh/m²/day
Loading request	3–5 kWh/day
Project lifespan	25 years
Discount rate	8%

2.6. HOMER pro optimization objectives

The main objective of HOMER pro optimization is to determine the most suitable solar PV system configuration based on technical performance and economic feasibility. This optimization compares various combinations of PV capacity, battery capacity, and inverter capacity to find a system that can reliably meet the electrical load at the lowest possible cost. The optimization objectives are to minimize NPC–reducing the total cost of the system over its lifetime, minimize LCOE–obtaining the lowest average cost for electricity generation, minimize UL–ensuring that electricity demand is adequately met, maximize renewable energy fraction–increasing the contribution of solar energy to the total electricity supply, maximize PV energy production–increasing the amount of useful electricity generated from solar energy and reduce EE–minimizing unused PV energy. The optimization can be generally expressed as (4):

$$min\ F = \omega_1 \frac{NPC}{NPC_{ref}} + \omega_2 \frac{LCOE}{LCOE_{ref}} + \omega_3 \frac{UL}{UL_{ref}} + \omega_4 \frac{EE}{EE_{ref}} \quad (4)$$

where: w_1, w_2, w_3, w_4 are weight of each parameter, NPC_{ref}, $LCOE_{ref}$, UL_{ref}, and EE_{ref} are reference values for normalization.

The final optimal configuration is selected by considering the balance between energy production, system reliability, renewable energy contribution, and total cost. This approach ensures that the proposed PV system is technically effective and economically feasible to support Indonesia's sustainable energy transition. The HOMER optimization process aims to minimize the NPC and LCOE while maintaining system reliability [28]. In full, it can be written as (5):

$$NPC = C_{capital} + C_{replacement} + C_{0\&M} + C_{fuel} - C_{salvage} \quad (5)$$

with: energy costs

$$(COE) = \frac{C_{ann}}{E_{served}} \quad (6)$$

Simulation results show that the optimized PV system significantly improves technical performance and economic feasibility. Annual energy production of approximately 1,750 kWh indicates that a small-scale PV system can effectively meet household electricity needs in tropical areas. Techno-economic analysis also shows that the LCOE of the optimized system is competitive compared to conventional electricity tariffs. These results support previous studies highlighting the economic feasibility of solar energy in developing countries. Furthermore, integrating PV systems into the national electricity grid can reduce carbon emissions and improve energy security. The implementation of hybrid PV systems combined with battery storage is crucial for remote areas and island-based energy systems in Indonesia.

2.7. Research novelty

The uniqueness of this study lies in the combined optimization of technical performance and economic feasibility of solar PV system integration for sustainable energy transition in Indonesia. Unlike studies that primarily focus on solar energy potential or PV electricity production, this study evaluates PV capacity, battery storage, and inverter size along with energy production, renewable energy fraction, UL, and EE. The study also integrates technical and economic indicators through HOMER Pro simulations. Key indicators such as NPC and LCOE are evaluated along with PV performance and system reliability. Several system configurations and operating scenarios are compared to identify the most appropriate configuration. Another important contribution is the development of an optimization approach that seeks to achieve a balance between high renewable energy utilization, reliable electricity supply, and low energy costs. The results of this study are intended to provide a practical basis for selecting a PV system configuration that is technically effective and economically feasible under Indonesian conditions. Thus, this research not only contributes to the optimization of solar power systems but also to broader planning on sustainable and economically efficient renewable energy integration in Indonesia.

3. RESULTS AND DISCUSSION

Simulation results show that the optimized PV system significantly improves system performance and economic feasibility. Results and discussions are presented regarding system performance, economic feasibility, and integration with existing energy systems.

3.1. System performance

The performance of the solar PV system in the study was assessed based on the system's ability to generate, store, and use electrical energy optimally. The evaluation was conducted by comparing the energy generated by PV with the load demand as well as the contribution of batteries and the electricity grid. The main parameters used included PV energy production, energy used by the load, energy stored in batteries, energy from the grid, EE, UL, and RF. In addition, economic performance was assessed based on NPC and LCOE. A system is said to have good performance if it is able to produce sufficient PV energy, meet load demand well, reduce energy use from the grid or conventional generators, and has a low UL value. High use of renewable energy also indicates the system's success in reducing dependence on fossil fuels. The results of the performance evaluation were used to determine the most optimal configuration of PV, batteries, and inverters. Thus, the selected system is expected to be able to provide sufficient energy, low cost, good reliability, and a high contribution of renewable energy to support the sustainable energy transition in Indonesia. The results in Table 2 show that the optimized PV system can meet most of the energy needs at competitive electricity costs.

Table 2. HOMER simulation results

Parameter	Results	Parameter	Results
PV capacity	1.1 kWp	Current net cost	4,850 USD
Annual energy production	1750 kWh	Payback period	7.1 years
LCOE	0.072 USD/kWh	RF	0.92

3.2. Economic feasibility

Economic feasibility in this study is used to determine whether the designed PV system can be implemented economically in the long term. The analysis is conducted by comparing the investment costs

and operating costs of the system with the electricity cost savings obtained from the use of solar energy. The main parameters used are NPC, LCOE, initial investment costs, operation and maintenance costs, and energy savings. NPC is used to determine the total system cost over the project's lifetime, while LCOE is used to determine the average cost of electricity generated by the system. The analysis also compares several configurations, such as PV–PLN, PV–battery–PLN, and a hybrid system. The best configuration is a system capable of producing high renewable energy with low NPC and LCOE, while still being able to meet load requirements. In addition, a sensitivity analysis is conducted to changes in investment costs, electricity prices, battery costs, and the discount rate. This analysis shows how strong the system's economic feasibility is to changing economic conditions. Thus, a PV system is declared economically feasible if it is able to reduce energy costs, provide adequate savings, have competitive energy costs, and remain economical throughout the project's lifetime. The results of this analysis form the basis for determining the most appropriate PV configuration to support the sustainable energy transition in Indonesia.

Economic analysis shows that solar PV systems are becoming increasingly competitive as technology costs decrease. Table 3 presents the results of the economic analysis of the PV system, including initial investment costs, operation and maintenance costs, component replacement costs, and the cost of energy generated. This analysis is used to assess the economic feasibility and long-term cost efficiency of the system. The techno-economic PV system configuration integrates key components such as solar modules, charge controllers, batteries, and inverters. This system is analyzed based on technical and economic aspects to determine the most optimal configuration for generating electrical energy efficiently, reliably, and with economical investment and operational costs.

Table 3. Economic analysis

Parameter	Sign
PV capacity	1.1 kWp
Annual energy production	1500–1800 kWh
LCOE	0.06–0.09 USD/kWh
Payback period	6–8 years

3.3. Integration with existing energy systems

Solar PV system integration is carried out by connecting PV generators to existing electricity systems, such as the PLN grid, batteries, and conventional generators. The goal is to maximize solar energy utilization without compromising the reliability of the existing electricity system. Energy from PV is used first to meet load demand. If PV production is greater than load demand, the excess energy can be stored in batteries or distributed to the grid. If PV production decreases due to weather or low solar radiation, electricity demand can be met by batteries, PLN, or conventional generators. In this study, PV integration is analyzed based on several parameters, such as PV energy produced, energy used by the load, battery energy, energy from the grid, excess energy, and unmet energy. In addition, economic aspects are analyzed using NPC and LCOE. Optimization is carried out to determine the PV, battery, and inverter capacities that best suit system needs. The results are expected to increase the use of renewable energy, reduce the use of fossil fuels, reduce electricity costs, and maintain system reliability. Thus, PV integration with existing energy systems is an important step to support a sustainable energy transition in Indonesia that is gradual, efficient, and reliable. Hybrid systems that combine PV solar panels with battery storage also increase system reliability and allow for energy supply at night or in low-sun conditions.

4. CONCLUSION

This study demonstrates that PV optimization and integration can support a sustainable energy transition in Indonesia. PV systems that combine solar panels, batteries, inverters, loads, and the grid can improve renewable energy utilization and electricity reliability. Simulations using HOMER pro help compare various configurations based on energy production, renewable energy, UL, excess energy, NPC, and LCOE. The best configuration is selected based on a balance between technical performance and cost. An optimal system should be able to produce sufficient energy, reduce electricity shortages, avoid unnecessary excess energy, and have competitive costs. The results of this study can be used as a basis for planning and developing PV systems in Indonesia. Future research should consider differences in solar potential in each region, battery life, changes in electricity prices, network conditions, as well as changes in weather and energy demand to achieve more accurate optimization results.

FUNDING INFORMATION

This research is supported by the university leadership and the Dean of Universitas Muhammadiyah Sumatera Utara under Contract No. 174/II.3.AU/UMSU-LP2M/C/2026 for the 2026 fiscal year.

AUTHOR CONTRIBUTION STATEMENT

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

Author Name	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Suwarno	✓	✓	✓	✓	✓	✓		✓	✓	✓			✓	
Catra Indra Cahyadi		✓				✓	✓	✓	✓	✓	✓	✓		✓

C : Conceptualization
M : Methodology
So : Software
Va : Validation
Fo : Formal analysis
I : Investigation
R : Resources
D : Data curation
O : Writing - Original Draft
E : Writing - Review & Editing
Vi : Visualization
Su : Suprovision
P : Project administration
Fu : Funding acquisition

CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY

Data supporting the findings of this study are available from the authors.

REFERENCES

[1] P. Chowdhury, T. Islam, I. J. Tasmia, and N. U. R. Chowdhury, "Power sector transformation in Bangladesh: Paving the pathways towards sustainable development," *Energy Strategy Reviews*, vol. 61, p. 101829, Sep. 2025, doi: 10.1016/j.esr.2025.101829.

[2] A. Soemanto *et al.*, "Strategies for Indonesia's low carbon energy transition based on a participatory energy system dynamic model," *Energy Research and Social Science*, vol. 127, p. 104231, Sep. 2025, doi: 10.1016/j.erss.2025.104231.

[3] L. Shen, A. Elshkaki, S. Zhong, X. Hu, X. Wu, and J. Ge, "Global Energy Transition and Low Carbon Technology Pathways," *Energies*, vol. 18, no. 21, p. 5701, Oct. 2025, doi: 10.3390/en18215701.

[4] Y. Zhang, "Circular economy innovations: Balancing fossil fuel impact on green economic development," *Heliyon*, vol. 10, no. 18, p. e36708, Sep. 2024, doi: 10.1016/j.heliyon.2024.e36708.

[5] O. G. Ndubuisi, S. E. Ali, U. T. Aku, O. Nesiama, and S. A. Gumi, "Accelerating the Transition to Renewable Energy: Sustainable Solutions for Low Carbon Future," *International Journal of Innovative Agriculture & Biology Research*, vol. 12, no. 1, pp. 63–71, 2025, doi: 10.5281/zenodo.15042049.

[6] S. Al-Ali, A. G. Olabi, and M. Mahmoud, "A review of solar photovoltaic technologies: developments, challenges, and future perspectives," *Energy Conversion and Management: X*, vol. 27, p. 101057, Jul. 2025, doi: 10.1016/j.ecmx.2025.101057.

[7] A. O. Ali *et al.*, "Advancements in photovoltaic technology: A comprehensive review of recent advances and future prospects," *Energy Conversion and Management: X*, vol. 26, p. 100952, Apr. 2025, doi: 10.1016/j.ecmx.2025.100952.

[8] Suwarno and D. Pinayungan, "Solar power forecasting model as a renewable generation source on virtual power plants," *Bulletin of Electrical Engineering and Informatics*, vol. 13, no. 2, pp. 702–712, 2024, doi: 10.11591/eei.v13i2.5870.

[9] L. Govindarajan, M. F. Bin M. Batcha, and M. K. Bin Abdullah, "Solar energy policies in southeast Asia towards low carbon emission: A review," *Heliyon*, vol. 9, no. 3, p. e14294, Mar. 2023, doi: 10.1016/j.heliyon.2023.e14294.

[10] N. A. Pambudi *et al.*, "Renewable Energy in Indonesia: Current Status, Potential, and Future Development," *Sustainability (Switzerland)*, vol. 15, no. 3, p. 2342, Jan. 2023, doi: 10.3390/su15032342.

[11] A. Massagony, R. Pandit, and B. White, "Political economy of energy policy in Indonesia towards net zero emissions by 2060," *Energy for Sustainable Development*, vol. 88, p. 101757, Oct. 2025, doi: 10.1016/j.esd.2025.101757.

[12] I. A. Aditya, T. Wijayanto, and D. F. Hakam, "Advancing Renewable Energy in Indonesia: A Comprehensive Analysis of Challenges, Opportunities, and Strategic Solutions," *Sustainability*, vol. 17, no. 5, p. 2216, Mar. 2025, doi: 10.3390/su17052216.

[13] S. Architram, J. V. Jain, S. Shrivastava, and S. A. Alexander, "Issues, perspectives and solutions on grid integration of renewable energy — A review," *Energy Reports*, vol. 16, p. 109603, Dec. 2026, doi: 10.1016/j.egyr.2026.109603.

[14] L. A. I. Carrera, G. Alfonso-Francia, C. D. Constantino-Robles, J. Terven, E. A. Chávez-Urbiola, and J. Rodríguez-Reséndiz, "Advances and Optimization Trends in Photovoltaic Systems: A Systematic Review," *AI*, vol. 6, no. 9, p. 225, Sep. 2025, doi: 10.3390/ai6090225.

[15] M. N. Hossain and H. M. Cho, "Techno-economic feasibility of photovoltaic-powered electric vehicle charging stations: a global review and future outlook," *Sustainable Energy Research*, vol. 13, no. 1, 2026, doi: 10.1186/s40807-025-00228-1.

[16] K. Osmani, A. Haddad, T. Lemenand, B. Castanier, and M. Ramadan, "A review on maintenance strategies for PV systems," *Science of the Total Environment*, vol. 746, p. 141753, Dec. 2020, doi: 10.1016/j.scitotenv.2020.141753.

[17] O. Bamisile, C. Acen, D. Cai, Q. Huang, and I. Staffell, "The environmental factors affecting solar photovoltaic output," *Renewable and Sustainable Energy Reviews*, vol. 208, p. 115073, Feb. 2025, doi: 10.1016/j.rser.2024.115073.

[18] S. Goel and R. Sharma, "Performance evaluation of stand alone, grid connected and hybrid renewable energy systems for rural application: A comparative review," *Renewable and Sustainable Energy Reviews*, vol. 78, pp. 1378–1389, Oct. 2017, doi: 10.1016/j.rser.2017.05.200.
[19] G. Rajendran, R. Raute, and C. Caruana, "A Comprehensive Review of Solar PV Integration with Smart-Grids: Challenges, Standards, and Grid Codes," *Energies*, vol. 18, no. 9, p. 2221, Apr. 2025, doi: 10.3390/en18092221.
[20] R. Mahmud, S. M. Moni, K. High, and M. Carbajales-Dale, "Integration of techno-economic analysis and life cycle assessment for sustainable process design – A review," *Journal of Cleaner Production*, vol. 317, p. 128247, Oct. 2021, doi: 10.1016/j.jclepro.2021.128247.
[21] P. Ren and S. H. Klausen, "The feasibility syndrome: a challenge to public policy," *Global Public Policy and Governance*, vol. 6, no. 1, pp. 1–22, Mar. 2026, doi: 10.1007/s43508-026-00140-4.
[22] S. Mohseni and A. C. Brent, "Long-term planning optimisation of sustainable energy systems: A systematic review and meta-analysis of trends, drivers, barriers, and prospects," *Energy Strategy Reviews*, vol. 57, p. 101640, Jan. 2025, doi: 10.1016/j.esr.2025.101640.
[23] A. Erdoğdu, F. Dayi, A. Yanik, F. Yildiz, and F. Ganji, "Innovative Solutions for Combating Climate Change: Advancing Sustainable Energy and Consumption Practices for a Greener Future," *Sustainability (Switzerland)*, vol. 17, no. 6, p. 2697, Mar. 2025, doi: 10.3390/su17062697.
[24] H. Abdulla, A. Sleptchenko, and A. Nayfeh, "Photovoltaic systems operation and maintenance: A review and future directions," *Renewable and Sustainable Energy Reviews*, vol. 195, p. 114342, May 2024, doi: 10.1016/j.rser.2024.114342.
[25] A. Akroot, M. Almaktar, and F. Alasali, "The Integration of Renewable Energy into a Fossil Fuel Power Generation System in Oil-Producing Countries: A Case Study of an Integrated Solar Combined Cycle at the Sarir Power Plant," *Sustainability (Switzerland)* , vol. 16, no. 11, p. 4820, Jun. 2024, doi: 10.3390/su16114820.
[26] A. O. Folorunso, O. O. Olusanya, and O. O. Fasipe, "the Effect of Sun Irradiance and Temperature on the Solar Energy Generation System," *Advanced International Journal of Material Science and Engineering*, vol. 1, no. 10, 2025, doi: 10.5281/zenodo.14726089.
[27] D. Zhou, Z. Wang, K. Xi, C. Zuo, and Y. Jia, "Optimization Configuration Analysis of Wind-Solar-Storage System Based on HOMER," *Energy Engineering: Journal of the Association of Energy Engineering*, vol. 122, no. 5, pp. 2119–2153, 2025, doi: 10.32604/ee.2025.061712.
[28] C. N. Nwagu, C. O. Ujah, D. V. V. Kallon, and V. S. Aigbodion, "Integrating solar and wind energy into the electricity grid for improved power accessibility," *Unconventional Resources*, vol. 5, p. 100129, Jan. 2025, doi: 10.1016/j.uncres.2024.100129.
[29] Aripriharta, S. Adiguna, A. N. Afandi, and M. C. Bagaskoro, "Techno-economic modeling and analysis of a PV EV charged with battery energy storage system (BESS) on Kalimantan Island," *Global Energy Interconnection*, vol. 8, no. 2, pp. 225–239, Apr. 2025, doi: 10.1016/j.gloei.2025.01.003.

BIOGRAPHIES OF AUTHORS



Suwarno completed his undergraduate education in electrical engineering in 1986, completed his postgraduate education in 1995 with an electrical engineering program, and completed his doctoral program in renewable energy in 2016. He currently works at the Universitas Muhammadiyah Sumatera Utara in the Electrical Engineering Study Program and conducts research in the fields of new and renewable energy, power electronics, and power electronics applications. He can be contacted at email: suwarno@umsu.ac.id.



Catra Indra Cahyadi completed a bachelor of applied science degree in Airport Electrical Engineering in 2004, and a Master of Educational Technology in 2008. Completed a major in energy management at the Postgraduate Program of the Universitas Muhammadiyah Sumatera Utara in 2022. Currently conducting research in the fields of aeronautical engineering, airport electrical engineering, transmission and distribution, and control systems. He can be contacted at email: catraindracahyadi@gmail.com.