AIMS Energy

AIMS Energy, 12(1): 304–320.
DOI: 10.3934/energy.2024015
Received: 01 December 2023
Revised: 15 January 2024
Accepted: 23 January 2024
Published: 04 February 2024

http://www.aimspress.com/journal/energy

Research article

Integrative analysis of diverse hybrid power systems for sustainable energy in underdeveloped regions: A case study in Indonesia

Kharisma Bani Adam[1], Jangkung Raharjo[2,*], Desri Kristina Silalahi[3], Bandiyah Sri Aprilia[4] and IGPO Indra Wijaya[5]

School of Electrical Engineering, Telkom University, Bandung, 40257, Indonesia

* **Correspondence:** Email: jangkungraharjo@telkomuniversity.ac.id; Tel: +62227566456.

Abstract: There is a goal for practical renewable electrification and renewable energy investments in underdeveloped regions. Indonesia's experience underscores the complexities and challenges in implementing such projects effectively. A study on the effects of various socio-economic factors on Carbon dioxide (CO_2) emissions in Indonesia highlights the significant impact of forest area, urbanization, and industrialization on carbon emissions. A hybrid system consists of PV, a Biogas Generator, and a Wind Turbine that are successfully deployed. However, no economic analysis has been conducted to obtain the best configuration of the hybrid system. We propose to delve into the effective integration combination of hybrid power systems. In this study, we thoroughly analyzed hybrid power systems in underdeveloped areas using the HOMER software. We examined five different hybrid system configurations: Solely biogas, complete generator integration, a biogas and hydrogen combo, biogas coupled with a PV system, and biogas combined with a wind turbine. Our findings indicated varying levels of economic viability, operational performance, and environmental impact across the configurations, providing crucial insights for policymakers and stakeholders in underdeveloped regions like Indonesia. The results showed the Wind-Hydrogen and Hydrogen Only schemes as the most cost-effective, with a Total Net Present Cost (NPC) of $48,969.27 and Levelized Cost of Energy (LCOE) at $0.218. Moreover, while CO_2 emissions were similar across all schemes, around 27,744 kg/year, the All-Generator scheme had slightly higher emissions at 27,667 kg/year but led in electricity production with 29,101 kWh/year. These results underscore the importance of balancing cost, energy output, and environmental impact in hybrid power system schemes for underdeveloped regions.

Keywords: renewable energy; electrification; underdeveloped regions; socio-economic; hybrid power system; cost-effective; environmental impact

1. Introduction

The quest for practical renewable electrification and renewable energy investments in underdeveloped regions is illuminated by contrasting studies. Sovacool's examination of World Bank Solar Home System projects in Sri Lanka and Indonesia highlights the critical factors contributing to the success and failure of solar energy initiatives. While Sri Lanka's project achieved significant success, Indonesia's experience underscores the complexities and challenges in implementing such projects effectively [1]. A study by Azzahrah, Hastuti, and Hartono, which delves into Indonesia's economic, social, and environmental impacts of renewable energy investments, complements the previous studies. By employing Social Accounting Matrix analysis, the research reveals the nuanced effects of different renewable energy sources, emphasizing the importance of a balanced approach to energy diversification [2].

Cheng Wen et al. explore the household willingness to pay for improved electricity services in Sumba Island, Indonesia. Their findings provide valuable insights into consumer preferences and the economic aspects of electricity service improvements in rural areas. In this study, we offer critical perspectives for policymakers and utility companies in developing strategies to enhance power infrastructure in underdeveloped regions [3]. Another article collectively underscores the multifaceted approach needed in designing sustainable energy solutions [4]. One emphasizes the economic and technical intricacies of creating off-grid hybrid renewable energy systems, highlighting the need of thorough techno-economic and sensitivity analyses, particularly in remote and rural locations [5]. In response to the COVID-19 pandemic's influence on energy usage patterns, a study offers a review by combining renewable energy sources with Smart Home Energy Management Systems (SHEMS) and optimizing SHEMS and Demand Response Programs (DRP) in the pandemic context [6]. This complements the other article's focus on balancing electricity costs and greenhouse gas emissions in household energy management by developing a multi-objective hybrid energy management system.

Recent advancements in renewable energy technologies and their implementation strategies offer transformative potential for rural electrification, particularly in Indonesia. Syahputra and Soesanti's exploration of renewable energy systems in Yogyakarta, Indonesia, combines micro-hydro and solar photovoltaic technologies, utilizing advanced optimization techniques [7]. Ogunjuyigbe et al. underscore the vital role of load management in optimizing energy utilization, particularly in solar photovoltaic power systems, and highlight the importance of automated systems for enhancing load control and energy efficiency, which aligns with the objectives of our study on sustainable energy solutions for underdeveloped regions [8]. Azevedo et al. provide pivotal insights into maximizing power efficiency in wind energy systems, particularly in small-scale applications, offering valuable parallels to our study's focus on optimizing hybrid power systems for underdeveloped areas [9]. Another article discusses the stability implications of incorporating small-scale hybrid systems into existing electric distribution networks, including solar photovoltaic and wind turbines. This results in this study are highly pertinent to our research, as they shed light on the complexities and benefits of integrating diverse renewable energy sources, an aspect critical to designing effective hybrid power systems in less developed areas [10]. This approach is echoed in the work of Saritha K.S. et al., who propose an optimal control strategy for hybrid microgrid systems, emphasizing cost-effective, and stable energy management [11].

Complementing these studies, Nicola U. Blum et al. assess the cost competitiveness of isolated renewable energy technologies in Indonesian village grids. Their findings highlight the economic and environmental advantages of micro-hydro and solar PV systems over traditional diesel solutions, emphasizing the feasibility of renewable energy in enhancing rural electrification [12].

Recent research in renewable energy and environmental studies provides valuable insights into the multifaceted impacts of energy systems. A survey of the effects of various socio-economic factors on CO_2 emissions in Indonesia highlights the significant impact of forest area, urbanization, and industrialization on carbon emissions [13]. Since the gas industry's waste of CO_2 gas contributes to global warming, it must be reduced or treated further [14]. One way to address this issue is to use Indonesia's enormous renewable energy potential, which will require more optimization in the future [15]. A life cycle assessment was used to examine the process's impact on the environment, and the levelized cost technique was used to investigate its economics [16].

Universities around the world have a vital role to play in addressing these issues. UI GreenMetric is one program for measuring and assessing academic institutions' contributions to environmental sustainability. Universities can act as centers for advocacy, knowledge, and innovation in the goal of sustainable development. Universities can produce comprehensive and relevant scientific research in various sustainability-related topics, from social economics to environmental science [17]. Another focus is on the economic and ecological benefits of a hybrid microgrid system at a university campus, demonstrating its potential to reduce energy costs and CO_2 emissions [18]. Additionally, research on an environmentally friendly factory in Egypt employing a hybrid PV/wind/diesel/battery system illustrates the balance between cost-effectiveness and environmental sustainability [19]. Another study presents valuable insights into developing energy utilization schemes tailored for low-income houses, emphasizing the significant role of computational methods in optimizing hybrid energy systems, which aligns with our exploration of hybrid power systems in underdeveloped regions [20]. Together, these studies underscore the importance of renewable energy systems in reducing carbon emissions and achieving sustainable development goals.

Five notable studies offer insightful perspectives in addressing the intersection of renewable energy systems, poverty reduction, and rural electrification. H. Wirawan and Y.M.L. Gultom investigate the role of renewable energy village grids in alleviating poverty in Indonesia's remote regions [21]. A. N. Shafira et al. analyze the techno-economics of hybrid renewable energy systems integrated with productive activities in underdeveloped rural areas in eastern Indonesia [22]. Using Sebira Island as a case study, V.Z.P. Hardjono et al. designed the integration of renewable energy systems with productive zones on remote islands [23]. Employing Anyar Beach, the Special Region of Yogyakarta, Indonesia, as a case study, D. Rachmawatie et al. examine the socio-economic effects of using renewable hybrid electricity to develop rural communities [24]. Additionally, A.J. Veldhuis et al. comprehensively analyze the viability and economic impact of off-grid photovoltaic systems in rural Indonesian provinces [25]. Thus, these articles underscore the critical role of renewable energy in enhancing living standards in rural areas, emphasizing its effectiveness in poverty reduction and electrification strategies [26].

Three pivotal papers stand out in the realm of hybrid renewable energy systems and optimization. One of these papers explains critical insights into various hybrid configurations' economic and environmental efficiency using advanced optimization techniques. This is relevant to our study's focus on effectively utilizing hybrid power systems in underdeveloped regions [27]. R. Nazir et al. delve into optimizing micro-grid models using renewable sources like micro-hydro and photovoltaics [28]. K.T. Akindeji and D.R.E. Ewim explore a hybrid microgrid system for a university, focusing on cost and emission reductions [29]. Muhammad Shahzad Javed et al. examines a hybrid system comprising PV, diesel, and batteries, introducing an innovative dispatch strategy [30]. These studies collectively advance our understanding of hybrid renewable energy systems, emphasizing optimization, economic feasibility, and environmental sustainability.

In pursuing sustainable energy solutions for Indonesia's diverse regions, we are informed by an array of critical research. Notably, we build upon insights from studies on renewable energy systems focused on micro-hydro and solar photovoltaics in rural areas, highlighting the importance of site-specific strategies for energy development [31]. Additionally, we draw on findings from the design of DC microgrids with load-based battery systems, underscoring the importance of tailored power solutions [32]. The sustainability challenges of micro-hydro power development are also considered, providing a context for the environmental and economic factors at play [33]. Moreover, the rich history of small hydropower projects in Indonesia over the past century offers a historical perspective on the evolution of renewable energy in the region [34]. Research on renewable energy resources for hybrid microgrid implementation also reinforces the significance of integrating diverse energy sources, such as solar and wind, in transforming diesel dependence in remote areas. Together, these studies provide a multifaceted understanding of Indonesia's complex landscape of renewable energy development, informing our approach to integrating hybrid power systems [35].

The previously discussed studies emphasize renewable energy's role in poverty reduction, rural electrification, and advancements in hybrid systems. As the approach our analysis of optimizing hybrid power systems, especially in a developing country like Indonesia with low electricity prices, it becomes crucial to consider cost-effectiveness and sustainability. We focused on identifying an optimal system design using HOMER software, balancing affordability, reliability, and environmental considerations in a context where energy costs are significant.

A Hybrid system consists of PV, a Biogas Generator, and a Wind Turbine successfully deployed for underdeveloped regions' energy emulation. However, no economic analysis has been conducted to obtain the best configuration of the hybrid system. In this paper, we propose a comprehensive analysis of hybrid power systems for underdeveloped regions utilizing the HOMER (Hybrid Optimization Model for Energy Renewable) software. Our methodology involves inputting various data sets, including electrical loads, solar irradiance, wind speed, temperature, economic parameters, and system controls. This research explores five distinct hybrid power system configurations: Biogas only, full generator integration, biogas and hydrogen hybrid, biogas with PV system, and biogas with wind turbine. The results emphasize each configuration's reliability and economic viability, considering operational and maintenance costs, initial investment requirements, and long-term financial implications. The study shows the Wind-Hydrogen and Hydrogen Only schemes as the most cost-effective, with a Total NPC of \$48,969.27 and LCOE of \$0.218. While CO_2 emissions were similar across all schemes, around 27,744 kg/year, the All-Generator scheme had slightly higher emissions at 27,667 kg/year, leading to 29,101 kWh/year of electricity production. These results underscore the importance of balancing cost, energy output, and environmental impact in hybrid power system schemes for underdeveloped regions.

2. Materials and methods

In this research, we conduct simulation modeling using HOMER software. HOMER is a tool that helps design optimized electric power systems and makes comparing different power generation technologies in other applications easier. Electric power systems' physical characteristics and life cycle costs, that is, the entire cost of installing and maintaining the system over its lifetime, were modeled by Homer. Software modeling simulations are one of the critical components of modern electrical planning. Electrical planning can be done more successfully and efficiently using modeling simulations. The ability to reduce planning expenses is one benefit of simulation modeling. This allows different planning options to be evaluated using modeling simulations instead of physically building them. As a result, planning expenses can be decreased because testing other options does not require creating the necessary infrastructure. The fact that modeling simulations take safety factors into account is another benefit.

Economic factors are critical when developing a renewable energy system. It entails choosing the best component sizes and carefully weighing numerous aspects connected to the economy to minimize the overall net present cost and energy cost. These variables include energy, projected system lifetime, operating and maintenance, and capital costs. A renewable energy system can provide a dependable and affordable energy supply by maximizing these factors.

2.1. Homer

The currently developed software is capable of accurately calculating and modeling electrical planning based on real-world conditions. The software utilizes complex and precise mathematical models to depict electrical systems. In this paper, HOMER software is employed to optimize hybrid power systems planning in underdeveloped regions. HOMER stands for Hybrid Optimization Model for Energy Renewable. The reason for choosing HOMER in this paper is to analyze and design the best configuration options for hybrid power systems in underdeveloped regions based on available data. HOMER is a software developed by "The National Renewable Energy Laboratory" and is well-suited for designing cost estimates, determining greenhouse gas emissions, and determining which components will be utilized [36]. The HOMER software comprises three essential sections: Input, simulation, and output, as illustrated in Figure 1.

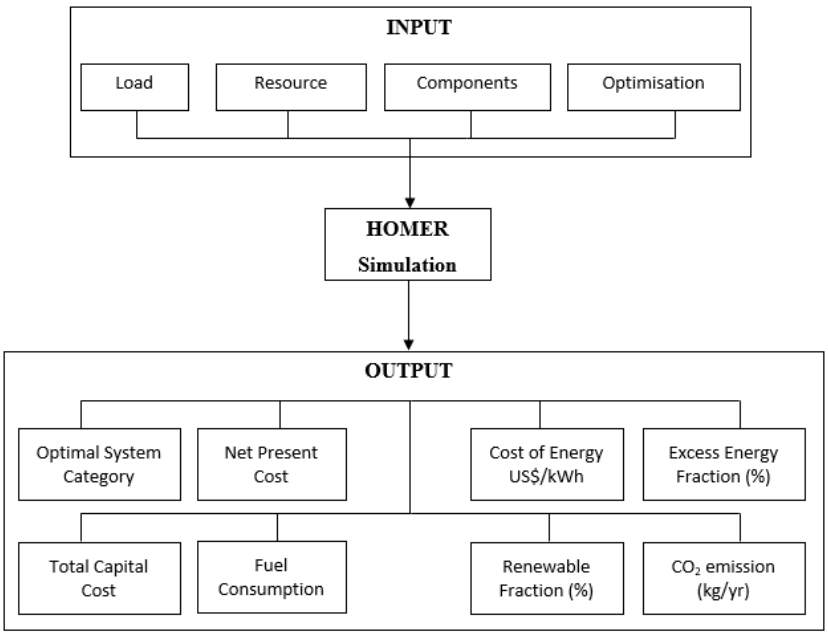

Figure 1. HOMER simulation and optimization architecture.

Table 1. Components and costs of hybrid power systems.

Component	Capacity (kW)	Capital ($)	Replacement ($)	Operation & maintenance ($/year)	Lifetime
Wind turbine	1	1,618	0	20	20 years
PV	4	3,108	0	30.40	25 years
Biogas generator	10	3,820	0	0	15000 hours
Hybrid-diesel-hydrogen generator	10	3,173	0	2,628	15000 hours
Bidirectional converter	5	970	0	0	10 years

The technical aspects and the mechanism of using the HOMER software for this paper can be initiated by selecting the components to be used, namely PV, wind turbine, bidirectional converter, and generators for biogas and hybrid-diesel-hydrogen. Before choosing the components, data such as electric load, solar irradiance data, wind speed data, temperature data, economic data, constraints data, system control inputs, emissions data, and solar prices in Indonesia are inputted. The costs associated with constructing a hybrid power system must also be input for simulation in the software. Table 1 above illustrates the components and the associated costs.

Another essential aspect is inputting load data according to the conditions at the case study location. The daily load curve in the underdeveloped region is obtained from the default HOMER, where the lowest load occurs from 00:00 to 04:00 in the early morning, averaging around 2 kW. Moreover, the peak load occurs from 18:00 to 21:00, averaging around 12 kW. Figure 2 represents the daily load curve displayed in the underdeveloped region.

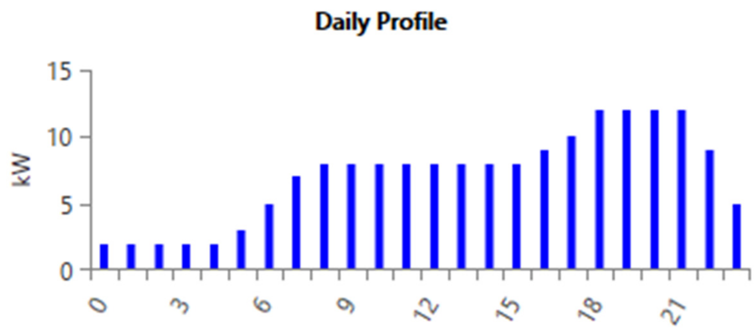

Figure 2. Daily loads in underdeveloped regions.

2.2. Economic model

One of the most critical financial evaluation metrics used in HOMER software to determine whether a renewable energy system is economically feasible is net present cost (NPC) [37]. It calculates the net present value (NPV) of all system costs throughout its lifetime, including initial capital expenditures, ongoing operating and maintenance costs, and salvage value at the end of the system's useful life [38].

The total net present cost (NPC) and energy cost (COE) of analyzing the system configurations are the primary outcomes of the HOMER simulation. NPC analysis is a suitable scale or metric for economic purposes, comparing the architecture and classification of various energy systems since it balances renewable and non-renewable sources' significantly differing cost characteristics. Furthermore, it investigates and compiles a comprehensive list of all pertinent expenses spent during a renewable energy project. The system's (NPC) and (COE) were examined economically. The system life cycle costs are represented by HOMER using the total net present cost (NPC). The NPC is determined by Eq (1) [39]:

$$NPC\ (\$) = \frac{TAC}{CRF} \tag{1}$$

where TAC is the total annual cost, and CRF is the capital recovery factor, which may be computed using the Eq (2) below:

$$CRF(\$) = \frac{i(1+i)^N}{(1+i)^N - 1} \tag{2}$$

N represents the number of years, and *i* denotes the real interest rate (%) per year. Moreover, the energy cost (COE), calculated as the average cost of electricity generated by the system in question per kilowatt-hour ($/kWh), is estimated as Eq (3) below:

$$COE\ (\$) = \frac{C_{ann,tot}}{E} \tag{3}$$

where E is the total amount of electricity produced annually, expressed in kWh, and $C_{ann,tot}$ is the total annual cost expressed in $. To determine a project's payback period (simple payback), use the following Eq (4):

$$Simple\ Payback\ (yr) = \frac{Initial\ Investment}{Annual\ Payback} \tag{4}$$

3. Results and discussion

In this paper, we propose an analysis of the hybrid power system using Homer Software. The analysis concentrates on the aspects of reliability and economic viability across five distinct configurations: Biogas only, full generator integration (encompassing biogas, hydrogen, PV, and wind), biogas and hydrogen hybrid, biogas with PV system, and biogas with wind turbine. For reliability, we examine each setup's ability to deliver consistent power, considering factors like the steadiness of biogas generation, the complementary nature of diverse energy sources in the fully integrated system, the energy density and consistency from the biogas and hydrogen hybrid, the fluctuation handling in the biogas and PV combination, and the intermittency management of wind energy when coupled with biogas. On the economic viability front, our assessment delves into the operational and maintenance costs, the initial investment requirements, and the long-term financial implications of each configuration. This includes analyzing the standalone expenses of operating a biogas system, the comprehensive investment in integrating multiple renewable sources, the cost-effectiveness of combining biogas with hydrogen, the capital costs versus savings in solar energy utilization for the biogas and PV setup, and the investment balance in wind turbine technology alongside biogas. We aim to uncover insights into which configuration presents the most practical and financially sound solution, underpinned by a balance of stable power supply and economic feasibility. Table 2 shows the simulation component of the proposed system.

Table 2. The simulation component of the proposed system.

Component	Specification
Wind turbine (AWS HC 650 W)	Rated Power: 650 Watts, Rotor Diameter: ~2–3 meters, Cut-in Wind Speed: ~3–4 m/s, Cut-out Wind Speed: ~25 m/s, Rated Wind Speed: ~12–14 m/s, Output Voltage: 24/48 V DC (AC option available)
PV system (Fronius Symo 4.5-3-S with Generic PV)	Maximum Power Output: 4.5 kW (inverter), Module Type: Mono-/Polycrystalline, Module Efficiency: 15–20%, Operating Temperature: –40 to 85 °C, Inverter Efficiency: >95%, System Voltage: 300–500 V DC
Biogas generator	Power Output Range: 1 kW to several MW, Fuel Type: Biogas (methane-rich), Fuel Consumption: Varies, Electrical Efficiency: ~30–40%, Heat Recovery: Possible in CHP systems
Diesel-Hydrogen generator (Hybrid)	Power Output Range: 5 kW to 10 kW+, Fuel Type: Diesel and Hydrogen blend, Efficiency: Higher than traditional diesel generators, Emission: Reduced compared to diesel-only, Operating Mode: Hydrogen-only, diesel-only, mixed
Converter (Leonics S-219Cp 5 kW)	Rated Power: 5 kW, Input Voltage Range: 48 V to 400 V DC, Output Voltage: Standard AC grid voltages, Efficiency: >90%, Features: MPPT, protection mechanisms

3.1. The all-gen scheme

Figure 3 shows the first scheme, which presents a comprehensive economic analysis of a configuration encompassing various generators: A wind turbine, photovoltaic (PV) system, biogas generator, and a hybrid diesel-hydrogen generator. This analysis is integral to understanding the financial implications of deploying such a hybrid system in real-world scenarios.

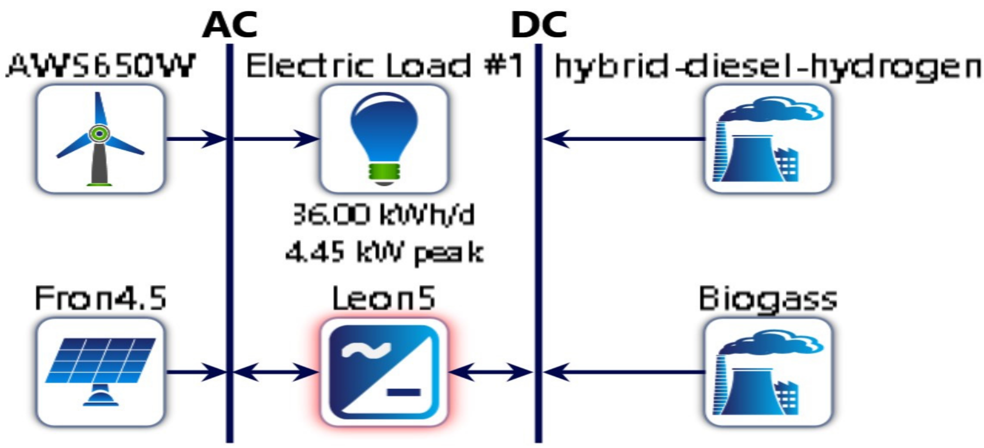

Figure 3. The schematic of all generators.

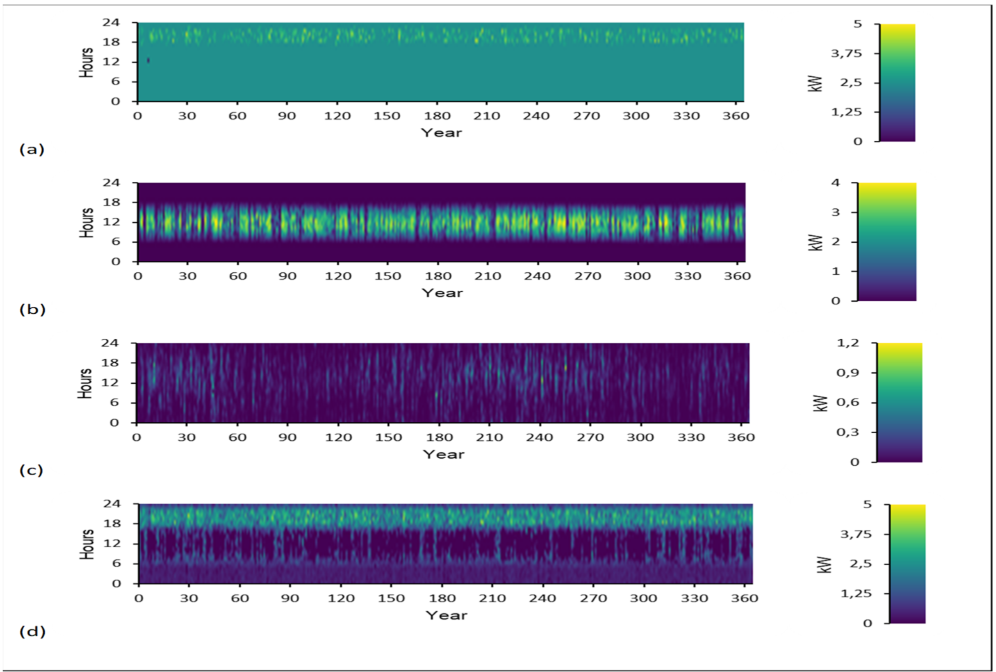

Figure 4. Power gens power output. (a) Hybrid diesel hydrogen, (b) PV, (c) Wind turbine, and (d) Inverter.

Concerning the Net Present Cost (NPC), the result indicates $58,369.55. This figure is critical as it represents the cumulative cost over the system's lifecycle, encapsulating initial capital investment, operational expenditures, and potential replacement costs. The Levelized Cost of Energy (LCOE) is calculated at $0.260 per kWh, a pivotal metric in assessing the average cost per unit of electricity generated throughout the system's operational lifespan. This LCOE value is essential for gauging the cost-effectiveness of the hybrid system in comparison to other energy alternatives [40].

The economic breakdown of the system reveals the costs associated with each component. The wind turbine (AWS HC 650 W) costs $1,959, while the biogas generator costs $3,820. The PV system (Fronius Symo 4.5-3-S with Generic PV) costs $3,626. Notably, the generic 10 kW fixed capacity genset (Diesel) presents a significantly higher cost of $47,994. Additionally, the converter (Leonics S-219Cp 5 kW) costs $970.

Regarding operational performance, the system's electrical summary showcases a total generation of 29,101 kWh/year. The primary load on the AC grid is 13,140 kWh/year. Significantly, the system reports no unmet electric load and no capacity shortage, underlining its reliability in providing a consistent electricity supply. In Figure 4, the output power of each generator configuration can be shown.

Figure 4 shows that the average output power of the hybrid diesel-hydrogen generator is approximately 2.55 kW over 8,759 hours per year. The PV system generates an average power of 0.709 kW with an operational time of 4,433 hours per year. The Wind Turbine has the lowest average output power, which is 0.064 kW over a time range of 6,291 hours per year. Moreover, the Inverter produces an average power of 0.919 kW with an operational time of 6,946 hours per year. Although not directly linked to economic viability, the result also encompasses environmental considerations, specifically the annual carbon dioxide emission, which stands at 27,667 kg. This emission rate is crucial to assessing the system's environmental impact [41].

3.2. The biogas-hydrogen hybrid

The second scheme result offers a comprehensive analysis of a hybrid power system designed with a biogas-hydrogen hybrid setup, tailored for underdeveloped areas in Indonesia. This configuration includes a biogas generator and a hybrid-diesel-hydrogen generator, interconnected through a bidirectional converter and controlled by an energy management system.

From an economic standpoint, this configuration's total Net Present Cost (NPC) is calculated to be $52,789.27, encompassing the system's entire lifecycle cost, including initial capital investments, operational expenses, and potential replacement costs. The Levelized Cost of Energy (LCOE), a crucial indicator of the average cost per unit of electricity generated over the system's lifetime, is determined to be $0.236 per kWh.

Regarding the capital expenditure breakdown, the biogas generator contributes $3,820. Notably, the biogas generator did not produce electricity in this configuration, prompting considerations regarding its optimal utilization and integration. In contrast, the generic 10 kW fixed capacity diesel generator plays a significant role in the system's operational capabilities but also adds substantially to the overall costs, with a capital cost of $3,173 and operating costs of $44,826. Additionally, the Leonics S-219Cp 5 kW converter, essential for managing power flow within the system, has a capital cost of $970.

Operationally, the system is characterized by a total electricity production of 22,430 kWh/year, solely from the diesel generator. This output efficiently meets the primary load of 13,140 kWh/year on the AC grid, indicating a reliable power supply with no unmet load. However, the environmental impact is notable, with an annual carbon dioxide emission of 27,744 kg, underscoring the environmental implications of this configuration.

3.3. The PV-hydrogen hybrid

The third scheme result offers a detailed assessment of a hybrid power system with a photovoltaic (PV)-hydrogen hybrid setup, aimed at underdeveloped regions in Indonesia. This specific configuration includes a PV system, a hybrid-diesel-hydrogen generator, and a bidirectional converter, all managed by an energy management system.

This configuration is evaluated economically with a Total Net Present Cost (NPC) of $52,595.52. This figure encompasses the entire lifecycle cost of the system, including initial investments, operational expenses, and potential replacement costs. The Levelized Cost of Energy (LCOE) is calculated at $0.235 per kWh, providing a metric for the average cost per unit of electricity generated over the system's lifespan.

The capital cost breakdown includes $3,108 for the Fronius Symo 4.5-3-S PV system with generic PV modules and $3,173 for the generic 10 kW fixed-capacity diesel generator. The operating costs for the diesel generator are a significant portion of the overall expenses, amounting to $44,826. Additionally, the Leonics S-219Cp 5 kW converter, integral to the system's operation, adds a capital cost of $970.

In terms of operational performance, the system produces a total of 28,602 kWh/year, with the PV system contributing 6,213 kWh/year (21.7%) and the diesel generator contributing 22,389 kWh/year (78.3%). The system efficiently meets the primary load of 13,140 kWh/year on the AC grid, ensuring a reliable power supply with no unmet electric load. The environmental impact, particularly the carbon dioxide emissions of 27,713 kg/year, is also a significant consideration, alongside other pollutants like carbon monoxide, unburned hydrocarbons, particulate matter, sulfur dioxide, and nitrogen oxides.

3.4. The wind-hydrogen hybrid

The fourth scheme result delivers an in-depth evaluation of a hybrid power system featuring a wind-hydrogen hybrid configuration developed explicitly for use in underdeveloped regions in Indonesia. This system comprises a wind turbine, a hybrid-diesel-hydrogen generator, and a bidirectional converter managed by an energy management system.

Economically, the configuration is assessed with a Total Net Present Cost (NPC) of $48,969.27. This figure represents the system's total cost, including initial investments, operational expenses, and potential future replacement costs. The Levelized Cost of Energy (LCOE) for this configuration is determined to be $0.218 per kWh.

Regarding capital costs, the wind turbine and the Leonics S-219Cp 5 kW converter are significant contributors, along with the diesel generator, which also forms a substantial part of the overall expenses. The operating costs of the diesel generator are notably high, totaling $44,826, highlighting the financial impact of each component within the hybrid system.

From an operational perspective, the system exhibits a total electricity production of 22,430 kWh/year, effectively meeting the primary load of 13,140 kWh/year on the AC grid. This indicates the system's ability to supply reliable power without any unmet electric load. However, the environmental impact is a concern, with carbon dioxide emissions amounting to 27,744 kg/year and other pollutants like carbon monoxide, unburned hydrocarbons, and nitrogen oxides.

3.5. The hydrogen hybrid generator

The fifth scheme result provides a comprehensive analysis of a hybrid power system configured with a hydrogen hybrid setup, designed for implementation in underdeveloped areas in Indonesia. This specific system configuration includes a hydrogen generator, a hybrid-diesel-hydrogen generator, and a bidirectional converter, all integrated and managed by an advanced energy management system.

Economically, this configuration's Total Net Present Cost (NPC) is reported to be $48,969.27, a figure that encompasses the entire lifecycle cost of the system, including initial capital investment, operational expenses, and future replacement costs. The Levelized Cost of Energy (LCOE) is determined to be $0.218 per kWh, serving as an essential metric to assess the cost-effectiveness of electricity generation over the system's operational life.

The capital cost breakdown shows significant contributions from the components, with the diesel generator accounting for a substantial portion of the total expenses. The operating costs for the diesel generator are notably high, totaling $44,826, which significantly impacts the overall financial assessment of the system.

Operationally, the system produces 22,430 kWh/year, efficiently meeting the primary load of 13,140 kWh/year On the AC grid. This performance highlights the system's ability to provide a reliable electricity supply without any unmet electric load. However, the environmental impact, particularly the annual carbon dioxide emissions of 27,744 kg, alongside other pollutants, is a notable concern.

3.6. Comparison analysis of schemes

The analysis of five distinct hybrid power system configurations, each designed for underdeveloped regions in Indonesia, reveals varying levels of economic viability, operational performance, and environmental impact. The first scheme, featuring an All-Generator Configuration, stands out with the highest electricity production of 29,101 kWh/year. However, it also incurs the highest costs, with a Total Net Present Cost (NPC) of $58,369.55 and a Levelized Cost of Energy (LCOE) of $0.260 per kWh. Despite its high output, this scheme is less economically favourable due to its higher costs. The following Table 3 shows a comparative analysis of the schemes.

Table 3. Comparison analysis of schemes.

Scheme	Configuration	Total NPC	LCOE	Electricity production (kWh/year)	CO_2 emissions (kg/year)
First	All generator	$58,369.55	$0.260	29,101	27,667
Second	Biogas-hydrogen	$52,789.27	$0.236	22,430	27,744
Third	PV-hydrogen	$52,595.52	$0.235	28,602	27,713
Fourth	Wind-hydrogen	$48,969.27	$0.218	22,430	27,744
Fifth	Hydrogen only	$48,969.27	$0.218	22,430	27,744

The second scheme, the Biogas-Hydrogen Hybrid, demonstrates a more moderate NPC of $52,789.27 and an LCOE of $0.236 per kWh. However, its operational efficiency is questioned due to the non-contribution of the biogas generator. Its electricity production is 22,430 kWh/year, which mirrors the first scheme in environmental impact, with 27,744 kg of CO_2 emissions annually.

The third scheme, incorporating a PV-Hydrogen Hybrid, shows a slightly lower NPC of $52,595.52 and an LCOE of $0.235 per kWh. It produces 28,602 kWh/year, with a notable 21.7% contribution from the PV system. This scheme indicates a better balance between cost and the utilization of renewable energy.

The fourth and fifth schemes, the Wind-Hydrogen Hybrid and the Hydrogen Hybrid Only, respectively, present the most economically viable options with the lowest NPC and LCOE, marked at $48,969.27 and $0.218 per kWh. These schemes generate the same amount of electricity (22,430 kWh/year) and have identical environmental impacts, with 27,744 kg of CO_2 emissions annually.

The economic performance of various energy schemes reveals some compelling insights. Notably, the Wind-Hydrogen (Fourth) and Hydrogen Only (Fifth) schemes emerge as the most cost-effective options. They boast the lowest Total Net Present Cost (NPC) at $48,969.27. Furthermore, these schemes achieve the lowest Levelized Cost of Energy (LCOE) at $0.218, which is notably below the local energy price for underdeveloped regions in Indonesia at $0.22. When it comes to environmental impact, all schemes exhibit a comparable effect on CO_2 emissions. However, the All Generator (First) scheme has marginally higher emissions, reaching 27,667 kg/year, while the other schemes hover around 27,744 kg/year in CO_2 emissions. In the realm of electricity production, the All-Generator scheme leads with an impressive output of 29,101 kWh/year. Following closely is the PV-Hydrogen (Third) scheme, which produces a substantial 28,602 kWh/year.

4. Conclusions

In choosing the proper configuration, considerations extend beyond economic feasibility to operational efficiency and environmental sustainability. Other hybrid optimization works that have been conducted by other researchers rarely consider the local energy price. This research investigates All-Generator Configuration. The Wind-Hydrogen Hybrid and Hydrogen hybrid-only configurations strike a more favorable balance between cost and performance. In this paper, we compare the 5 schemes and consider the LCOE scheme to ensure the energy cost is viable.

The results show clear economic and environmental performance distinctions across the five hybrid power system schemes. These are a few key points from the results of the hybrid power system schemes evaluation:

1) Economic performance:
    i) The Wind-Hydrogen (Fourth) and Hydrogen Only (Fifth) schemes are the most cost-effective.
    ii) These schemes have the lowest Total Net Present Cost (NPC) at $48,969.27.
    iii) They also have the lowest Levelized Cost of Energy (LCOE) at $0.218, which is below the local energy price for underdeveloped regions in Indonesia at $0.22.
2) Environmental impact:
    i) All schemes show a comparable impact on CO_2 emissions.
    ii) The All Generator (First) scheme has slightly higher emissions at 27,667 kg/year.
    iii) Other schemes are around 27,744 kg/year in CO_2 emissions.
3) Electricity production:
    i) The All-Generator scheme leads in electricity production with 29,101 kWh/year.
    ii) The PV-Hydrogen (Third) scheme is a close second, producing 28,602 kWh/year.

These findings are crucial for evaluating the trade-offs between cost, energy output, and environmental footprint when selecting the optimal hybrid power system scheme for underdeveloped regions.

Use of AI tools declaration

We hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct without using Artificial Intelligence (AI) tools in creating this article. We also declare that, as required by these rules and conduct, that we have fully cited and referenced all materials and results that are not original to this work.

Acknowledgments

Thank you to the National Research and Innovation Agency (BRIN) for facilitating this research. Thank you to the Education Fund Management Institute (LPDP) for funding this research through grant Decree Number KWR4.008/PNLT04/PPM-LIT/2023 and Agreement/Contract Number 128/IV/KS/11/2022 and 374/SAM4/PPM/2022. Thank you to the Directorate of Research and Community Service, Telkom University, for supporting this research.

Conflict of interest

All authors declare no conflicts of interest in this paper.

Author contributions

K.B. Adam: Conceptualization and methodology, writing—original draft, J. Raharjo; supervision and formal analysis, D. K. Silalahi: resources & project administration, B.S. Aprilia; writing—review and editing, validation, IGPOI Wijaya; editing and translating. All authors have read and agreed to the published version of the manuscript.

References

1. Sovacool BK (2018) Success and failure in the political economy of solar electrification: Lessons from World Bank Solar Home System (SHS) projects in Sri Lanka and Indonesia. *Energy Policy* 123: 482–493. https://doi.org/10.1016/j.enpol.2018.09.024
2. Azzahrah S, Hastuti SH, Hartono D (2023) Economic, social, and environmental impact of renewable energy investment: Empirical study of Indonesia. *Int Energy J* 23: 55–70.
3. Wen C, Lovett JC, Rianawati E, et al. (2022) Household willingness to pay for improving electricity services in Sumba Island, Indonesia: A choice experiment under a multi-tier framework. *Energy Res Social Sci* 88: 102503. https://doi.org/10.1016/j.erss.2022.102503
4. Barja-Martinez S, Rucker F, Aragues-Penalba M, et al. (2021) A novel hybrid home energy management system considering electricity cost and greenhouse gas emissions minimization. *IEEE Trans Ind Appl* 57: 782–2790. https://doi.org/10.1109/TIA.2021.3057014
5. Nallolla CA, Vijayapriya P (2022) Optimal design of a hybrid off-grid renewable energy system using techno-economic and sensitivity analysis for a rural remote location. *Sustainability* 14: 15393. https://doi.org/10.3390/su142215393
6. Ayub S, Ayob SM, Tan CW, et al. (2022) Analysis of energy management schemes for renewable-energy-based smart homes against the backdrop of COVID-19. *Sustainable Energy Technol Assess* 52: 1–17. https://doi.org/10.1016/j.seta.2022.102136
7. Syahputra R, Soesanti I (2021) Renewable energy systems based on micro-hydro and solar photovoltaic for rural areas: A case study in Yogyakarta, Indonesia. *Energy Rep* 7: 472–490. https://doi.org/10.1016/j.egyr.2021.01.015
8. Ogunjuyigbe ASO, Ayodele TR, Monyei CG (2015) An intelligent load manager for PV powered off-grid residential houses. *Energy Sustainable Dev* 26: 34–42. https://doi.org/10.1016/j.esd.2015.02.003
9. Azevedo J, Mendonça F (2015) Small scale wind energy harvesting with maximum power tracking. *AIMS Energy* 3: 297–315. https://doi.org/10.3934/energy.2015.3.297
10. Al Qaisi Z, Alsafasfeh Q, Harb A (2018) Stability impact of integrated small scale hybrid (PV/Wind) system with electric distribution network. *AIMS Energy* 6: 832–845. https://doi.org/10.3934/energy.2018.5.832
11. Saritha KS, Sreedharan S, Nair U (2023) A novel optimal control strategy for energy management in a hybrid microgrid system. *Int Energy J* 23: 55–70.

12. Blum NU, Sryantoro Wakeling R, Schmidt TS (2013) Rural electrification through village grids—Assessing the cost competitiveness of isolated renewable energy technologies in Indonesia. *Renewable Sustainable Energy Rev* 22: 482–496. https://doi.org/10.1016/j.rser.2013.01.049
13. Cahyo H, Purnomo SD, Octisari SK, et al. (2023) Environment, population, and economy on CO_2 emission in Indonesia. *Int J Energy Econ Policy* 13: 295–303. https://doi.org/10.32479/ijeep.14938
14. Martanto T, Nizami M, Purwanto WW (2023) Techno-economic evaluation of CO_2 utilization from gas processing facility to blue methanol using green hydrogen. *IOP Conf Ser: Earth Environ Sci* 1261: 012035. https://doi.org/10.1088/1755-1315/1261/1/012035
15. Pambudi NA, Firdaus RA, Rizkiana R, et al. (2023) Renewable energy in Indonesia: Current status, potential, and future development. *Sustainability* 15: 1–29. https://doi.org/10.3390/su15032342
16. Pratama MR, Muthia R, Purwanto WW (2023) Techno-economic and life cycle assessment of the integration of bioenergy with carbon capture and storage in the polygeneration system (BECCS-PS) for producing green electricity and methanol. *Carbon Neutrality* 2: 1–22. https://doi.org/10.1007/s43979-023-00069-1
17. Sari RF, Sidiyanto YA, Windiatmaja JH (2023) The role of universities in realizing sustainability: Analysis of UI GreenMetric contributions and publications related to sustainability. *E3S Web Conf* 450: 1–9. https://doi.org/10.1051/e3sconf/202345001001
18. Lee M, Soto D, Modi V (2014) Cost versus reliability sizing strategy for isolated photovoltaic micro-grids in the developing world. *Renewable Energy* 69: 16–24. https://doi.org/10.1016/j.renene.2014.03.019
19. Diab F, Lan H, Zhang L, et al. (2016) An environmentally friendly factory in Egypt based on hybrid photovoltaic/wind/diesel/battery system. *J Cleaner Prod* 112: 3884–3894. https://doi.org/10.1016/j.jclepro.2015.07.008
20. Kgopana K, Popoola O (2023) Improved utilization of hybrid energy for low-income houses based on energy consumption pattern. *AIMS Energy* 11: 79–109. https://doi.org/10.3934/energy.2023005
21. Wirawan H, Gultom YML (2021) The effects of renewable energy-based village grid electrification on poverty reduction in remote areas: The case of Indonesia. *Energy Sustainable Dev* 62: 186–194. https://doi.org/10.1016/j.esd.2021.04.006
22. Shafira AN, Petrana S, Muthia R, et al. (2023) Techno-economic analysis of a hybrid renewable energy system integrated with productive activities in an underdeveloped rural region of eastern Indonesia. *Clean Energy* 7: 1247–1267. https://doi.org/10.1093/ce/zkad068
23. Hardjono VZP, Reyseliani N, Purwanto WW (2023) Planning for the integration of renewable energy systems and productive zone in Remote Island: Case of Sebira Island. *Cleaner Energy Syst* 4: 100057. https://doi.org/10.1016/j.cles.2023.100057
24. Rachmawatie D, Rustiadi E, Fauzi A, et al. (2019) Analysis of the socio-economic impact of renewable energy hybrid electricity utilization for rural community development (case study: Pantai Anyar, Yogyakarta special region, Indonesia). *IOP Conf Ser: Earth Environ Sci* 383: 1–8. https://doi.org/10.1088/1755-1315/383/1/012013
25. Veldhuis AJ, Reinders AHME (2015) Reviewing the potential and cost-effectiveness of off-grid PV systems in Indonesia on a provincial level. *Renewable Sustainable Energy Rev* 52: 757–769. https://doi.org/10.1016/j.rser.2015.07.126

26. Aziz AS, Tajuddin MFN, Zidane TEK, et al. (2022) Techno-economic and environmental evaluation of PV/diesel/battery hybrid energy system using improved dispatch strategy. *Energy Rep* 8: 6794–6814. https://doi.org/10.1016/j.egyr.2022.05.021
27. Prakash SVJ, Dhal PK (2022) Cost optimization and optimal sizing of standalone biomass/diesel generator/wind turbine/solar microgrid system. *AIMS Energy* 10: 665–694. https://doi.org/10.3934/energy.2022032
28. Nazir R, Laksono HD, Waldi EP, et al. (2014) Renewable energy sources optimization: A micro-grid model design. *Energy Proc* 52: 316–327. https://doi.org/10.1016/j.egypro.2014.07.083
29. Akindeji KT, Ewim DRE (2023) Economic and environmental analysis of a grid-connected hybrid power system for a University Campus. *Bulletin National Research Centre* 47: 1–10. https://doi.org/10.1186/s42269-023-01053-6
30. Javed MS, Ma T (2019) Techno-economic assessment of a hybrid solar-wind-battery system with genetic algorithm. *Energy Proc* 158: 6384–6392. https://doi.org/10.1016/j.egypro.2019.01.211
31. Didik H, Bambang PN, Asep S, et al. (2018) Sustainability challenge of micro hydro power development in Indonesia. *IOP Conf Ser* 147: 1–8. https://doi.org/10.1088/1755-1315/147/1/012031
32. Faanzir F, Ashari M, Soedibyo S, et al. (2022) The design of dc micro grid with a load-based battery discharge method for remote island electrification utilizes marine currents and solar photovoltaic. *Kinetik: Game Technology, Information System, Computer Network, Computing, Electronics, and Control* 7: 409–420. https://doi.org/10.22219/kinetik.v7i4.1576
33. Burke PJ, Kurniawati S (2018) Electricity subsidy reform in Indonesia: Demand-side effects on electricity use. *Energy Policy* 116: 410–421. https://doi.org/10.1016/J.ENPOL.2018.02.018
34. Syahputra R, Soesanti I (2021) Renewable energy systems based on micro-hydro and solar photovoltaic for rural areas: A case study in Yogyakarta, Indonesia. *Energy Rep* 7: 472–490. https://doi.org/10.1016/j.egyr.2021.01.015
35. Hughes Arrocha EM (2022) Initial research of renewable energy resources for hybrid microgrid implementation, using solar and wind; transforming the diesel dependence. Case study of Mamburit Island—Indonesia. *J Advanced Res Electr Eng* 6: 13–18. https://doi.org/10.12962/jaree.v6i1.221
36. Kunaifi (2010) HOMER program for feasibility study of hybrid power plants in Riau Province. *National Inf Seminar,* 18–27.
37. Ghoniem RM, Alahmer A, Rezk H, et al. (2023) Optimal design and sizing of hybrid photovoltaic/fuel cell electrical power system. *Sustainability* 15: 1–19. https://doi.org/10.3390/su151512026
38. Alahmer A, Alsaqoor S (2019) Energy efficient of using chilled water system for sustainable health care facility operating by solar photovoltaic technology. *Energy Proc* 156: 65–71. https://doi.org/10.1016/j.egypro.2018.11.092
39. Setiawan A, Setiawan EA (2017) Optimization of a photovoltaic power plant in Indonesia with proper tilt angle and photovoltaic type using a system advisor model. *IJETech* 3: 539–548. https://doi.org/10.14716/ijtech.v8i3.8076
40. Kabeyi MJB, Olanrewaju OA (2023) The levelized cost of energy and modifications for use in electricity generation planning. *Energy Rep* 9: 495–534. https://doi.org/10.1016/j.egyr.2023.06.036

41. Al-Rumaihi A, McKay G, Mackey HR, et al. (2020) Environmental impact assessment of food waste management using two composting techniques. *Sustainability* 12: 1595. https://doi.org/10.3390/su12041595