International Information and Engineering Technology Association
Advancing the World of Information and Engineering

International Journal of Energy Production and Management
Vol. 9, No. 4, December, 2024, pp. 247-254
Journal homepage: http://iieta.org/journals/ijepm

Techno-Economic Evaluation of Hybrid Solar-Wind Power Plant for Generating Electricity at Toll Merak Rest Area Electric Vehicle Charging Station

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https://doi.org/10.18280/ijepm.090405

Received: 6 June 2024
Revised: 5 August 2024
Accepted: 18 December 2024
Available online: 31 December 2024

Keywords:
HOMER-Grid, PV, wind turbine, HRES EVCS, toll road

ABSTRACT

The research proposes a Hybrid Renewable Energy System (HRES) that integrates wind and solar energy to address the high initial investment challenges associated with renewable energy systems. The primary objective is to develop a cost-effective energy solution for Electric Vehicle Charging Stations (EVCS) located at rest areas along the Trans Java toll road, supporting Indonesia's transition to environmentally friendly land transportation. Utilizing HOMER-Grid software, the study analyzes the potential of wind and solar energy and associated investment costs. Key outcomes include energy production, consumption, surplus energy, energy cost ratios, Net Present Cost (NPC), and Cost of Energy (COE). The findings indicate that the hybrid system can achieve a 17.66% contribution of renewable energy when connected to the primary grid, highlighting its potential to enhance efficiency and sustainability in Indonesia's transportation sector.

1. INTRODUCTION

The global electricity demand is rapidly increasing, driven by population growth, economic progress, and the growing reliance on electricity across various sectors [1]. Addressing this rising demand while transitioning to cleaner energy sources poses a considerable challenge, necessitating sustained investments in renewable energy, grid modernization, and energy efficiency initiatives [2]. Numerous environmental concerns about electricity generation have arisen in recent years, primarily due to greenhouse gases like carbon dioxide emissions. These emissions, predominantly from fossil fuel-based energy production, are major contributors to global warming and have led to significant climate changes in many countries [3]. Consequently, adopting renewable energy has gained traction as a solution for mitigating global warming. Developed and developing nations have increasingly used renewable energy sources for electricity production [4, 5].

Renewable energy technologies encounter various economic and technical obstacles hindering their broader implementation. One of the primary challenges is the high upfront investment required for installation [6]. A Hybrid Renewable Energy System (HRES) addresses these issues by combining multiple renewable energy sources with storage solutions, ensuring energy reliability, minimizing emissions, and improving grid stability in urban and remote areas [7]. By leveraging this approach, the system optimizes available natural resources while achieving more cost-effective and efficient operation of renewable energy systems [8-10].

Indonesia, located in Southeast Asia, is increasingly adopting solar and wind energy due to its ease of installation compared to other renewable energy sources [11]. These energy sources are abundant, environmentally friendly, and do not produce CO_2 emissions. Positioned along the equator, Indonesia benefits from significant solar radiation throughout the year, offering substantial potential for solar energy utilization. Additionally, as an archipelagic nation with two distinct seasons, the seasonal wind variations enhance the potential for wind energy [12]. Combining solar and wind energy is a promising strategy, especially since solar energy is plentiful during the dry season and wind energy plays a vital role in the wet season. This approach is more logical and more efficient than depending solely on solar energy, particularly in some regions of Indonesia. The nation enjoys an average solar radiation of 4.82 kWh per square meter daily [13], while wind speeds range from 2 to 6 m/s, making small to medium-scale wind energy systems viable [14]. Indonesia is in a position to ensure a more dependable and consistent renewable energy supply through a broader utilization of its diverse natural resources. This hybrid system provides energy security and diversifies energy sources away from fossil fuels, further supporting the battle against climate change, a global concern [15-17].

Indonesia has excellent renewable energy possibilities, especially in the land transportation sector, which is primarily dependent on fossil fuels. Adopting electric vehicles is imperative in addressing environmental, economic, and societal concerns [18]. As a populous archipelagic country, Indonesia faces problems like air pollution, reliance on imported fossil fuels, and climate change. Transforming conventional automobiles into electric vehicles can drastically lower greenhouse gas emissions and reduce air pollution, one of the major pollutants in cities [19]. In addition to the environmental benefits, this change has excellent potential to boost local technology and the renewable energy sector, generate employment, improve the labor force's skills, and mitigate the dependency on oil imports for economic prosperity [20].

Adopting electric vehicles in Indonesia requires government support, including incentives for manufacturers and consumers and establishing critical infrastructure like Public Electric Vehicle Charging Stations (EVCS) [21]. Additionally, the private sector plays a crucial role in providing investments and driving technological advancements. Realizing sustainable mobility in the country hinges on collaboration among the government, private entities, and the public to strengthen energy independence and promote environmentally friendly development [22]. This transition aligns with Indonesia's commitment to mitigating climate change and achieving sustainable development objectives [23]. Considering the crucial role of toll roads in transportation and logistics, it is essential to equip toll road rest areas with facilities such as EV charging stations to support the growing use of electric vehicles [24].

Implementing EV charging stations in rest areas is increasingly common, and integrating a renewable energy supply system poses an intriguing challenge. This study analyzes the investment potential and feasibility of utilizing hybrid PV-Wind technology to supply power EVCS on toll roads. Using computational methods and HOMER-based algorithms, the study evaluates the performance and cost-effectiveness of the PV-Wind system, considering metrics such as Net Present Cost (NPC) and Levelized Cost of Energy (LCOE) [25-28]. The research examines the viability of a grid-connected photovoltaic system as a power source for EVCS, focusing on factors critical to sustainable investment, including energy demand, renewable energy availability, and system configuration.

This study incorporates operational costs and the investment payback period to establish the payback period using a technical and economic analysis method [29]. The study's outcomes are divided into two primary areas: energy production by the Hybrid Renewable Energy System (HRES) and a cost analysis covering the system's operational lifespan. The system's efficiency and economic feasibility are assessed using detailed metrics. The results contribute insights into the optimal design of autonomous energy systems that are cost-effectively serving EVCS.

2. MATERIALS AND METHODS

2.1 Regional selection

EVCS powered by renewable energy is planned for a Rest Area along the Trans Java toll road, a key land transportation route, and Java's longest toll road. Rest Area KM 45 is located on the Jakarta-Merak Toll Road in Gerem, Cilegon, Banten, Indonesia. This site is particularly noteworthy as it lies near Jakarta, Indonesia's capital and a central metropolitan hub. It is an ideal area for analysis and selecting Rest Area KM 45 as the SPKLU site offers several strategic advantages. Its proximity to Jakarta ensures convenient access for electric vehicle users traveling long distances, enhancing the reliability of EV charging infrastructure. Additionally, integrating renewable energy sources, such as solar power, supports environmental sustainability and green initiatives by reducing reliance on fossil fuels and lowering carbon emissions.

The electric vehicle charging system will utilize solar panels and wind turbines installed at the Rest Area, designed with sufficient capacity to meet the station's energy demands. The system will be integrated with the national grid to ensure uninterrupted service, especially during unfavorable weather conditions that limit solar energy production. Additionally, battery storage will be incorporated to stabilize the energy supply and maximize the utilization of renewable energy sources. The identification of suitable locations for Public EVCS was conducted using Global Energy Source Prediction Data provided by NASA integrated with HOMER software. HOMER's functions assist in determining the most appropriate project location by considering various ecological and topographical factors. More information about the geographical characteristics of the chosen location for this hybrid system is presented in Figure 1.

Figure 1. Mapping of location

2.2 Model description

The energy modeling of the system is performed using the HOMER-Grid software, which assists in simulating the feasibility of a hybrid PV-wind turbine-battery power system and evaluating the Cost of Energy (COE) of the system. This approach considers the availability of energy from wind and solar sources, energy demand curves, techno-economic considerations, and site-specific factors [30]. The framework applied in the HOMER is illustrated in Figure 2 [31].

This simulation aims to identify areas that require further economic and technical analysis. For a more detailed investigation, three locations on Java were selected. Figure 3 illustrates the projected inflation rates for each site on the island. The HOMER-Grid program utilizes the NASA database to gather energy resource data specific to each location. The HOMER program generated the necessary default parameters, including an office-scale load profile, without specifying a peak month, as shown in Figures 4 and 5. NASA POWER data is used in this simulation to ensure accuracy and relevance to local conditions. The load profiles incorporated in the HOMER program represent typical office energy needs, facilitating a realistic evaluation of the potential for adopting renewable energy systems. This approach helps assess the technical and economic feasibility, ensuring the proposed solution is environmentally sustainable and financially viable. This comprehensive study aims to contribute to developing a sustainable energy strategy for Java, promote green initiatives, and enhance regional energy efficiency.

This study will evaluate the advantages of hybrid solar panels and wind turbine systems in applying EVCS. Table 1 outlines various components suitable for hybrid systems, selected based on cost, replacement, service life, and operation and maintenance (O&M). Solar panels and wind turbines generate the power required to meet demand and are connected to the grid to address any surplus or shortage of electricity. AC/DC converters transform DC electricity into AC, making it suitable for household appliances. The entire system is evaluated using HOMER with predetermined investment costs. Operational costs in applying solar panels, wind turbines, and inverters pose challenges. Life Cycle Cost (LCC) analysis can also be described as a valuable tool for estimating the costs of this system [32].

The HOMER software automatically verifies electricity consumption for the EVCS energy needs. This load profile estimates electricity usage based on the rest area along the toll roads in the HOMER-Grid. For each city on Java Island included in the study, electricity consumption is assumed to be consistent, approximately 218.14 kWh/day, with a peak demand of around 20.11 kW. Monthly electricity consumption calculations are shown in Figure 3. Various requirements, including components, influence cost analysis for the PV-Wind hybrid system. The types and specific specifications of the elements required for this system are provided in Table 1.

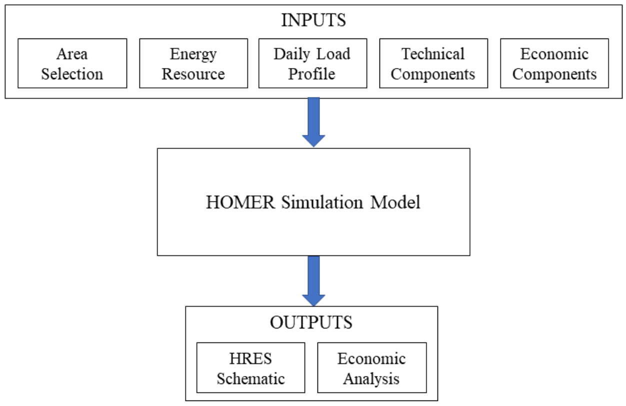

Figure 2. HOMER framework [31]

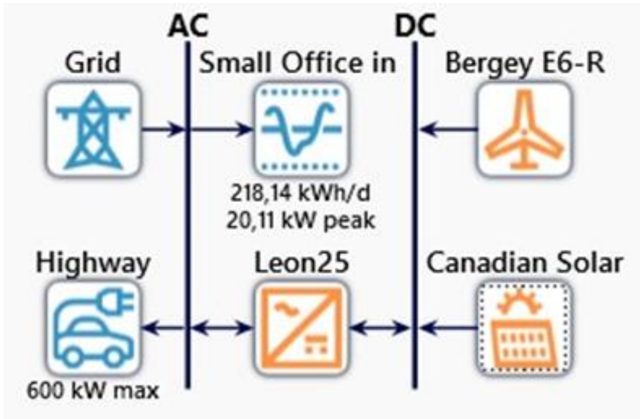

Figure 3. Schematic of a hybrid PV-wind turbine setup

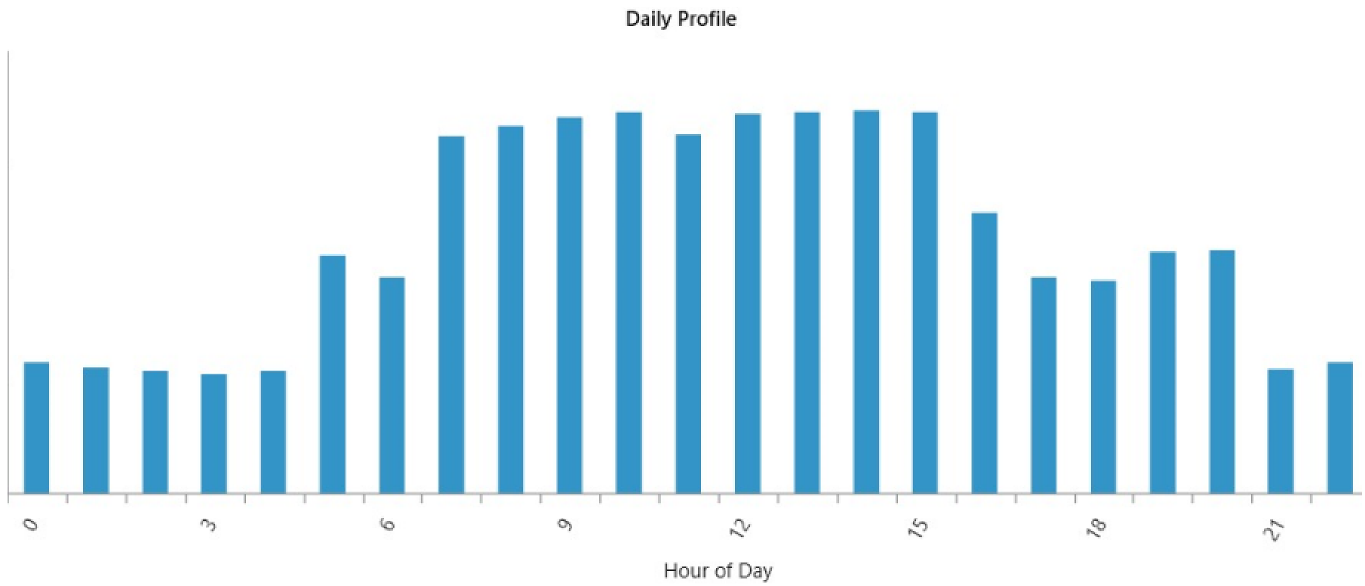

Figure 4. Electrical load in a charging station in kWh/day

Table 1. System components projection

	Inverters	Solar Panel	Wind Turbines
Type	Leonics MTP-413F	Canadian Solar CSGX-325-Po	Bergey Excel-6-Ro
Rated Capacity	25 kW	325 kW	36 kW
Capital Cost	IDR 36,000,000.00	IDR 65,007,647.00	IDR 168,500,000.00
Replacement Cost	IDR 12,728,714.00/kW	IDR 26,504,526.00	IDR 100,902,526.00
Operating & Maintenance	IDR 1,250,000.00/year	IDR 2,050,000.00/year	IDR 5,750,000.00/year
Lifespan	15 years	25 years	20 years

2.3 Component specification

2.3.1 Solar panels

Solar panels harness the photovoltaic effect of semiconductor materials to convert sunlight into electricity directly [33]. The solar panel used in the solar power generation system (PLTS) is the Canadian Solar CS6X-325 P model. More information about this solar cell can be seen in Table 2.

Table 2. Solar panel specifications

Specifications	Value
Optimum Power	325 Wp
Optimum Voltage	40.1 V
Optimum Current	9.23 A
Module Efficiency	19.07%
Derating Factor	80%

To establish the total capacity required for solar panels to provide electricity to EV charging stations (EVCS), it is crucial to first assess the system losses, the overall energy produced by the photovoltaic (PV) modules, and the capacity of the PV modules based on their nominal power of 325 Wp according to the specifications. Information regarding system losses can be found in Table 3.

Table 3. System losses

Types of Loss	Percentage
Solar Panel	11.5%
System Inverters	3%
Battery Conversion	6%
Wiring	2%
Storage	15%
Total Loss at Night	37.5%
Total Loss per Day	22.5%

2.3.2 Wind turbines

Wind turbines can convert the kinetic energy of the wind into electrical energy by harnessing the mechanical work done by the rotor [34]. Bergey Excel 6-R wind turbine was selected with a capacity of 6 kW. The estimated initial capital investment for this project is IDR 168,500,000.00. The exact amount must be spent again if a turbine replacement is necessary. The anticipated annual operating and maintenance expenses are expected to be IDR 5,750,000.00. The expected lifespan of the wind turbine is 20 years. Detailed specifications for the wind turbines in the system are listed in Table 4.

Table 4. Wind turbine specifications

Specifications	Value
Output Power	6 kW
Maximum Voltage (Vmax)	230 V
Furling Wind Speed	4-10m/s
Cut-in Wind Speed	2.5m/s
Number of Blades	3
Rotor Speed (RPM)	0-400M

2.3.3 System inverters

The system inverter can transform the solar panels' direct current (DC) into an alternating current (AC) suitable for everyday household electrical appliances [35]. The output power of the inverter remains constant regardless of the size of the connected load. However, the power output corresponds to the amount of energy the solar panels produce. As described in Table 5, the specifications for the selected inverter are provided for this simulation, as well as a Leonics MTP-413F, which is by the total load demanded by the system, amounting to 20.11 kW.

Table 5. Inverter specifications

Specifications	Value
Output Power	25 kW
Maximum Power	25 kW
Output Frequency	50/60 Hz
Input DC Voltage	100-1500 V
Efficiency	98.2%

2.4 Environmental parameters

NASA geospatial and environmental datasets have been utilized for this Study. These datasets are essential in the planning phase for developing proper and sustainable regional power plants. The highest average monthly temperature for the Rest Area is October, with an average temperature of 26.72℃. The average monthly wind speed analysis is presented in Figure 6, where January has the highest wind speed average of 4.33m/s. Also, Figure 7 summarizes the average solar radiation monthly intensity with the highest value of 5.50 kWh/m² per day achieved in September. This data can be crucial in defining the features of the EVCS at the Rest Area location.

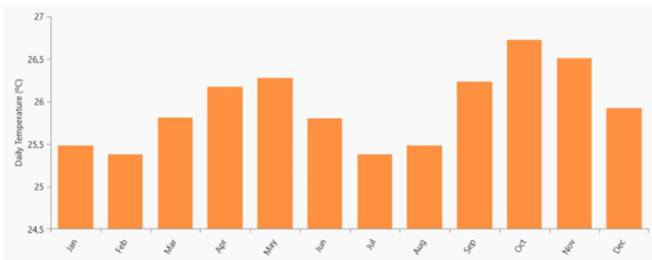

Figure 5. Environmental temperature for each month

Figure 6. Wind speed for each month

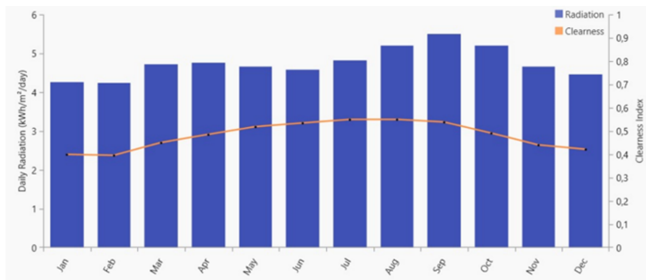

Figure 7. Solar irradiation for each month

This database allows for formulating the best strategies for implementing Public EV Charging Stations (EVCS). These insights raise discussions regarding answering crucial questions such as the best locations and charging power, the most suitable technologies, and energy management approaches. This allows us to identify specific needs and develop an effective EV charging network that fits electric vehicle owners' local context and requirements. Therefore, relying on data in the design of EV charging stations ensures successful implementation and is essential in advancing environmentally friendly transportation in the future.

2.5 Economic analysis

The HOMER simulation results consist of an economic assessment of the cost associated with output power. The output power analysis scope encompasses electricity generated from the PV panels and wind turbines, and the cost assessment covers the Net Present Cost (NPC) and the Cost of Energy (COE) [36]. The output power of the PV module is calculated using Eq. (1) below.

$$P_{PV} = Y_{PV} \times f_{PV} \times \left(\frac{G_T}{G_{T,STC}}\right) \times \left[1 + \alpha_P\left(T_c - T_{c,STC}\right)\right] \quad (1)$$

where, Y_{PV} refers to the nominal capacity of the PV module while f_{PV} is the reduction factor. G_T represents the solar radiation received and $G_{T,STC}$ refers to the radiation under standard test conditions. The notation denotes the power temperature coefficient α_P, with T_c being the temperature in question, while $T_{c,STC}$ is the temperature under standard test conditions [37]. Eq. (2) ensures the wind turbine's output power.

$$P_{WTG} = P_{WTG,STP} \times \left(\frac{\rho}{\rho_0}\right) \quad (2)$$

In this scenario, P_{WTG} signifies the power produced by the wind turbine, whereas $P_{WTG,STP}$ indicates the power generated by the wind turbine under standard conditions. The symbol ρ represents the actual air density while ρ_0 stands for the air density at standard conditions [38]. Economic factors play a crucial role in the HOMER simulation process, as the goal is to find the system configuration with the lowest Net Present Cost (NPC). HOMER calculates NPC using the equation provided in Eq. (3) [39].

$$NPC\ (Rp) = \frac{c_{ann,tot}}{CRF\ .i.\ Rproj} \quad (3)$$

In project cost analysis, several key terms are used: $c_{ann,tot}$ refers to the total annual costs expressed in dollars per year (IDR/year), which includes all operational and maintenance expenditures. *CRF* or Capital Recovery Factor, indicates the factor for recovering capital used to calculate the annual payments necessary to recoup the initial investment. Letter *i* represents the interest rate, which affects the cost of loans and investment returns, while *Rproj* refers to an asset's age or helpful life in years, determining how effectively it can be utilized before it needs replacement. All these elements are essential for accurate economic calculations in investment decision-making. Meanwhile, the Cost of Energy (COE) is the average cost incurred by the system in converting each kilowatt-hour of sound electric energy produced in a unit over several accounting years. COE is calculated as follows [40]:

$$COE = \frac{c_{ann,tot}}{L_{prim,AC} + L_{prim,DC}} \quad (4)$$

Related to the parameters $L_{prim,AC}$ and $L_{prim,DC}$, both define the AC and DC loads of the system, respectively. As shown in Figure 8, this technology is expected to have a substantial degradation curve, with a service life of 25 years.

Figure 8. Projection of HRES

3. RESULTS AND DISCUSSIONS

3.1 HOMER simulation results

The simulation of HOMER is capable of discovering the most effective system design. This involves modeling and developing a specific configuration and employing optimization techniques to identify the optimal arrangement. This configuration is designed to effectively meet the electrical load demands of electric vehicle (EV) charging stations. An advantage of this system is its ability to generate surplus electricity beyond consumption needs, enabling potential revenue from selling excess power. Table 6 compares the total energy produced by each hybrid system described for the station.

Table 6. Total annual energy production

Production	kWh/Year	Percent (%)
Canadian Solar CS6X-325P	17,484	6.3
Bergey Excel-6R	31,972	11.4
On-Grid	230,058	82.3
Total	279,514	100

The highest annual electrical energy production at the EVCS reached 279,514 kWh/year. This total production is categorized into three sources: on-grid use, Bergey Excel-6R wind turbines, and Canadian Solar CS6x-325P panels. The system predominantly relies on conventional energy, with a total of 230,058 kWh/year. Renewable energy still needs to meet the energy requirements fully; thus, traditional electrical energy is required for support. Wind energy contributes 31,972 kWh, while solar energy generates 17,484 kWh. The share of renewable energy use remains relatively low at 17.66%.

The difference in the amount of renewable energy generated demonstrates the extent of the emphasis placed on environmental impact in creating hybrid systems. The energy generated from this system is used to power the system itself and provide electric vehicle (EV) charging services. It is also possible to market the excess energy produced. Information about the system's energy expenditures over an entire year has been collected and presented in Table 7 below.

Table 7. Total use of energy annually

Consumption	kWh/Year	Percent (%)
Primary Load AC	79,620	28.8
Sales Grid	2,392	0.8
EV Charger Served	194,649	70.4
Total	276,661	100

Excess electricity is developed when the generated electricity in an electrical system or network exceeds the consumption or demand of a network cycle. It is not easy to strike a middle ground between electrical overload and underload, especially since the amount of energy stored over extended periods in substances present in electric systems is limited. Thus, some practical approaches to this problem include energy storage, relocation of unused energy to other networks, and intelligent automation systems. Such systems are adaptive and can use surplus energy by directing it to charge batteries or heat the water when the generation is too high.

3.2 Cost analysis

Evaluating parameters like operation costs, maintenance, investments, and profits allows several optimal size variables to be determined. As seen in Figure 8, HOMER can do this by looking at each configuration across multiple charging stations. Because of these factors, it becomes possible for the simulation to discern the most cost-effective and efficient way of operating EVCS.

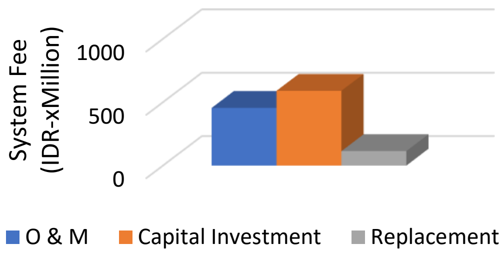

Figure 9. System cost

Figure 9 presents a year-by-year comparison of the return on investment. A high return on capital indicates that the project has strong potential for generating earnings. In addition to environmental factors that fluctuate throughout the year, this profit percentage is crucial for determining the optimal strategic location. The greater the profit from the investment measured by ROI and IRR values, the greater the return; however, the payback ratio indicates the capital's recovery rate.

Figures 9 and 10 highlight the potential for economic growth at the KM Rest Area at the 45 Jakarta-Merak Toll Road. This site offers optimal climatic conditions, with high wind speeds and favorable monthly average solar radiation intensity, which allows for the maximum generation of renewable energy. The amount of power generated influences the overall cost of energy per kWh (COE). Another critical element of the decision–making process is the system design's cost efficiency, expressed mainly in terms of the total system cost discounted to the present value or NPC. In this case, the HOMER program sorts the NPC values numerically from the least to the most, focusing on the most inexpensive design of the system. The importance of the proposed system NPC in assessing the project's economic feasibility is demonstrated in Figure 11.

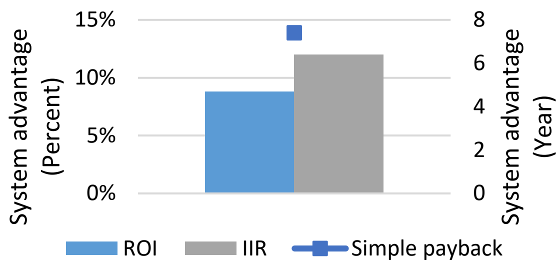

Figure 10. System advantage comparison

Total NPC:	Rp1.099.272.000,00
Levelized COE:	Rp2.048,68
Operating Cost:	Rp39.331.070,00

Figure 11. Total NPC

3.3 Monthly electric production

The accumulated electricity output of solar panels every month represents the total power it produces within a month. This period is relevant for assessing the system's performance throughout the year. The monthly power output is detailed in Figure 12 based on the simulation performed in the HOMER system. The simulations further recommend that the month with the highest or maximum expected output is January, which has around 25 megawatts to generate. This achievement of peak production can be explained by the fact that the month has a maximum wind speed of about 4.33 m/s. Wind speed is of greater significance in this rest area as it is predominantly low plains located on the northern coastal fringe of Java Island, where wind conditions are more conducive to installing wind turbines.

Figure 12. Monthly production

Considering the average monthly electricity production statistics for all systems, the electricity network could be regarded as the only energy source in a position to meet the needs of the Public EVCS. This is so because the demand has to be fully met due to the limitations on renewable energy resources. Several factors, such as its location and wind strength, determine the power generation by wind turbines. On the contrary, solar cells are much more ideal as they are not as sensitive to external variables, and their performance is not too reliant on wind speed, which could be sporadic. Thus, solar panels would be the optimal solution for high-insolation regions where photovoltaic energy is expected to be the most significant development. In the virtual modeling, on the other hand, solar panels produced the lowest output; this was, in fact, due to the materials utilized for the solar panels.

4. CONCLUSIONS

This research evaluates the operational performance and cost-effectiveness of a hybrid microgrid system that integrates wind and solar technologies to supply electrical support facilities for public services in rest areas along the Trans Java Toll Road. The HOMER grid analysis reveals that wind and solar energy can contribute 17.66% of the total energy requirement at Electric Vehicle Charging Stations (EVCS). This indicates a need for further development to enhance the contribution of renewable energy within the system.

The study employs optimization techniques to analyze key metrics such as Net Present Cost (NPC) and Levelized Cost of Energy (LCOE), aiming to increase the penetration of renewable energy sources and reduce reliance on conventional grid power. By incorporating regional weather data, technology performance, and economic conditions, the design of the hybrid system is tailored for improved efficiency. The findings provide valuable insights into the challenges and benefits of implementing hybrid renewable energy systems at toll road rest areas, contributing to the sustainable energy infrastructure industry. This research encourages the adoption of Hybrid Renewable Energy Systems (HRES) in EVCS, promoting greater use of renewable energy along the Trans Java toll road.

ACKNOWLEDGMENT

This study received funding through a PNBP grant from Universitas Sebelas Maret, Indonesia, identified by contract number 194.2/UN27.22/PT.01.03/2024, as part of the Penelitian Hibah Grup Riset (penelitian Hgr-uns) initiative.

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