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Assessing the Technological and Financial Feasibility of PV-Wind Hybrid Systems for EV Charging Stations on Indonesian Toll Roads

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ABSTRACT

This research evaluates the planning and development of a hybrid renewable energy system that combines photovoltaic (PV) panels and wind turbines for electric vehicle (EV) charging stations along the Cipali, Semarang-Solo, and Surabaya-Mojokerto highways. As energy demands rise and sustainability becomes increasingly recognized, incorporating renewable energy sources is vital for diminishing reliance on fossil fuels. By employing HOMER Pro software, the study analyzes this hybrid approach's operational performance and economic practicality, emphasizing key metrics such as Internal Rate of Return (IRR), Return on Investment (ROI), and Payback Period. The findings reveal that the PV-Wind hybrid system reduces energy expenses and improves the efficiency and sustainability of EV charging infrastructure. Notably, the Surabaya - Mojokerto site displays the most favorable outcomes, featuring an IRR surpassing 25% and the shortest payback period of four years. These results underscore the critical role of effective management, strategic planning, and sustainable development of renewable energy systems to bolster environmentally conscious transportation infrastructure in Indonesia.

1. INTRODUCTION

1.1 Background

The transportation sector in Indonesia continues to experience significant growth, which is marked by an increasing number of motorized vehicles on the roads [1]. This growth directly impacts high fossil fuel consumption and greenhouse gas (GHG) emissions, among the primary contributors to climate change [1, 2]. With the urgent need to reduce carbon footprints, adopting electric vehicles (EVs) has emerged as a promising solution to create a more sustainable transportation system [3, 4]. However, the success of this transition heavily depends on the availability of supporting infrastructure and exceptionally environmentally friendly and efficient charging stations. Therefore, comprehensive research is needed to evaluate integrating renewable energy systems, such as photovoltaic (PV) and wind power, to support EV charging needs in strategic locations like toll roads [4, 5].

The Cipali, Semarang-Solo, and Surabaya-Mojokerto toll roads are major transportation arteries connecting strategic regions across Indonesia [6, 7]. The high vehicle volume on these routes presents a significant opportunity to develop renewable energy-based EV charging station infrastructure. In this context, a hybrid photovoltaic-wind system emerges as a highly relevant choice [8-10]. Such systems can harness the abundant solar energy available in tropical regions like Indonesia while leveraging wind as a complementary energy source to enhance system reliability. This approach reduces carbon emissions and contributes to national energy diversification efforts [11, 12].

This study aims to evaluate the potential of hybrid photovoltaic-wind systems for EV charging stations along the Cipali, Semarang-Solo, and Surabaya-Mojokerto toll roads using a techno-economic analysis approach [13, 14]. The analysis encompasses key performance indicators such as Internal Rate of Return (IRR), Return on Investment (ROI), and Payback Period, providing a comprehensive overview of the economic feasibility of this project [15-17]. This software integrates various technical and economic parameters, delivering in-depth insights into the optimal potential of this hybrid system [18, 19].

Beyond economic analysis, this research also seeks to identify technical challenges that may arise during the implementation of the system [20, 21]. Factors such as fluctuations in energy supply from renewable sources, energy storage requirements, and integration with the national grid are central to the discussion [22, 23]. Consequently, this study provides insights into the economic advantages of hybrid systems and examines their technical feasibility for field applications [24]. The findings are expected to serve as a foundation for policymakers, project developers, and academics in designing and implementing renewable energy solutions for transportation [25, 26].

Overall, this research aligns with the United Nations' Sustainable Development Goals (SDGs), particularly in achieving clean energy targets and reducing carbon emissions [27, 28]. By offering a sustainable alternative for EV charging stations, this study contributes to global efforts to create environmentally friendly transportation systems [29, 30]. The article will present significant findings that enrich scientific literature and provide practical solutions to energy and environmental challenges in Indonesia [31, 32].

1.2 State of the art

Integrating renewable energy systems into electric vehicle (EV) charging infrastructure has been extensively explored in various contexts, showcasing diverse methodologies and applications to address energy demands sustainably. For instance, a study by Racmanto et al. [10] focuses on optimizing hybrid PV-Wind systems to supply energy for EV charging stations in four Indonesian cities. The research uses HOMER Pro software to evaluate economic performance through IRR, ROI, and Payback Period metrics, highlighting its applicability to urban settings like Bandung and Surabaya. Similarly, Mastoi et al. [33] address the challenges of EV adoption by employing mathematical models and genetic algorithms to optimize charging station placement, incorporating multistage stochastic programming to adapt to dynamic charging demands, validated through robust numerical simulations.

In another study, Prasetyo et al. [12] evaluated the potential of solar power plants on river land in Surakarta, Indonesia. This research combines literature reviews, data collection, and HOMER Pro simulations to explore both on-grid and off-grid solar configurations, demonstrating innovative approaches to land utilization for renewable energy. Expanding the scope, Prasetyo et al. [20] investigate the feasibility of hybrid PV-Wind energy systems for government buildings in five major Indonesian cities, including Semarang and Jakarta. The research applies HOMER optimization to assess the integration of solar and wind energy, emphasizing the role of such systems in urban sustainability initiatives.

Further extending the exploration of hybrid renewable systems, Khalil et al. [34] emphasize optimizing solar and wind power to minimize dependence on conventional energy sources while reducing greenhouse gas emissions. This study employs HOMER Pro to analyze physical and economic behavior, focusing on operational costs, Net Present Costs (NPC), and emissions. Conducted on the Baluchistan Coast in Pakistan, this research exemplifies how hybrid systems can be tailored to specific geographic and environmental conditions to achieve the most cost-effective and sustainable solutions. These studies collectively underline renewable energy systems' versatility and transformative potential in diverse applications, providing a solid foundation for further research and innovation.

Table 1. Current advances in research

Article	Focus	Methodology	Scope/Sample/Validation
[10]	The primary aim of this study is to assess a hybrid PV-wind renewable energy system designed to meet the demand for EV charging stations across four cities in Indonesia.	This study uses HOMER Pro software to optimize energy resources and design a hybrid photovoltaic-wind system for electric vehicle charging stations. Additionally, it conducts economic analyses focusing on IRR, ROI, and Payback Period.	Bandung, Yogyakarta, Surakarta, and Surabaya are the four cities in Indonesia.
[33]	This research focuses on optimizing and integrating electric vehicle (EV) charging infrastructure into the power system, including charging station placement, charging technology, and challenges faced in EV adoption.	This research methodology includes using mathematical models and genetic algorithms to determine the location of electric vehicle charging stations and applying multistage stochastic programming to optimize charging station placement based on dynamic charging demand.	The article was validated using numerical results to demonstrate the extension of the proposed model.
[12]	This research evaluates the feasibility of establishing a solar power plant on river land in Surakarta, Indonesia, using HOMER Pro software to simulate on-grid and off-grid solar power systems.	This research methodology begins with a literature study, data collection, simulation, and analysis of results, where simulations of river land use for on-grid and off-grid solar power plants are carried out using HOMER software to determine the ideal configuration of solar power plants.	River land in Surakarta, Indonesia.
[20]	This research evaluates the technical and economic feasibility of hybrid photovoltaic (PV) and wind energy systems for government buildings in five urban cities in Indonesia: Semarang, Surabaya, Yogyakarta, Jakarta, and Denpasar.	This research uses a hybrid optimization model for renewable energy (HOMER) to analyze the potential and viability of integrating solar and wind power as a sustainable solution in Indonesia.	Five urban cities in Indonesia: Semarang, Surabaya, Yogyakarta, Jakarta, and Denpasar.
[34]	This research focuses on optimizing and designing hybrid power systems that combine solar and wind energy, aiming to reduce dependence on conventional energy sources and minimize greenhouse gas emissions. This research also analyzes various configurations to determine the most economical solution regarding operational costs, net current costs (NPC), and emissions.	The method used in this research is analyzing and optimizing a hybrid power system using HOMER Pro. HOMER is used to analyze the physical behavior of a power system and its life cycle costs, including installation or capital costs and operational costs over the entire life period of the system.	A hybrid power system that combines solar and wind energy is applied to a project on the Baluchistan Coast, Pakistan.

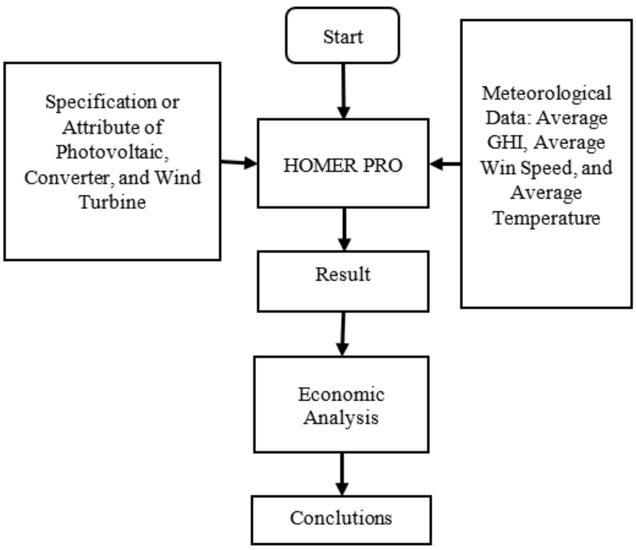
While previous studies extensively explore renewable energy systems for EV charging infrastructure, significant gaps remain unaddressed. The study by Racmanto et al. [10] focuses on optimizing hybrid PV-Wind systems in urban contexts such as Bandung and Surabaya. However, it does not consider the unique challenges and opportunities presented by toll road locations with high and variable energy demands. Similarly, Mastoi et al. [33] introduce advanced optimization techniques for EV charging station placement using genetic algorithms and stochastic programming but do not address the integration of renewable energy systems in these stations. The study by Prasetyo et al. [12], which evaluates solar power plants on river land in Surakarta, highlights innovative land-use strategies but lacks consideration of hybrid energy systems' adaptability to diverse energy needs. Furthermore, Prasetyo et al. [20] and Khalil et al. [34] provide insights into hybrid PV-Wind systems and their economic and environmental benefits in urban and coastal settings, respectively, but do not explore their application to high-demand transport corridors like toll roads. This study builds upon these foundational works by applying a hybrid PV-Wind system analysis to strategic toll roads in Indonesia, offering a comprehensive evaluation of technical feasibility and economic performance through HOMER Pro simulations. By targeting these underexplored aspects, the study provides actionable insights to enhance the sustainability and efficiency of EV charging infrastructure in Indonesia.
The latest articles used as references for writing this article are also summarized in Table 1.

2. METHODS

2.1 HOMER tools for simulating energy software

This study utilized HOMER Pro, a simulation tool, to evaluate photovoltaic-wind hybrid energy systems' performance and economic feasibility. Specific data was tailored for each research location, including the Cipali, Semarang-Solo, and Surabaya-Mojokerto toll roads, such as meteorological data like Global Horizontal Irradiance (GHI), wind patterns and temperature variations to reflect local conditions. Additional parameters included daily energy demand, component characteristics like efficiency and lifespan, and economic inputs such as investment costs, replacement and maintenance expenses, inflation, and discount rates. Technical specifications, such as installed capacity and energy storage needs, were also incorporated to ensure simulation accuracy [35, 36]. Figure 1 shows the appearance of the HOMER Pro software.

(a)



(b)

Parameters	Indicator
Discount rate	6.6%
Inflation Rate	2.54%
Project lifetime	15 years

(c)

Figure 1. (a) Appearance of the HOMER Pro software (b) Flowchart of the research process (c) Economic viability metrics

HOMER Pro analyzed this dataset to assess system performance in energy production, efficiency, and power availability while calculating economic feasibility through parameters such as Internal Rate of Return (IRR), Return on Investment (ROI), and Payback Period. The simulation explored various scenarios to identify optimal, efficient, and financially viable scenarios, including component cost fluctuations, energy demand variations, and weather conditions [20, 37]. With this holistic approach, HOMER Pro provided a comprehensive evaluation of the hybrid system's potential, ensuring it is environmentally sustainable, reliable, and economically sound for EV charging stations at the research locations [38, 39].

2.2 Description of the chosen location

Indonesia's diverse geographical conditions result in varied climatic characteristics across its regions [40]. Most areas experience a humid tropical climate influenced by the nation's equatorial location and distinct topography [41]. For this study, three strategic toll roads, Cipali (Cikampek-Palimanan), Semarang-Solo, and Surabaya-Mojokerto, were selected to evaluate the technical and economic potential of renewable energy-powered Electric Vehicle (EV) charging stations. These toll roads are vital corridors for transportation and commerce, making them suitable locations for renewable energy integration. The following Table 2 outlines the selected toll roads, their corresponding provinces, lengths, and geographic coordinates, which are critical for analyzing renewable energy potential in the regions:

Table 2. Geographical coordination of the selected location

Province	Toll Road	Length (km)	Latitude (ºS)	Longitude (ºE)
West Java	Cipali	116	-6.9147	107.6098
Central Java	Semarang-Solo	75.5	-7.6123	110.2431
East Java	Surabaya-Mojokerto	36.27	-7.5764	112.6321

The selected toll roads Cipali in West Java, Semarang-Solo in Central Java, and Surabaya-Mojokerto in East Java exhibit significant potential for integrating renewable energy systems to support Electric Vehicle (EV) charging infrastructure. The Cipali Toll Road, spanning 116 km, benefits from high solar radiation and flat topography, making it ideal for solar photovoltaic (PV) installations. While the wind speeds in the region are moderate, they can still contribute as a supplementary energy source, enhancing the overall energy system's reliability.

2.3 Meteorological data

2.3.1 Monthly Average Global Horizontal Irradiance (GHI)

Figure 2 highlights the monthly average Global Horizontal Irradiance (GHI) across three Indonesian locations: Cipali, Semarang-Solo, and Surabaya-Mojokerto, expressed in kWh/m²/day. GHI patterns demonstrate relative consistency throughout the year, with observable fluctuations between wet and dry seasons. Cipali's GHI ranges from 3.5 to 5 kWh/m²/day, with peak values of around 5 kWh/m²/day occurring in July and August and the lowest values, approximately 3.5 kWh/m²/day, recorded in January and February. Semarang-Solo, by comparison, shows slightly higher GHI levels, fluctuating between 4 and 5.5 kWh/m²/day. Its peak values, close to 5.5 kWh/m²/day, are observed in August and September, while January records the lowest levels at approximately 4 kWh/m²/day. These patterns indicate that Semarang-Solo offers relatively stable solar energy availability year-round, exceeding Cipali's potential.

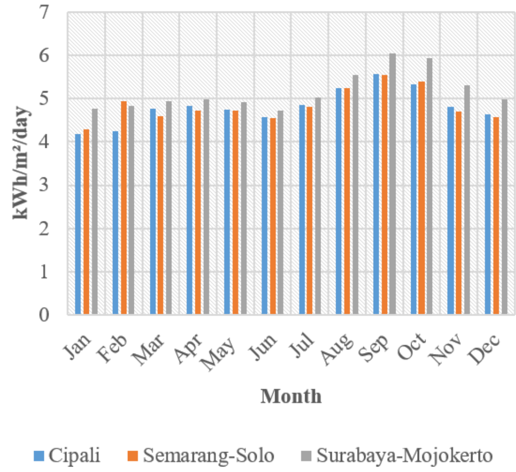


Figure 2. Monthly average GHI

Surabaya-Mojokerto consistently demonstrates the highest GHI values, ranging from 4.5 to 6 kWh/m²/day. The maximum GHI, approximately 6 kWh/m²/day, occurs during August and September, while the minimum, around 4.5 kWh/m²/day, is observed in December. This suggests that Surabaya-Mojokerto offers the most favorable solar energy conditions among the three locations, particularly during the dry season. Overall, while all three regions exhibit significant solar energy potential, the consistently higher GHI values in Surabaya-Mojokerto, especially during peak months, position it as the most advantageous site for solar power development.

To better understand the feasibility of solar power development across these locations, a sensitivity analysis was conducted to evaluate the impact of variations in GHI on solar energy production. Seasonal variations show that a 10% increase in GHI during peak months (July to September) results in additional energy yields of approximately 0.5 kWh/m²/day in Cipali, 0.55 kWh/m²/day in Semarang-Solo, and 0.6 kWh/m²/day in Surabaya-Mojokerto. Conversely, a 10% decrease in GHI during the wet season leads to reductions of 0.35 kWh/m²/day in Cipali, 0.4 kWh/m²/day in Semarang-Solo, and 0.45 kWh/m²/day in Surabaya-Mojokerto. Surabaya-Mojokerto demonstrates the least sensitivity to GHI reductions due to its higher baseline irradiance, maintaining relatively stable energy yields even during adverse conditions. Cipali, on the other hand, is more vulnerable to production losses due to its lower GHI values, highlighting the importance of site selection in solar power development.

2.3.2 Monthly data on average wind speeds

Figure 3 illustrates the Monthly average wind speed across Cipali, Semarang-Solo, and Surabaya-Mojokerto, highlighting regional differences in wind energy potential. Semarang-Solo consistently records the highest wind speeds throughout the year, followed closely by Surabaya-Mojokerto, while Cipali exhibits the lowest values. Wind speeds peak during July and August across all locations, with Semarang-Solo reaching approximately 4.5-4.8 m/s, Surabaya-Mojokerto achieving 4.8-5.1 m/s, and Cipali ranging from 4.0-4.2 m/s. Conversely, November marks the lowest wind speeds, averaging around 2.5-3.0 m/s across the regions. During January and February, moderate wind speeds are observed, with Semarang-Solo at 3.8-4.0 m/s, Cipali at 3.2-3.3 m/s, and Surabaya-Mojokerto at 4.3-4.5 m/s. A gradual decrease occurs from March to May, particularly in Cipali and Semarang-Solo, followed by a resurgence during mid-year. Wind speeds declined in September, reaching their lowest in November, before recovering slightly in December to approximately 3.5 m/s across all regions.

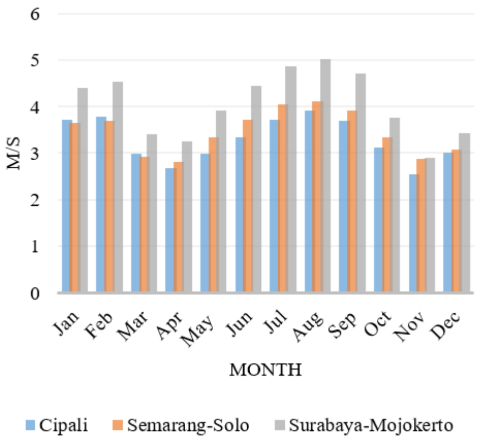


Figure 3. Monthly data on average wind speeds

The data suggest that Surabaya-Mojokerto offers the highest potential for deploying horizontal-axis wind turbines (HAWTs), given its consistently favorable wind speeds, particularly during mid-year peaks. With wind speeds frequently exceeding 4 m/s, Surabaya-Mojokerto's conditions are ideal for HAWTs, which operate most efficiently under such conditions. However, Semarang-Solo presents a feasible option with marginally lower wind energy generation potential. Conversely, Cipali's lower average wind speeds may restrict the viability of HAWTs, except during peak wind months. These findings underscore the importance of selecting optimal sites and timing for wind energy projects to maximize efficiency and energy output.

A sensitivity analysis furthers the critical role of wind speed variations in influencing energy output. A 10% increase in wind speeds during peak months (July and August) produces proportional increases in wind energy generation. Surabaya-Mojokerto achieves an additional 10-12% output due to its higher baseline speeds. Semarang-Solo follows closely with an increase of 9-11%, while Cipali sees a modest 7-9% gain. In contrast, a 10% decrease in wind speeds during the low-wind month of November leads to reductions in energy generation potential by 8-10% in Surabaya-Mojokerto, 7-9% in Semarang-Solo, and 5-7% in Cipali.

2.3.3 Data on average monthly temperatures

Figure 4 depicts the monthly average temperature for Cipali, Semarang-Solo, and Surabaya-Mojokerto, demonstrating a consistent temperature range throughout the year across all three locations. Cipali records the lowest temperatures, ranging from approximately 23°C to 25°C, with its lowest values occurring in January and February. In contrast, Semarang-Solo and Surabaya-Mojokerto exhibit higher temperatures, fluctuating between 25°C and 28°C. The peak temperature for all locations is observed around September and October, with Surabaya-Mojokerto slightly exceeding Semarang-Solo at its highest point. This consistency highlights minimal seasonal temperature variation in the regions.

Numerically, the temperature difference between Cipali and the other two regions averages around 2°C to 3°C throughout the year, indicating Cipali's relatively cooler climate. While Semarang-Solo and Surabaya-Mojokerto share similar patterns, Surabaya-Mojokerto consistently records marginally higher temperatures, peaking close to 28°C in September. These temperature trends suggest that while all three regions are suitable for renewable energy systems, particularly solar energy, Surabaya-Mojokerto may experience slightly reduced solar panel efficiency due to higher operating temperatures, affecting photovoltaic performance. Conversely, Cipali's lower temperatures may enhance efficiency but require evaluation alongside solar irradiance data for a comprehensive energy potential assessment.

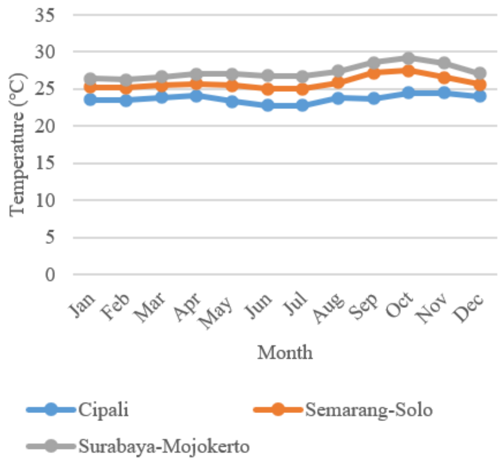


Figure 4. Data on average monthly temperatures

2.4 Data on energy loads

Figure 5 illustrates the daily load analysis for electric vehicle (EV) charging stations, with the horizontal axis representing time over 24 hours and the vertical axis indicating power demand in kilowatts (kW). The load begins to rise significantly at 8:00 AM, surging from approximately 50 kW to a peak of 200 kW. This peak demand remains constant from 9:00 AM to 4:00 PM, marking the hours of highest energy usage, likely corresponding to high EV charging activity during travel and work-related hours. After 4:00 PM, the load gradually decreases, reaching around 150 kW at 5:00 PM and returning to approximately 50 kW by 8:00 PM, where it remains stable during nighttime and early morning hours. This pattern indicates that EV charging demand is concentrated during the day, tapering off significantly in the evening and staying low during non-peak hours.

This load profile provides critical insights for energy system planning. The high demand during peak hours underscores the need for robust system capacity to ensure uninterrupted energy supply, while the lower demand during off-peak hours presents opportunities for optimizing energy storage systems or utilizing excess renewable energy generation. Understanding this demand pattern enables efficient design and management of photovoltaic-wind hybrid systems, ensuring they meet the energy needs of EV charging stations while maintaining operational sustainability and economic feasibility.

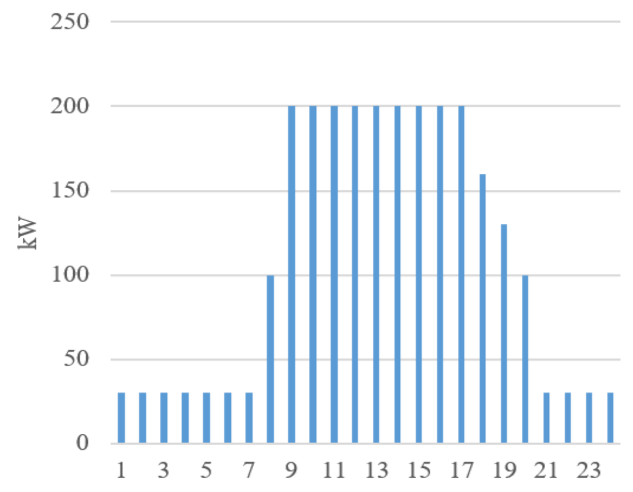


Figure 5. Daily load analysis for EV charging stations

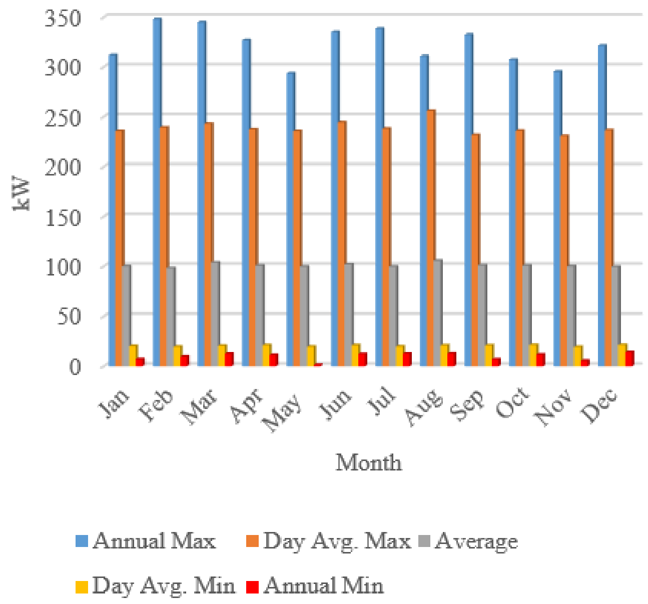


Figure 6. Energy consumption patterns for EV charging stations by season

Figure 6 presents the seasonal energy consumption patterns for EV charging stations, with the horizontal axis representing months and the vertical axis indicating energy demand in kilowatts (kW). The graph distinguishes between various energy demand levels, including Annual Maximum, Daily Average Maximum, Average, Daily Average Minimum, and Annual Minimum, providing a comprehensive view of how energy requirements fluctuate throughout the year.

The Annual Maximum demand remains consistently high across all months, hovering around 350 kW, which signifies the peak capacity required to support EV charging stations at their busiest times. The Daily Average Maximum shows slightly lower values, stabilizing around 250 kW, reflecting the typical upper daily usage threshold. The Average energy demand throughout the year lies near 150 kW, serving as a baseline for typical energy consumption. Meanwhile, the Daily Average Minimum and Annual Minimum values are much lower, fluctuating between 50 kW and 100 kW, representing periods of minimal usage, likely during non-peak hours or days with reduced EV traffic.

This pattern reveals that while the demand for EV charging exhibits relatively stable trends throughout the year, the infrastructure must be designed to accommodate the highest energy consumption levels. The consistent Annual Maximum values suggest that peak demand does not vary significantly between seasons, emphasizing the need for reliable system capacity to handle year-round operational requirements. Simultaneously, the significant differences between the maximum and minimum values highlight opportunities for energy optimization, such as storing excess energy during low-demand periods or integrating renewable energy systems to address peak loads efficiently. These insights are vital for designing hybrid energy systems that ensure sustainability, cost-effectiveness, and reliability in EV charging station operations.

Table 3 outlines key parameters related to EV charging station operations on the toll road, including daily EV charging capacity, charger output, maximum load demand, mean load demand, and average daily energy consumption. These data points offer valuable insights into the EV charging infrastructure's energy requirements and operational characteristics.

Table 3. Details of the load requirements for the charging station

Region	Toll Road
Daily EV Charging Capacity	30 kW
EV Charger Output	250 kW
Maximum Load Demand	348.08 kW
Mean Load Demand	101.01 kW
Average Daily Energy Consumption	2424.25 kWh/day

The daily EV charging capacity of 30 kW reflects the energy demand per individual EV. In comparison, the EV charger output of 250 kW indicates the charging station's capability to deliver high-power charging, enabling faster recharging for multiple vehicles simultaneously. The maximum load demand of 348.08 kW represents the peak energy required to support the charging needs during the busiest hours, underscoring the need for a robust energy supply system. The mean load demand, calculated at 101.01 kW, provides a baseline measure of typical energy usage throughout the day, highlighting periods of moderate activity.

The average daily energy consumption of 2424.25 kWh/day underscores the substantial energy requirements for operating the charging station. This value suggests that the charging station handles significant traffic, requiring a hybrid energy system capable of consistently meeting daily demands. The gap between the maximum and the mean load demand highlights the variability in usage patterns, suggesting opportunities to optimize energy resources by integrating renewable energy and energy storage systems. This optimization could reduce reliance on grid power during peak times, enhance system efficiency, and lower operational costs, ensuring the EV charging infrastructure's long-term sustainability and economic viability.

The block diagram in Figure 7 illustrates integrating a hybrid photovoltaic (PV) and wind turbine energy system with a grid connection to power an electric vehicle (EV) charging station. This innovative system combines three primary energy sources: solar energy harnessed through PV panels, wind energy captured via wind turbines, and supplementary electricity from the grid. The hybrid configuration ensures a reliable and consistent energy supply by optimizing renewable energy utilization while compensating for fluctuations in solar radiation or wind availability [42].

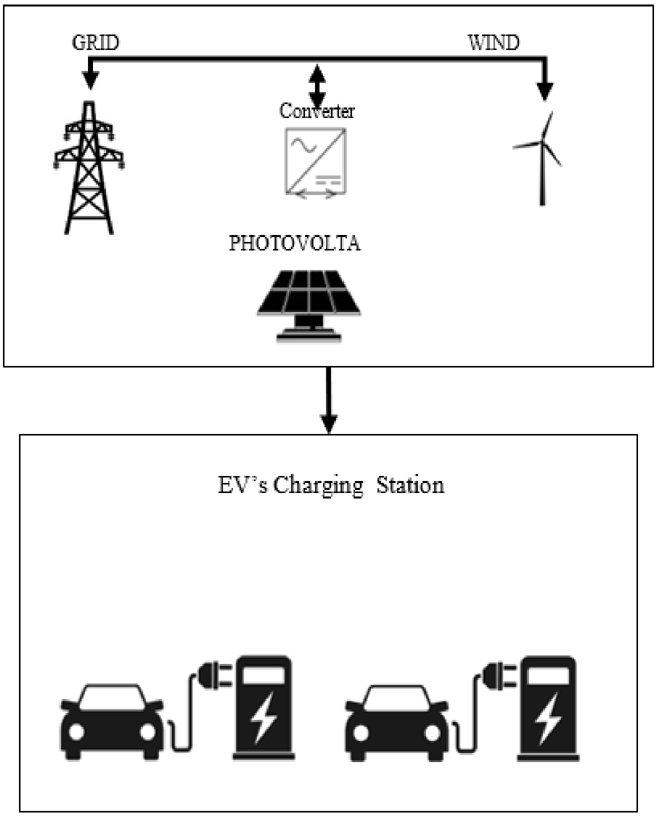


Figure 7. Block diagram of PV-wind hybrid on the grid for EV charging station

In this setup, the PV-Wind Turbines are the primary renewable energy sources, converting sunlight and wind into electrical energy. However, the power generated by these systems may not always match the voltage, frequency, or form required by the EV charging station. To address this, the converter plays a critical role. It processes the electricity from PV (DC) and wind turbines (which may vary in voltage) into a standardized form, typically alternating current (AC), that is compatible with the EV charging station [43]. The converter also ensures efficient energy management by combining inputs from all sources (PV, wind, and the grid) seamlessly [44].

The grid acts as a backup, providing additional power during periods of low renewable energy generation or increased energy demand, ensuring uninterrupted operation. By integrating multiple energy sources with advanced conversion technology, this system enhances energy reliability, reduces dependency on fossil fuels, and aligns with global sustainability goals. It offers a forward-thinking solution for green mobility infrastructure, efficiently supporting the energy demands of electric vehicles.

3. ANALYSIS OF DATA

3.1 Economic formulas for analysis

Table 4 serves as a comprehensive overview of renewable energy systems' financial and performance indicators, explicitly focusing on solar photovoltaic (PV) technology. It includes crucial metrics such as Net Present Cost (NPC), Capital Recovery Factor (CRF), nominal interest rate, payback period, Levelized Cost of Energy (LCOE), and an Energy Performance Analysis for Solar PV [10, 27, 39]. These metrics are instrumental in evaluating long-term financial obligations, determining annual costs, calculating the present value of expected returns, assessing the initial investment return, and analyzing the economic feasibility of solar PV systems. The table's significance lies in its ability to guide evaluation and investment decisions in solar renewable energy systems.

3.2 Analysis of energy performance for the system

Tables 5 and 6 present an extensive overview of a renewable energy system integrating Solar PV and Wind Turbine technologies. It details how solar PV systems operate, highlighting their minimal maintenance needs and ease of installation, as well as a formula for calculating power output [45]. The section on wind turbines explains the conversion of wind's kinetic energy into mechanical energy, noting that higher positions produce more incredible energy [46]. A segment describes the function of converters in transforming the AC output from wind turbines into stable DC power for a smooth energy transition. The solar panel specifications cover output, efficiency, operational temperature range, durability, initial and reinstallation costs, and yearly maintenance expenses [47]. However, specific details about wind component specifications are absent. The accompanying table offers a thorough summary of the components and specifications of the renewable energy system [48].

Table 6 illustrates the system's primary components designed for tropical environmental conditions, such as in Indonesia. Solar panels with an output of 350 Wp and an efficiency of 18.1% need to be equipped with protective coatings to cope with the high humidity and potential corrosion due to salt air in coastal areas. Wind turbines, with a capacity of 250 kW and a lifespan of more than 20 years, should use corrosion-resistant materials and undergo regular inspections to overcome the challenges of humid tropical weather. The 25 kW converter with 96% efficiency should also be designed with moisture protection and a sound ventilation system to ensure durability and optimal performance in Indonesia's tropical climate. All of these components must be adapted to the characteristics of the Indonesian climate to ensure an efficient and long-lasting system.

Table 4. Economic formulas for analysis

Subchapter	Description
Net Present Cost (NPC)	NPC assesses the total costs of a renewable energy system over its entire lifecycle, considering investment, operational, and maintenance expenses. This provides insight into the long-term financial commitment. **Formula:** The NPC (USD) $= \sum_{t=0}^{N} \frac{C_t}{(1+r)^t}$ where, C_t: Total cost in year t, r: Interest rate (%), N: Project Age (years),

Capital Recovery Factor (CRF)	The Capital Recovery Factor (CRF) is important for financial analysis because it helps determine the annual cost associated with an initial investment and a discount rate. This calculation helps evaluate the yearly financial obligation of systems that require significant upfront costs. **Formula:** $\text{CRF(USD)} = \frac{r(1+r)^N}{[(1+r)^N - 1]}$ where, r: Interest rate (%), N: Project lifespan (years),
Nominal Interest (Discount) Rate	The nominal interest rate assesses the present value of future financial returns without considering inflation, which is crucial for long-term capital evaluation. **Formula:** $\text{NIR(USD)} = \frac{1+r_{real}}{1+f} - 1$ where, $r_{nominal}$: Nominal interest rate (%) r_real: Actual interest rate (%) f: Inflation rate
Payback Period	The payback period is an important metric in analysis, as it measures how quickly the initial investment in a renewable energy system is recouped through savings or income generated. This provides a clear and essential profitability assessment. **Formula:** Payback Period $= \frac{Initial\ Investment}{Annual\ Savings}$ where, *Initial Investment* = The total capital costs incurred (USD), *Annual Savings* = Yearly savings or revenue generated (USD),
Levelized Cost of Energy (LCOE)	LCOE indicates the average cost of producing one unit of energy throughout the system's lifetime, serving as a vital measure for assessing the economic feasibility of energy projects. **Formula:** $\text{LCOE} = \frac{\text{NPC}}{\text{E}_{\text{total}}}$ where, NPC = Total system cost (USD), $Etotal$ = Total energy produced (kWh).

Table 5. Analysis of energy performance for the system

Subchapter	Description
Solar PV	Photovoltaic (PV) systems convert sunlight into electricity using semiconductors, offering low maintenance costs and quick installation. Recent advancements in solar technology have enhanced both efficiency and cost-effectiveness. **Formula for Power Output:** $\text{P}_{\text{PV}} = \text{Y}_{\text{PV}} \times f_{PV} \times \left(\frac{\text{NPC}}{\text{G}_{\text{T,STC}}}\right) \times [1 + \propto_p (T_c - T_{c,STC})]$ where, PPV = Output power from PV (Watt), YPV = Installed capacity of PV (Watt), fPV = PV system derating factor, GT= Solar irradiation received at a particular time (W/m²), GT,STC = Solar irradiation under standard conditions (1000 W/m^2), αP= PV power temperature coefficient (%/°C), Tc = Current PV cell temperature (°C), Tc,STC = Cell temperature at standard conditions (25°C).
Wind Turbine	Wind turbines convert kinetic energy into mechanical energy, which is then transformed into electricity. Turbines installed at higher altitudes generally provide more stable energy output. **Formula for Power Output:** $\text{P}_{\text{WTG}} = \text{P}_{\text{WTG,STP}} \times \left(\frac{\rho}{\rho_0}\right)$ where, $PWTG$ = Output power from PV (Watt), $PWTG,STP$ = Installed capacity of PV (Watt), ρ_0= PV system derating factor, ρ= Solar irradiation received at a particular time (W/m²).
Converter	From wind turbines into stable DC power for usage by the load, ensuring a smooth transition of energy flow. It stabilizes and converts the power through rectification.

Table 6. Components system

System Components' Specifications	Description
Solar Panel (Peimar LONGi Solar LR6-72)	The solar panel has a 350 Wp output, 18.1% efficiency, and operates in temperatures up to 47°C. The system's durability is 25 years, with initial and reinstallation costs of USD 2,000 and annual maintenance costs of USD 15/kW.
Wind Turbine (Lagerwey LW30/250)	The wind turbine produces 250 kW with a rotor diameter of 12 meters and a hub height of 30 meters. It has a lifespan of over 20 years and incurs annual operational costs of USD 2,000. The initial and replacement costs are USD 225,000.
Converter (Leonics MTP-413F 25kW)	The converter is rated at 25 kW with 96% efficiency and a 15-year lifespan. It costs USD 600, with similar costs for replacement. The system adapts the AC power from the wind turbine to stable DC power for the load.

4. RESULT

This study evaluates the technical and economic aspects of on-grid electric vehicle (EV) charging stations in various regional conditions. It emphasizes the significance of utilizing solar energy through photovoltaic panels and wind power to meet the energy needs of these stations. The geographical and climatic differences across locations significantly impact the system's performance. The research seeks to identify the best ways to integrate renewable energy sources to improve the efficiency and sustainability of electric vehicle charging stations in strategically important areas within each province.

4.1 Performance evaluation of the proposed system

This research evaluates three potential energy generation systems for each location: grid-connected photovoltaic (PV), grid-connected wind power, and hybrid PV-wind systems. Figure 8 compares the initial capital investment (ICP) and operation and maintenance (O&M) costs associated with these systems, including the hybrid PV-wind system, wind system connected to the grid (Wind on Grid), and solar power system connected to the grid (PV on Grid). Among these, the Hybrid PV-Wind system incurs the highest initial capital cost, around 250,000 USD, but its O&M expenses remain relatively low compared to its upfront investment. In contrast, the wind and PV systems on the grid show a more balanced relationship between their initial capital costs and O&M expenditures. The PV system on the grid, which has the lowest initial capital cost of less than 50,000 USD, also faces the highest O&M costs among the three systems. This comparison underscores each renewable energy system's unique cost structures and maintenance needs.

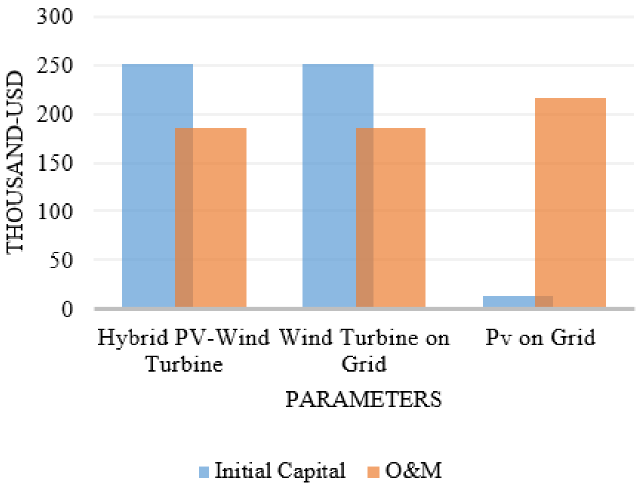


Figure 8. Cost relationship in each proposed system

A comparison with existing EV charging infrastructures in Indonesia or similar tropical regions could provide deeper insights into the advantages or limitations of the proposed system, particularly in terms of energy efficiency, cost, and sustainability.

Figure 9 shows a bar chart comparing the share of energy produced from renewable sources, photovoltaic (PV), and wind turbine sources across three locations: Cipali, Semarang-Solo, and Surabaya-Mojokerto. The data indicates substantial differences in the contributions of these two energy sources across the sites.

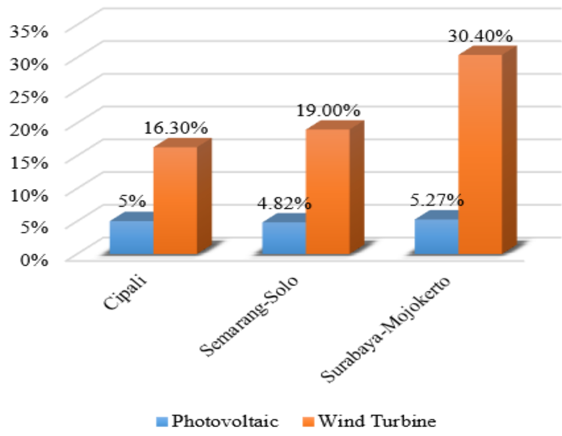


Figure 9. Evaluating the proportion of renewable energy generated at different toll road

Wind power in Cipali contributes significantly, accounting for 16.30% of the total energy generated, while solar energy plays a more minor role at just 5%. Similarly, wind energy remains dominant in Semarang-Solo, providing 19%, compared to 4.82% from solar panels. Surabaya-Mojokerto exhibits the highest wind energy contribution, reaching 30.40%, while solar energy remains modest at 5.27%. These results demonstrate a consistent trend across all locations where wind energy outperforms solar energy in terms of its share of renewable energy generation.

4.2 Energy generation across three different toll roads

Electricity output from three distinct generation systems—grid-connected photovoltaic (PV) systems, grid-connected wind turbines, and hybrid PV-wind systems—exhibits variability across the examined locations. Figure 10 highlights the differences in total annual energy production necessary to satisfy the demands of electric vehicle charging stations in these areas. The Surabaya-Mojokerto region achieves the highest energy output, generating an impressive 938 MW annually, predominantly through the hybrid photovoltaic wind system. In contrast, Cipali records the lowest energy production, approximately 887 MW per year. While the energy contributions from the grid-connected photovoltaic and wind turbine systems show comparable trends across the different locations, the wind turbine system consistently produces slightly more energy in most instances.

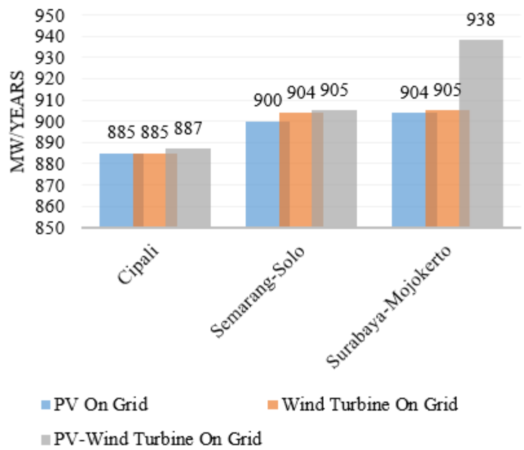


Figure 10. Annual energy output for each site

Figure 11 depicts the energy each system needs to source from the grid. Among all the systems analyzed, the Hybrid PV-Wind on-grid system efficiently minimizes grid energy consumption across various locations. Specifically, in Surabaya-Mojokerto, grid purchases are reduced to just 620 kWh. In contrast, the Cipali location shows the most significant reliance on grid electricity, with energy acquisitions totaling approximately 840 kWh for the photovoltaic on-grid system. The on-grid wind turbine systems and on-grid photovoltaic systems demonstrate comparable levels of energy procurement from the grid; however, their effectiveness in decreasing dependence on grid electricity is not as pronounced as that of the hybrid system.

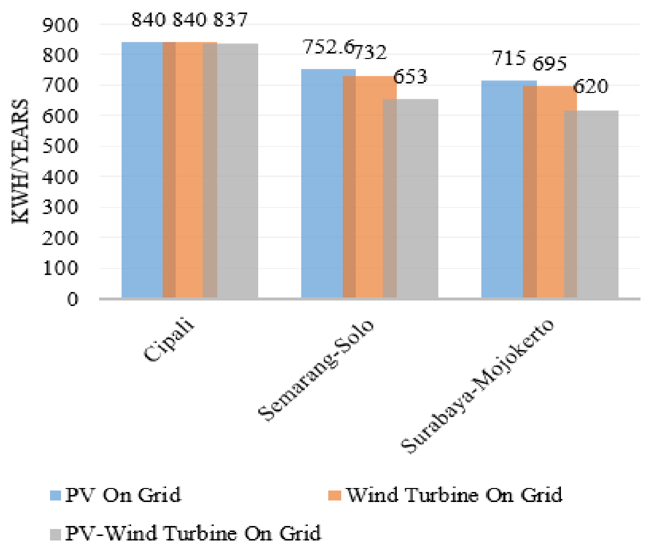


Figure 11. Electricity grid purchases over the year

4.3 Comparison of economics in three toll roads

An economic evaluation of the proposed renewable energy systems across three locations, Cipali, Semarang-Solo, and Surabaya-Mojokerto, was conducted using key feasibility parameters: Internal Rate of Return (IRR), Return on Investment (ROI), Investment Value, and Payback Period. Based on the results shown in Figure 12, Surabaya-Mojokerto demonstrates the highest economic feasibility, with an IRR exceeding 25% and an ROI of approximately 30%, indicating a strong potential for profitable investment. This location also has the shortest payback period, requiring only 4 years to recover the initial investment. Semarang-Solo shows moderate feasibility with an IRR of around 15%, an ROI of 20%, and a payback period of approximately 6 years. Cipali, however, has the lowest IRR (about 10%) and ROI (15%) and the most extended payback period of nearly 8 years, making it the least attractive location economically.

The evaluation of the economic viability of proposed renewable energy systems at three locations—Cipali, Semarang-Solo, and Surabaya-Mojokerto—was conducted by analyzing key feasibility metrics: Internal Rate of Return (IRR), Return on Investment (ROI), Investment Value, and Payback Period. Figure 12 demonstrates that Surabaya-Mojokerto shows the highest economic viability, with an IRR exceeding 25% and ROI approaching 30%, indicating significant investment potential. This location has a notably short payback period, requiring only 4 years to recover the initial investment.

In contrast, the economic outlook for the Semarang-Solo region is moderate, featuring an IRR of approximately 15%, an ROI of 20%, and a payback period estimated at around six years. Cipali presents the lowest internal rate of return at approximately 10%, an ROI of 15%, and the most extended payback period of nearly 8 years, making it the least financially attractive location.

Figure 12 also compares the Net Present Cost (NPC) associated with three renewable energy systems: grid-connected photovoltaic (PV) systems, wind turbines, and hybrid PV-wind configurations. Across various locations, the grid-connected photovoltaic system consistently incurs the highest investment costs, ranging from 2.1 million USD in Surabaya-Mojokerto to over 2.5 million USD in Cipali. The investment costs for on-grid wind turbines and hybrid PV-wind systems vary by location but typically range from 1.9 million USD to 2.2 million USD. The Surabaya-Mojokerto route exhibits the most significant cost efficiency across all systems, while the Cipali route requires the highest investment for each configuration.

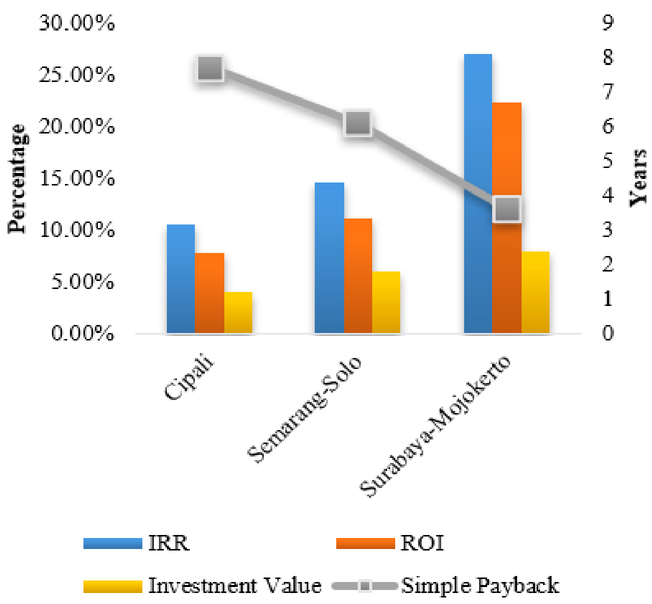


Figure 12. The economic viability of the system at each site

Figure 13 compares the NPC associated with three renewable energy systems—PV On-Grid (solar energy integrated with the grid), Wind Turbine On-Grid (wind energy integrated with the grid), and PV-Wind Turbine On-Grid (a hybrid system combining solar and wind power)—across the three locations: Cipali, Semarang-Solo, and Surabaya-Mojokerto.

In Cipali, the NPC values for all systems are similar, approximately 2.5 million USD, with the PV On-Grid system presenting the highest value, followed closely by the hybrid system. In the Semarang-Solo region, NPC values are generally higher than in the other locations, approaching 3 million USD. The PV On-Grid system remains the most expensive, followed by the Wind Turbine On-Grid system, while the hybrid system shows better cost efficiency. In Surabaya-Mojokerto, the NPC values are the lowest compared to the other two locations, with the hybrid system being the least costly, highlighting its economic efficiency in this context.

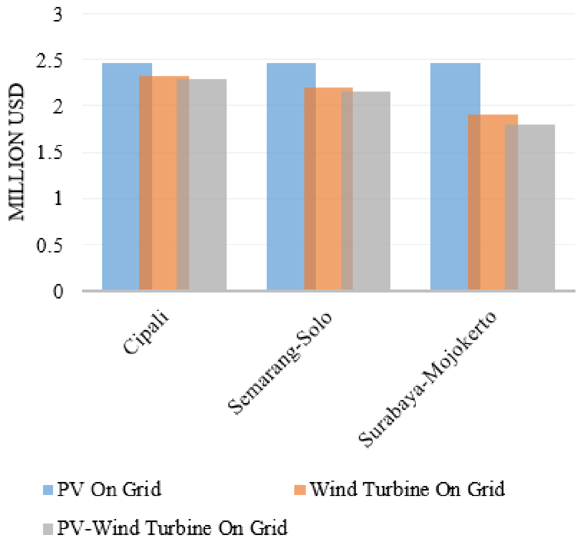


Figure 13. Contrast of NPC values for each system

Figure 14 illustrates the Levelized Cost of Energy (LCOE) for the same systems and locations. In Cipali, the PV On-Grid has the highest LCOE (0.25 USD/kWh), followed by the Wind Turbine On-Grid (0.23 USD/kWh), while the hybrid system achieves the lowest LCOE (0.20 USD/kWh). A similar trend is observed in Semarang-Solo, where PV On Grid remains the most expensive (0.25 USD/kWh), and the hybrid system is the most cost-effective (0.19 USD/kWh). In Surabaya-Mojokerto, the overall LCOE values are lower than in the other locations, with the hybrid system recording the lowest value (0.15 USD/kWh). This indicates that Surabaya-Mojokerto is the most suitable location for implementing a hybrid energy system.

In summary, Figures 13 and 14 demonstrate that the PV-Wind Turbine On Grid hybrid system offers superior economic efficiency across all locations, particularly in Surabaya-Mojokerto. This system achieves the lowest NPC and LCOE, making it the most cost-effective option for energy generation. The findings emphasize the advantage of integrating solar and wind energy resources, especially in areas with diverse renewable energy potential. Surabaya-Mojokerto emerges as the most economically viable location for deploying such systems.

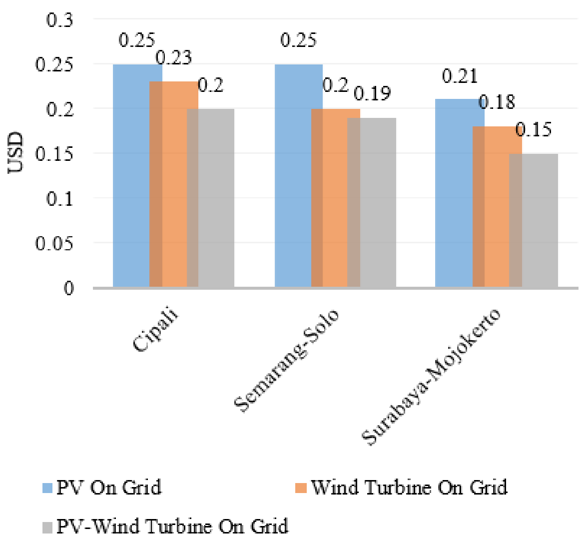


Figure 14. The LCOE for each study site

5. CONCLUSIONS

This research underscores the significant potential of renewable energy solutions, particularly the integration of solar panels and wind turbines (Hybrid PV-Wind on-grid), to meet the energy needs of electric vehicle (EV) charging stations located along major toll roads in Indonesia: Cipali, Semarang-Solo, and Surabaya-Mojokerto. The findings reveal that the hybrid PV-Wind system consistently achieves the lowest Levelized Cost of Energy (LCOE) across all examined locations, positioning it as the most economically advantageous option. Notably, the Surabaya-Mojokerto project stands out for its performance, attaining the lowest levelized cost of electricity at $0.15 per kWh while also exhibiting remarkable energy production efficiency. With a discount rate of 6.6% and an inflation rate of 2.54%, the financial viability of these systems remains robust over the project's lifetime of 15 years.

While the hybrid system necessitates a more significant initial investment, its operational and maintenance costs are significantly lower when compared to standalone systems, such as photovoltaic or wind on-grid configurations. Economic feasibility evaluations highlight the advantages of the Hybrid PV-Wind system. Surabaya-Mojokerto boasts the highest Internal Rate of Return (IRR) and Return on Investment (ROI), with a payback period of just four years, establishing it as the most financially advantageous location. Conversely, Cipali demonstrates the lowest IRR and ROI, indicating less favorable economic conditions.

The hybrid system contributes between 20% and 40% of the total energy demand at each site, necessitating additional power procurement from the grid to address any shortfall. This highlights the importance of ongoing optimization efforts, including enhancements in energy conversion efficiency, adopting advanced storage technologies, and implementing more effective management strategies to decrease dependence on conventional grid electricity. Additionally, exploring potential grid upgrades or alternatives, such as expanded battery storage capacity or microgrid integration, could reduce reliance on conventional grid power and improve overall energy resilience.

The study emphasizes the critical role of hybrid renewable energy systems in advancing sustainable and efficient EV charging infrastructure. These results strongly advocate for the accelerated deployment of renewable energy technologies in the transportation sector to significantly reduce greenhouse gas emissions and enhance energy security. Policy interventions such as government-supported incentives, tax relief programs, and regulatory frameworks encouraging renewable energy adoption are essential to facilitate this transition. Additionally, collaborations between the private sector and local communities can drive innovative business models and pilot projects, promoting the widespread adoption of renewable energy within Indonesia's transportation system and fostering long-term energy independence.

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