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EVALUATING THE FEASIBILITY OF ROOFTOP PV SYSTEMS FOR HOME EV CHARGING IN INDONESIA: TECHNICAL, ECONOMIC, AND EMISSION PERSPECTIVES

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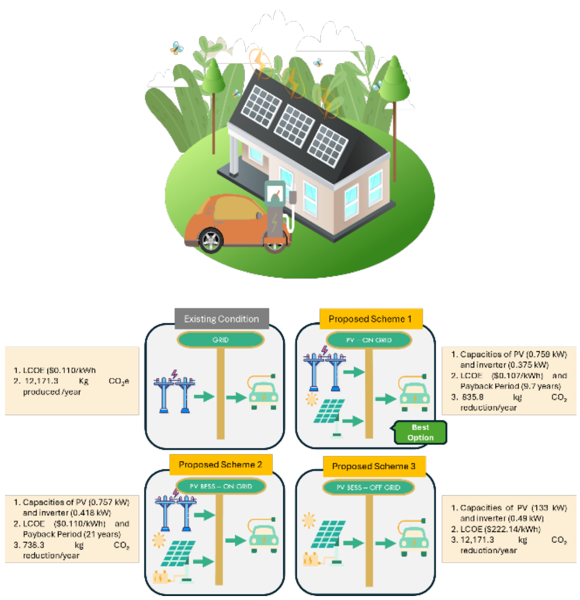
Graphical abstract



Abstract

Energy and transportation sectors contribute significantly to high greenhouse gas (GHG) emissions, triggering urgency to accelerate electric vehicles (EVs) adoption and their supporting infrastructure in order to achieve national decarbonization targets. Study aims to evaluate the feasibility of rooftop photovoltaic (PV) systems for electric vehicles (EVs) home charging from technical, economic, and emissions aspects. Three configurations (PV On-Grid, PV On-Grid with Battery Energy Storage System (BESS), and PV Off-Grid) were compared with the existing condition (Grid) and analyzed using HOMER Pro software. This configuration results in an energy cost of $0.107/kWh, Internal Rate of Return (IRR) of 8.6%, and payback period of 9.7 years. This system reduce CO2 equivalent (GHG mass equivalent to CO2; hereinafter referred as CO2) emission by approximately 835.8 kg per year per household. Sensitivity analysis indicates that when the costs of PV components, inverters, and BESS decrease by 12% and 8% per year, energy costs could decrease to $0.086/kWh by 2044, with payback period of only 2.4 years. The study provides recommendations to PT PLN Persero and relevant stakeholders to develop joint investment schemes, partnerships with electric vehicle manufacturers, and Time-of-Use (ToU) tariffs to promote the adoption of sustainable energy and decarbonization of the transportation sector.

Keywords: Electric Vehicles, Home Charging, Decarbonization, Rooftop Photovoltaic, Renewable Energy

1.0 INTRODUCTION

Indonesia's total greenhouse gas (GHG) emissions, especially carbon dioxide (CO_2), increased significantly in 2021 [1]. The increase is two times greater than in 2020, reaching nearly 600 million tons ($MTCO_2$). The power sector is the most significant contributor, with 40% of total CO_2 emissions caused by coal-fired power plants. The industrial sector contributes around 25% of total emissions, while road transportation contributes 90% of CO_2 emissions from the transportation sector [1]. Indonesian government responded by setting decarbonization targets, including increasing the share of renewable energy to 23% by 2025 and 30% by 2050 in the electricity sector. It is also accelerating the adoption of electric vehicles (EV), with a target of 2 million electric cars and 13 million electric motorcycles by 2030 as part of the National Energy Grand Strategy [1]. Jakarta's role as Indonesia's economic and transportation center is critical to achieving these targets, especially in reducing transportation-related emissions and integrating sustainable energy solutions to support the zero emissions target by 2050. Jakarta contributes about 16% to Indonesia's GDP, so it has an important role in economic policies that can support decarbonization efforts [2].

Electric vehicles are considered a key decarbonization technology in the transportation sector for reducing fossil fuel dependence and minimizing emissions. The development of EV in Indonesia has shown significant progress, supported by various government incentives to accelerate electrification [3]. Policies such as subsidies for electric vehicle purchases, tax exemptions, and incentives for battery charging infrastructure development have contributed to the increasing adoption of electric vehicles [4]. Indonesia recorded 7,679 electric cars in 2022, a fourfold increase from 2021 [5]. However, one of the key challenges in sustaining this growth and EV adoption is the availability and accessibility of charging facilities [5]. This is because inadequate infrastructure can create range anxiety and limit user convenience.

Developing a comprehensive EV charging network, especially at-home charging, is crucial to ensure the transition from conventional vehicles to electric mobility [6]. The increased use of EV directly correlates with an increased demand for electricity to power EV charging infrastructure [7]. However, this transition raises concerns when electricity used for charging is still sourced from non-renewable energy. This is supported by 2023 data showing that 86.9% of electricity generation in Indonesia still relies on fossil fuels [8]. While adopting electric vehicles contributes to reducing CO_2 emissions in the transportation sector, it simultaneously increases fossil fuel consumption in the electricity sector for vehicle charging. Therefore, it is imperative to shift to renewable energy sources for electric vehicle charging to maximize the environmental benefits of electric vehicle use [9], [10], ensuring a cleaner and more sustainable energy ecosystem. A promising solution in this context is integrating rooftop photovoltaic (PV) systems with home charging stations [6].

Perusahaan Listrik Negara (PLN/Indonesia state-owned electric utility company) is one company that contributes to the energy transition to achieve net-zero emission (NZE). PLN has various programs or business models to develop the electric vehicle ecosystem, including home charging services (HCS). HCS products are integrated service products for customers who buy electric cars from manufacturers that work with PLN [11]. Through this service, customers get electric vehicles and electric vehicle charging equipment at home (home charger), increasing or installing electric power and integrating home charger equipment into the PLN system [12]. This integration aims to ensure that the electricity used for charging electric vehicles can be recognized and separated from other electricity uses. The total number of home chargers for electric vehicle owners integrated with the PLN system until January 2024 is 4,988 units, with a total electricity usage of 3.88 GWh.

Indonesia has a significant potential for renewable energy resources of more than 3,600 GW, where the potential of solar power reaches more than 3,200 GW. However, its current utilization is only about 200 MW. One utilization of solar potential is rooftop solar power plants, which offer large-scale solar energy options in the early phase of the transition to renewable energy [13]. According to the national strategic project roadmap, implemented rooftop solar PV capacity is targeted to reach 3,610 MW by 2025 [8]. Rooftop PV systems can reduce dependence on grid electricity, lower electricity costs [14], and support decarbonization efforts [15]. In regions with high electricity prices, rooftop PV systems often achieve a lower levelized cost of electricity (LCOE) compared to grid electricity [16]. Moreover, it helps reduce greenhouse gas emissions, as shown by a commercial PV system that saves about 506,898 metric tons of CO_2 over 25 years [17]. In the context of EV home charging, utilizing solar energy from rooftop PV systems can significantly reduce CO_2 emissions from electricity consumption while supporting the development of a clean and resilient energy system.

Towards supporting the energy transition in Indonesia, this research was conducted to evaluate the technical, economic, and emission feasibility of utilizing rooftop PV systems as a source of electricity for home EV charging in Jakarta, Indonesia. The potential for rooftop PV integration was evaluated by modelling and simulation using HOMER Pro software to reduce electricity costs and carbon emissions. While previous global studies have explored PV–EV integration, most rely on generic load profiles and assume stable grid conditions. This study offers distinct contributions by integrating real-world EV charging behaviour using Connected Smart Metering System (CSMS) data from residential users in Jakarta, which reflects actual customer behaviour and grid interaction. Additionally, this analysis is contextualized within Indonesia's evolving regulatory landscape, particularly following the issuance of the Ministry of Energy and Mineral Resources Regulation No. 2/2024, which eliminates net-metering schemes. Compared to similar studies in ASEAN countries such as Thailand, Malaysia, and the Philippines, this research combines empirical data, policy-based assumptions, and long-term cost sensitivity (to 2044), providing a regionally relevant and timely contribution toward accelerating clean energy transition through rooftop PV and EV integration.

2.0 LITERATURE REVIEW

The implementation of photovoltaic (PV) systems in the residential sector has been widely studied, especially in its integration with electric vehicle (EV) charging. Previous research has explored various aspects, including optimizing charging schedules based on PV energy production predictions, utilizing battery energy storage systems (BESS) for energy management, and assessing the impact on power distribution networks. In terms of economic perspective, studies have shown that integrating PV with BESS and electric vehicle charging can save electricity costs. Although the initial investment cost of PV and BESS remains a major consideration, studies have shown the potential for CO_2 emission reduction. However, further research is needed to evaluate the economic feasibility, considering electricity price dynamics, incentive policies, and advances in energy storage technologies.

2.1 Relevant Studies Regarding the Application of Rooftop Solar PV for Electric Car Home Charging

Research related to utilizing rooftop solar power plants to meet energy needs for electric car charging has been performed by several researchers.

Hong Xian Li et al. [18] studied battery usage in rooftop PV systems using Smart Meter data in 2019. The researchers present an intelligent algorithm for calculating the amount of energy imported from the grid, energy from PV exported to the grid, and energy stored in batteries with various sizes. The results show that at the current electricity tariff price of \$0.30/kWh and export tariff price of \$0.10/kWh in the study area, a battery cost of \$0.20/kWh or more is not considered economically viable. However, as electricity tariffs increase and battery prices change, the economic viability impact may change under current tariff conditions. In addition, this study did not analyze CO_2 emission reduction by utilizing PV for EV energy supply.

In other research, Ramadhani et al. in 2021 [19] studied the probabilistic impact of EV charging on loads and low-voltage distribution networks. This research models the mobility of EVs in a distributed and centralized approach at certain hours, household loads, and the use of rooftop PV systems in homes. Smart or distributed electric vehicle charging schemes can positively impact low-voltage distribution networks, reducing voltage deviations, phase imbalances, peak loads, and power grid losses. Smart charging can improve the correlation of the distribution network with PV systems installed in homes due to the more simultaneous charging of electric vehicles during periods of PV supply. This study has no economic or emission studies as it focuses on the impact of EV and PV applications on the grid.

In 2022, Martin et al. [20] analyzed the coverage of energy production from PV installed in each home for EV charging. The research used a case study of 78 EV users in Switzerland using mathematical modeling and regression analysis. The results showed that with a controlled charging scenario that maximizes the use of PV energy compared to energy from the grid, the PV coverage to meet EV charging needs is more than 90% without BESS and 95% to 100% with BESS. The study also analyzed emission reductions from various scenarios with savings of 2.93 $kgCO_2$ to 4.11 $kgCO_2$ per week. However, this study did not analyze the economic feasibility of using PV for EV charging.

Research in Australia conducted by Merrington et al. in 2023 [21] developed an optimal sizing model of grid-connected PV and BESS in homes with EVs. They used two system configurations to minimize electricity costs: (1) PV-EV and (2) PV-BESS-EV. The results from mathematical modeling and case studies show that the optimal capacity size of the system is 10 kW for PV and 1 kWh for BESS. Although the net present cost (NPC) of the PV-BESS-EV configuration is slightly lower than that of PV-EV, the COE of both configurations is almost similar, dropping by about 7¢/kWh. However, this study has no investigation into CO_2 emission reduction by utilizing PV for EV energy supply.

2.2 States of the Arts

Based on a review of previous studies which has analyzed PV use to meet the demand for charging electric vehicles at home, there is still a gap where there is no study in terms of economic feasibility, technical and CO_2 emission reduction studies in one study. Table 1 provides an overview of mapping related to previous research. Therefore, the research analyzes technical and economic feasibility related to the use of rooftop solar power plants in meeting energy needs for charging electric cars at home. In addition, this research looks at the emission aspect by calculating the reduction of CO_2 emissions. This study also uses data on the charging history of customer electric cars connected to PLN's Charging Station Management System (CSMS) to determine the load to be supplied by PV. CSMS is a platform used to manage multiple EV charging stations. This software platform interacts with charging stations through open protocols to monitor and control data and status. The technical, economic, and CO_2 emission assessment results provide an optimal PV configuration scheme, deliver recommendations to PT PLN (Persero) and relevant stakeholders, and benefit consumers by promoting a sustainable energy model that is aligned with Indonesia's broader energy decarbonization strategy.

Table 1 Previous Studies on Rooftop Solar PV for Electric Car Charging

Previous Study	Research Location	Scope		Methods	Aspect		
		EV	PV		Technical	Economy	Emission
Li et al (2019) [18]	Australia	✓	✓	Smart Meter Data/Intelligent Algorithm	✓	✓	
Ramadhani et al (2021) [19]	Switzerland	✓	✓	Particle Swarm Optimization (PSO) algorithm	✓		
Martin et al. (2022) [20]	Swiss	✓	✓	• Mathematical Modeling • Regression Analysis	✓		✓
Merrington et al. (2023) [21]	Australia	✓	✓	• Mathematical Modeling • Case Study • Sensitivity Analysis • Uncertainty Analysis	✓	✓	
This research (2024)	Indonesia	✓	✓	• Mathematical Modeling • Homer Simulation	✓	✓	✓

3.0 METHODOLOGY

This research is conducted in Jakarta, Indonesia, which has the most Home Charging customer data. Based on data obtained from PLN's Charging Station Management System (CSMS) platform, 2,010 household customers were recorded as having charged their electric vehicles at home from January to July 2024. The CSMS data used in this study were obtained anonymously and with the consent of the data provider for academic research purposes. No personally identifiable information (PII) was accessed, stored, or disclosed during the analysis. This study complies with applicable data privacy regulations in Indonesia and adheres to ethical standards for the use of secondary data. The coordinates of the research location are 6°10′30.00″ south and 106°49′35.76″ east. Techno-economic analysis of rooftop solar PV installations for electric car owner customers with Home Charging Equipment consists of five stages as presented in Figure 1.

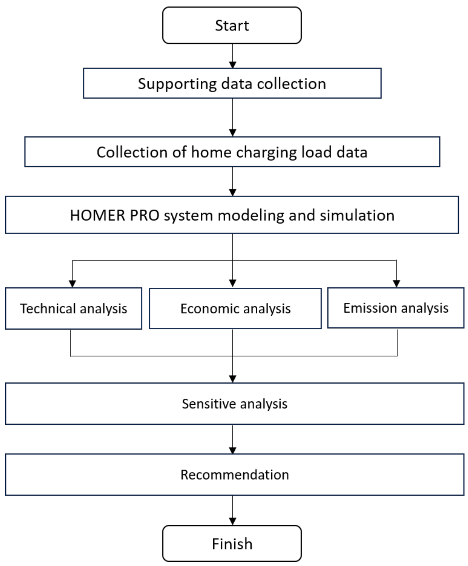


Figure 1 Research flow chart

3.1 Supporting Data Collection

The supporting data used to conduct techno-economic analysis. These supporting data include, temperature and irradiation data, home charging customer usage history data and technical and economic specification data. The temperature and solar irradiation data were obtained from the HOMER Pro application integrated with NASA. Temperature and solar irradiation data were used in the city of Jakarta for sampling calculations. Then, historical data on customer Home Charging (HC) usage is used to calculate the detailed daily load in 24 hours. This data is collected from the customer's HC integrated with PLN's CSMS. Thus, the energy usage for HC is monitored in the CSMS database. Samples of customer HC usage are taken from data located in Jakarta by cleaning the data first. The specifications for home charging used by customers are 7 kW AC. In addition, technical data includes types of PV panels, inverters, Battery Energy Storage Systems (BESS), and other necessary data. Economic data includes capital cost, replacement, and Operation and Maintenance (O&M) of PV, inverters, and BESS. Other data include discount rate, inflation rate, and annual capacity shortage. The technical and economic data used are based on references. These data will be used in modeling and simulating the system in the Homer Pro application.

3.2 Home Charging Load Data Processing

In the home charging data integrated with PLN CSMS determined at the time of data collection, processing will be carried out to obtain a daily load profile from the use of home charging. The data processing steps taken are as follows: a) Determination of cut-off data, the data taken uses HC customers who charge from January to July 2024. The customer data selected is customer data that has been integrated with CSMS from 2021 to 2023 in the Jakarta area with an assumed HC capacity of 7 kW. It is done to avoid the addition of integrated customer data in the middle of the charging data collection period from January to July 2024. At the data cut-off stage, 2,010 customers charged during the specified period; b) Cleansing data, in the cut-off data, data cleansing is then carried out to eliminate anomalous data due to several conditions of customer HC status that are not connected (disconnected) with CSMS, causing usage data to be unreadable. Data cleansing was carried out twice, firstly to ensure the existence of customer charging kWh from January to July 2024. From a total of 2,010 previous customers, only 1,461 customers met the first cleansing stage. Next, the second cleansing was carried out by processing each customer's average daily usage data.

The average usage is calculated from the total kWh for seven months of each customer divided by 213 days (total days from January to July 2024). In this study, the threshold for average daily usage data was set at 6.28 kWh. This was based on previous research by Martin et al. (2022) [20], which found that the average daily energy consumption of electric vehicles generally ranges from 6.28 kWh to 6.56 kWh, depending on the type of vehicle and usage patterns in urban environments. Therefore, residential customers with consumption below this level were excluded from the simulation to ensure alignment with realistic electric vehicle energy usage patterns. The second data cleansing found that the data to be used in this study were 728 customers with a total kwh usage from January to July 2024 of 1,428,459 kWh; c) charging Period Grouping, after cleansing, the next step is to categorize customer data based on weekday or holiday periods every hour in a day from January to July 2024. The result at this stage is the total kWh per hour each month from the number of customers charging for two categories, namely working days and holidays; d) load profile determination, the total kWh per hour in the results of the previous stage is divided by the number of customers in each month who charge on weekdays and holidays. This procedure is to get the average kWh usage of each customer per hour in a day. Details of the average kWh usage per hour in a day can be seen in Appendix A. Based on the data from Appendix A, the average kWh usage on weekdays is 9.74 kWh, and for holidays, it is 9.37 kWh. According to this data, average usage is the basis of the HOMER. The maximum value of the highest average customer HC usage of 37.13 kWh used to reflect changes in energy demand on the kWh scale. Figure 2 showed that the daily load graph of the kWh usage data. The trend of HC usage on weekdays and holidays is almost the same, with the majority of usage occurring at night. This is supported by research conducted by [19] related to statistical data on EV mobility within 24 hours, as shown in Figure 3.

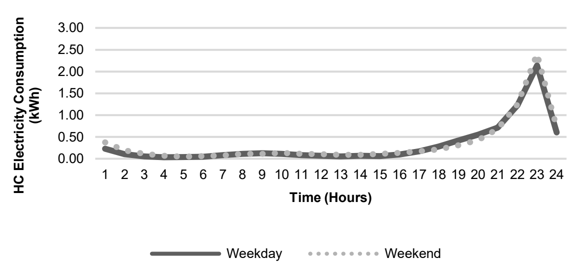


Figure 2 Load Profile of Home Charging Usage

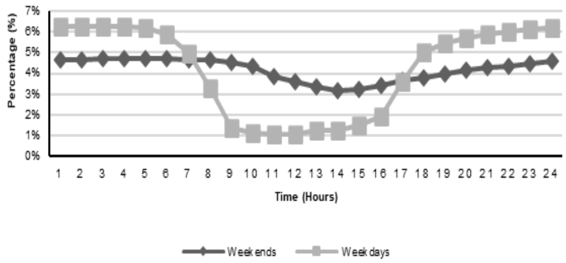


Figure 3 Statistical Percentage of Car Availability at Home [19]

Figure 3 shows that the highest probability of car availability occurs during nighttime, indicating that the majority of home charging (HC) activity also takes place at night. These hourly probability values were adapted from [19], which modelled smart charging behavior based on residential usage patterns. While the shape is representative, local assumptions derived from CSMS data were also taken into account in the load modelling. The corresponding weekday and weekend load profiles shown in Figure 2 serve as the input basis for system simulation in HOMER Pro.

Although the overall load profiles between weekdays and weekends appear visually similar, the simulation differentiates them based on the distinct probability of EV availability. Household energy consumption patterns tend to remain relatively consistent across the week; however, electric vehicle usage typically varies, with higher availability and charging potential during weekends. In this study, weekday and weekend load profiles were modelled separately, incorporating different car usage assumptions, despite the total EV charging load remaining small compared to the household base load. This difference is embedded in the simulation input but may not be easily distinguishable in the aggregate plotted curve due to the dominant proportion of household consumption.

3.3 System Modeling and HOMER Pro Simulation

3.3.1 System Configuration

The modeled system includes rooftop solar PV and BESS as electricity supply for electric vehicles through home charging. The modeled system configuration is categorized into 3 (three) schemes for comparison based on technical and economic feasibility analysis, including (i) On Grid-PV; (ii) On Grid-PV-BESS, and (iii) Off Grid-PV. i) On-Grid PV Scheme, which the output generated by the PV system is directly used as a supply for charging at home to charge the EV's battery. The availability of energy from the PV is backed up by the power grid each time the PV output is insufficient for charging or when there is a shortage of sunlight or irradiation. ii) On-Grid PV-BESS Scheme, this includes a Battery Energy Storage System (BESS) as the main backup when the PV output is insufficient. The PV output is used to charge the BESS when it is not used to charge the electric vehicle battery. The BESS directly takes over when the PV supply is insufficient for charging. The power grid serves as the last backup if PV and BESS cannot meet the energy demand. iii) Off-Grid PV-BESS Scheme, which the energy used to charge the electric vehicle battery is only supplied by the PV and BESS. This setup operates similarly to the second scheme. However, if the PV and BESS fail to provide enough energy for charging, the process will stop as there is no connection to the power grid. Simulations that have been conducted with HOMER Pro software for 3 (three) schemes are presented in Table 2.

Table 2 Scheme Comparison with HOMER Pro

Scheme	Grid	PV	BESS
Grid	✓	-	-
On Grid-PV	✓	✓	-
On Grid-PV-BESS	✓	✓	✓
Off Grid-PV-BESS	-	✓	✓

The analysis is carried out to determine the most optimal and efficient scheme along with the value of PV and battery capacity used to supply the needs of the Home Charging load. Afterward, it is compared with the currently existing conditions that are supplied by PLN electricity. After simulation and modeling, the results obtained are analyzed in terms of technical, economic, and emission aspects. In the technical analysis, the most optimal and efficient scheme will be studied regarding the opportunity to install and or apply it in housing units that use EV Charging. From an economic point of view, it focuses more on the study of economic feasibility if the scheme is implemented. Lastly, the emission analysis will discuss the impact of CO_2 emission reduction resulting from the selected scheme. The scheme diagram used in the Homer Pro simulation is shown in Figure 4.

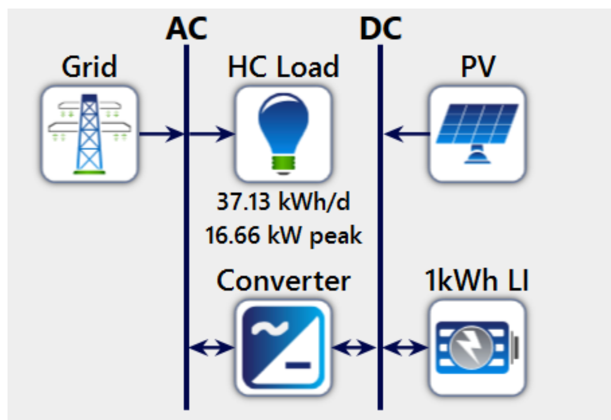


Figure 4 Hybrid system configuration of EV charging system in HOMER Pro.

3.3.2 System Input Parameters

The three key components used in the system simulation are PV modules, inverters, and batteries. Each of these components has certain parameters, such as power rating, capital cost, and lifetime, that are used as inputs for HOMER. Detailed parameter specifications are shown in Table 3. The values of the specifications entered are based on research references from residential PV construction [22].

Table 3 Input Component Parameters in HOMER

Description	Specification
PV	
Modul Type	Crystalline silicone
Capital costs	$882.35/kW
Replacement cost	$441/kW
Operation & maintenance (O&M) cost	$8.82/year
Degradation factor	80%
Lifetime	27
Inverter	
Capital costs	$317.65/kW
Replacement cost	$158.8/kW
Operation & maintenance (O&M) cost	$3.18
Efficiency	95%
Lifetime	12.5
BESS	
Model	Lithium-Ion
Capital costs	$470/kWh
Replacement cost	$235/kWh
Operation & maintenance (O&M) cost	$4.7/year
Lifetime	15

The solar module used in this study is Trina Solar. It is because during the licensing period for rooftop solar power plants in July 2024, the Trina Solar brand was the most widely used solar module for residential customers.

The solar module used in this study refers to the Trina Solar datasheet type Vertex NE19R, which has a length of 2.38 meters and a width of 1.13 meters. In Nominal Operating Cell Temperature (NOCT), this module is able to produce power in the range of 454 - 459 Wp. The solar Module electrical parameters can be seen in Table 4.

Table 4 Solar Module Electrical Parameters [26]

Maximum Power-P_{MAX} (Wp)	454	459	462	466	470	474	477
Maximum Power Voltage-V_{MPP} (V)	37.6	37.9	38.1	38.3	38.6	38.8	39.0
Maximum Power Current-I_{MPP} (A)	12.07	12.11	12.13	12.16	12.19	12.20	12.21
Open Circuit Volage-V_{OC} (V)	45.70	46.00	46.20	46.50	46.80	47.10	47.30
Short Circuit Current-I_{SC} (A)	12.69	12.73	12.75	12.78	12.80	12.82	12.84

*NOCT: Irradiance at 800 W/m², Ambient Temperature 20˚C, Wind Speed 1 m/s.

3.3.3 Irradiation and Temperature Data Input Parameters

This study obtained hourly and monthly solar energy profiles at the research location, Jakarta, from NASA (HOMER Pro application). Jakarta is located at -6.175247°, 106.827049°, with an average daily irradiation of 4.76 kWh/m²/day. Daily irradiation data for one year and the brightness index in Jakarta can be seen in Figure 5. The solar irradiation in September to October is higher than in other months. This is an indication of a possible increase in solar power during that period, which correlates with higher energy demand during that period. On other hand, the average daily temperature data for one year in Jakarta is shown in Figure 6. The highest temperature is in October, with an average daily temperature in one year of 25.93 °C.

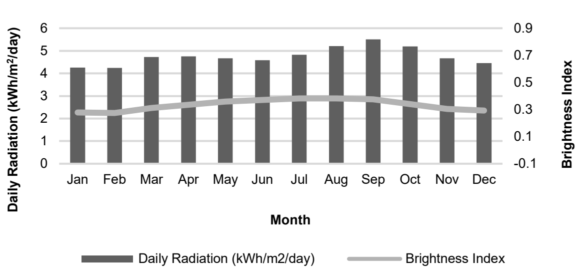


Figure 5 Solar irradiation intensity and brightness index.

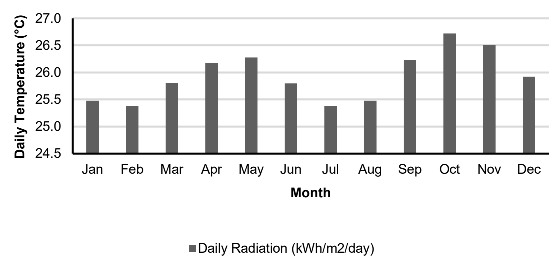


Figure 6 Average Daily Temperature per Month in a Year

3.4 Economic Indicators Calculation

To increase transparency and facilitate validation of simulation results, this study incorporates the basic economic formulas employed in HOMER Pro to calculate Net Present Cost (NPC), Levelized Cost of Energy (LCOE), and operating costs. Net Present Cost (NPC) represents the total life-cycle cost of the system, discounted to its present value. The calculation is as shown in equation 1:

$$C_{NPC} = \frac{C_{ann,tot}}{CRF(i, R_{proj})} \quad (1)$$

Where $C_{ann,tot}$ is the total annualized cost of the system [$/year], i is the real annual interest rate [%], R_{proj} is the project lifetime (years), and CRF is the capital recovery factor.

The Levelized Cost of Energy (LCOE) is defined as the average cost per kilowatt-hour of useful electrical energy produced over the lifetime of the system. It is expressed as presented in equation 2:

$$LCOE = \frac{C_{tot}}{E_{served}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

Where C_{tot} is the total lifetime cost of the system, and E_{served} is the total energy served [kWh] during the project period. The annual operating cost includes all recurring expenses such as fuel (if applicable), maintenance, and component replacements. These calculations are embedded within HOMER Pro and are applied uniformly across all simulated configurations.

4.0 RESULTS AND DISCUSSION

4.1 HOMER Pro Simulation and Modeling

Summary of simulation results of the three schemes evaluated in this study which include component capacity values, cost results and other economic parameters are presented in the following sub-sections.

4.1.1 Simulation Results of On Grid-PV Scheme, On Grid-PV-BESS Scheme, Off Grid-PV-BESS Scheme

The results of the three schemes that were tested previously can be seen in Table 5 when compared with the baseline or with the grid. Capital Expenditure (Capex) refers to the total upfront cost of installing the system, including the PV modules, converters, and batteries. In Table 5, each scheme is compared based on several performance indicators such as Capex, Net Present Cost (NPC), Levelized Cost of Energy (LCOE), Internal Rate of Return (IRR), and renewable energy contribution.

Table 5 provides comparison of the three schemes conducted before, the On Grid-PV scheme obtained an NPC value of $22,664 and LCOE of $0.107/kWh. In comparison with grid supply which has NPC and LCOE values of $23,081 and $0.011/kWh, this scheme generates savings from the NPC by $417 and LCOE by $0.003/kWh. Meanwhile, for the second scheme, On Grid-PV-BESS, the NPC value is $23,312 and the LCOE is $0.110/kWh, which is above the NPC value of the grid supply of $231, while the LCOE value is the same. The third scheme, Off Grid-PV-BESS, obtained an NPC value of $46.6 M and LCOE of $222.14/kWh. Capacity values of PV, Inverter and Battery as well as the NPC and LCOE values in this scheme are extremely high compared to the other schemes, because the entire supply for serving Home Charging is from PV.

Table 5 Comparison of Simulation Results of 3 (Three) Schemes with Existing

Parameters	Grid	Schemes		
		On Grid-PV	*On Grid-PV-BESS*	*Off Grid-PV-BESS*
PV (kW)	-	0.759	0.757	133
Converter (kW)	-	0.375	0.418	49
Battery (kWh)	-	-	1	57
Capex ($)	-	788.61	1.271	159.694
NPC ($)	23,081	22,664	23,312	46.6 M
LCOE ($/kWh)	0.110	0.107	0.110	222.14
Operating Cost ($/yr)	1.491	1.413	1.424	3.00 M
IRR (%)	-	8.6	2.3	-
Simple Payback (yr)	-	9.7	21	-
Renewable Fraction (%)	0	6.56	6.83	100

4.2 Technical Analysis

The minimal difference in PV capacity between the On-Grid PV and On-Grid PV-BESS configurations (0.759 kW vs. 0.757 kW) is due to the zero export assumption applied in the HOMER Pro simulation. This is because there is no financial compensation for surplus energy exported to the grid, in line with the abolition of the export-import scheme under Indonesian Government Regulation No. 2/2024. Consequently, HOMER limits PV capacity to align with the household's direct consumption profile. The addition of a small-scale BESS does not significantly alter this calculation, as battery costs remain relatively high and the additional benefits for PV utilisation are relatively small within the current tariff structure and incentive framework.

The solar module used in this study refers to the Trina Solar datasheet type Vertex NE19R, where the module has a length of 2.38 meters and a width of 1.13 meters. At Nominal Operating Cell Temperature (NOCT), the module is capable of producing power in the range of 454-459 Wp. In the On Grid-PV scheme, the PV capacity factor is 16% and PV capacity proposed by HOMER is 0.759 kW, the system requires 2 (two) panels. The roof area required for installation is (2.38 m x 1.13 m) times 2 (two) or equal to 5.38 m^2. Referring to the data on the average floor area of houses as shown in Table 6, the floor area of houses in the range of 20 – 49 m^2 is 39% and the floor area of 50 – 99 m^2 is 24%. Thus, it can be seen that the majority of house floor areas in DKI Jakarta range from 20 – 99 m^2. Assuming that the rooftop area is approximately equal to the floor area, the potential for PV installation under the On-Grid PV scheme can be considered technically feasible in terms of available rooftop space. This assumption is supported by IESR [23], which utilises floor area as a proxy for estimating residential rooftop PV potential across Indonesian provinces [23].

Table 6 Percentage of Households by Floor Area

District/City	Percentage of Households by Floor Area					
	< 19 m²	20 – 49 m²	50 – 99 m²	100 – 149 m²	150+ m²	Total
Kepulauan Seribu	4.68	29.46	50.1	11.22	4.54	100
South Jakarta	7.54	39.94	24.21	12.65	15.66	100
East Jakarta	7.42	39.74	27.49	13.55	11.8	100
Central Jakarta	21.91	39.5	23.02	8.3	7.27	100
West Jakarta	10.37	43.05	23.31	11.81	11.47	100
North Jakarta	24.53	32.46	18.4	11.23	13.38	100
DKI Jakarta	12.38	39.34	23.87	12.04	12.37	100

On Grid-PV-BESS scheme could also be carried out with the same roof area requirement as the On Grid-PV scheme. While for Off Grid-PV-BESS scheme with a capacity of 133 kW, 224 PV panels are required with a roof area of 620.43 m^2. Since this is not feasible to be implemented considering the average roof area data, the Off Grid-PV-BESS scheme was not recommended from a technical point of view since it requires a large roof area. On the other hand, although it is not feasible for residential systems, it may be favorable for charging stations in public areas, such as hotels, apartments, government offices, etc. The summary of the roof area requirement for the three schemes can be seen in Table 7.

Table 7 Comparison of Technical Studies on the Need for Number of PV Panels and Roof Area in residential housing

Schematic	PV Power (kW)	Number of PV Panels	Roof Area (m²)	Technical Review
On Grid - PV	0.759	2	5.48	Feasible
On Grid - PV - BESS	0.757	2	5.48	Feasible
Off Grid - PV - BESS	133	224	602.43	Not Feasible

4.3 Economic Analysis

In this section, an economic analysis is presented based on the simulation results that have been carried out using HOMER Pro software. The analysis is performed by comparing the NPC, LCOE, IRR and Payback Period values of the schemes: (i) On Grid-PV, (ii) On Grid-PV-BESS, and (iii) Off Grid-PV with benchmarking to the existing conditions (Grid).

4.3.1 Net Present Cost (NPC)

4.3.1.1 Net Present Cost Scheme On Grid-PV

Simulations were carried out with the On Grid-PV scheme using a PV capacity of 0.759 kW and an inverter of 0.375 kW. Table 8 presents the implementation of On Grid-PV scheme that requires an NPC cost of $22,664.01.

Table 8 NPC of On Grid-PV Scheme

No	Component	PV Module	Inverter	Grid	Total
1	Investment Costs	$669.61	$118.99	$0.00	$788.60
2	O&M Cost	$103.58	$18.42	$21,699.50	$21,821.50
3	Replacement Cost	$0.00	$72.14	$0.00	$72.14
4	Salvage Cost	-$18.23	$0.00	$0.00	-$18.23
	Total	$754.96	$209.55	$21,699.50	$22,664.01

4.3.1.2 Net Present Cost Scheme On Grid-PV-BESS

Simulations are carried out using the On Grid-PV-BESS scheme with the PV capacity is 0.757 kW, the inverter is 0.418 kW while the battery capacity is 1 kW which is shown in Table 9. It demonstrates that the implementation of the On Grid-PV-BESS scheme requires an NPC cost of $23,311.97.

Table 9 NPC of On Grid-PV-BESS Scheme

No	Component	PV Module	Inverter	BESS	Grid	Total
1	Investment Costs	$667.81	$132.78	$470.00	$0.00	$1,270.59
2	O&M Cost	$103.43	$20.59	$72.77	$21,682.59	$21,879.38
3	Replacement Cost	$0.00	$80.50	$128.35	$0.00	$208.85
4	Salvage Cost	-$18.18	$0.00	-$28.67	$0.00	-$46.85
Total	$753.05	$233.87	$642.45	$21,682.59	$23,311.97	

4.3.1.3 Net Present Cost Scheme Off Grid-PV-BESS

Simulations carried out with the Off Grid-PV-BESS scheme using a PV capacity of 133 kW, an inverter of 49 kW and a battery of 57 kW as presented in Table 10. This presents the implementation of the Off Grid-PV-BESS scheme which required an NPC cost of $46,561,496.73.

Table 10 NPC Off Grid-PV BESS Scheme

No	Component	PV Module	Inverter	BESS	Total
1	Investment Cost	$117,352.55	$15,551.61	$26,790.00	$159,694.16
2	O&M Cost	$18,162.41	$2,410.54	$4,147.88	$24,720.82
3	Replacement Cost	$0.00	$9,428.27	$46,370,848.49	$46,380,276.75
4	Salvage Cost	-$3,195.01	$0.00	$0.00	-$3,195.01
	Total	$132,319.95	$27,390.42	$46,401,786.36	$46,561,496.73

4.3.1.4 Net Present Cost Comparison between Schemes

Total life cycle costs of the On Grid-PV, On Grid-PV-BESS, Off Grid-PV-BESS schemes by benchmarking against the existing system (Grid) and using Bank Indonesia (BI) interest rates in 2024 (Discount rate: 6% and inflation rate: 1.84%), can be seen in Table 11 and Figure 7.

Figure 8 illustrates the highest NPC is the Off Grid-PV-BESS scheme, which amounted to $46,561,496.73. In this scheme, the NPC value is very high when compared to the other 2 (schemes) and the existing system. Factors that make the Off Grid-PV-BESS system have a high NPC value are BESS capacity which is big enough to properly store energy from PV which is not directly usable. In addition, the cost of replacing the BESS contributes to the highest NPC value in this scheme. The simulation results also show that the scheme with lowest NPC value and the only scheme with the lower NPC value than the existing system is the On Grid-PV scheme. According to Figure 8, NPC value for On Grid-PV scheme is $22,664.01, which is slightly lower than the NPC value for Existing (Grid) system of $23,081.49. This indicates that although not significant, integration of PV with the grid provides a slight saving in overall cost over the system lifecycle.

Table 11 Comparison of NPC 3 (Three) Schemes with Existing

No	Component	Grid	Schemes		
			On Grid-PV	On Grid-PV-BESS	Off Grid-PV-BESS
1	PV Module	$0,00	$754.96	$753.05	$132,319.95
2	Inverter	$0,00	$209.55	$233.87	$27,390.42
3	BESS	$0,00	$0.00	$642.45	$46,401,786.36
4	Grid	$23.081,49	$21,699.50	$21,682.59	$0.00
	Total	$23.081,49	$22,664.01	$23,311.97	$46,561,496.73

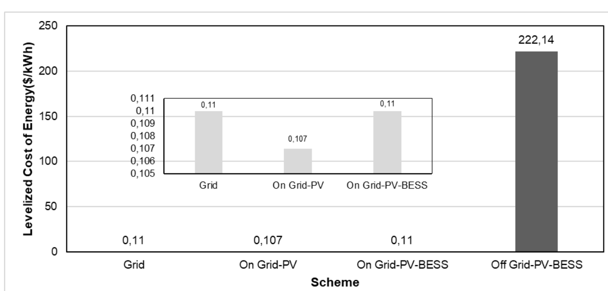


Figure 7 NPC Comparison of 3 (Three) Schemes against Existing Conditions

4.3.2 Levelized Cost of Energy (LCOE)

Simulation conducted with the HOMER Pro tool, the Levelized Cost of Energy (LCOE) values of the 3 (schemes) with comparisons to the existing conditions (Grid) are shown in Table 12 and Figure 8.

Table 12 Comparison of LCOE Three Schemes with Existing

Parameters	Existing (Grid)	Scheme		
		On Grid-PV	On Grid-PV-BESS	Off Grid-PV-BESS
LCOE ($/kWh)	$0.110	$0.107	$0.110	$222.14

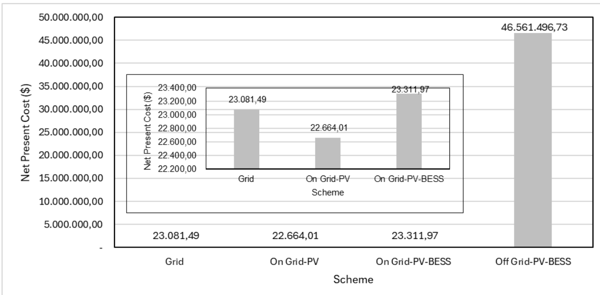


Figure 8 Comparison Chart of LCOE from 3 (Three) Schemes against Existing Conditions

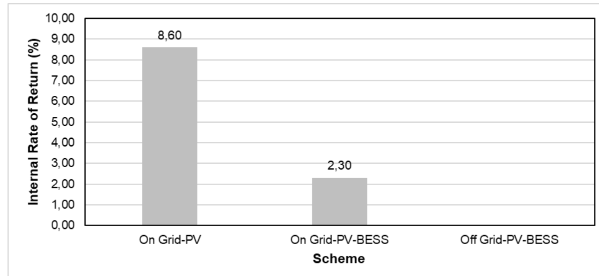


Figure 9 Comparison Chart of IRR from 3 (Three) Schemes

Table 12 presents the differences in LCOE between the existing system and the three proposed schemes. The existing grid-based system has an LCOE of $0.110/kWh. The cost is derived from the electric power rate of R-3 rate group. For the On Grid-PV scheme, there is a slight decrease in LCOE to $0.107/kWh. This decreases, around 2.7% compared to the existing system, reflects the contribution of PV which has low operating costs. Despite the insignificant amount of savings, this scheme indicates initial potential to integrate renewable energy into the grid system without adding an excessive investment burden. In addition, On Grid-PV-BESS schemes which combine PV with BESS yield the same LCOE as the existing system, which is $0.110/kWh. This was caused due to the high cost of investment, maintenance and replacement of BESS which balanced out the operational cost savings from PV. Meanwhile, for the Off Grid-PV-BESS scheme, the LCOE increased significantly to $222.14/kWh. This scheme relies fully on PV and BESS without support from the Grid. This extremely high cost is due to the need for large investments in batteries as well as maintenance and replacement costs to ensure a stable energy supply, especially during the night when the majority of the Home Charging demand is high. Overall, based on energy cost efficiency, the On Grid-PV scheme is the best option as it offers savings and reduces dependency on fossil energy with the lowest LCOE value.

4.3.3 Internal Rate of Return (IRR)

From the simulation results carried out with the HOMER Pro tool, the Internal Rate of Return (IRR) values of the 3 (schemes) are obtained as shown in Table 13 and Figure 9 below.

Table 13 Comparison of IRR of 3 (Three) Schemes

Parameters	On Grid-PV	On Grid-PV-BESS	Off Grid-PV-BESS
IRR (%)	8.60	2.30	-

In the On Grid-PV scheme, the IRR was recorded at 8.60%, which is above the discount rate of 6.00%. This indicates that the project is financially viable, as the rate of return generated is higher than the capital cost required. This relatively high IRR value can be attributed to the nature of the scheme which utilizes the grid to support operations, thus not requiring energy storage systems such as batteries which have high investment and maintenance costs. Therefore, On Grid-PV schemes are a better option to be developed in locations with stable grid access.

Contrary to this, for the On Grid-PV-BESS scheme, the IRR only reached 2.30%, well below the discount rate of 6.00%. This indicates that the project is considered less financially feasible because the rate of return does not cover the capital cost. The decrease of IRR value compared to the On Grid-PV scheme was due to the addition of Battery Energy Storage System (BESS) which increased the investment and operational costs significantly without providing a comparable increase in profit. Therefore, this scheme is only worth considering if there are policy incentives, such as subsidies for energy storage systems or setting higher electricity tariffs for renewable energy, to improve its economic feasibility.

For Off Grid-PV-BESS scheme, IRR is not included in the simulation results. This was due to the fact that HOMER Pro calculates IRR by comparing 2 (systems) where the selected system should have a lower initial capital value and higher operational costs than the existing system with the grid. If these criteria are not met, then IRR is not calculated in the simulation results. This is because off-grid schemes rely entirely on energy storage to meet electricity demand without the support from the grid. The high investment costs for battery installation, operation and replacement costs are not compensated by the savings.

Overall, only On Grid-PV scheme indicates obvious financial feasibility with IRR exceeding the discount rate. This scheme could be an appropriate solution in locations with suitable grid infrastructure in our case study, such as DKI Jakarta. Meanwhile, the On Grid-PV-BESS and Off Grid-PV-BESS schemes require further optimization or policy support to improve their economic competitiveness.

4.3.4 Payback Period

Based on the simulation results performed using HOMER Pro, the Payback Period values of the 3 (schemes) are obtained as shown in Table 14 and Figure 10.

Table 14 Comparison of Payback Period of 3 (Three) Schemes

Parameters	On Grid-PV	On Grid-PV-BESS	Off Grid-PV-BESS
Payback Period (yr)	9.7	21	-

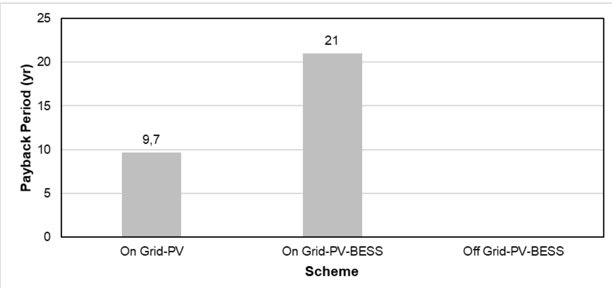


Figure 10 Payback Period Comparison Chart of 3 (Three) Schemes

Payback period data from the three schemes used for the system in this study can be analysed regarding the feasibility of the investment payback period compared to the expectations of consumers in Indonesia, which generally want a payback period for rooftop solar installations in the range of 6 to 10 years [24].

In the On Grid-PV scheme, the payback period was recorded as 9.7 years. This value is within the range of investment payback period that is considered feasible by consumers in Indonesia, which is 6-10 years. This study suggests that the scheme is suitable for residential customers, especially Home Charging customers, who would like to set up rooftop solar power plants and would like a reasonable return-on-investment period.

Conversely, for the On Grid-PV-BESS scheme, the payback period was recorded at 21 years. This value far exceeds consumer expectations, which makes the scheme less financially attractive for most households. The long payback period reflects the high initial, operational and replacement costs of a system using BESS. While BESS provides greater flexibility and energy independence, these benefits are not large enough to cover the additional costs in the time consumers expect.

For the Off Grid-PV-BESS scheme, there was no payback period data, which most likely indicates that the system does not produce enough savings to meet the payback point. This is reasonable considering the off-grid system depends completely on energy storage with no support from the grid, which results in extremely high installation and maintenance costs.

In summary, the On Grid-PV scheme is the most suitable option for Indonesian consumers, with a payback period that matches the desired payback period. Meanwhile, the On Grid-PV-BESS and Off Grid-PV-BESS schemes show a payback period that is neither too long nor financially feasible for the majority of Home Charging users in Indonesia, unless supported by additional incentives or more efficient technologies.

4.3.5 Comparative Economic Analysis

The results of the comparative economic analysis which include the NPC, LCOE, IRR and Payback Period values of the schemes: (i) On Grid-PV, (ii) On Grid-PV-BESS, and (iii) Off Grid-PV with benchmarking to the existing condition (Grid) as shown in Table 15. On Grid-PV scheme as the most economically feasible option by fulfilling all feasibility parameters (NPC, LCOE, IRR, and Simple Payback). In contrast, the BESS usage in both On Grid and Off Grid schemes significantly decreases the economic feasibility, where the On Grid-PV-BESS scheme is only feasible from the LCOE standpoint, while the Off Grid-PV-BESS scheme is not feasible in all parameters. Hence, it indicates that the solution without BESS is currently more cost-efficient to be implemented in order to fulfill the charging needs of Home Charging customers.

Despite the current economic infeasibility of BESS adoption in residential rooftop PV systems, battery storage offers important technical and practical benefits. One of the most critical is the provision of backup power during grid outages, which enhances energy security and reliability for households. Additionally, BESS can support load shifting and peak shaving, enabling users to reduce their reliance on the grid during high-tariff periods. While these benefits are not directly monetized in the current simulation, they play a significant role in user satisfaction and resilience, particularly in areas with frequent blackouts or poor power quality.

Although the Off-Grid PV-BESS scheme is currently not economically viable, it was included to serve as a boundary scenario that highlights the technical and financial limitations of achieving complete self-sufficiency. This provides context for future discussions on grid independence and emphasizes the critical role of policy support in enabling such systems.

Table 15 Results of Economic Analysis of 3 (Three) Schemes

Parameters	Basic	Scheme: On Grid-PV		On Grid-PV-BESS		Off Grid-PV-BESS	
		Value	Feasibility	Value	Feasible	Value	Feasible
NPC ($)	23,081	22,664	Feasible	23,312	Not Feasible	46.6 M	Not Feasible
LCOE ($/kWh)	0.110	0.107	Feasible	0.110	Feasible	222.14	Not Feasible
IRR (%)	6.00	8.6	Feasible	2.3	Not Feasible	-	Not Feasible
Simple Payback (yr)	10	9.7	Feasible	21	Not Feasible	-	Not Feasible

4.3.6 On Grid-PV Scheme Savings

Monthly electricity consumption in a year in the On Grid-PV scheme and shown in Figure 11. Based on the On Grid-PV scheme, the electrical energy purchased from the grid is 12,728 kWh/year, while without the PV addition scheme the purchased electrical energy should be 13,552 kWh/year. Therefore, in the On Grid-PV scheme, savings in purchasing electrical energy from the network are 824 kWh/year or $ 90.64/year.

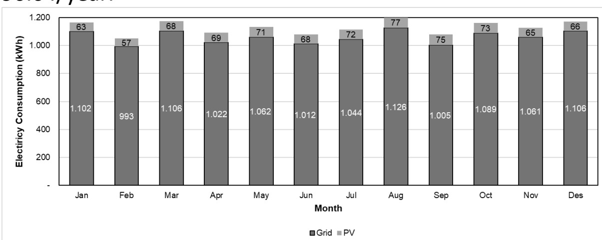


Figure 11 Monthly Electricity Consumption of On Grid-PV Scheme

4.4 Emmision Analysis

Emissions were calculated using a grid emission factor of 0.894 kg CO_2/kWh [25]. The total reduction per customer was obtained by multiplying this factor by the difference in annual grid electricity consumption between the Grid-only and On Grid-PV scenarios. The emission assessment in this study is limited to a gate-to-gate boundary, focusing solely on emissions generated during the operational phase (i.e., electricity usage) and excluding upstream or lifecycle emissions from manufacturing or installation.

Neither Grid schemes or On Grid-PV-BESS schemes are inevitably produced CO_2 and other particulate emissions. Total emissions of the three types of particulates carbon dioxide (CO_2), sulfur dioxide (SO_2), and nitrogen dioxide (NO_2) from the two systems are presented in Table 16.

Table 16 Comparison of Emission Simulation Results

Particulate Name	Grid	On Grid-PV	On Grid-PV-BESS	Off Grid PV-BESS
Carbon Dioxide, CO_2 (kg/year)	12,116	11,284	11,381	0
Sulfur Dioxide, SO_2 (kg/year)	37.1	34.6	34.9	0
Nitrogen Dioxide, NO_2 (kg/year)	18.2	16.9	17.1	0
Total (kg/year)	12,171.3	11,335.5	11,433	0

The On-Grid PV system produces total emissions of 11,335.5 kg of CO_2/year, while the Grid-only system results in 12,171.3 kg of CO_2/year. This indicates that the use of an On-Grid PV system by a single home charging (HC) customer can reduce emissions by approximately 835.8 kg CO_2/year (around 6%) compared to the Grid-only system. In contrast, a 37% reduction in emissions was reported by Martin et al. [20] for a European case where rooftop PV was able to cover a higher share of EV charging demand due to more favorable solar potential and system sizing. Despite the lower percentage, the result in this study still confirms the consistency of emission reduction trends from rooftop PV integration for residential EV charging, particularly in urban ASEAN settings.

When scaled up to the current number of electric vehicle (EV) owners with home charging in Jakarta, as recorded in the CSMS system, which is approximately 2,010 customers, the total potential emission reduction reaches 1,716,138 kg CO_2/year. Furthermore, if Indonesia achieves its long-term EV adoption target of 2 million electric cars by 2060, all of which are supported by rooftop PV systems, the cumulative emission reduction could reach 1.67 billion kg CO_2/year.

This result highlights that the integration of renewable energy—particularly rooftop PV—into the electricity grid for EV charging is highly effective in reducing greenhouse gas emissions. More importantly, these reductions align with Indonesia's Enhanced Nationally Determined Contribution (NDC), which targets a 31.89% reduction in GHG emissions by 2030 (unconditionally), and up to 43.20% with international support. Rooftop PV adoption for EV home charging can therefore serve as a complementary pathway to decarbonise both the power and transport sectors simultaneously, reinforcing national climate commitments and contributing to long-term sustainability.

4.5 Sensitivity Analysis

A sensitivity analysis was conducted to assess the impact of component cost reductions on system feasibility, particularly for PV modules, inverters, and BESS. The projected annual cost decline for PV modules and inverters is assumed to be 12%, based on trends reported by IESR (2024) in the Indonesia Solar Energy Outlook 2025 [26], [27]. Meanwhile, the BESS cost is projected to decrease by 8% per year, following global market trends as reported by BloombergNEF (2023) [28]. These assumptions are used to simulate realistic future cost scenarios in both national and international contexts.

The results of the component price sensitivity simulation and its effects on the component capacity and economic parameters of each of three schemes within a 5-year time span up until 2044 are presented in Table 17.

Table 17 Sensitivity Simulation Results of 3 (three) Schemes

Year	Schemes	Component Capacity			Economic Parameters			
		PV (kW)	Inverter (kW)	BESS (kWh)	NPC ($)	LCOE ($/kWh)	IRR (%)	PBP (yr)
2024	On Grid-PV	0.759	0.375	-	22,664	0.107	8.6	9.7
	On Grid-PV-BESS	0.757	0.418	1	23,312	0.110	2.3	21.0
	Off Grid-PV-BESS	133.00	49.00	57	46.5 M	222.14	-	-
2029	On Grid-PV	1.43	0.55	-	22,041	0.102	15.0	6.4
	On Grid-PV-BESS	1.39	0.54	1	22,465	0.104	9.2	9.3
	Off Grid-PV-BESS	100.00	45.60	58	30.8 M	146.94	-	-
2034	On Grid-PV	2.38	0.67	-	21,512	0.098	22.0	4.5
	On Grid-PV-BESS	2.43	0.67	1	21,791	0.099	16.0	6.0
	Off Grid-PV BESS	97.40	25.00	62	20.3 M	96.81	-	-
2039	On Grid-PV	3.90	0.86	-	21,064	0.092	30.0	3.3
	On Grid-PV-BESS	4.18	0.09	1	21,250	0.092	23.0	4.3
	Off Grid-PV-BESS	97.40	24.00	62	13.4 M	63.79	-	-
2044	On Grid-PV	5.91	1.08	-	20,697	0.086	42.0	2.4
	On Grid-PV-BESS	5.98	1.08	1	20,818	0.086	35.0	2.9
	Off Grid-PV-BESS	97.40	24.00	62	8.81 M	42.03	-	-

Sensitivity simulation results above demonstrate that a decrease in component prices had a significant impact in increasing the capacity of system components and improving the economic parameters in all schemes. The trend is more obvious in the On Grid-PV and On Grid-PV-BESS schemes, while the Off Grid-PV scheme still faces economic challenges despite efficiency improvements.

In the On Grid-PV scheme, PV capacity and Inverter components increase significantly over time. In 2024, the PV capacity was only 0.759 kW, but increased sharply to 5.91 kW in 2044. The increase indicates that the price of PV panels is declining and allows the installation of larger capacity at a lower cost. In addition, the economic parameters of the scheme have improved significantly. The NPC decreased from $22,664 in 2024 to $20,697 in 2043. This indicates total cost efficiency within the simulation period. Consistent with that, LCOE also decreased from 0.107 $/kWh to 0.086 $/kWh, which indicates lower electricity production costs. In terms of profitability, the IRR increased sharply from 8.6% in 2024 to 42% in 2043. This increase is followed by a decrease in the Payback Period from 9.7 years to only 2.4 years, making the On Grid-PV scheme more economically viable and attractive to customers and service providers.

Meanwhile, On Grid-PV-BESS scheme, which involves the integration of Battery Energy Storage System (BESS), shows a slightly different performance. The PV capacity also increases from 0.757 kW in 2024 to 5.98 kW in 2043, which is almost the same as On Grid-PV scheme. However, the use of batteries leads to higher overall costs, which is reflected in the relatively higher NPC values of $23,312 in 2024 and $20,818 in 2043. The LCOE in this scheme is also higher than On Grid-PV, which is 0.110 $/kWh in 2024 and drops to 0.086 $/kWh in 2043. Starting in 2029, the LCOE of the On Grid-PV-BESS scheme is already lower than the grid price. However, the IRR value of the scheme increases significantly from 2.3% to 35%, which indicates a significant increase in profitability as the price of technology components decreases. However, PBP value of this scheme remains longer than that of On Grid-PV, from 21 years in 2024 to 2.9 years in 2043. This indicates that despite being more expensive, battery integration provides additional flexibility that can be an attractive option for energy supply stability for Home Charging customers.

On the other hand, Off Grid-PV schemes, which rely entirely on Energy Storage Systems, are facing a greater economic challenge. Although the PV and Inverter capacities are quite large at the beginning of the simulation, at 133 kW and 49 kW in 2024, they tend to decrease until 2034 and stabilize until 2044. The BESS capacity, while remaining stable at 57-62 kWh, adds cost complexity to the scheme. The economic parameters show that Off Grid-PV Scheme is still not competitive when compared to the Grid- Connected Scheme. The NPC of this scheme is very high at the beginning of the period, which reaches $46.5 million in 2024, although it eventually drops to $8.81 million in 2044. Similarly, the LCOE starts very high at $222.14/kWh in 2024, before dropping to $42.03/kWh in 2044. These high costs indicate that although solar technology is getting cheaper, complete reliance on storage systems is limiting the competitiveness of Off Grid-PV schemes, especially in areas with no access to the grid.

Overall, sensitivity simulation results demonstrate that the On Grid-PV scheme is the most environmentally favourable with the highest IRR, lowest LCOE, and fastest PBP. However, the On Grid-PV-BESS scheme offers additional benefits in terms of Energy Storage but at a much higher cost. Meanwhile, Off Grid-PV schemes still require a significant amount of innovation to become more competitive, especially in terms of reducing the cost of energy storage. These trends illustrate that the decline in price of solar energy technology components has a significant positive impact on the development of solar power systems, both in terms of capacity and profitability, especially for grid-connected systems.

4.6 Discussion

The On Grid-PV schemes from a customer perspective for electric vehicles home charging offer significant economic and environmental benefits, and combine long-term advantages for sustainability. Despite high initial installation costs, the On Grid-PV schemes payback period shortens dramatically from 9.7 years in 2024 to 2.4 years by 2044 as rooftop PV panel component prices decline, ensuring substantial energy cost savings over time. The On Grid-PV schemes Levelized Cost of Energy (LCOE) of $0.107/kWh in 2024 already undercuts PLN's grid electricity ($0.110/kWh), yielding annual savings of 824 kWh (valued at $ 90.64), with further cost reductions expected as technology prices drop and efficiency improves. Environmentally, the system enables eco-friendly electric vehicles home charging using renewable energy, aligning with global carbon reduction goals and promoting sustainable energy adoption, an appealing choice for customers who seek for both financial returns and a Greener Lifestyle, considering the increasing concern of climate change, renewable energy projects such as the use of solar PV are necessary [29].

From the perspective of the *Perusahaan Listrik Negara* (PLN), implementing On Grid-PV scheme for charging electric vehicles at home poses challenges, such as potential annual lost sales of 822 kWh ($90.64 per customer), but on the other hand the adoption of On Grid-PV scheme also provides an opportunity to diversify the business. By leveraging sub holding, PLN can compensate for the decline in revenue by offering Operation and Maintenance (O&M) services for rooftop PV panel systems which provide technical support for installation, monitoring, and maintenance to Home Charging customers, thus creating a new income stream other than kWh sales. Integrating these services with its existing Home Charging product could further enhance customer retention. Additionally, PLN could develop tailored incentive schemes or special rate for customers of solar-powered electric vehicles charging, reinforcing its role as a partner in energy transition while driving renewable energy adoption in transportation. This dual approach transforms potential revenue losses into sustainable growth opportunities, aligning with broader goals of increasing renewable penetration and maintaining market relevance.

5.0 CONCLUSION

5.1 Conclusion

On Grid-PV system is the most technically and economically viable solution for home electric vehicle charging in Jakarta. With a 0.759 kW PV panel and a 0.375 kW inverter, the On Grid-PV reduces grid energy demand by 824 kWh annually, requiring only 5.38 m² of roof space, which is feasible for most homes in the DKI Jakarta region. Economically, the On Grid-PV scheme offers a lower Levelized Cost of Energy (LCOE) around $0.107/kWh compared to PLN's $0.110/kWh, with an initial net present cost of $22,664.01, an 8.6% Internal Rate of Return (IRR), and a 9.7-year payback period. This payback period is projected to drop to 2.4 years by 2044 as solar component prices decline.

Environmentally, the On Grid-PV scheme reduces annual CO_2 emissions by 6% (835.8 kg CO_2/year/household), scaling to 1.72 million kg CO_2/year if adopted by 2,010 households. In other words, with Indonesia's target of 2 million electric cars by 2060, the adoption of PV panels could reduce emissions by 1.67 billion kg CO_2/year in 2060, supporting the country's national climate change mitigation goals. Sensitivity analysis highlights that declining component prices—12% annually for PV/inverters and 8% for batteries—will further enhance affordability, reducing LCOE to $0.086/kWh and boosting IRR to 42% by 2044. While integrating a Battery Energy Storage System (BESS) with the On-Grid PV requires a higher initial investment, it ensures long-term energy stability, making future investments increasingly economical. These findings underscore the growing feasibility of rooftop solar systems for sustainable energy transition, combining immediate environmental benefits with improving financial returns over time.

Despite the positive techno-economic outcomes, the adoption of rooftop PV systems in the residential EV segment still faces significant practical barriers, such as the high upfront system installation costs and the lack of export compensation under Ministry of Energy and Mineral Resources Regulation No. 2/2024. In order to overcome these challenges, this study recommends the following strategies for PLN and other stakeholders, such as establishing a co-investment mechanism, such as a leasing or co-ownership model, in which PLN or a third-party investor funds the installation in exchange for profit sharing. Moreover, build partnerships with electric vehicle manufacturers or dealers to integrate rooftop PV and charging infrastructure into vehicle sales packages, and also introduce Time-of-Use (ToU) tariff schemes that incentivize electric vehicle owners to charge their vehicles during peak solar power production periods. These strategies can support equitable adoption and accelerate decarbonization in the residential and transport energy sectors.

5.2 Future Scope Recommendation

To further enhance the impact of this research, several potential areas for future studies can be proposed. First, a more comprehensive analysis can be conducted by considering the impact of electricity price fluctuations and the adoption of household battery storage systems, which could significantly influence the economic feasibility of PV-BESS-EV integration. Second, case studies in different regions across Indonesia with varying economic conditions and climate characteristics should be explored to assess the adaptability and effectiveness of the proposed system under diverse environmental and socioeconomic scenarios. Lastly, a detailed business model applicable to PLN customers should be developed, outlining viable pricing structures, incentives, and regulatory frameworks to support the widespread adoption of home-based solar PV and EV charging solutions. These future studies will contribute to a more holistic understanding of the technical, economic, and policy aspects of integrating renewable energy with electric mobility.

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Conflict of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper

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