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Original Research Paper

Techno-Economic Analysis of On-Grid Rooftop PV Systems Integrated with BESS for Meeting the Energy Needs of Residential EV Home Charging Customers in Jakarta

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Abstract: The growing adoption of electric vehicles (EVs) in Indonesia, especially in urban areas like Jakarta, is expected to increase household electricity consumption. Rooftop solar photovoltaic (PV) systems integrated with battery energy storage systems (BESS) offer a promising solution to supply clean and self-sufficient energy. This study aims to assess the techno-economic feasibility of on-grid rooftop PV systems combined with BESS for residential EV home charging in Jakarta under various export compensation schemes and cost scenarios. Using the HOMER Grid software, three system configurations were simulated: grid-only, PV + BESS without export, and PV + BESS with 65% export compensation. The optimal setup consists of an 8.97 kW PV and 5 kWh BESS, yielding an internal rate of return (IRR) of 18%, a levelized cost of energy (LCOE) of \$0.042/kWh, and a payback period of 5 years. Sensitivity analysis highlights that a minimum export compensation of 40% and projected cost reductions, especially in BESS are critical for long-term viability. A larger system with 15 kWh BESS becomes economically feasible after 2028, achieving a 16% IRR. Integrating rooftop PV and BESS could reduce CO_2 emissions by up to 9,932 kg/year compared to a grid-only system. Policy recommendations include export compensation of at least 40%, targeted investment incentives, and co-investment models involving PLN, PV providers, and EV dealers.

Keywords: Battery Energy Storage, EV Charging, Export Compensation, Rooftop PV, Techno-Economic Feasibility.

1. Introduction

The increasing urgency of the global climate crisis has driven countries, including Indonesia, to commit to reducing greenhouse gas (GHG) emissions [1]. Indonesia's CO_2 emissions in 2021 exceeded 600 Mt, more than double the previous year, underscoring the significance of rapid climate action [2]. Through its Enhanced Nationally Determined Contribution (NDC), the Indonesian government targets a 31.89% GHG reduction by 2030 (43.20% with international support) [3], with the energy sector, contributing around 40% of total emissions, playing a pivotal role [2].

The transport sector is the second-largest emitter, contributing 23% of national emissions, over 90% of which stem from road transport. In response, battery electric vehicles (BEVs) have emerged as a promising solution [4], supported by government incentives under Presidential Regulation No. 55/2019 and its update No. 79/2023 [5]. With 7,679 EVs registered by 2022 and projections indicating rapid growth, attention must now shift to the source of electricity for charging these vehicles [4].

However, increased EV adoption also presents new challenges, particularly regarding the source of electricity for charging [6]. In 2023, 86.9% of electricity generation in Indonesia was still based on fossil fuels [7]. If EVs are charged using electricity from a fossil-fuel-dominated grid, the environmental benefits of transportation electrification will be limited [8][9]. Integrating EVs with renewable energy, particularly solar power, thus offers a strategic solution for achieving a truly sustainable transportation system [6] [8] [10].

Rooftop solar PV offers a decentralized and clean energy source for urban households. Indonesia’s solar potential is estimated at 3,294 GW, yet only 717.71 MW had been installed as of August 2024, with residential deployment still limited [11]. In Jakarta, daily solar irradiation ranges between 4.4–4.8 kWh/m², making rooftop PV technically feasible. However, the implementation of Ministerial Regulation No. 2/2024, which eliminates net energy export compensation, creates new challenges. Under this regulation, surplus electricity from rooftop PV that is not self-consumed is not credited or purchased by PLN, significantly reducing the economic value of excess daytime generation [11].

These changes highlight a critical policy and technical gap: how can rooftop PV remain viable for households, particularly those with EVs that require significant energy mostly at night? Prior studies have explored PV-EV integration [6] [8] [10], but few address the combined impact of zero-export regulations, time-of-use mismatch [12] [13], and battery energy storage systems (BESS) [14], in the Indonesian context using actual load profiles and policy scenarios. There is a lack of empirical studies assessing the feasibility of household PV+BESS systems under shifting regulations and component cost trajectories.

Therefore, this study aims to analyze the techno-economic feasibility of rooftop PV systems integrated with BESS to support EV home charging in Jakarta, considering different export compensation scenarios and projected cost reductions. Using real-world residential and EV load data with HOMER Grid simulations, the study explores optimal system configurations and economic indicators such as IRR, LCOE, and payback period.

The contributions of this research are twofold. Theoretically, it enriches the limited literature on PV-BESS-EV integration in Indonesia under real regulatory and consumption conditions. Practically, it provides insights for households making clean energy investment decisions, for PLN in anticipating shifting load patterns, for PV and EV ecosystem stakeholders in designing solutions, and for policymakers in formulating adaptive and inclusive regulations.

2. Literature Review

2.1. Relevant Studies Regarding the Application of Rooftop Solar PV for EV Home Charging

Several previous studies have examined the integration of rooftop photovoltaic (PV) systems with electric vehicle (EV) charging, focusing on technical performance, economic viability, and system design. However, most of these studies have not specifically addressed the influence of national policies such as zero-export schemes, especially in the context of residential households in Indonesia.

A residential renewable energy-based microgrid system integrating solar panels, small wind turbines, battery storage, and EV charging stations was developed and simulated using HOMER Pro. The study showed that a configuration consisting of an 8 kW PV system and a 6-kWh battery offered the best cost efficiency and could reduce EV charging time by up to 49% [15]. However, it did not consider regulatory aspects such as zero-export schemes, nor did it employ real household load profiles or conduct quantitative carbon emission assessments.

The technical and economic feasibility of PV-based EV charging stations in residential areas across three major cities in Vietnam was analyzed using HOMER Grid. The study evaluated multiple PV and battery configurations under varying solar irradiation levels. Results indicated that the site with the highest irradiation offered the lowest cost of energy (COE) at $0.08/kWh, with the optimal setup comprising a 50 kW PV system and battery storage [16]. However, the EV load was estimated based on the assumed number of vehicles charging daily, without reference to specific household consumption profiles or rooftop PV systems. Consequently, the study did not address household-level home charging, zero-export policies, or household carbon emission reductions.

The extent to which rooftop solar energy could support EV home charging was examined using real-world data from 78 EV users in Switzerland over a 10-month period. The study revealed that under uncontrolled charging behavior, only 15% of EV energy demand could be fulfilled by solar power. However, with the application of smart charging strategies and energy storage systems, this figure could increase to 90–99% [17]. The study's strength lies in its use of actual mobility patterns and PV models tailored to household-level geographic and climatic conditions. Nonetheless, it did not take into account utility regulations or energy policy frameworks.

A technically advanced EV charging system integrated with rooftop PV, battery storage, and a single-phase grid connection intended for residential parking spaces was proposed and validated. The system supported both AC and DC charging across a wide voltage range (50–400 V) to accommodate various EV types, including two-, three-, and four-wheelers, and also supplied power to household loads. Utilizing an Orthogonal Signal Generator (OSG)-based controller and a bidirectional converter, the system showed strong performance in maintaining power quality and efficiency under varying conditions of irradiation, load, and grid distortion [18]. Despite its technical sophistication, the study did not conduct an economic feasibility analysis, did not account for regulatory frameworks, and did not evaluate the system's potential for CO_2 emission reduction.

The technical and economic feasibility of rooftop PV systems with and without battery energy storage systems (BESS) for supporting residential electricity consumption and EV charging in Chile was assessed using actual household electricity bill data. The study modeled eight PV system configurations and five BESS scenarios. Results showed that systems without BESS were more economically viable, achieving an internal rate of return (IRR) of up to 16.2% and a payback period of 5.9 years [19]. However, despite utilizing real consumption data and exploring multiple system configurations, the study did not evaluate the systems' impact on carbon emissions and did not address energy regulatory frameworks such as net billing or zero-export policies.

A city-scale planning model for EV charging infrastructure was developed by integrating rooftop renewable energy technologies, including photovoltaic (PV) panels, micro-concentrated solar power (CSP), and wind turbines, within a multi-energy hub framework. Using MATLAB-based image segmentation to analyze actual rooftop areas, the study evaluated several scenarios: EV-only charging, integration with city-wide electricity demand, and life-cycle emissions from EVs and renewable energy technologies (RETs). The findings showed that wind-based systems were the most effective for emission reduction, with the potential to reduce up to 187,000 tons of CO_2 annually under a 10% EV penetration scenario [20]. However, the study did not focus on household-level EV charging, did not utilize hourly household or EV load profiles, and did not consider electricity policy frameworks.

A comprehensive review of photovoltaic (PV)-based smart home integration with electric vehicles (EVs), energy storage systems (ESS), and home energy management systems (HEMS) was presented, with a particular focus on the Australian context. The study explored various enabling technologies, including vehicle-to-home (V2H), vehicle-to-grid (V2G), smart metering, and demand response strategies designed to improve energy efficiency, reduce carbon emissions, and enhance the resilience of residential electricity systems. It also highlighted policy support from the Australian government and future technological roadmaps involving energy communities, virtual power plants, and smart grids [8]. Despite its wide scope and relevance, the study remained theoretical and literature-based, lacking system modeling based on real household energy consumption data or analysis of specific policy scenarios such as Indonesia's zero-export scheme. Furthermore, it did not assess the technical or economic feasibility of integrated PV-EV systems.

The technical feasibility, environmental impact, and financial benefits of solar-panel-based carport canopies for supporting EV charging in Taiwan were evaluated. Using HelioScope and PVWatts simulations, a 50 kW PV system was estimated to generate approximately 140 MWh annually, capable of serving up to 3,592 vehicles per month in short-duration parking scenarios. The system demonstrated a potential CO_2 emission reduction of up to 94% compared to conventional grid electricity [21]. The study also analyzed how parking tariffs and carbon taxes affected the system's economic feasibility from the perspective of EV users. However, the focus was on public EV charging infrastructure rather than household-level rooftop PV systems, and it did not include zero-export energy scenarios or simulations based on actual residential consumption profiles.

A comprehensive literature review on photovoltaic (PV)-based electric vehicle (EV) charging systems was conducted, covering market trends, technical requirements, grid integration, and future challenges and opportunities. The study reviewed various EV–PV system topologies, global EV charging standards, power management strategies, and converter control techniques for both charging and discharging processes. It also discussed the role of PV-EV integration in enhancing grid stability through smart charging and highlighted relevant international standards such as IEC and SAE, including vehicle-to-grid (V2G) integration strategies [22]. While systematic and extensive, the study was purely literature-based and did not present technical or economic simulations using real household or EV charging data, nor did it evaluate applicable regulatory policy frameworks.

Cost-effective electric vehicle (EV) charging strategies for prosumer households with small-scale rooftop photovoltaic (PV) systems in Finland were investigated using six years of actual household energy consumption and PV generation data. The study compared smart charging scenarios with uncontrolled charging behavior. Findings showed that smart charging could reduce annual charging costs by up to 54.5% and increase PV self-consumption by 46.6%, depending on the availability of the vehicle and the charging capacity [23]. Although the study incorporated real-world data and accounted for dynamic electricity pricing, it did not evaluate policy scenarios related to energy regulations, nor did it comprehensively assess carbon emissions or the system's economic feasibility using metrics. Additionally, the PV system used in the study was 21.1 kWp significantly larger than the average residential PV capacities typically found in developing countries like Indonesia.

In conclusion, while the reviewed studies contribute significantly to understanding the technical, economic, and operational aspects of PV-EV integration, most do not focus on residential home charging with rooftop PV under zero-export regulations. Very few studies use real household consumption data or provide comprehensive techno-economic and environmental analyses relevant to Indonesia's policy and market context.

2.2. State of the Art

The literature review indicates that integrating rooftop photovoltaic (PV) systems with electric vehicle (EV) home charging is a growing and relevant topic in supporting the transition toward a cleaner energy system. While various studies have explored technical, economic, and environmental aspects, most remain partial and do not comprehensively address the specific context of developing countries like Indonesia. To clarify the contribution of this research, a classification was conducted on ten previous studies along with the current study based on six main criteria: (1) use of actual household and EV data, (2) technical analysis, (3) economic analysis, (4) carbon emission (CO_2) evaluation, (5) discussion of relevant energy policies, and (6) integration of energy storage systems. The classification results are presented in Table 1 using ✓ and ✗ symbols to indicate whether each aspect is addressed.

Table 1. State of The Art

No	Ref	Actual Data (Household+EV)	Analysis			Energy Policy Consideration	Battery Integration
			Tech	Eco	CO_2		
1	[8]	✗	✗	✗	✓	✓	✗
2	[15]	✗	✓	✓	✗	✗	✓
3	[16]	✗	✓	✓	✗	✗	✓
4	[18]	✗	✓	✗	✗	✗	✓
5	[19]	✓	✓	✓	✗	✗	✓
6	[20]	✗	✓	✗	✓	✗	✓
7	[21]	✗	✓	✓	✓	✗	✓
8	[22]	✗	✗	✗	✗	✓	✗
9	[23]	✓	✓	✓	✗	✗	✓
10	[24]	✓	✓	✗	✓	✗	✓
11	Proposed	✓	✓	✓	✓	✓	✓

The classification results in Table 1 highlight existing research gaps, as most prior studies have not comprehensively addressed key aspects related to the development of rooftop PV systems for residential EV charging. The use of actual household and EV data, economic analysis, CO_2 emission evaluation, and consideration of energy policies, such as Indonesia's current zero-export scheme remain limited.

This study aims to bridge those gaps through system modeling using real consumption data, incorporating technical, economic, environmental, and regulatory dimensions. As such, it contributes not only to the academic discourse on renewable energy integration but also provides practical insights for policy development to support the sustainable adoption of rooftop PV and EVs in Indonesia's residential sector.

3. Methodology

This study is conducted in Jakarta, Indonesia, a strategic urban center with the highest adoption rate of home EV charging. From January to July 2024, a total of 2,010 customers were recorded using home charging, making Jakarta the most data-rich region for this analysis. The city offers stable grid infrastructure, broad PLN network coverage, and favorable solar potential for rooftop PV installation. Residential building characteristics, including available rooftop area, were also considered to determine the feasible system capacity. The geographical coordinates of the study area are 6°10′30.00″ S and 106°49′35.76″ E. The research flow is illustrated in Figure 1, outlining stages from data collection to system simulation using HOMER Grid, sensitivity analysis, and policy recommendation.

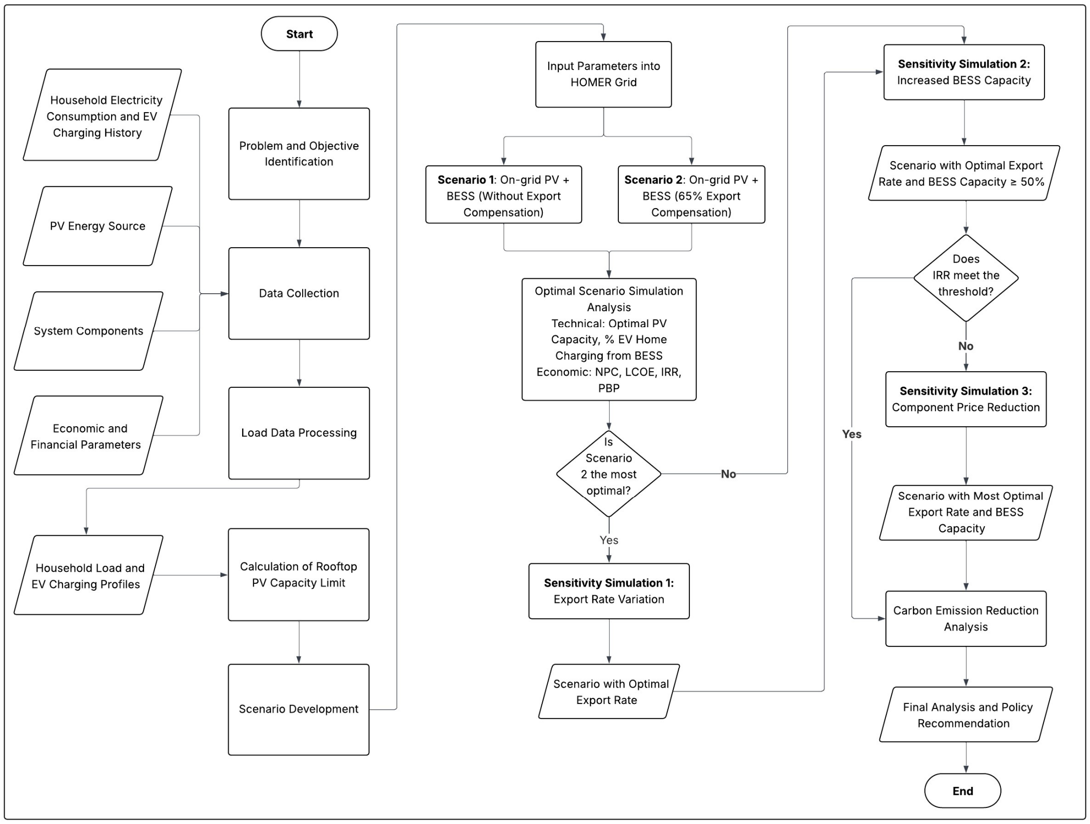

Figure 1. The Research Flow

3.1 Data Collection

This study utilizes a combination of primary and secondary data, grouped based on their relevance to the modeling and simulation of rooftop photovoltaic (PV) systems for residential electric vehicle (EV) charging. The first category involves load profile data, which includes hourly electricity consumption from R-2 tariff customers equipped with Advanced Metering Infrastructure (AMI) and historical EV charging session data. The EV charging data, obtained from PLN's Charging Station Management

System (CSMS), contains information on charging dates, durations, and energy used per session. Additionally, technical specifications of EVs and home chargers such as battery capacity, charging power, and maximum input limits were gathered from official manufacturer sources and market data.

The second category covers solar energy resource data used to estimate rooftop PV potential in the study area, Jakarta. Average daily solar irradiation and ambient temperature data were sourced directly from the HOMER Grid database, which integrates satellite data from NASA.

The third category consists of technical specifications for key system components. These include the rated power (W), efficiency, and lifetime of PV modules; nominal capacity, conversion efficiency, and operational lifespan of inverters; and the depth of discharge (DoD), round-trip efficiency, and cycle life of battery storage systems.

The final category involves economic and financial parameters used for cost analysis and sensitivity testing. This includes electricity tariffs applicable to R-2 customers using EV home charging (≥7,700 VA), energy export policies as stipulated in MEMR Regulation No. 26/2021 which allows 100% energy export but with 65% compensation and the latest MEMR Regulation No. 2/2024, which eliminates export compensation. Additional financial assumptions such as discount rate, inflation rate, and acceptable annual capacity shortage were also incorporated. All technical and economic data were derived from market surveys, vendor pricing, and relevant literature, and were used as key inputs in the HOMER Grid simulation model.

3.2 Load Data Processing

1) EV Home Charging Load

The EV home charging load profile in this study was constructed based on actual data obtained from PLN's Charging Station Management System (CSMS), which tracks residential EV charging sessions in Jakarta. A total of 728 customers with complete data from January to July 2024 were selected after a two-stage data cleansing process. These users represent the most reliable data sample for building a realistic and representative load profile for simulation in HOMER Grid.

The assumed EV type in this study is a battery electric SUV with a 60-kWh battery capacity, reflecting the dominant market segment in Indonesia between 2020 and 2024 from GAIKINDO and has been processed for analytical purposes as show in Figure 2. Charging is assumed to occur using a 7 kW AC home charger, which is the most common configuration for residential charging.

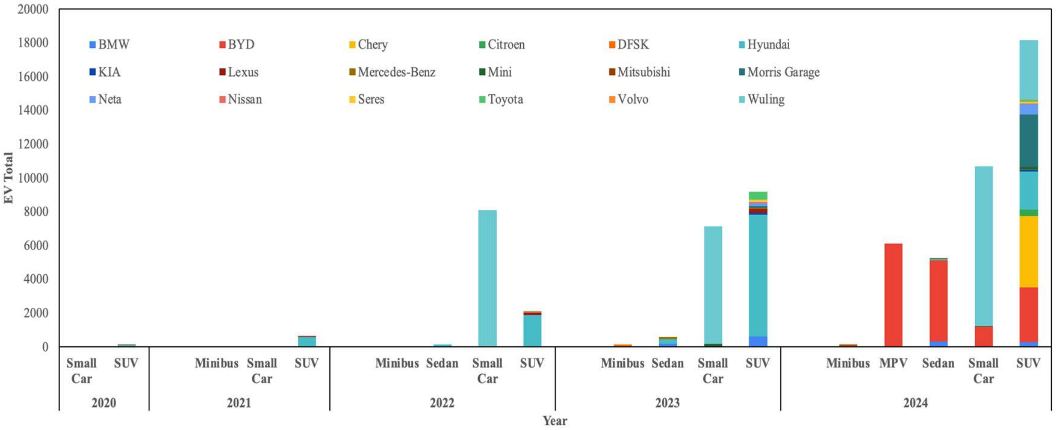

Figure 2. Electric Vehicle Sales by Type and Brand (2020–2024)

The processed CSMS data showed that most users charged their EVs between 6 to 10 times per month, indicating an average of 2 sessions per week, or approximately 0.29 sessions per day as shown in Figure 3. This finding supports the assumption that residential EV users in Jakarta typically do not charge their vehicles daily, but every two to three days. Therefore, 0.29 charging sessions/day was used as a key simulation parameter.

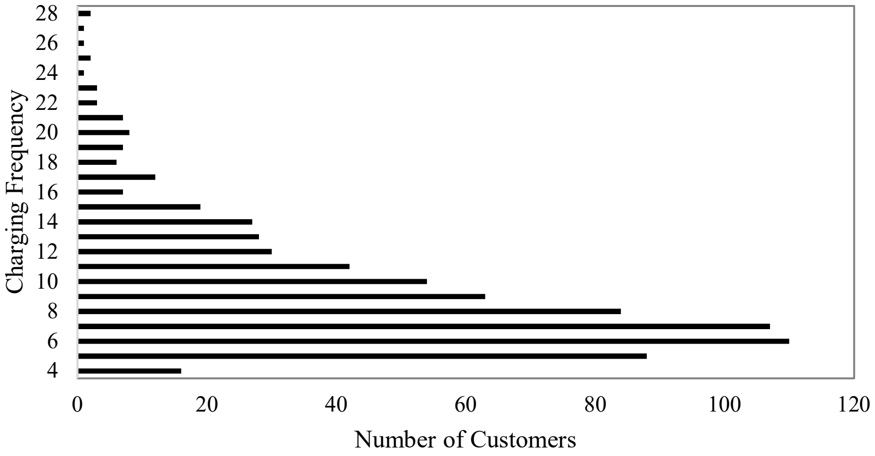

Figure 3. Distribution of Average Monthly EV Charging Frequency

Further analysis of charging time distribution revealed that most users-initiated charging between 19:00 and 23:00, with a peak around 22:00 on weekdays as shown in Figure 4. A similar but slightly less intense pattern was observed on weekends. This nighttime charging behavior aligns with residential electricity consumption patterns and provides a realistic daily load profile for simulation purposes.

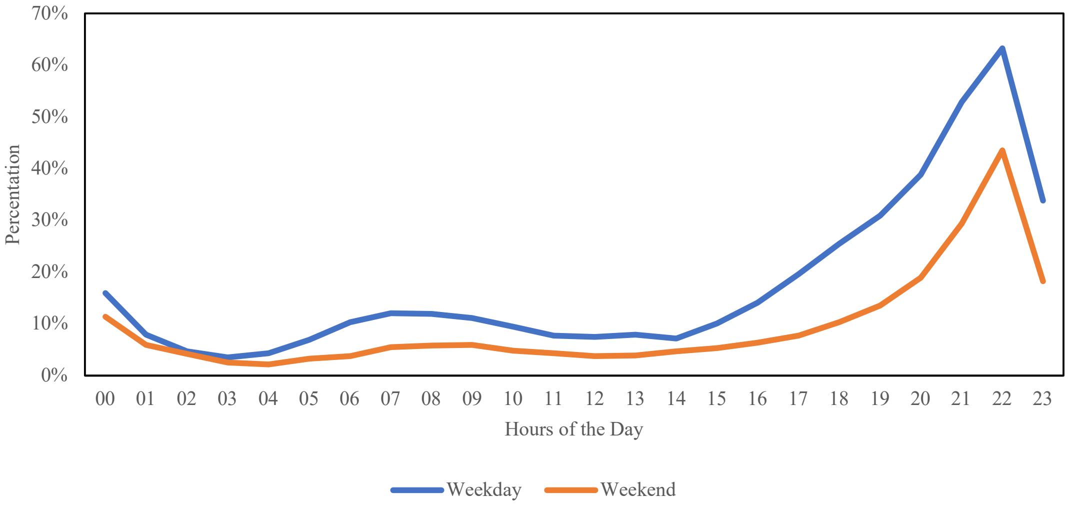

Figure 4. Daily Percentage of EV Charging Sessions

The average daily energy consumption from the CSMS dataset was calculated to be approximately 9.2 kWh/day per customer, as shown in the actual usage data. This figure was validated using a theoretical energy estimation based on a state-of-charge (SOC) range from 20% to 80% [25], which corresponds to 36 kWh per full session. When multiplied by the average session frequency (0.29 sessions/day), the estimated daily energy consumption is approximately 10.4 kWh/day, which closely matches the empirical result.

Charging duration per session was calculated using the basic power-energy-time formula, assuming a constant 7 kW charging power. Dividing the required energy (36 kWh) by the charger output yields an estimated average charging time of approximately 5.14 hours or 308 minutes. This duration is considered acceptable given the use of residential-level AC charging and the nighttime charging window.

2) Household Load

The residential load profile was developed using high-resolution electricity consumption data from Jakarta households with R-2 tariffs (3,500–5,500 VA), which represent middle- to upper-income segments likely to adopt electric vehicles and rooftop PV systems. The data were collected from customers equipped with Advanced Metering Infrastructure (AMI), providing 15-minute interval consumption logs for the entire month of July 2024. Out of 500 sampled customers, 442 with complete records were selected, consisting of 134 customers with 3,500 VA, 154 with 4,400 VA, and 154 with 5,500 VA. The 15-minute data were aggregated into hourly intervals, resulting in 24 data points per day per customer. These were then averaged over 31 days to generate a representative daily load curve for each user.

The analysis revealed an average daily electricity consumption of approximately 25.3 kWh per household, with a typical consumption pattern that begins to rise around 15:00, peaks between 17:00 and 20:00, and tapers off after 21:00. This reflects common urban household routines such as the evening use of air conditioning, lighting, entertainment, and kitchen appliances. Compared to lower-capacity residential customers, the load curve of R-2 customers shows a slightly earlier rise starting at 15:00, which is attributed to the behavior of middle- to high-income households who tend to use air conditioning and other energy-intensive appliances more frequently in the afternoon. Despite differences in subscribed power capacity, the temporal consumption patterns across all three R-2 customer groups were found to be highly similar. Therefore, an aggregated average profile of all R-2 customers was adopted as the representative household load input for HOMER Grid simulations. The resulting curve is illustrated in Figure 5.

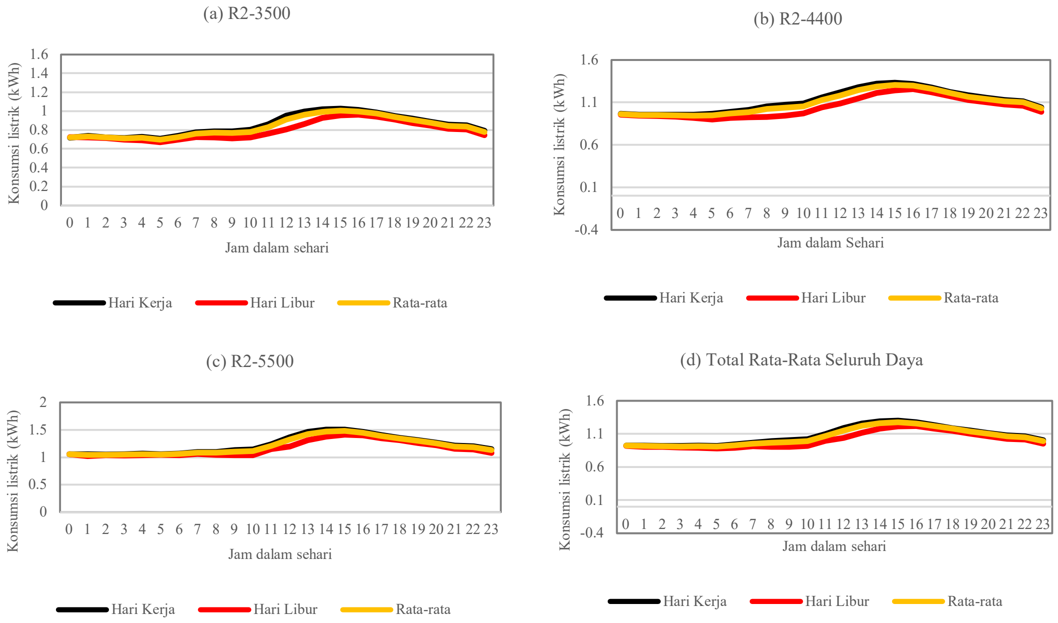

Figure 5. Daily Load Profile of R-2 Residential Customers in Jakarta

3.3. Determination of Maximum System Capacity

In accordance with Indonesia's Regulation No. 2/2024, which no longer limits rooftop PV capacity to the customer's contracted load, this study defines system size based on technical feasibility, particularly effective roof area. Referring to [26] and Indonesian housing standards, a typical middle-class house has a roof area of about 120 m². With a PV access factor of 33% [27], the effective area available is 39.6 m². Using Trina Solar Vertex S panels (625 Wp, 2.7 m²/module), this area supports up to 15 modules, resulting in a maximum installable capacity of 9 kW. The power density used is 231 Wp/m², based on the panel's datasheet.

3.4. System Modelling and HOMER Grid Simulation

1) Scenario Development and Simulation Framework

To evaluate the technical and economic feasibility of utilizing rooftop photovoltaic (PV) systems combined with battery energy storage systems (BESS) for residential energy needs and electric vehicle (EV) home charging, a series of simulations were conducted using the HOMER Grid software. The simulation framework was developed through a stepwise approach, starting from baseline and primary scenarios, followed by sensitivity analyses on key parameters such as energy export rates and component pricing.

- **Primary Scenarios**

Three primary scenarios were designed to establish baseline conditions and compare system variations:

- Scenario 0 (Grid Only): Represents the base case in which all household and EV charging demands are fully supplied by the utility grid. No PV or BESS components are installed. This scenario serves as the reference for comparing technical, economic, and environmental performance.
- Scenario 1 (PV + Grid + BESS, 0% Export): Models a self-consumption-only system with rooftop PV and BESS, with zero export compensation. In HOMER Grid, the export tariff is set to Rp 0. This reflects the regulatory condition stipulated in MEMR Regulation No. 2/2024, which prohibits energy export compensation.
- Scenario 2 (PV + Grid + BESS, 65% Export): Represents a system with PV and BESS allowed to export surplus electricity to the grid, compensated at 65% of the import tariff. This setup corresponds to the policy context under MEMR Regulation No. 26/2021 and is intended to capture the potential maximum economic benefit from surplus energy export.

The outcomes of these three scenarios are used to identify the most viable configuration based on both technical and economic criteria. Technical feasibility is evaluated based on optimal PV capacity (up to 9 kW) and the proportion of EV charging demand supplied by PV-stored energy in the BESS. Economic performance is assessed using indicators such as Net Present Cost (NPC), Levelized Cost of Electricity (LCOE), Internal Rate of Return (IRR), and Payback Period (PBP). Depending on which scenario yields the best overall performance, sensitivity analyses are developed accordingly: If Scenario 1 is optimal, two sensitivity analyses are conducted: BESS capacity enhancement and component cost reduction. If Scenario 2 is optimal, three stages of sensitivity analyses follow: export rate variation, BESS capacity enhancement, and component cost reduction.

- **Sensitivity Analysis Scenarios**

The sensitivity analyses aim to explore system responses under varying conditions and improve decision robustness:

- Sensitivity Simulation 1 – Export Rate Variation: This stage identifies the minimum export compensation rate that still results in a system with superior performance compared to Scenario 1. IRR is used as the primary benchmark. Export tariffs simulated include 35%, 40%, 45%, 50%, 55%, 60%, 70%, 75%, and 80%. The outcome defines the optimal export rate for subsequent scenarios.
- Sensitivity Simulation 2 – BESS Capacity Optimization: Building on the optimal export rate, this stage evaluates the minimum battery capacity required to supply at least 50% of EV home charging demand from PV-stored energy. BESS capacity is simulated incrementally (e.g., 10–30 kWh). The goal is to determine the technically optimal configuration and assess whether it also meets economic thresholds (e.g., IRR > Scenario 1).
- Sensitivity Simulation 3 – Component Price Reduction: If the target IRR is still unmet, simulations are performed using projected component price reductions. PV and inverter costs are assumed to decline by 12% annually [11], while BESS prices decline by 8% per year [28]. This analysis determines when the system becomes economically viable over time, even if technical targets have already been met.

2) System Input Parameter

This study utilizes the HOMER Grid software to simulate and evaluate the technical performance and economic feasibility of a rooftop solar photovoltaic (PV) system integrated with a battery energy storage system (BESS) for residential energy consumption and electric vehicle (EV) home charging in Jakarta. To ensure the accuracy and relevance of the simulation outcomes, the input data are categorized into three main groups: climate data (solar irradiation and temperature), technical system component parameters, and economic and financial parameters.

- **Climate Data: Solar Irradiation and Temperature**

Hourly and monthly solar irradiation data for the Jakarta area were retrieved from NASA's database via the HOMER Grid platform. Jakarta is located at coordinates 6.175247°S and 106.827049°E, with an average daily solar irradiation of 4.76 kWh/m²/day. The highest levels of irradiation occur in September and October, indicating higher solar generation potential during these months, which coincides with increased energy demand. Annual average daily temperature data indicate that the highest average temperatures occur in October, with a mean annual temperature of approximately 25.93°C.

- **Technical Component Parameters**

The technical characteristics of the rooftop PV system components are based on market surveys and manufacturer datasheets, and are input into HOMER Grid for simulation. A summary of the technical specifications is as follows in Table 2.

Table 2. Technical Parameter Data of System Components

Component	Technical Parameter	Value / Range	Source / Assumption
PV	System capacity	Up to 9 kW	Calculation in Subsection 3.3
	Module efficiency	23%	Trina Solar Vertex S TSM-NE19R datasheet
	Lifetime	15 years	Based on project lifetime assumption
	Derating factor	80%	HOMER default
Inverter	Capacity	Matched to PV system	HOMER Optimizer
	Conversion efficiency	±95%	Growatt Hybrid Inverter datasheet
	Lifetime	15 years	Inverter datasheet
BESS	Capacity	Multiples of 5 kWh	Growatt Hope 5.5L-A1 datasheet
	Type	Lithium-ion	Growatt Hope 5.5L-A1 datasheet
	Depth of Discharge (DoD)	93%	Growatt Hope 5.5L-A1 datasheet
	Cycle lifetime	> 6,000 cycles (~15 years)	Growatt Hope 5.5L-A1 datasheet
	Minimum State of Charge	20%	Growatt datasheet / HOMER default
	Round-trip efficiency	90%	HOMER default

- **Economic and Financial Parameters**

Economic parameters are entered into HOMER Grid to calculate key financial indicators such as Net Present Cost (NPC), Levelized Cost of Energy (LCOE), Internal Rate of Return (IRR), and Payback Period (PBP). The investment structure for the rooftop PV system is based on market prices and official guidelines from the Indonesian Ministry of Energy and Mineral Resources (MEMR). The capital costs are as follows:

PV modules: $316.55/kW, Inverter: $123.20/kW, Balance of System (BoS): 18% of PV + inverter costs [29], Installation and other costs (labor, transport, supervision): 29% of PV + inverter costs [29] and Total installed cost: approximately $439.74/kW (with inverter) and $ 316,6/kW (just PV system).

The full set of economic assumptions used in the simulation shown in Table 3.

Table 3. Economic and Financial Parameters

Parameter	Value / Assumption	Source / Reference
PLN Electricity Tariff	Rp 1,699.53/kWh	PLN R-2 Tariff (2024)
PV Cost	$316.6/kW	Calculated before
Inverter Cost	$123.2/kW	Calculated before
Battery Cost	USD 247/kWh	Growatt Hope 5.5L-A1
O&M Cost	1% of total system cost	[30]
Discount Rate	6%	Bank Indonesia, 2024
Inflation Rate	1.6%	Bank Indonesia, 2024
Project Lifetime	15 years	Assumed

- **System Configuration**

The system configuration used in this study is illustrated in Figure 6. It integrates rooftop PV, a lithium-ion battery (1 kWh unit basis), and grid electricity to supply both household loads and EV home charging demand. The average household consumption is 25.24 kWh/day with a peak of 2.19 kW, while EV charging is modeled at a maximum of 7 kW using an AC charger. A bidirectional converter links the AC and DC buses, enabling energy flow between the PV system, battery storage, and household or EV loads. This hybrid setup forms the basis for simulations conducted in HOMER Grid under various technical and economic scenarios.

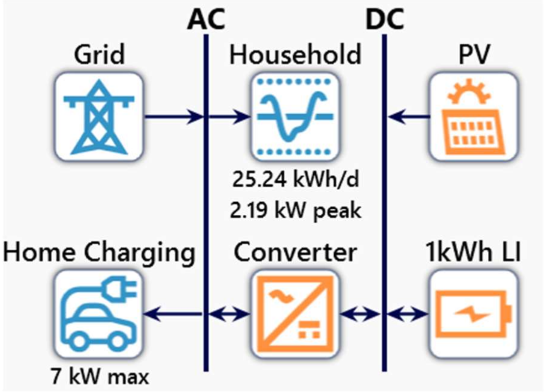

Figure 6. System Configuration in HOMER Grid

4. Finding and Discussion

4.1. Results and Analysis of the Main Scenario Simulation

- **Scenario 0 – Grid Only**

This baseline scenario represents a residential household fully reliant on grid electricity, without any integration of solar PV or battery storage. Annual energy consumption reaches 12,605 kWh, comprising 9,212 kWh for household usage and 3,393 kWh for EV charging. With no self-generation, all energy is supplied by PLN.

From the Table 4, the system incurs a Levelized Cost of Energy (LCOE) of $0.103/kWh and a Net Present Cost (NPC) of $14,107, with annual operating costs of $1,298. Environmentally, this scenario results in the highest emissions, 7,966 kg CO_2/year in total, including 2,144 kg CO_2 from EV charging. As a benchmark, this scenario highlights the economic burden and high emissions of a fully grid-dependent household, serving as a reference to assess the benefits of renewable energy integration in subsequent configurations.

Table 4. Simulation Results Scenario 0 (Grid Only)

Parameter	Value	Unit
Grid Energy Consumption	13	kWh/year
EV Energy Demand	3,393	kWh/year
Household Energy Demand	9,212	kWh/year
LCOE	0.072	$/kWh
Net Present Cost (NPC)	14	$
Operating Cost	1	$/year
CO_2 Emissions (Household + EV)	8	kg/year
CO_2 Emissions (EV only)	2	kg/year

- **Scenario 1 – PV + Grid + BESS (0% Export)**

This scenario simulates a grid-connected PV and BESS system without any export compensation, in line with MEMR Regulation No. 2/2024. Excess solar energy exported to the grid receives no financial credit, reducing the economic value of surplus generation.

Table 5. Technical Results of Scenario 1 Simulation (PV + Grid + BESS, 0% Export)

Parameter	**Value**	**Unit**
PV Capacity	4.75	kW
Inverter Capacity	1.49	kW
BESS Capacity	5.00	kWh
Grid Energy Consumption	8,076.00	kWh/year
PV Energy Production	6,640.00	kWh/year
EV Energy Demand	3,393.00	kWh/year
Household Energy Demand	9,212.00	kWh/year
PV Energy Exported to Grid	418.00	kWh/year
Battery Output	1,268.00	kWh/year
Household Load During EV Charging Time	1,950.00	kWh/year
EV Charging Supplied from BESS	805.23	kWh/year
EV Charging from BESS	24.00	%

Technically, the system utilizes a 4.75 kW PV, 1.49 kW inverter, and 5 kWh BESS (Table 5). Annual solar production reaches 6,640 kWh, reducing grid dependence to 8,076 kWh. The battery discharges 1,268 kWh annually, with 805 kWh used to charge EVs, equivalent to 24% of total EV charging demand. This highlights the battery's role in supplying nighttime loads, though overall PV utilization remains suboptimal due to export restrictions.

Table 6. Economic Results of Scenario 1 Simulation (PV + Grid + BESS, 0% Export)

Parameter	**Value**	**Unit**
Net Present Cost (NPC)	11,992.00	$
Levelized Cost of Energy (LCOE)	0.085	$/kWh
Internal Rate of Return (IRR)	14	%
Payback Period	6	years
Electricity Bill Savings	466.54	$/year
Initial Investment Cost	2,635.00	$
Annual Operating Cost	861.14	$

Economically, the system yields a Net Present Cost (NPC) of $11,992, and a Levelized Cost of Energy (LCOE) of $0.085/kWh, lower than the grid-only case ($0.103/kWh). With an Internal Rate of Return (IRR) of 14% and a payback period of 6 years, the system is economically viable. However, the lack of export incentives limits PV capacity to 4.75 kW (well below the 9-kW rooftop potential), constraining both energy savings and long-term system performance. This underscores the impact of restrictive export policies on system optimization.

- **Scenario 2 – PV + Grid + BESS (65% Export)**

This scenario simulates a PV and BESS system connected to the grid with a 65% export compensation rate reflecting earlier policies that provided economic incentives for surplus solar energy. The availability of export value encourages full utilization of rooftop capacity and improves system economics.

Technically, the system utilizes 8.97 kW of PV, an 8.81 kW inverter, and a 5-kWh battery (Table 7). Annual PV production reaches 12,534 kWh, with 6,497 kWh exported to the grid and the rest consumed locally or stored. Grid dependency reduces to 7,329 kWh per year. Battery utilization remains the same as in previous scenarios, 1,268 kWh/year of discharge, supplying 805 kWh or 24% of EV charging needs, due to unchanged BESS capacity.

Table 7. Technical Results of Scenario 1 Simulation (PV + Grid + BESS, 65% Export)

Parameter	Value	Unit
PV Capacity	8.97	kW
Inverter Capacity	8.81	kW
BESS Capacity	5.00	kWh
Grid Energy Consumption	7,329.00	kWh/year
PV Energy Production	12,534.00	kWh/year
EV Energy Demand	3,393.00	kWh/year
Household Energy Demand	9,212.00	kWh/year
PV Energy Exported to Grid	6,497.00	kWh/year
Battery Output	1,268.00	kWh/year
Household Load During EV Charging Time	1,950.00	kWh/year
EV Charging Supplied from BESS	33.56	kWh/year
EV Charging from BESS	24.00	%

The availability of export incentives enables near-maximum PV capacity deployment, significantly increasing system output and grid interaction. However, battery contribution remains limited by its size, suggesting that further improvements in self-consumption require BESS capacity scaling.

Table 8. Economic Results of Scenario 1 Simulation (PV + Grid + BESS, 65% Export)

Parameter	Value	Unit
Net Present Cost (NPC)	7,355.00	$
Levelized Cost of Energy (LCOE)	0.035	$/kWh
Internal Rate of Return (IRR)	21	%
Payback Period	5	years
Electricity Bill Savings	1,102.00	$/year
Initial Investment Cost	4,732.00	$
Annual Operating Cost	241.33	$

Economically, this configuration yields the most favorable results across all simulated scenarios (Table 8). The Net Present Cost (NPC) drops to $8,766, while the Levelized Cost of Energy (LCOE) falls to $0.042/kWh, nearly half that of the no-export case. The Internal Rate of Return (IRR) reaches 18%, with a payback period of only 5 years. Annual electricity bill savings of $978.75 (~IDR 16.2 million) and relatively low operating costs further underscore the system's cost-effectiveness.

Overall, this scenario demonstrates the highest techno-economic performance, driven by export policy support and optimal PV sizing, making it the most attractive configuration for residential adoption under compensated export frameworks.

- **Selection of the Optimal Scenario**

Based on the technical and economic analysis of the three main scenarios, Scenario 2: PV + Grid + BESS with 65% export compensation is identified as the most optimal configuration for residential EV users in Jakarta. Technically, this scenario enables the deployment of nearly maximum rooftop PV capacity (8.97 kW), resulting in an annual PV generation of 12,534 kWh, significantly higher than the 4.75 kW installed under the no-export scenario. The compensated export of surplus energy enhances system performance and encourages greater PV adoption.

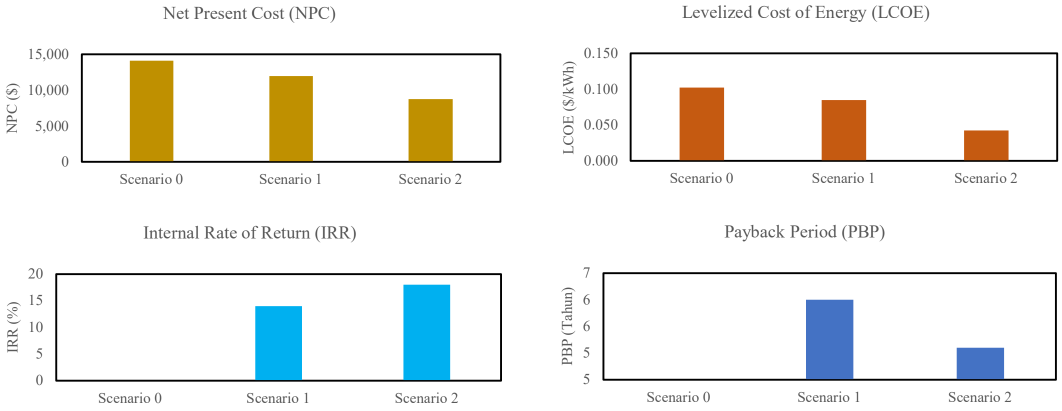

Figure 7. Comparison of Key Economic Parameters Across Scenarios

Economically, Scenario 2 outperforms other configurations, with the lowest Net Present Cost ($8,766), LCOE of $0.042/kWh, the highest IRR (18%), and the shortest payback period (5 years). Annual electricity bill savings reach $978.75, equivalent to approximately IDR 16.2 million. As illustrated in Figure 7, these metrics demonstrate clear advantages over both the Grid Only and non-export scenarios.

Although a 65% export compensation scheme is no longer in effect following the implementation of MEMR Regulation No. 2/2024, this simulation highlights its strong potential in incentivizing rooftop PV adoption particularly among EV-owning households with high evening loads.

Therefore, Scenario 2 is selected as the optimal configuration in the main simulations. However, with only 24% of EV charging fulfilled from stored solar energy and a substantial portion of PV output still exported, further optimization is required. Subsequent sensitivity analyses are recommended to explore improvements in battery sizing and export policy structures to maximize direct renewable energy utilization for EV charging.

4.2. Results and Analysis of the Sensitivity Scenario Simulation

- **Sensitivity Analysis 1 – Export Compensation Rate Variation**

The first sensitivity analysis explores the effect of varying export compensation rates on the technical and economic performance of the rooftop PV system, motivated by the recent regulatory changes under Indonesia's Ministry of Energy and Mineral Resources Regulation No. 2/2024, which eliminates net energy metering for rooftop PV. While previous simulations identified a 65% export compensation scenario as technically and economically optimal, this level of incentive may no longer be applicable under current policy. Therefore, it is important to determine the minimum viable export compensation rate that still ensures system feasibility.

From the technical perspective as show in Tabel 9, varying export compensation between 25% and 85% in 5% intervals yielded consistent results in terms of PV sizing and system architecture. The optimal PV capacity remained around 8.98–9 kW, with inverter capacity ranging between 5–8.8 kW and BESS fixed at 5 kWh. Annual solar energy production remained stable at approximately 12,534–12,576 kWh, reflecting uniform system design across scenarios. Likewise, the total annual household and EV load remained unchanged at 12,606 kWh. The main variation occurred in exported energy volumes. As export compensation increased, the system exported more solar energy, reaching up to

6,497 kWh annually in scenarios with 60% or higher export rates. However, due to the limited BESS capacity, battery discharge and the share of EV charging from stored solar energy remained constant at around 1,268 kWh/year (24%). This indicates that the system's energy flow behavior is largely dictated by export policy incentives, rather than storage flexibility. Higher export incentives shifted the energy balance towards grid export, while lower incentives encouraged greater on-site self-consumption.

Table 9. Technical Results of Sensitivity Analysis 1 – Export Compensation Variation

Export	PV	Inverter	BESS	Grid Energy Consumption (kWh/year)	PV Production (kWh/year)	PV Energy Exported to Grid (kWh/year)	Battery Output (kWh/year)	EV Charging Supplied from BESS
30%	8.98	5.66	5.00	7,328	12,544	6,12	1,268	24%
35%	9.00	5.89	5.00	7,326	12,576	6,245	1,269	24%
40%	9.00	6.33	5.00	7,328	12,576	6,393	1,269	24%
45%	9.00	6.33	5.00	7,326	12,576	6,392	1,269	24%
50%	9.00	6.16	5.00	7,326	12,576	6,342	1,269	24%
55%	8.98	6.61	5.00	7,328	12,544	6,426	1,268	24%
60%	8.97	8.81	5.00	7,329	12,534	6,497	1,268	24%
65%	8.97	8.81	5.00	7,329	12,534	6,497	1,268	24%
70%	8.97	8.81	5.00	7,329	12,534	6,497	1,268	24%
75%	8.97	8.81	5.00	7,329	12,534	6,497	1,268	24%
80%	8.97	8.81	5.00	7,329	12,534	6,497	1,269	24%
85%	8.97	8.81	5.00	7,329	12,534	6,497	1,268	24%

Economically, the simulation revealed that export compensation rates have a substantial influence on key financial indicators as illustrated in Table 10.

Table 10. Economic Results of Sensitivity Analysis 1 – Export Compensation Variation

Ekspor	NPC ($)	LCOE ($/kWh)	IRR (%)	Payback Period (year)	Electricity Bill Savings ($/year)	Initial Investment Cost ($)	Operating Cost ($/year)
25%	11,338	0.056	12	6.6	703,22	4,351	643,00
30%	11,006	0.054	13	6.3	733,25	4,346	612,91
35%	10,661	0.052	14	6.1	768,59	4,381	577,93
40%	10,316	0.050	15	5.9	805,81	4,435	541,25
45%	9,969	0.048	16	5.6	837,77	4,435	509,29
50%	9,626	0.047	17	5.4	867,19	4,414	479,65
55%	9,286	0.045	17	5.2	903,35	4,462	443,97
60%	9,119	0.044	17	5.3	946,26	4,732	403,75
65%	8,766	0.042	18	5.1	978,75	4,732	371,27
70%	8,413	0.041	19	4.9	1,011,00	4,732	338,78
75%	8,061	0.039	20	4.8	1,044,00	4,732	306,30
80%	7,708	0.037	20	4.6	1,076,00	4,732	273,81
85%	7,355	0.035	21	4.5	1,102,00	4,732	241,33

As the export rate increased, improvements were seen across Net Present Cost (NPC), Levelized Cost of Energy (LCOE), and Payback Period, with a corresponding rise in the Internal Rate of Return (IRR). At a 25% export rate, the IRR was 12%, while a 40% export rate yielded an IRR of 15% and a payback period of 5.9 years, surpassing the no-export scenario (IRR 14%). Based on this, the 40% compensation rate can be considered the economic feasibility threshold for household investment.

Given these findings, the 40% export compensation scenario was selected as the optimal case for this sensitivity analysis. It provides a balance between customer benefit and system simplicity, achieving a favorable IRR of 15%, an annual electricity bill saving of $805.81, and maintaining the base configuration of a 9 kW PV system with a 5 kWh BESS. Furthermore, this scenario offers policy relevance: while full net-metering has been revoked, a partial export compensation scheme remains viable and could serve as a realistic, balanced policy alternative to encourage rooftop PV adoption among EV-owning households. It aligns both with consumer incentives and grid stability concerns.

Nevertheless, system utilization for EV charging remains suboptimal. With only 24% of EV energy demand met by stored solar power, most charging still relies on grid electricity. This indicates the need for further analysis on battery capacity expansion to improve energy autonomy. The next section therefore explores sensitivity to BESS size, aiming to enhance the alignment between solar energy availability and EV charging patterns, especially during nighttime peaks.

- **Sensitivity Analysis 2 – Increasing BESS Capacity**

This analysis examines the impact of increasing battery storage capacity on the technical utilization of rooftop PV for EV charging. Under the previous configuration (5 kWh BESS, 40% export compensation), only 24% of EV energy demand was met using stored solar energy. With PV capacity and export scheme held constant, battery capacity was incrementally increased to evaluate its effect on solar energy usage for nighttime EV charging.

Table 11. Technical Results of Sensitivity Analysis 2 – Incresing BESS Capacity

Ekspor	NPC ($)	LCOE ($/kWh)	IRR (%)	Payback Period (year)	Electricity Bill Savings ($/year)	Initial Investment Cost ($)	Operating Cost ($/year)	EV Charging Supplied from BESS
5	9.00	6.33	10	7,328	12,576	6,393	1,269	24%
10	9.00	6.33	10	6,257	12,576	5,209	2,394	45%
15	8.99	5.20	15	5,282	12,560	3,786	3,421	64%
20	8.99	5.20	20	4,588	12,560	3,125	4,151	78%
25	9.00	5.01	25	4,227	12,576	2,729	4,530	85%
30	9.00	5.01	30	3,923	12,576	2,435	4,850	91%

The results show (Table 11) that increasing BESS capacity significantly enhances solar utilization. At 15 kWh, the system meets 64% of EV demand from stored PV, exceeding the technical target of 50%. A further increase to 30 kWh pushes this share to 91%, while also reducing grid reliance and exported surplus energy. Grid energy consumption drops by nearly 50%, and exported energy decreases substantially, indicating more efficient local energy use.

Table 12. Economic Results of Sensitivity Analysis 2 – Incresing BESS Capacity

Ekspor	NPC ($)	LCOE ($/kWh)	IRR (%)	Payback Period (year)	Electricity Bill Savings ($/year)	Initial Investment Cost ($)	Operating Cost ($/year)
5	10,316	0.050	15	5.9	805.81	443,5	541.25
10	10,888	0.056	12	6.9	867.43	554.1	492.13
15	11,514	0.065	9.6	7.8	909.54	650.4	461.09
20	12,274	0.072	7.6	8.8	953.82	760.9	429.31
25	13,264	0.080	5.7	9.9	974.79	869.3	420.64
30	14,296	0.088	4.1	11	994,03	979.8	413.90

However, these technical improvements come with economic trade-offs. Higher battery capacity results in increased investment and operating costs as shown in Table 12. The system's Net Present

Cost rises from $10,316 (5 kWh) to $14,296 (30 kWh), while IRR declines from 15% to just 4.1%. At 15 kWh, the system achieves strong technical performance but only yields a 9.6% IRR below the feasibility threshold of 14%.

Thus, while 15 kWh is technically optimal for meeting EV charging needs from solar, it remains economically marginal under current cost structures. This underscores the need for policy support or cost reductions to make higher-capacity systems more financially viable. The subsequent analysis explores the effect of component price declines on system feasibility.

- **Sensitivity Analysis 3 – Export Compensation Rate Variation**

This final sensitivity analysis evaluates the economic feasibility of a rooftop PV system with a 15 kWh BESS and 40% export compensation, previously shown to meet technical targets but fall short economically. Annual component cost reductions were assumed: 12% for PV modules and inverters [11], and 8% for batteries [28]. The objective is to determine when this configuration becomes economically viable (IRR > 14%), thus identifying the optimal adoption timeline for EV-owning households.

Technically, the system maintains consistent performance across the 2025–2035 projection period (Table 13). Solar output remains stable at around 12,560 kWh/year, while grid import hovers near 5,280 kWh/year. Exported energy slightly increases from 3,786 to 4,251 kWh/year, and battery output stays at approximately 3,422 kWh/year. The share of EV energy met from stored solar remains constant at 64%, indicating no degradation in system performance despite changing component efficiency assumptions.

Table 13. Technical Results of Sensitivity Analysis 3 – Export Compensation Rate Variation

Ekspor	NPC ($)	LCOE ($/kWh)	IRR (%)	Payback Period (year)	Electricity Bill Savings ($/year)	Initial Investment Cost ($)	Operating Cost ($/year)	EV Charging Supplied from BESS
2025	8.99	5.20	15	5,282	12,560	3,786	3,421	64%
2026	8.99	5.72	15	5,283	12,565	3,982	3,422	64%
2027	9.00	5.91	15	5,281	12,576	4,046	3,423	64%
2028	8.99	5.89	15	5,283	12,565	4,036	3,422	64%
2029	9.00	6.00	15	5,281	12,576	4,070	3,423	64%
2030	9.00	6.44	15	5,281	12,576	4,162	3,423	64%
2031	9.00	7.12	15	5,281	12,576	4,239	3,423	64%
2032	8.97	8.93	15	5,286	12,539	4,231	3,420	64%
2033	8.97	8.93	15	5,286	12,539	4,231	3,420	64%
2034	8.99	9.17	15	5,283	12,563	4,251	3,422	64%
2035	8.99	9.17	15	5,283	12,563	4,251	3,422	64%

Economically, the projected component price decline significantly improves system feasibility. The IRR, initially at 9.6% in 2025, surpasses the 14% threshold by 2027 and reaches 36% by 2035, driven by falling capital costs from $6,504 to $2,464 and decreasing Net Present Cost (NPC), which drops from $11,514 to $6,780 (Table 13). LCOE follows a similar trend, falling from $0.0646/kWh to $0.0370/kWh. While annual savings remain steady at around $910, the relative financial benefit increases as upfront investment shrinks. Payback period improves sharply, from 7.8 years to only 2.7 years by 2035.

These results confirm that the system becomes financially viable by 2028, when the IRR reaches 16%, exceeding the economic threshold set in the base scenarios. As the system already meets the technical benchmark covering 64% of EV charging with stored solar energy 2028 emerges as the earliest year when investment becomes attractive without requiring subsidies. This reinforces the importance of timing in system adoption, and highlights the role of cost decline in bridging the gap between technical and economic feasibility. These insights provide a strong foundation for designing forward-looking policy incentives and financing strategies to accelerate early adoption of rooftop PV with storage among EV-owning households.

Table 14. Economic Results of Sensitivity Analysis 3 – Export Compensation Rate Variation

Ekspor	NPC ($)	LCOE ($/kWh)	IRR (%)	Payback Period (year)	Electricity Bill Savings ($/year)	Initial Investment Cost ($)	Operating Cost ($/year)
2025	11,514	0,0646	9.6	7.8	909.54	6,504.00	461.09
2026	10,764	0,0597	12	6.9	917.50	5,913.00	446.53
2027	10,099	0,0558	14	6.2	920.25	5,345.00	437.47
2028	9,510	0,0526	16	5.6	919.52	4,812.00	432.31
2029	8,971	0,0495	19	5.0	921.22	4,348.00	425.46
2030	8,483	0,0466	21	4.5	925.01	3,950.00	417.22
2031	8,059	0,0440	24	4.1	928.17	3,602.00	410.18
2032	7,771	0,0425	26	3.7	927.38	3,339.00	407.95
2033	7,405	0,0405	29	3.4	927.38	3,012.00	404.35
2034	7,077	0,0386	32	3.0	928.49	2,729.00	400.11
2035	6,780	0,0370	36	2.7	928.49	2,464.00	397.19

4.3. CO_2 Emission Reduction Analysis

To evaluate the environmental impact of system adoption, a comparative analysis was conducted between the baseline Grid Only scenario and the optimized configuration, PV + Grid + 15 kWh BESS with 40% export compensation, identified as economically feasible starting in 2028. Under the Grid Only scenario, annual CO_2 emissions from household consumption and EV home charging reach 11,269 kg, with EV charging alone accounting for 3,033 kg (Table 15).

Table 15. CO_2 Emission Reduction

Scenario	Household CO_2 Load and EV (kg/year/customer)	Specific CO_2 from EV Home Charging (kg/year/customer)
Grid Only	11,269	3,033
Solar PV + Grid + BESS 15 kWh (export, 40%)	1,337	360
Reduction	9,932	2,673

In contrast, the integrated PV-BESS system reduces total emissions to just 1,337 kg CO_2 annually, including only 360 kg from EV charging. This represents an annual reduction of 9,932 kg CO_2 for combined residential and EV loads, and 2,673 kg for EV charging alone highlighting the substantial decarbonization potential of decentralized solar with storage.

When scaled across Jakarta's 10,445 EV customers as of March 2025 (PLN CSMS data), full adoption of this system could result in an annual emission reduction of approximately 103,740 tons of CO_2, with around 27,924 tons attributable to EV charging. This emphasizes that rooftop solar integrated with battery storage not only reduces grid dependency but also offers a substantial contribution toward national emission reduction targets and supports the transition to a cleaner, more sustainable energy system.

4.4. Policy Implication Discussion

Based on the main and sensitivity simulation results, several strategic policy recommendations can be proposed to accelerate the adoption of integrated rooftop PV and BESS systems among residential EV owners in Jakarta. First, the export compensation mechanism for surplus PV electricity sent to the PLN grid should be reconsidered. Simulations indicate that a compensation rate of 40% of the retail electricity tariff represents a viable economic compromise, achieving an IRR of ≥15% while minimizing potential stress on the distribution network. Such a scheme can incentivize customers to maximize rooftop PV capacity without over-reliance on grid remuneration.

Second, fiscal incentives or investment subsidies, especially for BESS components are crucial to bridge the gap between technical and financial feasibility. The analysis shows that by 2028, declining technology costs will render the PV + 15 kWh BESS configuration economically viable (IRR > 14%). However, without interim policy support, early adoption may stagnate. Therefore, a targeted incentive program between 2025 and 2028 could catalyze residential uptake and accelerate the transition to distributed clean energy systems.

Furthermore, this study recommends exploring co-investment models between PLN and customers as a transformative policy alternative. Rather than positioning itself solely as an electricity supplier, PLN could act as a shared investor in customer rooftop PV systems through profit-sharing or leasing arrangements. Such schemes would lower the capital barrier for households, provide PLN with new revenue streams, and significantly accelerate renewable energy deployment in urban residential sectors. This approach aligns with global trends in utility business model innovation and presents a pathway for PLN to retain economic relevance in the evolving energy landscape while supporting national decarbonization goals.

5. Conclusion

This study identifies the optimal configuration as a rooftop PV system of approximately 8.97 kWp coupled with a 5-kWh battery energy storage system (BESS) and grid connection, operating under a 65% export compensation scheme. This setup yields strong techno-economic performance, achieving an internal rate of return (IRR) of 18% and a payback period of 5 years, while maximizing rooftop potential. Export compensation levels significantly affect feasibility; a 40% compensation rate offers a viable trade-off, balancing customer economics (IRR of 15%) and grid considerations, and thus forms the basis for further sensitivity analyses.

Although higher-capacity BESS (e.g., 15 kWh) can increase solar utilization—covering up to 64% of EV energy needs—these systems are not yet cost-effective under current market conditions. A 5 kWh BESS remains the most feasible configuration, supporting approximately 24% of EV energy demand. Sensitivity analysis indicates that declining battery and inverter costs will improve the feasibility of larger systems after 2028, with IRRs exceeding 16% and payback periods under 6 years.

From an environmental perspective, implementing rooftop PV systems with BESS and a 40% export compensation scheme—combined with projected component cost reductions by 2028—can reduce carbon emissions by up to 9.9 tons CO_2 per household annually. If widely adopted across EV-owning households in Jakarta, the total emission reduction potential exceeds 100,000 tons CO_2 per year, making this solution a strategic pathway to support Indonesia's national decarbonization targets.

To bridge the economic gap and accelerate adoption, the study recommends several policy measures: (1) maintaining a minimum export compensation rate of 40%, (2) providing targeted investment incentives for BESS installations before 2028, (3) promoting co-investment models as inclusive and accelerated public–private partnerships. These policy interventions should be underpinned by technical and economic analysis to ensure scalable and effective implementation in Indonesia's residential clean energy transition.

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The authors hereby declare significant contributions to the research process, manuscript preparation, and publication stages.

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