



Circular Economy Approach for PV-Grid Charging Station and Economic Feasibility Analysis. Case Study: Central Java Provinces, Indonesia

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ARTICLE INFO

Article history:

Received November 9, 2025

Revised February 23, 2026

Accepted March 2, 2026

Available online March 12, 2026

Published May 24, 2026

Keywords:

PV-Grid Charging Station,
Circular Economy,
Renewable Energy,
Electric Vehicle,
Economic Feasibility.

ABSTRACT

This study identifies the sustainability challenges of transportation carbon emissions in Central Java, which remains dominated by coal-fired power plants (62%), rendering electric vehicle (EV) adoption less effective in reducing carbon emissions while simultaneously facing limited Public Electric Vehicle Charging Station (PEVCS) infrastructure. To address this gap, this study develops a hybrid solar-grid PEVCS business model using a circular economy 9R framework approach—with a specific focus on the R2 (Reduce) strategy to minimize carbon emissions as non-recyclable waste by reducing PEVCS dependence on fossil fuel-based grid electricity—and engineering economic feasibility analysis. A three-stage sensitivity simulation was conducted, iterating from 100% to 30% solar PV ratios, to identify the optimal energy mix that maximizes carbon reduction while satisfying all four engineering economics feasibility criteria (NPV > 0, ROI > 10%, PP < investment horizon, and BC Ratio > 1). Results reveal an optimal ratio of 36% solar PV and 64% grid power, which constitutes the mathematical realization of the R2 strategy, capable of reducing carbon emissions by 36% compared to grid-powered PEVCS—from 302,940 kg CO₂ to 193,882 kg CO₂ annually—while remaining economically viable with an NPV of IDR 2.461 billion, ROI of 10.5%, BC Ratio of 1.5, and a payback period of 9.5 years. This study provides practical solutions for policymakers and entrepreneurs in accelerating sustainable electric vehicle transition in Central Java.

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1. INTRODUCTION

The development of electric vehicles in Indonesia has been increasing alongside government support through Presidential Regulation Number 79 of 2023 concerning the Acceleration Program for Battery Electric Motor Vehicles for Road Transportation. Based on data from the Ministry of Transportation, as of the end of November 2024, there were 195,084 battery electric motor vehicles in Indonesia. This number consists of 160,578 electric motorcycles, 33,555 electric cars, and 951 other battery electric motor vehicles (Abdurrahman, 2025). In addition to government support for accelerating the electric vehicle program, Central Java province faces issues with high carbon emissions. Total carbon emissions in Central Java amount to 69 million tons CO₂, with the fossil fuel car sector contributing 41 million tons CO₂ and the motorcycle sector contributing 28 million tons CO₂, making cars responsible for 59% of carbon emissions in urban areas (Salatiga, 2023). The adoption of electric vehicles faces infrastructural constraints as the number of PEVCS in Central Java and DIY is only 98 units (Wijaya & Anugrah, 2024). Of these 98 PEVCS units, all use energy from the state electricity company (PLN), while PLN power plants still derive 62% of their energy from coal (Salatiga, 2023), meaning the goal of replacing fossil fuel vehicles with electric vehicles to address sustainability issues has not been achieved. Therefore, PEVCS utilizing renewable energy sources are needed. However, PEVCS that fully utilize renewable energy sources tend to be unstable due to weather fluctuations (Wijaya & Anugrah, 2024). Consequently, hybrid solar and PLN power PEVCS are being developed in Solo city. This approach aligns with previous studies (Singla et al., 2024; Tabassum et al., 2025; Wahedi & Bicer, 2021) that combine renewable energy and stable energy as PEVCS energy sources.

1.1 Literature review

Several studies implementing hybrid PEVCS globally have been examined in depth. Wahedi & Bicer (2021) developed a PEVCS design combining concentrated PV (CPV), wind turbines, and bio-generators in Qatar using a techno-economic approach. Singla et al. (2024) developed a PEVCS design combining solar power and the national electricity grid in India using simulation with the P&O algorithm. Tabassum et al. (2025) developed an adaptive energy management strategy for hybrid solar and national grid PEVCS in India using MATLAB simulation with fuzzy logic. Racmanto et al. (2024) developed hybrid PV-Wind-Grid in 4 Indonesian cities (Yogyakarta, Surakarta, Bandung, and Surabaya) using an engineering economics approach. Schnek (2020) developed hybrid PV-Grid in Amsterdam, Netherlands using a circular economy approach.

Subsequently, the reviewed literature focuses on methods and approaches used to study PEVCS in Indonesia. Sholichah & Sutopo (2020) developed a business model using the business model canvas approach for battery swap PEVCS. Nugrahadi et al. (2020) developed a business model using MILP and engineering economics approaches for electric pedicab PEVCS in Solo city. Sutardi et al. (2023) used a techno-economic approach to evaluate PLN-owned solar-powered PEVCS.

Finally, a literature review was conducted to map the state-of-the-art research over the past 5 years, presented in Table 1. From the reviewed literature, research focusing on hybrid PEVCS remains scarce, with only one study using a circular economy approach on hybrid PEVCS without analyzing its economic feasibility.

Therefore, this research formulating research questions: (1) How can the circular economy approach on hybrid PEVCS reduce carbon emissions compared to emissions from grid-powered PEVCS? (2) How is the economic feasibility of the hybrid PEVCS designed and simulated in this paper?

Table 1. State of the art

Publications	Sustainability Issue	Hybrid Charging Station	Circular Economy	Economic Feasibility
Sholichah & Sutopo, 2020	V			
Nugrahadhi et al., 2020				V
Schnek, 2020	V	V	V	
Baars et al., 2021	V		V	
Zellagui et al., 2021	V			
Wahedi & Bicer, 2021	V	V		V
Goncearuc et al., 2022	V			V
Istiqomah et al., 2022	V			V
Thakur et al., 2022	V		V	
Allouhi & Rehman, 2023	V	V		V
Alrubaie et al., 2023	V			
Sutardi et al., 2023	V			V
Campaña & Inga, 2023	V			
Deveci et al., 2023	V			
Etxandi-Santolaya et al., 2023	V		V	
Hasan et al., 2023	V			V
Hassini et al., 2023	V		V	
Marchesano et al., 2023	V			
Parlikar et al., 2023	V			V
Rachmanto et al., 2023	V	V		V
Ribeiro da Silva et al., 2023	V		V	
Yadav et al., 2023	V			
Yu et al., 2023				V
Faisal et al., 2024	V			V
Khan et al., 2024	V			
Mohammed et al., 2024	V			V
Nasab et al., 2024	V			
Anandan et al., 2024	V			V
Racmanto et al., 2024	V	V		V
Singla et al., 2024	V	V		V
Zhao & Hao, 2024	V			
Tabassum et al., 2025	V	V		V
This Research	V	V	V	V

1.2 Application of circular economy and engineering economics analysis

1.2.1 Circular economy 9R framework

Circular economy represents an approach that has become a central focus in addressing sustainability challenges. According to a systematic literature review conducted by Arruda et al. (2021), circular economy is defined as a systemic model aimed at minimizing the use of non-renewable resources, achieving zero waste that cannot be recycled such as carbon emissions, and returning recyclable waste to the value chain, replacing the linear "take-make-dispose" approach. Several studies on implementing circular economy within the scope of electric vehicles (Baars et al., 2021; Etxandi-Santolaya et al., 2023; Ribeiro da Silva et al., 2023; Thakur et al., 2022) employ a circular economy approach to process electric vehicle battery waste to address sustainability issues. Meanwhile, Schnek (2020) utilized a circular economy approach on hybrid PEVCS by implementing the 9R framework. The 9R framework is explained in detail by Hunger et al. (2024), consisting of: Refuse, Rethink, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle, Recover. In several previous PEVCS case studies (Goncearuc et al., 2022; Singla et al., 2024; Zellagui et al., 2021), the sustainability aspect benchmarks used are carbon emission reduction and reducing dependence on the electricity grid with fossil fuel-based generation. Therefore, this research will focus on Reduce from the 9R framework to reduce hybrid PEVCS carbon emissions, which will be compared with emissions from grid-powered PEVCS.

1.2.2 Economic feasibility analysis with engineering economics parameters

In addition to sustainability considerations, PEVCS must also be examined for economic feasibility so that entrepreneurs are interested in establishing new PEVCS and accelerating the electric vehicle transition in Indonesia. Based on previous research examining economic feasibility of hybrid PEVCS (Allouhi & Rehman, 2023; Gabbar & Siddique, 2023; Anandan et al., 2024; Racmanto et al., 2024; Singla et al., 2024; Tabassum et al., 2025; Yadav et al., 2023), the parameters used as references are net present value (NPV), payback period (PP), rate of interest (ROI), benefit-cost ratio (B/C Ratio) with feasibility criteria of (NPV > 1, PP < investment horizon, ROI > 10%, and B/C Ratio > 1).

2. METHODS

2.1 Methodology

2.1.1 Research object

This research focuses on developing a business model for Hybrid PEVCS using a circular economy approach and feasibility analysis utilizing engineering economics parameters with a case study in Central Java province. In this model, carbon emissions constitute intangible, non-recyclable waste generated during PEVCS operation. Unlike material waste that can re-enter the value chain through recycling, CO₂ emitted from coal-fired grid electricity (0.85 kg CO₂ /kWh) represents an irreversible linear output—extracted, burned, and accumulated in the atmosphere with no pathway for re-entry into the operational cycle. The circular economy's 'close the loop' principle is violated each time grid-dependent PEVCS converts fossil-sourced electricity into a transport service. By substituting 36% of grid power with solar PV, this study closes 36% of the carbon loop, reducing annual waste from 302,940 kg CO₂ to 193,882 kg CO₂. The prototype of the research object is shown in Figure 1.

2.1.2 Data collection

In this study, primary data utilized includes direct observation and expert interviews, while secondary data comprises journals, books, and previous articles related to circular economy implementation for

designing economically and sustainability-viable business models. Direct observation was conducted to collect actual sample data of cars arriving daily at PEVCS Surakarta. Research limitations include the Central Java province scope, direct observation for demand data collection at grid-powered PEVCS rather than hybrid PEVCS due to the absence of public hybrid PEVCS, and the assumption of stagnant annual demand data for the next 10 years.



Fig 1. Hybrid PEVCS Prototype

2.1.3 Data processing

The circular economy approach is employed to model a sustainable business concept with 9R principles at PEVCS by analyzing and focusing on the reduction (reduce) strategy of PLN grid dependence, enabling PEVCS to reduce carbon emissions resulting from PLN grid usage and decrease operational costs from PLN grid utilization.

The second stage employs engineering economics as an instrument for analyzing business feasibility from an economic perspective, for both conventional PEVCS that fully utilize PLN electricity.

The third stage conducts sensitivity analysis to identify the optimal point of solar versus PLN power ratio that still meets economic feasibility criteria, and analyzes the comparison of economic feasibility and sustainability aspects between PLN PEVCS and hybrid PEVCS with the most optimal ratio.

2.2 Collected data

2.2.1 Observation data

Based on direct observation results and user interviews, the data is presented in Table 2.

2.2.2 Secondary data from literature

Secondary data collected from various sources (government regulations, official prices from supplier catalogs, PT XYZ financial reports, research papers) is presented in Table 3.

Data sources used in Table 3 in detail as follows:

- Based on research (Sigirot et al., 2024) in Indonesia, carbon emissions produced by PLN power plants amount to 0.85 kg CO₂ per kWh.

- Minister of Energy and Mineral Resources Decree Number 182.K of 2023 establishes the bulk electricity cost per kWh for PEVCS entrepreneurs at IDR 714, while the maximum sales tariff is IDR 2,466.
- Fixed costs (maintenance, overhead, salary, rent) per year are based on expert interviews at PT XYZ.
- The 10-year investment horizon is based on previous research in Brunei (Danial et al., 2021) and previous research in Indonesia (Hanun et al., 2023).
- The inflation rate is based on average inflation data from Bank Indonesia for the period January 2024 - October 2025, amounting to 2.04%.

Table 2. PEVCS Observation Data

Parameters	Values
Average PEVCS Users	22 cars per day
Average Maximum EV Capacity	60 kW
Average Charging per Transaction	75% of maximum capacity
Average Lead Time	45 minutes
Operating Hours	24 Hours
Sales Tariff per kW	IDR 2,466

Table 3. Secondary Data

Parameter	Value
Grid-powered PEVCS carbon emissions in Indonesia	0.85 (kg CO ₂) / kWh
Purchase tariff per kW	IDR 714
DC Fast Charging CCS2 (150 kW) price / unit	IDR 1.2 Billion
Maintenance cost / year	IDR 12 million
Overhead cost / year	IDR 24 million
Employee salary / year	IDR 24 million
120m land rent / year	IDR 120 million
Average Inflation Rate	2.04%
Investment horizon	10 years

3. APPLICATION OF CIRCULAR ECONOMY

3.1 Hybrid PEVCS business model

The business model presented in Figure 2 illustrates an integrated value flow, starting from basic component suppliers to end users. This structure reflects the implementation of circular economy that optimizes sustainability at every stage.

3.2 9R Framework on Hybrid PEVCS

In addition to the implemented business model, this study has also applied the 9R strategy focused on reduction (Reduce) of dependence on the national electricity grid (PLN) with the ultimate goal of reducing carbon emissions generated from state-owned power plants, where 62% still utilize coal energy sources (Salatiga, 2023). The complete 9R strategy implemented at PT XYZ is presented in Table 4.

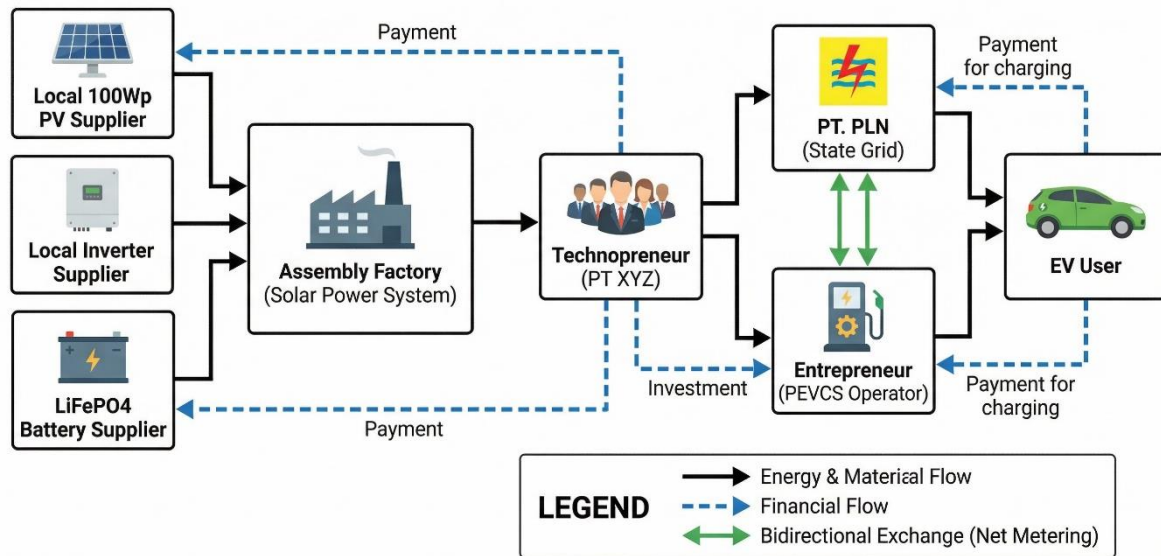


Fig 2. Hybrid PEVCS Business Model

R2 was selected for this paper focused objective because (1) Immediate deployability, Grid-tied solar PV is proven technology with established Indonesian supply chains, whereas R3 (second-life batteries) and R8 (recycling) require reverse logistics infrastructure not yet available in Central Java. (2) Direct carbon linkage, R2 directly addresses the core sustainability problem—PLN grid's 62% coal dependence—by reducing grid electricity consumption by 128,304 kWh/year. (3) Economic feasibility first, R2 achieves economic viability (11% ROI, 9.5-year payback) to establish revenue streams that can fund future R3–R9 implementations.

Table 4 identifies R3 (Reuse) as: "Reuse used electric vehicle batteries as an energy storage system (ESS) in solar PV systems"—flagged as a future improvement opportunity. A comprehensive review confirms several critical barriers, (1) Insufficient supply volume. The Ministry of Transportation recorded 207,478 battery electric vehicles in Indonesia as of June 2025 (Darat, 2025). Most are under 3 years old, meaning retired batteries won't reach meaningful volumes until 2028–2032. (Dong et al., 2023) (2) Diagnostic and safety challenges, Second-life battery utilization faces "arduous safety certification requirements" and "lack of homogeneity of battery packs from different EV models". Without standardized health diagnostics, integrating retired batteries into PEVCS ESS carries unacceptable technical risk. (Rudijanto, 2025) (3) Uncertain economic advantage, While second-life batteries can reduce LCOS by ~40% compared to new batteries, the rapidly declining cost of new LiFePO₄ batteries (already IDR 12.7M/unit in this study) narrows the economic incentive. (Steckel et al., 2021) (4) Potential carbon penalty, Research shows that second-life batteries used for load shifting can "increase carbon footprint compared to the grid-only scenario due to electricity losses during charging and discharging", potentially undermining the R2 Reduce gains. (Rudijanto & Sudiro, 2024) (5) Regulatory gaps, Indonesia lacks clear standards for second-life battery safety and warranty in commercial PEVCS applications, unlike the EU's proposed battery passport system (*Indonesia Second Life Electric Vehicle Battery Market Report*).

The implementation of the R2 (Reduce) strategy is applied after obtaining the optimal ratio of solar power to grid power. The R0 (Refuse) and R1 (Rethink) strategies have become the foundation for developing the hybrid PEVCS business model, while strategies R3–R9 are identified as improvement opportunities for future research, which will be discussed in the conclusion section.

Table 4. 9R Framework Circular Economy Implementation

CE Strategy		Implemented Strategy	Identified Improvement Opportunities Based on FGD and Interviews
R0	Refuse	Refusing partial use of electricity from non-renewable sources.	Completely refuse the use of electricity from non-renewable sources.
R1	Rethink	Redesigning the business model from grid-powered PEVCS to hybrid solar-grid PEVCS.	Redesign the PEVCS business model that implements all 9R frameworks.
R2	Reduce	Reducing carbon emissions from PEVCS by reducing PEVCS dependence on non-renewable energy sources.	Reduce raw materials composing PEVCS that are not environmentally friendly.
R3	Re-use		Reuse used electric vehicle batteries as energy storage system
R4	Repair		Conduct scheduled periodic repairs on hybrid PEVCS to maintain operational efficiency.
R5	Refurbish		Rejuvenate used EV batteries into refurbished batteries for stationary storage applications.
R6	Remanufacture		Remanufacture battery components that cannot be repaired for material recovery.
R7	Repurpose	Not Implemented	Integrate several other renewable energy sources to reduce fossil fuel-based energy use.
R8	Recycle		Recycle electronic components and metal materials from PEVCS reaching end-of-life.
R9	Recover		Recover residual energy from PEVCS operational waste to minimize waste.

4. ECONOMIC FEASIBILITY ANALYSIS

4.1 Economic and technical feasibility analysis of Grid-Powered PEVCS

Based on observation results in Table 3, the PEVCS equipment requirement to prevent bottlenecks is 1 unit with 2 CCS2 connectors, with investment cost calculations in Table 5.

Based on observation results in Table 3, assumptions for daily and annual electricity energy (kW) requirements per PEVCS are presented in Table 6.

Based on secondary data results in Table 4 and annual demand assumptions in Table 6, the financial journal for grid-powered PEVCS is presented in Table 7.

Table 5. Grid-Powered PEVCS Investment Cost

PEVCS Equipment Type	Price	Number of Units	Total Investment Cost
DC Fast Charging CCS2 (150 kW)	IDR 1.2 Billion	1 Unit with 2 connectors	IDR 1.2 Billion
Total investment cost / PEVCS area			IDR 1.2 Billion

Table 6. PEVCS Demand Assumptions

Parameter	Value
Average Transactions per day	22
Average kW per transaction	45
Daily Average kW	990
Yearly Average kW	356,400

Table 7. Grid-Powered PEVCS Profit-Loss Balance Sheet

Item	TOTAL
REVENUE	
Electricity Sales (IDR 2,466 × 356,400)	IDR 878,882,400
Total Revenue	IDR 878,882,400
COSTS	
Maintenance	IDR 12,000,000
Overhead	IDR 24,000,000
700 m ² Land Rent	IDR 120,000,000
Employee Salary (IDR 2,000,000 × 12 months)	IDR 24,000,000
Energy Cost (IDR 714 × 356,400)	IDR 254,469,600
NET PROFIT	IDR 444,412,800

4.2 Optimal Hybrid PEVCS ratio point

Tables 8 and 9 show the detailed investment costs for PEVCS using full solar power. This data serves as the basis for simulation to determine the optimal point of solar energy to grid energy ratio with the goal of achieving the smallest carbon emissions while remaining economically feasible according to engineering economics standards.

Based on detailed cost breakdown is presented in Table 8, solar PV system is designed to meet the 100% solar scenario (990 kWh/day), serving as the baseline for sensitivity simulation. The system utilizes ST Solar Monocrystalline panels rated at 100 Wp each, with a module efficiency of 15–17%. Based on Central Java's average Peak Sun Hours (PSH) of 4.8 h/day and a system Performance Ratio (PR) of 0.79—accounting for temperature derating, soiling, and wiring losses—each panel produces approximately 0.38 kWh/day. A total of 2,600 panels (260 kWp installed capacity) are required to generate the full 990 kWh/day demand, with an expected annual degradation rate of 0.5–0.7% over the 25-year panel lifetime.

Table 8. Detailed Solar PV system specification

Component	Specification	Units Required	Price per Unit (IDR)	Total (IDR)
Solar Panels	ST Solar Monocrystalline, 100 Wp/panel	2,600 panels	550	1,430,000,000
Inverter	Cellcronic Axpert Max Hybrid 3.6 kW–24V (8 kWp/unit)	~19 units	13,500,000	159,375,000
Battery (ESS)	Powerwall LiFePO ₄ built-in BMS, 9.6 kWh/unit, 25-year lifetime	144 units	12,700,000	1,828,800,000
Installation	Cabling & support structures (15% of panel cost)	—	—	214,500,000
Total				3,632,675,000

The battery energy storage system (ESS) employs LiFePO₄ (Lithium Iron Phosphate) chemistry with built-in Battery Management System (BMS), selected for its high cycle life ($\geq 6,000$ cycles), thermal stability, and 25-year calendar lifetime. Each pack has a nominal capacity of 9.6 kWh, and 144 packs are configured to provide a total nominal capacity of 1,382.4 kWh. With a Depth of Discharge (DoD) of 80% and round-trip efficiency of 95%, the usable capacity is 1,050.6 kWh—equivalent to approximately 23 full EV charging sessions at 45 kWh per transaction. At the optimal 36% solar ratio, the daily solar energy requirement is 356.4 kWh; the ESS therefore provides approximately 2.9 days of solar-portion autonomy, ensuring operational continuity during cloudy weather. Under maximum CCS2 charger load (150 kW), the battery operates at only 0.11C—well within the safe continuous discharge limit of 0.5C for LiFePO₄ chemistry.

The system uses Cellcronic Axpert Max Hybrid inverters (3.6 kW–24V, 8 kWp per unit) in a grid-tied hybrid configuration, enabling simultaneous input from both solar panels and the PLN grid. Approximately 19 units provide a total inverter capacity of 152 kWp to accommodate the 260 kWp panel array.

The first iteration conducted to find the optimal point that maximizes carbon reduction while remaining economically feasible was done by reducing the solar power ratio by 10% from initially 100% down to 70%, as shown in Table 10.

Table 9. Solar-Powered PEVCS Investment Cost

PEVCS Equipment Type	Price	Number of Units	Total Investment Cost
DC Fast Charging CCS2 (150 kW)	IDR 1.2 Billion	1 Unit with 2 connectors	IDR 1.2 Billion
Solar power plant system	IDR 3.632 Billion	100% solar power (990 kW)	IDR 3.632 Billion
Total investment cost / PEVCS area			IDR 4.832 Billion

Table 10. Sensitivity Analysis Simulation at 70% - 100% Ratio

Solar PV	70%	80%	90%	100%
NPV (IDR)	IDR	IDR	IDR	IDR
	2,180,170,281	2,101,485,555	2,022,800,829	1,932,732,058
BEP (kWh)	319,248	338,783	358,318	378,577
BEP (IDR)	IDR	IDR	IDR	IDR
	787,265,574	835,438,433	883,611,293	933,571,721
ROI (Percent)	6%	6%	5%	4%
PP (Years)	15.6	17.6	19.8	22.4
B/C Ratio	1.4	1.4	1.3	1.3
Carbon Emissions (kg CO ₂ /year)	90,882	60,588	30,294	0

Table 9 has not yet identified the optimal ratio as all ROI values remain below 10% and payback periods still exceed 10 years. Subsequently, the second iteration was conducted by reducing the solar power ratio by 10% from initially 60% down to 30%, as shown in Table 11.

Table 11 has identified the optimal ratio between 30% and 40%. Subsequently, the third iteration was conducted to find the point that most minimizes carbon emissions by reducing by 1% between 30% - 40%, as shown in Table 12.

Table 12 and figure 3 has identified the most optimal solar power to grid power ratio of 36:64 because it achieves lower carbon emissions compared to the 30% ratio while remaining economically feasible with ROI (11%) > 10%, payback period (9.5 years) < investment horizon (10 years), B/C ratio (1.5) > 1, and NPV (IDR 2,461,368,167) > 1. Subsequently, a financial journal was created for the most optimal hybrid PEVCS in Table 13.

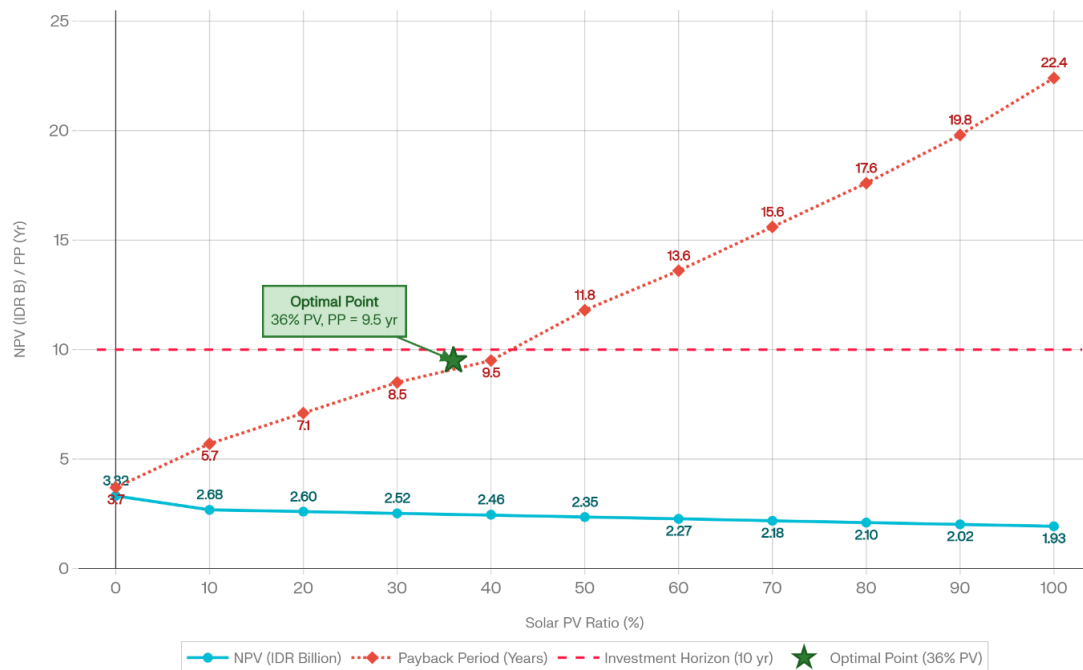


Fig 3. Sensitivity analysis payback period and NPV Chart

Table 11 Sensitivity Analysis Simulation at 30% - 60%

Solar PV	30%	40%	50%	60%
NPV (IDR)	IDR	IDR	IDR	IDR
	2,517,677,274	2,461,368,167	2,348,923,778	2,270,239,052
BEP (kWh)	239,659	251,959	279,453	298,988
BEP (IDR)	IDR	IDR	IDR	IDR
	590,998,998	621,331,361	689,132,286	737,305,146
ROI (Percent)	12%	11%	8%	7%
PP (Years)	8.5	9.5	11.8	13.6
B/C Ratio	1.5	1.5	1.4	1.4
Carbon Emissions (kg CO ₂ /year)	212,058	193,882	151,470	121,176

Table 12 Sensitivity Analysis Simulation at 36% - 39%

Parameter	36%	37%	38%	39%
NPV (IDR)	2,461,368,167	2,461,255,080	2,444,488,335	2,444,575,248
ROI (%)	10.5%	10.4%	10.2%	10.1%
PP (Years)	9.5	9.6	9.8	9.9
BC Ratio	1.5	1.5	1.4	1.4
Carbon (kg CO ₂ /yr)	193,882	190,852	187,823	184,793

Table 13 Hybrid PEVCS Profit-Loss Balance Sheet

Item	TOTAL
REVENUE	
Electricity Sales (IDR 2,466 × 356,400)	IDR 878,882,400
Total Revenue	IDR 878,882,400
COSTS	
Maintenance	IDR 12,000,000
Overhead	IDR 24,000,000
700 m ² Land Rent	IDR 120,000,000
Employee Salary (IDR 2,000,000 × 12 months)	IDR 24,000,000
Energy Cost (IDR 714 × 228,096)	IDR 162,860,544
NET PROFIT	IDR 536,021,856

The total site area is 700 m², comprising ground-level infrastructure for the charging station (approximately 88 m²—including two charging bays of 12.5 m² each, a DC charger cabinet of 6 m², a vehicle access lane of 48 m², and an operator service area of 9 m²) and an elevated solar carport canopy structure covering the entire site. The solar canopy serves a dual function: providing weather protection for charging vehicles and mounting surface for PV panels. At the optimal 36% solar ratio, 936 panels (each approximately 0.55 m²) require a total panel surface area of 515 m². With a tilt angle of 5°—appropriate for Central Java's equatorial latitude—and a Ground Coverage Ratio (GCR) of 0.90, the 700 m² canopy provides 630 m² of effective mounting area, comfortably accommodating all 936 panels on-site. This rate is consistent with prevailing commercial land rental prices in periurban Surakarta, which range from IDR 75,000 to IDR 320,000/m²/year based on market data from property platforms, in this

specific area based on direct observation and interview, the annual land rent is IDR 171,500/m²/year, yielding a total of IDR 120 million/year for the 700 m² site.

4.3 Comparison of sustainability aspects and economic feasibility between Grid-Powered PEVCS and Hybrid PEVCS

The comparison between grid-powered PEVCS and hybrid PEVCS from sustainability and economic perspectives is presented in the following tables 14 and 15.

Table 15 reveals a clear profitability-sustainability trade-off. The grid-only model outperforms economically with 27% ROI and IDR 3.32 billion NPV, while the hybrid model yields 10.5% ROI and IDR 2.46 billion NPV—a sacrifice of IDR 860 million in NPV (26% reduction) and 16 percentage points of ROI. However, this economic premium purchases a 36% annual carbon reduction, from 302,940 kg CO₂ to 193,882 kg CO₂ (109,058 kg CO₂ /year). Under Indonesia's carbon tax floor of IDR 30,000/ton CO₂ e (Law No. 7/2021) and IDXCarbon average market price of IDR 52,295/ton CO₂ e (2024–2025 period), this reduction translates to a potential carbon credit value of IDR 3.27–5.70 million/year—a figure expected to appreciate as carbon prices rise under Presidential Regulation No. 110/2025. Critically, the hybrid model still satisfies all four engineering economics feasibility thresholds (NPV > 0, ROI > 10%, PP < 10 years, BC > 1), confirming that the environmental gain does not compromise investment viability.

The comparison on figure 4 demonstrates that while grid-powered PEVCS offers superior economic metrics, hybrid PEVCS achieves a 36% reduction in carbon emissions while maintaining economic viability. This trade-off between environmental sustainability and economic performance represents the optimal balance for sustainable electric vehicle infrastructure development in Central Java.

Table 14. Sustainability aspect comparison grid vs PV-Grid (Hybrid)

Parameter	Grid-Powered PEVCS	Hybrid PEVCS
PLN Requirement (kWh)	356,400	228,096
Solar PV Requirement (kWh)	0	128,304
Total Carbon Emissions (kg CO ₂)	302,940	193,881.60
Reduction Efficiency		36%

Table 15. Economical aspect comparison grid vs PV-Grid (Hybrid)

Parameter	Grid-Powered PEVCS	Hybrid PEVCS
Investment Cost	IDR 1,200,000,000	IDR 2,614,325,000
Investment Horizon	10 years	10 years
Discount Rate	2%	2%
Average Revenue	IDR 878,882,400	IDR 878,882,400
Fixed Cost + Depreciation	IDR 300,000,000	IDR 441,432,500
NPV (IDR)	IDR 3,321,462,984	IDR 2,461,368,167
ROI (Percent)	27%	11%
PP (Years)	3.7	9.5
B/C Ratio	2.4	1.5

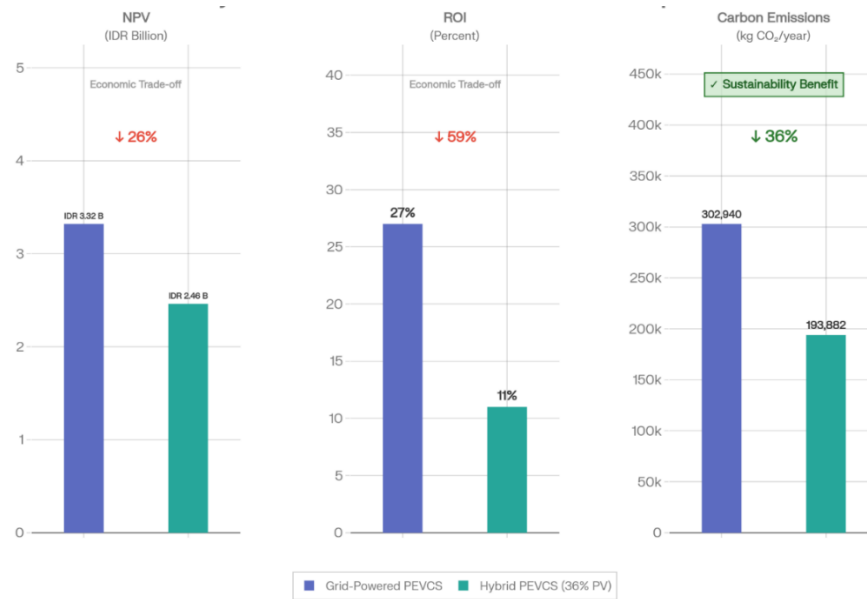


Fig 4. Grid vs Hybrid Comparison Chart

5. CONCLUSION

This paper applies a circular economy approach with the 9R framework to hybrid PEVCS, with a deliberate focus on the R2 (Reduce) strategy as the highest-impact, immediately deployable intervention within the 9R hierarchy. The R2 strategy was operationalized through a three-stage sensitivity simulation that systematically varied the solar PV-to-grid energy ratio from 100% to 30%, iterating in decreasing intervals (10%, then 1%) to identify the precise threshold at which carbon emissions are maximally reduced without compromising economic feasibility. The resulting optimal ratio of 36% solar PV and 64% PLN grid represents the mathematical realization of the R2 (Reduce) strategy—translating the circular economy principle of "minimizing non-recyclable waste" into a quantifiable engineering parameter. At this ratio, the hybrid PEVCS achieves a 36% carbon emission reduction compared to grid-powered PEVCS (from 302,940 kg CO₂ to 193,882 kg CO₂ annually), thus answering the first research question (RQ1). The second research question (RQ2) is answered through engineering economic feasibility analysis demonstrating that the optimal hybrid PEVCS is economically viable with a positive NPV of IDR 2,461,368,167, ROI of 10.5%, BC Ratio of 1.5, and a payback period of 9.5 years—all satisfying the four feasibility thresholds while accepting a deliberate trade-off of lower profitability compared to the grid-only configuration (27% ROI, 3.7-year payback) in exchange for significant environmental gains.

This research provides three main contributions: first, a comprehensive implementation of the 9R circular economy framework on hybrid PEVCS that has not been previously conducted; second, a sensitivity-based optimization methodology that translates the R2 circular economy principle into a mathematically derived optimal energy ratio; third, simultaneous integration of circular economy, economic feasibility, and sustainability analysis within a single framework.

However, this research has limitations: (1) the single case study of PT XYZ in Surakarta may not be representative of all Central Java regions, and demand data collected from grid-powered PEVCS may not fully represent hybrid PEVCS consumer behavior, particularly as customer preferences increasingly shift toward green charging stations; (2) sensitivity analysis is limited to the solar PV–PLN ratio, not yet exploring external variables such as annual customer demand growth, solar panel degradation, PLN

tariff fluctuations, or Vehicle-to-Grid (V2G) technology; (3) the selection of the optimal 36/64 ratio is based on balancing economic feasibility and sustainability but has not yet incorporated monetization of carbon credits or green premium pricing that could fundamentally alter the economic equation.

Based on these findings, the following specific recommendations are proposed for future research and policy:

Future research:

1. Second-life battery integration (R3 strategy): Explore the use of retired EV batteries as energy storage systems (ESS) for load shifting and peak shaving at hybrid PEVCS, which would advance the 9R framework from R2 to R3 implementation and potentially increase the feasible solar PV ratio beyond 36%.
2. Dynamic sensitivity modeling: Incorporate PLN tariff escalation scenarios, solar panel degradation curves (0.5–0.7%/year), and demand growth projections (CAGR 7% based on Indonesia's EV adoption trend) into the sensitivity simulation to assess long-term robustness of the 36/64 ratio.
3. Multi-location network optimization: Conduct comparative analysis across Central Java's heterogeneous regions (urban Semarang, periurban Solo, toll road corridors) to determine location-specific optimal ratios accounting for varying solar irradiance, land costs, and demand densities.

Policy recommendations:

1. Carbon credit monetization: Under Indonesia's Presidential Regulation No. 110/2025, which formalizes the voluntary carbon market and establishes the IDXCarbon exchange platform, hybrid PEVCS operators reducing 109,058 kg CO₂ /year could generate tradeable carbon credits. At the proposed carbon tax rate of IDR 30,000/ton CO₂ (~USD 2/ton), this would yield approximately IDR 3.3 million/year in additional revenue—modest but symbolically significant for market development. Policymakers should establish PEVCS-specific carbon credit methodologies within the IDXCarbon framework to incentivize hybrid station deployment.
2. Solar PV subsidy for PEVCS: The government should extend fiscal incentives currently available for rooftop solar PV under MEMR Regulation No. 2/2024 to commercial PEVCS installations, including VAT reductions on solar components and import duty exemptions for PV panels, which could reduce the hybrid PEVCS investment cost by 10–15% and improve ROI from 10.5% to approximately 13–14%, making hybrid stations significantly more attractive to private investors.

These findings have important practical implications for policymakers in Central Java in accelerating the electric vehicle transition. By implementing hybrid PEVCS at the optimal 36/64 ratio, operators can achieve break-even in 9.5 years while contributing a 36% carbon emission reduction from the transportation charging sector—demonstrating that the circular economy R2 strategy can be economically viable when translated into precise engineering parameters through sensitivity analysis.

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