Challenges in Sustainability
https://www.acadlore.com/journals/CIS

Sustainable Energy Solutions in Urban Management: Carbon Emissions and Economic Assessment of Photovoltaic Systems at Electric Vehicle Stations in Hybrid Buildings

Mochamad Subchan Mauludin[1,2*], Moh. Khairudin[1], Rustam Asnawi[1], Singgih Dwi Prasetyo[3], Yuki Trisnoaji[3], Marsya Aulia Rizkita[4], Zainal Arifin[5], Mohd Afzanizam Mohd Rosli[6]

[1] The Doctoral Program on Engineering Science, Universitas Negeri Yogyakarta, 55281 Yogyakarta, Indonesia
[2] Department of Informatics Engineering, Faculty of Engineering, Universitas Wahid Hasyim, 50236 Semarang, Indonesia
[3] Power Plant Engineering Technology, State University of Malang, 65145 Malang, Indonesia
[4] Applied Marketing Management, Faculty of Vocational Studies, State University of Malang, 65146 Malang, Indonesia
[5] Mechanical Engineering Department, Faculty of Engineering, Universitas Sebelas Maret, 57126 Surakarta, Indonesia
[6] Department of Mechanical Engineering, Faculty of Engineering, Universiti Teknikal Malaysia Melaka, 76100 Melaka, Malaysia

[*] Correspondence: Mochamad Subchan Mauludin (aan.subhan18@unwahas.ac.id)

Received: 05-21-2025 **Revised:** 07-23-2025 **Accepted:** 07-31-2025

Citation: Mauludin, M. S., Khairudin, M., Asnawi, R., Prasetyo, S. D., Trisnoaji, T., Rizkita, M. A., Arifin, Z., & Rosli, M. A. M. (2025). Sustainable energy solutions in urban management: Carbon emissions and economic assessment of photovoltaic systems at electric vehicle stations in hybrid buildings. *Chall. Sustain.*, *13*(3), 377–397. https://doi.org/10.56578/cis130305.

© 2025 by the author(s). Published by Acadlore Publishing Services Limited, Hong Kong. This article is available for free download and can be reused and cited, provided that the original published version is credited, under the CC BY 4.0 license.

Abstract: The accelerating demand for sustainable energy solutions in urban environments has prompted the application of building-integrated photovoltaic (BIPV) systems in electric vehicles (EVs). This study assessed the impact of BIPV-EV systems in Surabaya, Indonesia, forecasting its energy production, environmental advantages, and economic viability between 2026 and 2036. Simulations conducted using HOMER Pro and photovoltaic system (PVsyst) suggested that the rooftop photovoltaic (RPV) capacity will increase from 4.6 GW in 2026 to 6.0 GW by 2036, while facade photovoltaic (FaPV) capacity is projected to grow from 1.6 GW to 2.0 GW. The combined generation of RPV and FaPV is anticipated to reach 9.71 GWh annually by 2036, ultimately reducing grid dependency to 36.6%. Additionally, carbon emissions from the BIPV-EV systems are expected to decrease from 616 tons per year in a grid-based scenario to 520 tons annually, hence reducing carbon intensity to 0.05 kg CO_2/kWh. Although the initial investment is projected at USD 3.2 billion and USD 4.8 billion in 2026 and 2036, respectively, the implementation of BIPV-EV systems is advantageous owing to significant savings on energy costs in the long run and decreasing reliance on fossil fuels. These findings underscored the potential of BIPV in advancing urban sustainability and accomplishing the objectives of energy transition in Indonesia.

Keywords: Building-integrated photovoltaic; Electric vehicles; Renewable energy; Urban sustainability; Energy transition

1. Introduction

In recent decades, rapid urbanization in major cities including Surabaya, has considerably increased energy consumption (Cheng et al., 2020). The demand for urban energy surges as population grows and economic activities expand, thus cities become primary contributors to global carbon emissions. According to the International Energy Agency (IEA), urban areas accounted for more than 70% of the global carbon emissions, underscoring the urgency for sustainable energy solutions to mitigate environmental impacts (Dan et al., 2025). One promising approach is the implementation of building-integrated photovoltaic (BIPV) systems, which is to install solar panels in building structures direct (Makhmudov et al., 2025; Reddy & Selvajyothi, 2020). Unlike large-scale solar power plants that require vast land areas, BIPV systems utilize unused surfaces such as rooftops and facades, optimizing urban space without disrupting city planning. Besides the generation of electricity, BIPV offers benefits such as reducing ambient temperatures, minimizing indoor cooling loads, and improving overall energy efficiency (El Mokhi et al., 2023; Ghosh, 2025). As one of the largest metropolitan city in Indonesia, Surabaya faces growing challenges in meeting increasing energy demands while maintaining environmental sustainability (Güven et al., 2025; Schmid et al., 2025). The transition to renewable energy sources forms an essential part of urban development as the industrial and commercial sectors prosper. By year 2022, the global installed capacity of rooftop photovoltaic (RPV) systems had already reached 118 GW and was expected to increase significantly in the coming decades (Nurwidiana et al., 2024). Therefore, integrating BIPV technology into modern urban architecture in Surabaya presents a vital strategy for developing a greener and low-emission city (Alhazmi, 2025; Amini Toosi, 2025).

The adoption of BIPV, apart from the generation of electricity, provides a broad range of economic and environmental benefits, hence attracting interest from researchers and technology developers (Pan et al., 2023). The cost of PV systems has dropped by nearly 80% since 2010, making them more competitive than fossil fuels. Several countries, including Australia (Pan et al., 2023), Spain (Saez et al., 2023), and Thailand (Gamonwet & Dhakal, 2023), have implemented incentive policies to encourage the deployment of BIPV. Recent studies have further highlighted the potential of PV-EV integration, since combining solar energy systems with electric vehicles could offer an innovative solution to combat the challenges faced by the shortage of urban energy (Purlu & Ozkan, 2023; Zhang et al., 2023). Given the increasing relevance of BIPV systems, various studies have analyzed their technical, economic, and environmental impacts across different regions. For instance, a study by (Anang et al., 2021) monitored the performance of a grid-connected RPV system in Kuala Terengganu, Malaysia, and focused on derating factor determination to improve the accuracy of simulation. The results indicated a performance ratio of 75.72% with a capacity factor between 13% and 16%, highlighting the efficiency of the system under real-world conditions. Meanwhile, Irshad et al. (2023) explored the optimization of hybrid PV-grid-battery systems in Japan, Afghanistan, and Saudi Arabia using HOMER Pro software. Their study compared different PV technologies; among them, monocrystalline silicon (mono-Si) was found to outrun others with a performance ratio (PR) of 83.9%. Similarly, Jahangiri et al. (2023) conducted a techno-economic-environmental analysis of BIPV across eight climatic regions in Iran and ranked the cities based on their suitability for the use of BIPV. The study identified Jask as the most suitable city and Ramsar as the least appropriate, offering valuable insights into climate-based PV performance (Ni et al., 2025).

To plan for better consumption of urban energy, Freitas et al. (2021) integrated the use of PV energy into building construction in Brazil, hence developing a Geographic Information System (GIS)-Based optimization model to assess the feasibility of incorporating PV into the design of urban buildings. Additionally, Dehkordi & Jahangiri (2022) conducted a sensitivity analysis of a 3E BIPV system in Abadan, Iran, evaluating the impact of PV tilt angles and azimuth orientations on energy costs. The findings indicated that a 30° tilt and 0° azimuth resulted in the most economical configuration. Hybrid systems have also been a key focus in BIPV research. Loghmania & Khosravi (2024) examined the integration of solar water heaters (SWH) and PV into building facades in Shahrekord, Iran; their study demonstrated the increase in both electricity production by 44.6% and heat production by 59.3%. Similarly, Felseghi et al. (2021) investigated the feasibility of a hybrid PV-hydrogen system for the supply of green power in Romania, revealing that PV supplied 32% of the total energy. In comparison, fuel cells contributed 68%, ensuring a stable and renewable energy source. The advancement in artificial intelligence (AI) has been applied to BIPV optimization. Nur-E-Alam et al. (2024) utilized machine learning techniques to enhance the performance of PV systems in cities such as Kuala Lumpur, Sydney, and Toronto. This study demonstrated that an AI-enhanced hybrid PV system, in combination with BIPV and solar windows, could meet up to 78% of the total energy demand of a building and make a big stride toward innovative energy solutions. Finally, Quddus et al. (2024) simulated and validated a BIPV system with PVsyst in Lucknow, India, when the actual performance was compared with simulated data. The study reported that the difference in annual production was less than 10%, proving the high accuracy of PV performance modeling. These findings collectively emphasize the potential of BIPV and PV-EV integration in enhancing the efficiency of urban energy, reducing carbon emissions, and improving economic feasibility, thus offering more sustainable energy solutions in urban environments.

The current study analyzed the impact of building-integrated photovoltaics and electric vehicle (BIPV-EV) systems on the decarbonization efforts of Surabaya. Additionally, it estimated the Levelized Cost of Energy (LCOE) for years 2026 till 2036. Both technologies, with great potential for large-scale development, are anticipated to be pivotal in the pursuit of a carbon-neutral society. However, the capacities of RPV and FaPV as essential components of BIPV in urban energy systems have not been extensively explored within Surabaya and other cities. Accordingly, this study aimed to evaluate the contributions of RPV and FaPV to BIPV systems and to assess the environmental and economic advantages of an integrated BIPV-EV system (Fernandez et al., 2024). Table 1 summarizes key studies on BIPV systems, focusing on the methods used, areas for application, research novelty, and key findings to comprehensively understand the latest advancement in the field. These studies highlight various aspects, including performance optimization, economic feasibility, energy planning, and hybrid system integration.

Table 1. State of the art

References	Method	Application	Novelty	Research Findings
Anang et al. (2021)	Performance monitoring of grid-connected RPV & Techno-economic-environmental BIPV analysis in different climates using HOMER	Kuala Terengganu, Malaysia & Iran (8 climatic regions)	Derating factor determination to improve simulation accuracy & climate-based BIPV city ranking	Performance ratio 75.72%, capacity factor 13%-16%. Jask is the most suitable, and Ramsar is the least.
Dehkordi & Jahangiri (2022); Freitas et al. (2021**)**	Urban PV energy planning with construction compatibility & Sensitivity analysis of 3E BIPV system	Brazil & Abadan, Iran	GIS-based PV planning model & evaluation of tilt and azimuth angles	The GIS model for PV siting, with 30° tilt and 0° azimuth, is the most economical.
Felseghi et al. (2021); Loghmania & Khosravi (2024**)**	Combination of SWH and PV on facades & Hybrid PV-hydrogen for green supply	Shahrekord, Iran & Romania	Facade-based thermal-electric PV systems & PV-H_2 integration	Electricity↑ is 44.6%, heat↑ is 59.3%, PV is 32%, and fuel cell is 68%.
Nur-E-Alam et al. (2024); Quddus et al. (2024**)**	Machine learning optimization & PVsyst simulation validation	Kuala Lumpur, Sydney, Toronto & Lucknow, India	AI-enhanced hybrid BIPV-solar windows & actual vs. simulated accuracy	AI-PV system meets 78% energy needs; <10% difference in the simulation accuracy.
Prasetyo et al. (2023); Yu et al. (2024**)**	3E impact with HOMER-PVsyst & techno-economic analysis with HOMER	Xiong'an, China & Ngawi, Indonesia	Impact of FaPV on BIPV-EV & surplus energy feasibility	FaPV↑ generation by 67.6%, CO_2 ↓41.91%; 562,227 kWh/year, and COE: IDR 1,966/kWh.
Grande et al. (2018); Prasetyo et al. (2024**)**	Viability analysis of off-grid PV-BESS & On-grid PV economic simulation	Yogyakarta & Indonesia (residential)	Excess energy and ROI analysis & household EV charging impact	Off-grid COE IDR 17,783/kWh, ROI -7%; on-grid ROI 46.6%, profit IDR 374 juta/25 tahun.

2. Methodology

2.1 Design of the Scenario

This study proposed a framework for evaluating (BIPV-EV) charging systems connected to the power grid. As shown in Figure 1, this study consisted of three main stages, i.e., data pre-processing, system simulation, and output analysis. The pre-processing stage included collecting data on solar radiation, BIPV areas, and social and economic factors that affect the system. Next, the system was simulated using HOMER Pro and PVsyst software under various scenarios, including a combination of the electricity grid and renewable energy sources (Mahir et al., 2024; Mohammadi & Gezegin, 2022). The results of simulation were evaluated based on the potential of energy, environment, and economy (3E), encompassing the energy efficiency and environmental impacts of the system, such as carbon emissions and economic feasibility based on investment and operational costs (Elaouzy & El Fadar, 2022; Mauludin et al., 2025). This approach aimed to identify optimal sustainable solutions to implement renewable energy-based EV charging systems (Güven & Yücel, 2023; Rehman et al., 2023). By incorporating both RPV and FaPV into the analysis, this study further examined the impact of different BIPV configurations on the overall system performance. The integration of FaPV was particularly crucial due to its potential to enhance energy generation in urban settings, where rooftop space was often limited (Amini et al., 2024). However, FaPV presented challenges such as higher installation complexity and maintenance costs when considering its feasibility (Khan et al., 2023). Multiple system scenarios were designed to thoroughly assess the influence of FaPV, as summarized in Table 2, given the variations in PV placement, grid dependency, and the implementation of Vehicle-to-Grid (V2G) technology. Definitions of the scenario were developed by analysing practical urban constraints and technological feasibility. For instance, the EV-only scenario assumed grid-reliant charging without PV support, while RPV-EV and FaPV-EV examined partial solar integration. The complete RPV+FaPV-EV configuration assumed optimal solar harvesting using rooftops and vertical facades; such assumptions included uniform building distribution, average tilt optimization, and moderate EV penetration aligned with national EV roadmaps. These scenarios compared in detail the effects between different configurations and energy balance, environmental benefits, and financial viability of the BIPV-EV charging system. By classifying BIPV systems based on their energy output, this study provided insights into the most effective deployment strategies for maximizing renewable energy utilization.

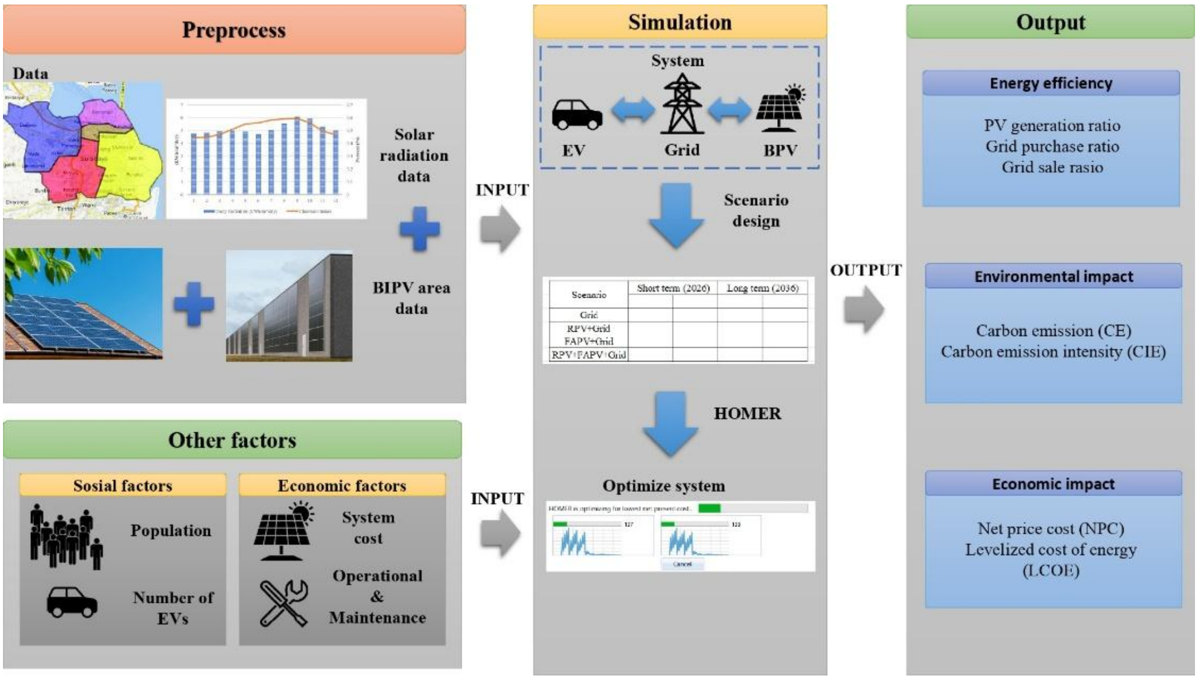


Figure 1. Assessment framework of this study

Table 2. Definitions of each scenario of the system

Scenario	Definition
EV	The direct integration of EVs into the power grid represents the most straightforward V2G configuration.
RPV-EV	The highest potential utilization of RPV is in urban areas when combined with EV charging infrastructure.
FaPV-EV	The optimal capacity of FaPV is found in urban environments when PV systems and EVs were integrated.
RPV+FaPV-EV	The maximum feasible deployment of RPV and FaPV is identified in urban settings when merged with PV-based EV charging systems.

2.2 Energy, Environmental, and Economic (3E) Impact Assessment of the BIPV-EV Systems

2.2.1 Effect of energy optimization

The impact of BIPV-EV system on the reliability and stability of urban power supply was analyzed using three primary metrics: the BIPV output ratio, the electricity purchase ratio, and the electricity sales ratio. The BIPV output ratio measures the contribution of the BIPV system to the overall energy consumption of a city, serving as a significant indicator of urban energy sustainability. The electricity purchase ratio assesses the amount of power that a city requires from external electricity grids. This dependency could be markedly diminished through the adoption of BIPV-EV systems. In contrast, the electricity sales ratio reflects the stability of power supply from the grid to the total energy demand of a city. This stability may be enhanced through the integration of BIPV-EV systems. The mathematical equations employed to compute these metrics are as follows:

$$BIPV_G ratio = \frac{BIPV_G}{BIPV_G + Grid_P} \times 100\% \quad (1)$$

$$Grid_P ratio = \frac{Grid_P}{BIPV_G + Grid_P} \times 100\% \quad (2)$$

$$Grid_S ratio = \frac{Grid_S}{Total\ consumption} \times 100\% \quad (3)$$

where, $BIPV_G$ refers to the electricity produced by the BIPV system, $Grid_p ratio$ represents the electricity acquired from the external grid and $Grid_s$ denotes the electricity fed back into the grid (Liu et al., 2022; Yu et al., 2024). A higher $BIPV_G$ ratio suggests that the BIPV system is making a more significant contribution to meeting the energy needs of the city, thereby reducing dependence on the external grid. This indicates that a substantial portion of the energy demand from a building is being met by the PV system, hence improving the energy sustainability. However, surplus electricity is often redirected to the grid due to the mismatch between energy generation from the PV system and the actual energy demand. As a result, a lower grid sales ratio typically implies that a more significant portion of the PV-generated electricity is being consumed directly within the building, increasing the self-consumption rate. The self-consumption rate is a key indicator of the efficiency and the ability of the system to reduce its reliance on external energy sources.

2.2.2 Environmental impact

With the increasing adoption of BIPV-EV systems, this integrated approach is anticipated to significantly diminish carbon dioxide (CO_2) emissions in an urban scale. This study employed carbon emissions (CE) and emission intensity (CEI) as primary metrics to accurately assess the reduction in carbon output (Prasetyo et al., 2025). The evaluation encompassed various scenarios to analyze the total fuel consumption and emissions from grid-supplied electricity for electric vehicles (EVs) and other sectors. The formulas utilized for these calculations were presented below:

$$CE_{system} = EF_g \times EI_{system} + CE_{FV} \quad (4)$$

$$CEI_{system} = \frac{CE_{system}}{p} \quad (5)$$

where, CE_{system} represents the total carbon emissions of the system, which is a comprehensive measure of the environmental impact of the system, including both direct and indirect emissions. EF_g denotes the emission factor of grid electricity and EI_{system} refers to the electricity supplied by the grid. Additionally, CE_{FV} accounts for the carbon emissions produced by fuel-powered vehicles, CEI_{system} = Indicates carbon emission intensity, and PP represents the total electricity generation from the system (Khan et al., 2024; Yu et al., 2024).

A high carbon emission level implies substantial contribution from a region to environmental degradation and climate change. Likewise, a high Carbon Emission Intensity (CEI) value indicates dependence on carbon-intensive energy sources, highlighting the urgency of transitioning to cleaner alternatives. To mitigate these effects, adopting low-carbon energy systems is beneficial and essential for sustainable development. Analyzing environmental impact indicators at the city level helps identify emission sources and assess reduction strategies. This study provided a detailed evaluation of urban carbon emissions and examined the potential benefits of deploying BIPV-EV systems under different scenarios.

2.2.3 The impact of the levelized cost of energy on economic feasibility

This research investigated the financial dimensions of BIPV-EV systems by focusing on two primary indicators: the total cost and Levelized Cost of Electricity (LCOE). The total cost includes initial capital investment, operational and maintenance (O&M) expenses, and system replacement costs. These components are critical for evaluating the financial viability of the project. Conversely, LCOE denotes the cost per unit of electricity generated, serving as a vital metric for assessing the economic efficiency of a PV system. This parameter also allows comparative analyses across different power generation technologies. The formula employed to calculate LCOE is set out below:

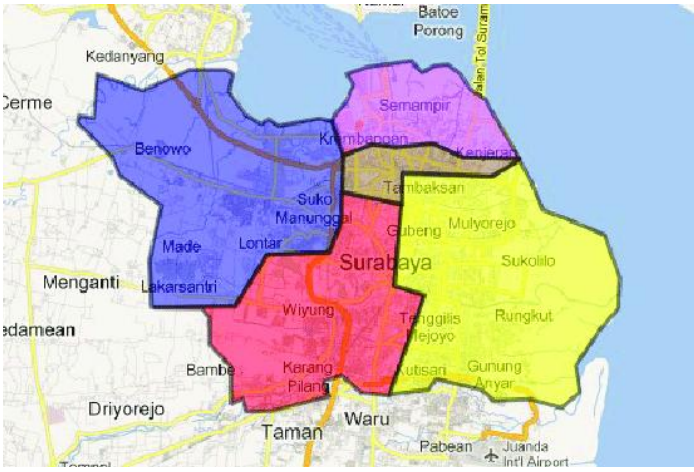
$$LCOE = \frac{total\ lifetime\ costs}{total\ electricity\ generation} \quad (6)$$

A higher LCOE signifies an increased cost per unit of electricity, which could result from substantial upfront investment, high O&M costs, or system inefficiencies. Therefore, a lower LCOE value indicates better cost-effectiveness, making the system more financially sustainable (Hanig et al., 2025).

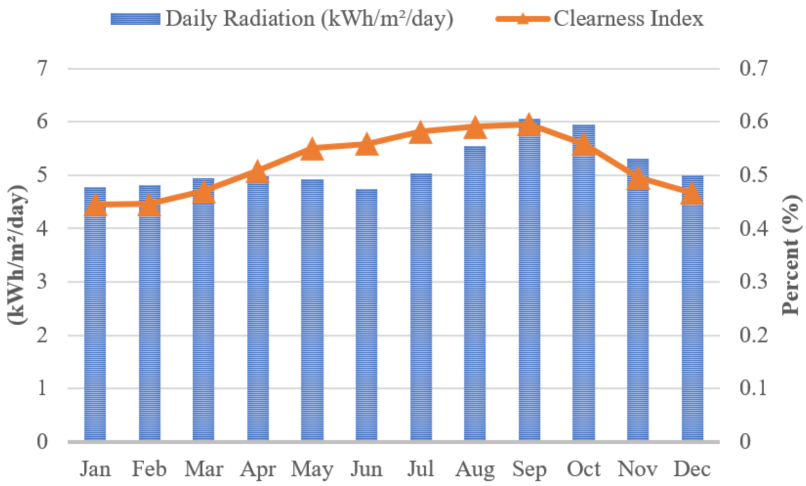
3. Data Input

3.1 Information on the Selected Location

Surabaya, located in Indonesia at coordinates 7.25° S and 112.75° E, covers an area of approximately 374.1 km² with a relatively flat topography (Safitri et al., 2024). The city receives significant solar exposure, with an average annual sunshine duration of around 2,200 hours. Based on the data of daily irradiation, the total solar irradiation intensity in Surabaya reaches 1,887 kWh/m² per year, highlighting its great potential for utilizing solar energy (Nishanthy et al., 2024). One crucial factor in enhancing the efficiency of solar energy systems depends on the angle for the installation of solar panels and this could affect the amount of energy received by RPV and FaPV systems. As illustrated in Figure 2, optimizing the tilt angle could maximize the absorption of solar energy, thereby improving the overall performance of the system.



(a)



(b)

Figure 2. Data sources: (a) Surabaya map illustration (Aminah et al., 2018), (b) Global horizontal and irradiance (GHI)

3.2 Building Rooftop and Facade Planning Data

To achieve the ambitious goal of 100% clean energy consumption by 2036, this paper attempted to analyze the electricity demand in Surabaya. It established two key timeframes: the short term by 2026 and the long term by 2036, having considered the duration required for the adoption of BIPV and the rollout of Vehicle-to-Grid (V2G) technologies. The fundamental difference between these two timeframes resided in the fluctuations in electricity demand driven by urban growth and the escalation of electrification. Surabaya, a rapidly evolving metropolitan area, undergoes continuous infrastructural development and urban renewal, resulting in notable changes in its landscape. However, challenges arising from the limited access to Geographic Information Systems (GIS) and building data rendered it difficult for the city to conduct precise assessments. Given that Surabaya adheres to the urban zoning regulations outlined in the capital development plan of East Java, the building land area and density parameters are essential for estimating the available rooftop area for solar PV deployment. Both Eqs. (7) and (8), which calculate the developable areas for RPV, are derived from the urban construction land area in Surabaya; they help ensure alignment with the objectives of the city in respect of spatial planning and development:

$$BRA_i = CA_i \times BD_i \tag{7}$$

$$TBRA = \sum_{i=1}^{5} BRA_i \tag{8}$$

where, BRA represents the total roof surface of a structure, TBRA signifies the cumulative rooftop space across all buildings, CA corresponds to the construction zone for different building categories, BD indicates the concentration of buildings within a given area, and i denotes the specific building classification (Paradongan et al., 2024).

The expansion of various building categories in Surabaya has undergone dynamic changes over the past five years, with residential areas consistently occupying the most significant portion of urban space, followed by industrial zones, as shown in Table 3. This trend reflected the growing energy demand, which aligned with the increasing potential for solar PV integration on rooftops and building facades. To support future energy needs, Table 4 presented an estimated RPV and FaPV deployment plan, projecting that the total rooftop area available for solar PV installation will have reached 40 km² by 2036. In addition, the capacity of facade PV systems is expected to increase across different city regions, contributing to a more sustainable energy mix. As illustrated in Figure 3, electricity consumption per capita in Indonesia has shown a steady rise, underscoring the urgency of expanding renewable energy to ensure a reliable and efficient energy supply in the coming years.

Table 3. Expansion of various building categories in Surabaya over the past 5 years (km^2)

Year	Residential	Administration	Commercial	Industrial	Warehouse	Subtotal
2022	42.10	12.20	7.10	28.50	3.20	93.10
2021	41.50	12.00	6.90	27.80	3.10	91.30
2020	40.00	11.80	6.70	27.00	3.00	88.50
2019	45.30	12.50	7.30	30.10	3.50	98.70
2018	44.00	12.80	7.50	29.50	3.60	97.40

Table 4. Plans for short- and long-term RPV and FaPV in Surabaya (km²)

Year	Rooftop	Facade				
		East	South	West	North	Total
2026	30	10	10	10	10	40
2036	40	14	14	14	14	56

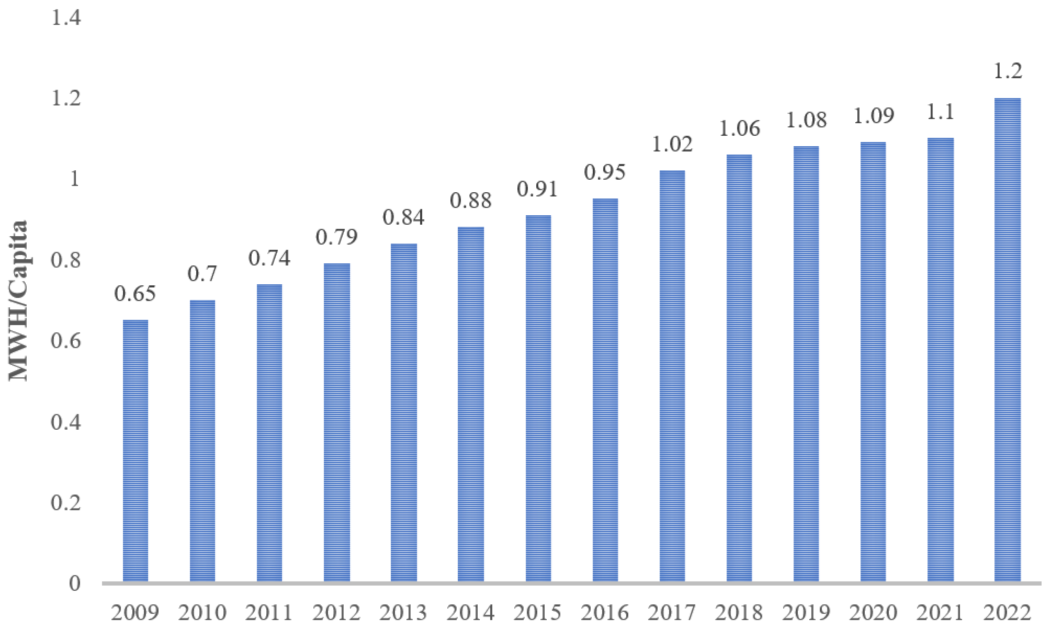


Figure 3. Electricity consumption per capita in Indonesia (MWH/Capita)

3.3 Economic Metrics of the System

As illustrated in Table 5, the costs for the installation of PV systems in Surabaya are expected to decrease over time. The projected cost of RPV systems is about 800 USD/kW in 2026 and 589 USD/kW in 2036. The projection of these costs is derived from the historical global trends and adjusted based on International Renewable Energy Agency (IRENA) reports as well as estimates from the Indonesian market. Over a decade, a decline of 26% in the projected cost has reflected continued technological advancement, economies of scale, and local manufacturing capacity. The costs of FaPV system were modeled with a more conservative decline due to their higher complexity and limited market maturity. Inflation and currency adjustments were incorporated based on the forecasts of Bank Indonesia and International Energy Agency (IEA). Likewise, the costs of flat-plate PV (FaPV) systems are expected to decline to 1,071 USD/kW in 2026 and 790 USD/kW in 2036. The operation and maintenance (O&M) costs will remain steady at 8 USD/kW/year for RPV systems and 10 USD/kW/year for FaPV systems. Furthermore, an inverter system will be essential for integrating PV power into the grid, with an installation cost estimated at 985 USD/kW, O&M costs at 101 USD/kW/year for a lifespan of 25 years. Electricity consumption in Surabaya is projected to increase from 5,680 GWh to 5,952 GWh in 2026 and reach 8,760 GWh up to 9,105 GWh in 2036, in line with the projection of national electricity consumption, which is expected to rise from 1,893 kWh per capita in 2026 to 3,035 kWh per capita in 2036. Meanwhile, the emission factor is projected to decrease from 1.053 kg CO_2/kWh to 0.678 $kgCO_2$/kWh, reflecting the transition toward cleaner energy. Regarding the introduction of vehicle electrification, Surabaya is expected to have 403,000 EVs in 2026 and reach 545,000 by 2036, each driving 12,000 km/year with a battery capacity of 77 kWh, as outlined in Table 4. The Feed-in Tariff (FIT) remains at 0.145 USD/kWh, with a sell-back price of 0.6 USD/kWh. Financially, a discount rate of 6.6% and an inflation rate of 2.54% are considered stable for long-term projections. (Li et al., 2025). These estimates have highlighted the feasibility of adopting PV and EV in Surabaya over the next decade.

Table 5. Economic aspects of combining BIPV and EV systems

Name data	Items	Data of 2026	Data of 2036	Unit
RPV	Total rooftop area	30	40	km^2
	RPV system cost	800	589	$/kW
	O&M	8	8	$/kW/year
FaPV	Total facade area	40	55	km^2
	FaPV system cost	1071	790	$/kW
	O&M	10	10	$/kW/year
Converter	Converter cost	985	985	$/kW
	O&M	101	101	$/kW/year
Electricity	Electrical consumption	16.939	39,906	GWh
	Emission factor	1.053	0.678	$KgCO_2$/kWh
	FIT	0.145	0.145	$/kWh
	Sellback price	0.6	0.6	$/kWh
Vehicle	Number	403,000	545,000	Car
	EV battery capacity	77	777	kWh
	Average annual driving distance	12,000	12,000	Km/year/car
Others	Discount rate	6.6	6.6	%
	Inflation rate	2.54	2.54	%

4. Results

4.1 Potential for Electricity Production from BIPV

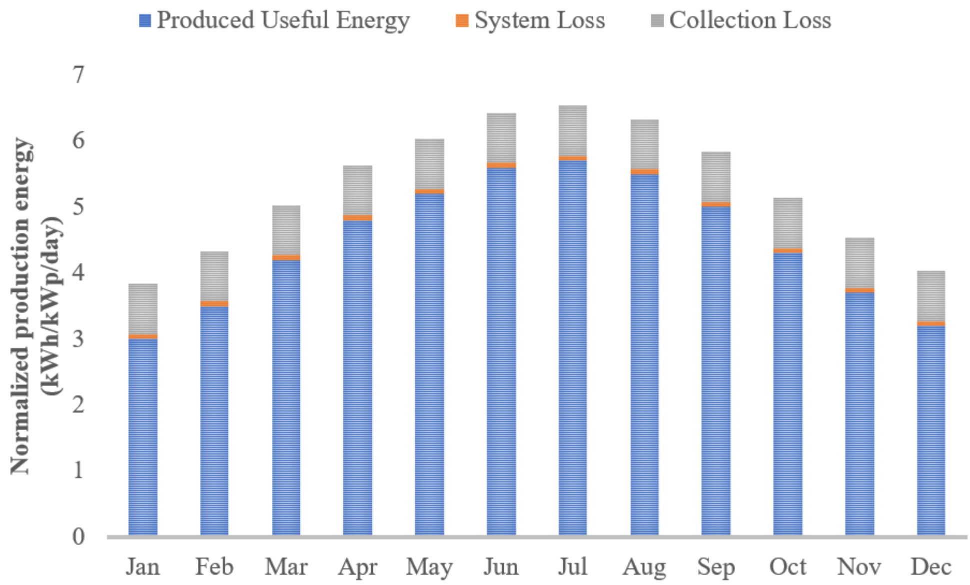
The simulation, conducted using PVsyst, assumed that PV installations would reach their maximum potential, with RPV capacity projected to be 4.6 GW in 2026 and increase to 6.00 GW in 2036. Meanwhile, the maximum PV capacity on building facades (North, South, East, and West) was estimated to be 1.6 GW in 2026, rising to 2.00 GW in 2036, representing an expansion of approximately 36.2% in BIPV development. As shown in Table 6, the RPV system was installed with a tilt angle of 40° and an azimuth of 0°, whereas the facade PV system had a fixed tilt angle of 90° with azimuths varying by orientation (North = 180°, South = 0°, East = -90°, and West = 90°). These angles were selected based on the benchmarks in literature and the solar irradiation profile of Surabaya. A tilt of 40° for RPV was generally recommended in tropical regions for maximizing yearly output (Yu et al., 2024) whereas a 90° vertical tilt for facades reflected typical architectural constraints in dense urban environments. Besides, azimuth angles followed cardinal orientation to ensure coverage across different sun paths throughout the day. These differences in tilt and azimuth angles significantly impacted radiation reception, influencing the overall energy yield of the system. RPV received the highest total radiation at 1773 kWh/m²/year, while the East and West facades received 1067 kWh/m²/year each, the South facade received 911 kWh/m²/year, and the North facade received the lowest at only 663 kWh/m²/year.

Based on Figure 4, the pattern of energy production shows that RPV has the highest production throughout the year, with an average monthly production of 4.5–6.5 kWh/kWp/day. Production peaks in May to July at around 6.5 kWh/kWp/day, while the lowest production occurs from December till January at approximately 4.5 kWh/kWp/day. In contrast, the South FaPV exhibits an opposite trend, with peak production in December to January at around 3.2 kWh/kWp/day and the lowest production in June to July at about 2.2 kWh/kWp/day. The North FaPV has a more stable production pattern throughout the year, ranging between 1.5 and 2.5 kWh/kWp/day.

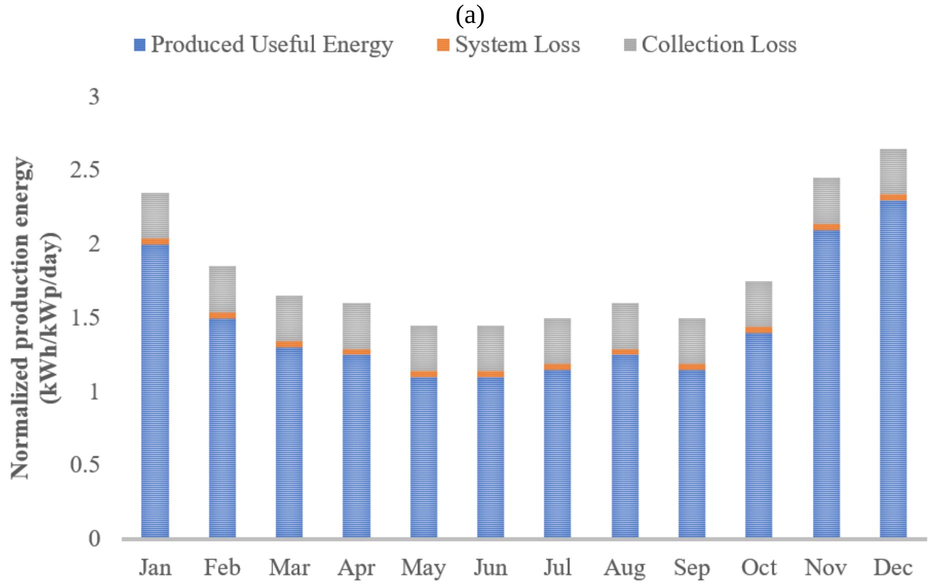
However, it remains lower than the other facades due to limited exposure to solar radiation. Meanwhile, the East and West facades show symmetry in their patterns of energy production, whereas the East facade generates more energy in the morning. In contrast, the West facade produces more in the afternoon. Their annual production ranges between 2.0 and 3.0 kWh/kWp/day, showing higher productivity than the North facade but lower productivity than the rooftop and South facade. As observed in Figure 4, system loss and collection loss remain relatively consistent across all PV orientation, accounting for approximately 5–10% of the total energy production. Nevertheless, RPV maintains the highest efficiency due to its more optimal angle of installation than FaPV. Therefore, BIPV development contributes significantly to the transition to renewable energy, particularly if panel design and orientation are optimized based on local environmental conditions.

Table 6. Angel of optimization PV

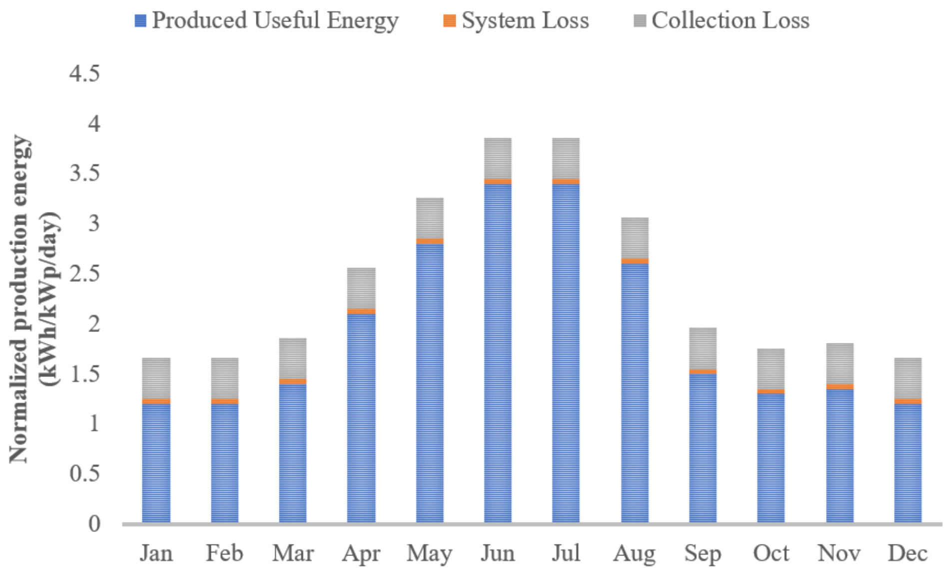
Angle	Rooftop	Facade			
		North	South	East	West
Tilt (°)	40	90	90	90	90
Azimuth (°)	0	180	0	-90	90
Capacity in 2026 (GW)	4.6	1.6	1.6	1.6	1.6
Capacity in 2036 (GW)	6.00	2.00	2.00	2.00	2.00
Total Radiation (kWh/m^2/year)	1773	663	911	1067	1067



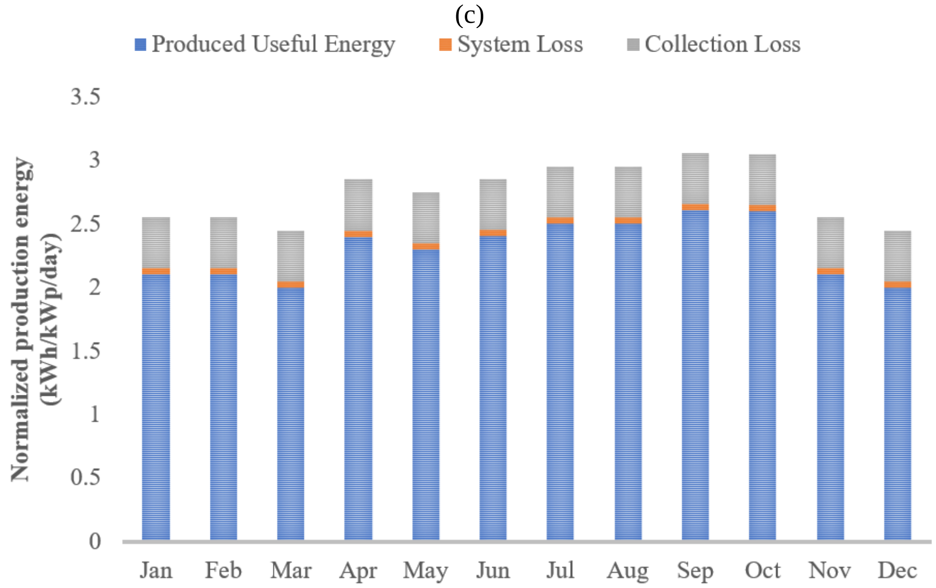
(a)



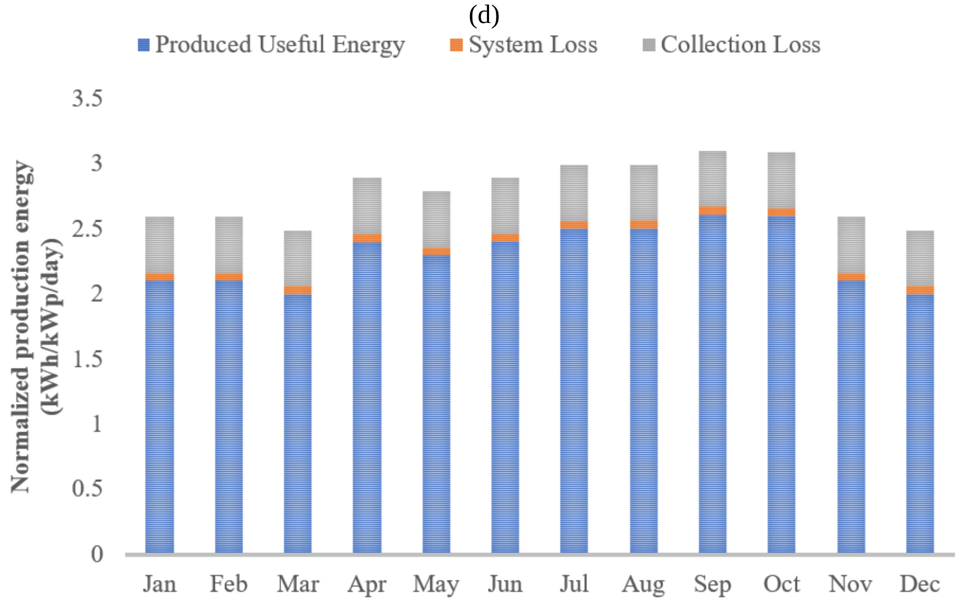
(b)



(c)



(d)



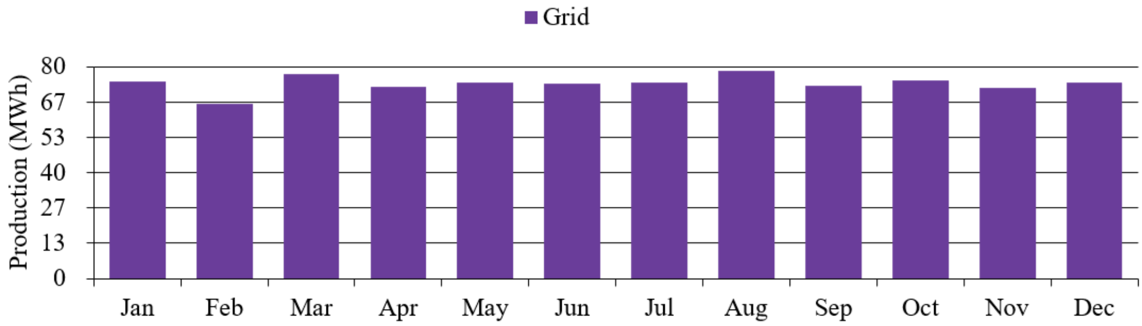
(e)

Figure 4. Normalized PV Energy Production on (a) Rooftop, Facade (b) North, (c) South, (d) East, (e) West

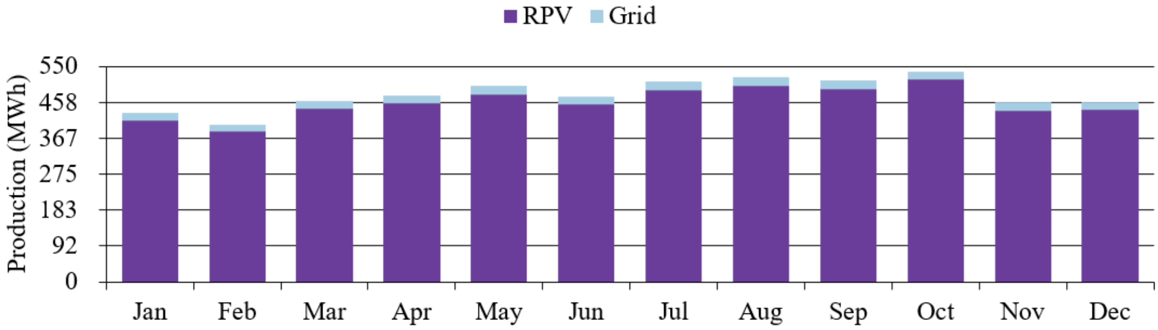
4.2 Simulation Results

The short- and long-term power outputs of the integrated grid and PV system were obtained through simulation optimization, given different PV configurations, as illustrated in Figures 5 and 6. The results indicated that RPV consistently provided the highest energy production throughout the year, with peak generation occurring between May and July, while the lowest output was observed between December and January. In contrast, the south FaPV followed the opposite trend, reaching its peak in production in December and January and experiencing a minimum in June and July. Meanwhile, the north FaPV maintained a relatively lower but more stable production profile across all months, contributing to a balanced energy supply. The east and west facades also exhibited symmetrical generation patterns, where the east facade generated more energy in the morning. In contrast, the west facade produced higher output in the afternoon, ensuring a more evenly distributed energy supply throughout the day.

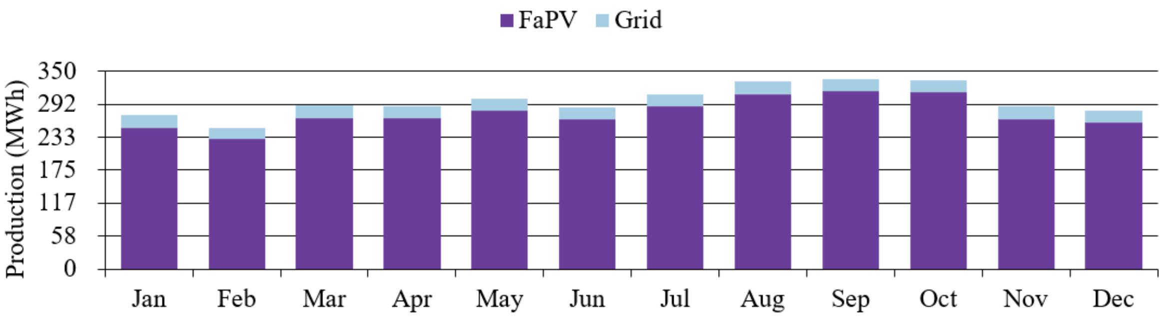
As shown in the short-term scenario in Figure 5, the total power production reaches 412.6 MWh, with RPV contributing 229.6 MWh and FaPV adding 180 MWh. In this case, the grid dependency remains high due to the limited PV capacity. Meanwhile, Figure 6 presents the long-term scenario, where an increased share of PV further enhances energy independence. In the long run, the integration of FaPV results in an increase of approximately 67.60% in the total PV generation , with RPV producing 5.35 GWh per year and FaPV contributing 2.35 GWh per year. The combined BIPV output reaches 9.71 GWh annually, reducing grid reliance to 36.6% of the total demand. The increased PV penetration indicates a gradual shift towards renewable-based power generation, improving energy sustainability in urban environments. The results also suggested that system and collection losses remained relatively consistent across all PV orientation, as observed in both scenarios. Despite these, RPV continued to demonstrate the highest efficiency. The expansion of PV capacity, especially the incorporation of FaPV, largely enhanced the potential of BIPV to generate energy. Optimizing rooftop and facade PV placements is strategically significant to achieve higher self-sufficiency and reduce reliance on grid electricity.



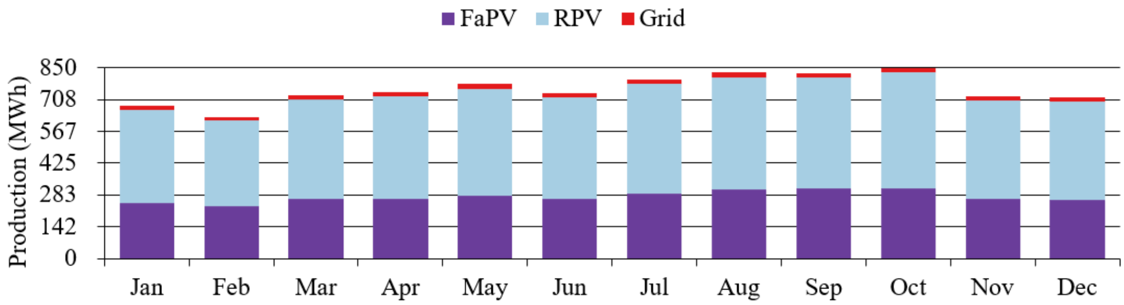
(a)



(b)



(c)



(d)

Figure 5. The short term of (a) Grid-EV, (b) RPV-EV, (c) FaPV-EV, (d) RPV+FaPV-EV

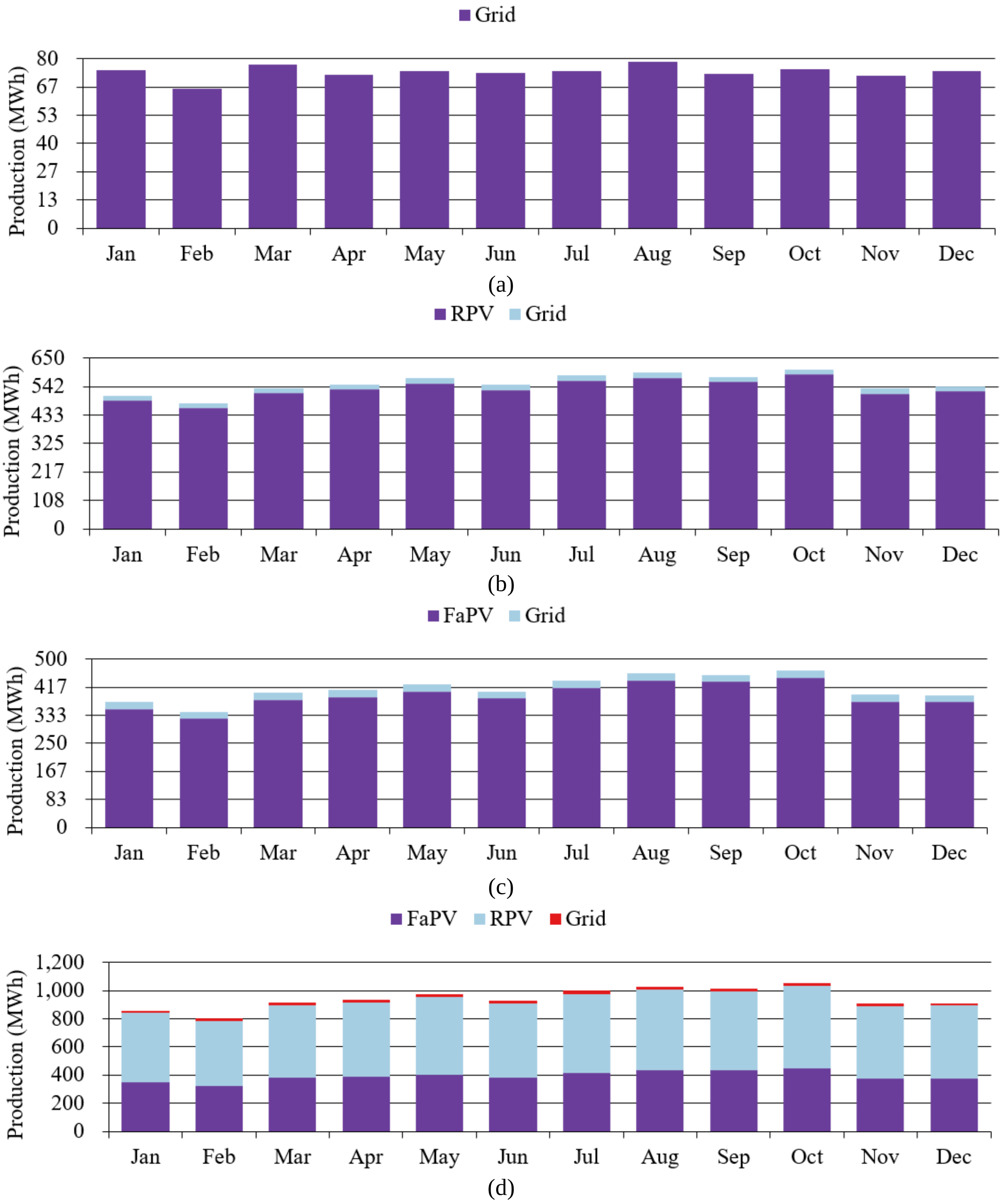


Figure 6. The long term of (a) Grid-EV, (b) RPV-EV, (c) FaPV-EV, (d) RPV+FaPV-EV

4.2.1 Power generation

To evaluate the performance of the BIPV-EV system, an analysis was conducted on various scenarios of power generation to assess their effectiveness in meeting the demands for energy. This study examined the contributions of different configurations, including RPV, FaPV, and grid connections, in supplying electricity efficiently. Insights into the evolution of energy dependency and utilization were obtained through analyzing the scenarios between 2026 and 2036. The comparative analysis helped identify trends in renewable energy integration, hence highlighting the increasing role of solar PV in reducing reliance on conventional power sources. Ultimately, this analysis provided valuable data for optimizing energy plan and improving the sustainability of future urban energy systems.

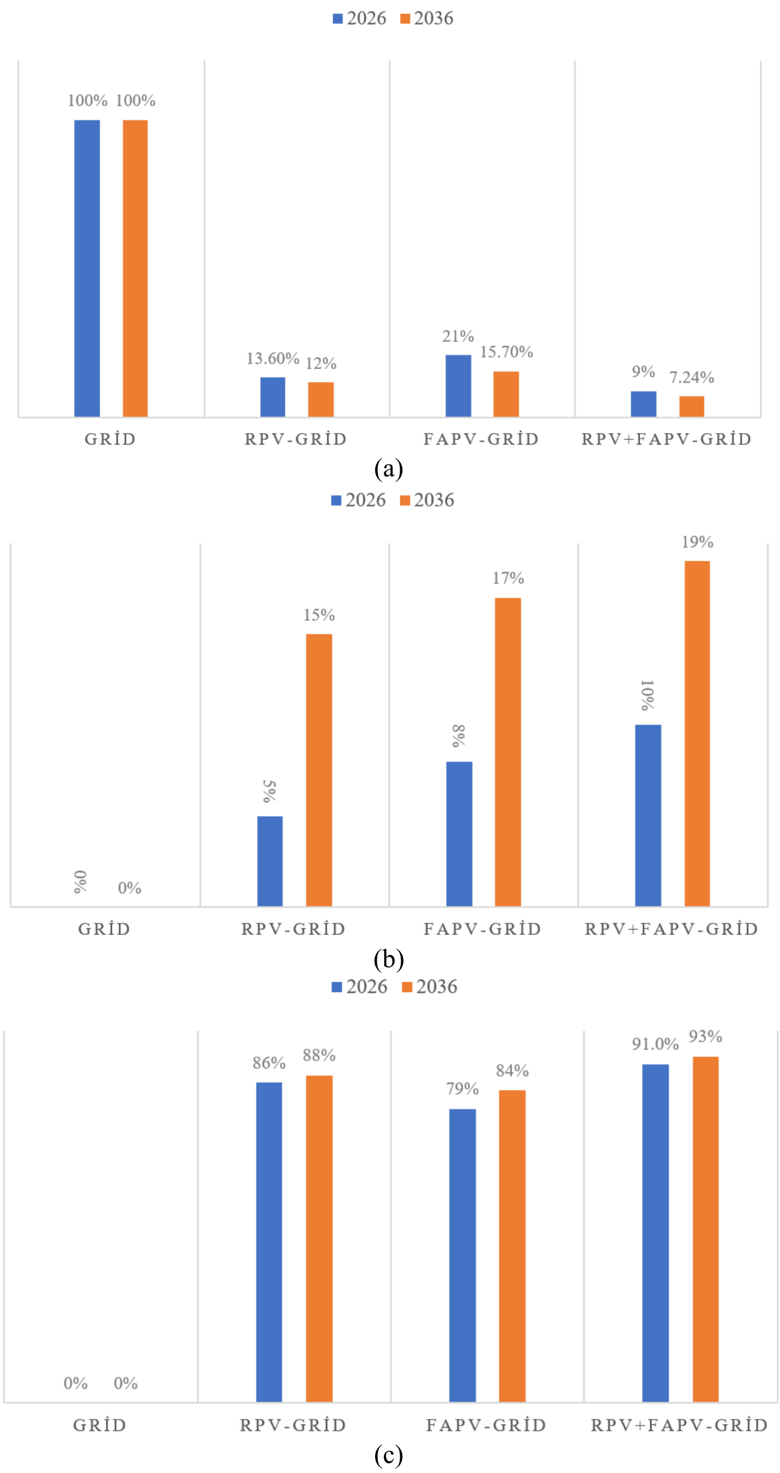
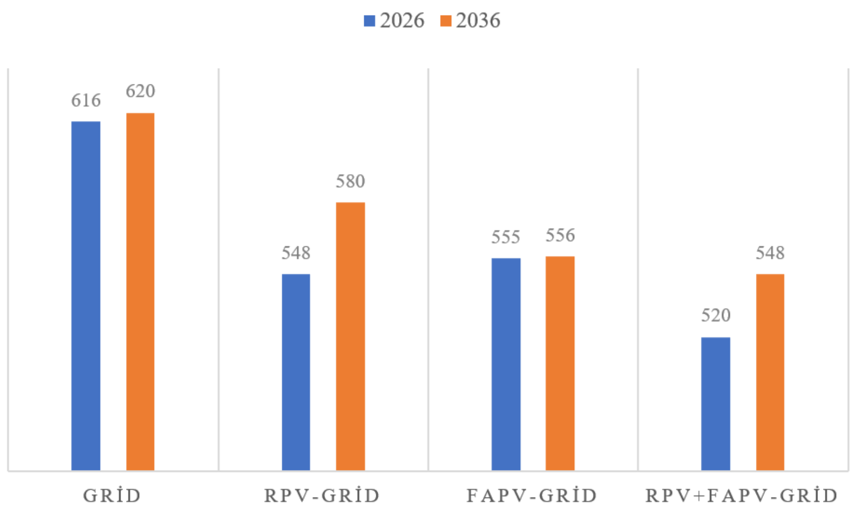


Figure 7. Evaluation of energy parameters across different scenarios: (a) Grid purchases ratio, (b) Grid sell-back ratio, (c) BIPV ratio

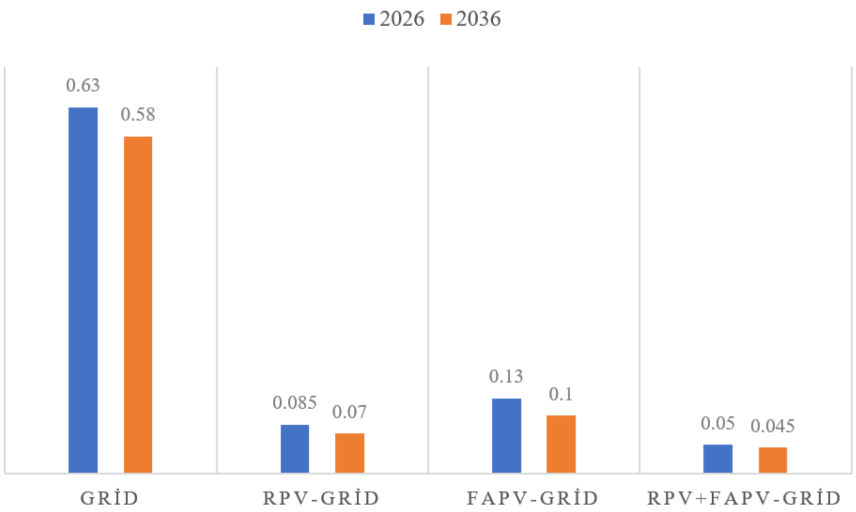
Figure 7 presents the evaluation of three key energy parameters: (a) grid purchase ratio, (b) grid sell-back ratio, and (c) BIPV utilization ratio. In Figure 7(a), the GRID scenario shows a 100% dependency on grid electricity in both years, while hybrid configurations significantly reduce this dependency. For instance, in 2026, the RPV-GRID and FaPV-GRID configurations reduce grid purchases to 13.6% and 12%, respectively. The combination of RPV+FaPV-GRID further lowers this value to 9%. By 2036, these values will have decreased to 12%, 15.7%, and 7.2%, respectively, indicating improved energy independence. Figure 7(b) highlights the energy exported to the grid. As expected, the pure GRID scenario does not contribute energy, while hybrid systems increase grid exports. The highest export is observed in the RPV+FaPV-GRID configuration, which will reach 10% in 2026 and 19% in 2036. This suggests that adopting a hybrid system reduces grid reliance and enables energy sharing. Figure 7(c) focuses on the BIPV utilization ratio, representing the effectiveness of using and exporting generated solar energy. The RPV-GRID scenario maintains a stable utilization of 88% for both years. Meanwhile, the FaPV-GRID system improves from 79% in 2026 to 84% in 2036. The highest efficiency is achieved with the RPV+FaPV-GRID system, reaching 91% in 2026 and increasing to 93% in 2036. These findings demonstrated that integrating rooftop and floating PV systems enhanced energy efficiency and self-sufficiency. The combined RPV+FaPV-GRID configuration consistently outperformed individual setups, making it the most viable solution for future sustainable energy systems.

4.2.2 Environmental generation

BIPV-EV systems aim to reduce the costs of electricity and play a crucial role in lowering carbon emissions. By integrating renewable energy sources such as RPV and FaPV, the dependence on fossil-fuel-based grid electricity could be minimized, significantly reducing environmental impact.



(a)



(b)

Figure 8. Evaluation of environmental parameters across different scenarios: (a) Carbon emission (ton/year), (b) Kilowatt hour carbon emission (CO_2/kWh)

To assess this aspect, Figure 8 evaluates the environmental parameters across different scenarios by analyzing (a) total carbon emissions (ton/year) and (b) carbon emissions per kilowatt-hour (CO_2/kWh) for years 2026 to 2036. Figure 8(a) illustrates the annual carbon emissions for different configurations. The GRID scenario has the highest emissions, with values increasing from 616 tons in 2026 to 620 tons in 2036. When RPV-GRID is integrated, the emissions are reduced to 548 tons in 2026 but slightly increase to 550 tons in 2036. Similarly, FaPV-GRID shows a minor increase from 545 to 556 tons over the same period. The most significant reduction is observed in the RPV+FaPV-GRID configuration, which lowers emissions to 520 tons and 543 tons in in years 2026 and 2036, respectively, hence highlighting the effectiveness of hybrid renewable energy in mitigating environmental impact.

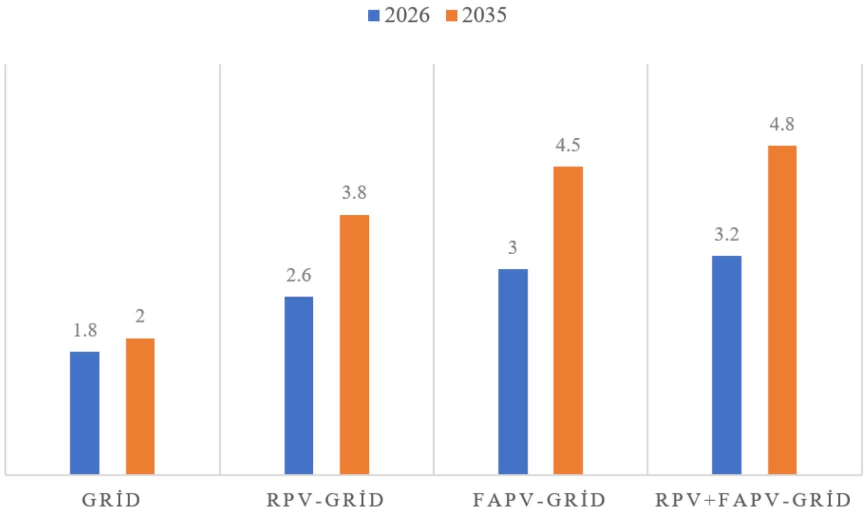
Figure 8(b) presents the carbon emissions per kilowatt-hour generated electricity. The GRID scenario exhibits the highest emission factor at 0.63 CO_2/kWh for both years. The integration of RPV-GRID significantly reduces this value to 0.05 CO_2/kWh in 2026 and 0.07 CO_2/kWh in 2036. FaPV-GRID also demonstrates improvement by decreasing emissions from 0.13 CO_2/kWh in 2026 to 0.1 CO_2/kWh in 2036. The lowest emissions are recorded in the RPV+FaPV-GRID scenario, which achieves 0.05 CO_2/kWh in both years; the hybrid configuration is confirmed to be the most sustainable solution in terms of environmental impact. These findings indicated that adopting BIPV-EV systems, particularly in the hybrid RPV+FaPV-GRID setup, was pivotal in reducing carbon emissions. The data supported the argument that increasing renewable energy penetration in the energy mix was essential for achieving long-term sustainability and carbon neutrality.

4.2.3 Economic results

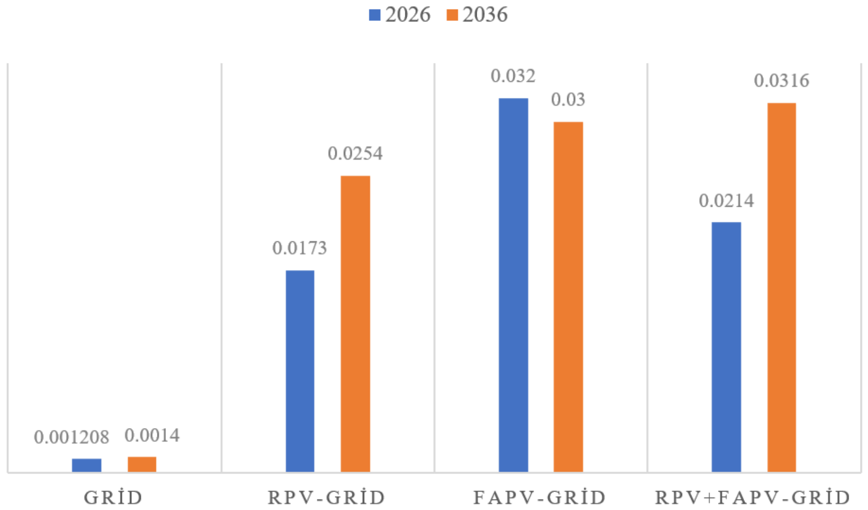
The economic feasibility of implementing BIPV-EV systems is crucial in determining their viability as a sustainable energy solution based on a thorough assessment of both costs and benefits. Apart from the environmental advantages, the financial viability of integrating renewable energy should be carefully analyzed to ensure long-term affordability and competitiveness. The evaluation involves calculating the total investment required for system deployment and the levelized cost of energy (LCOE), which represents the cost for each unit of electricity generated throughout the operational lifespan of the system. The most cost-effective strategies for optimizing BIPV-EV implementation were identified by comparing different scenarios in urban environments. As illustrated in Figure 9, insights into the economic parameters between 2026 and 2036 help stakeholders make informed decisions about investments in energy in the future.

Figure 9(a) illustrates the total cost of each energy configuration in billion USD. The GRID scenario shows the lowest cost with a slight increase from USD 1.8 billion in 2026 to USD 2.0 billion in 2036. When RPV-GRID is integrated, the cost rises to USD 2.6 billion in 2026 and USD 3.8 billion in 2036. A similar trend is observed in the FaPV-GRID scenario, with costs rising from USD 3.0 billion to USD 4.5 billion. The highest cost is recorded in the RPV+FaPV-GRID configuration, which requires USD 3.2 billion in 2026 and USD 4.8 billion in 2036. These results suggested that although hybrid renewable energy systems required higher initial investment, they might provide long-term benefits such as savings of energy costs and emission reductions. Figure 9(b) displays the LCOE (USD/kWh) of each scenario. The GRID scenario exhibits the lowest LCOE, with values of 0.0128 USD/kWh in 2026 and 0.014 USD/kWh in 2036. However, when renewable energy sources are incorporated, the LCOE increases. The RPV-GRID scenario has an LCOE of 0.0173 USD/kWh in 2026 and 0.0254 USD/kWh in 2036. The FaPV-GRID system records slightly higher values at 0.032 USD/kWh in 2026 and 0.03 USD/kWh in 2036. The highest LCOE is in the RPV+FaPV-GRID scenario, with values rising from 0.0214 USD/kWh in 2026 to 0.0316 USD/kWh in 2036. These findings indicated that although the integration of renewable energy might lead to higher LCOE in the short term, it offered significant benefits for sustainability, including reduced dependency on fossil fuels and potential cost reductions in the long run. The economic analysis suggested that while implementing BIPV-EV systems involved substantial investment, the long-term advantages of environmental sustainability and energy security justified their incorporation. A cost-benefit analysis is indispensable to optimize financial planning and balance affordability and sustainability.

Figure 10 evaluates the sales ratios of grid electricity across different scenarios, with and without electric vehicles (EVs), in 2026. In Figure 10(a), the RPV-GRID scenario shows a grid sales ratio of 5% without EVs, which decreases to 3% when EVs are integrated. Similarly, the FaPV-GRID scenario exhibits a lower grid sales ratio of 0.30% without EVs, dropping to 0.25% with EVs. Meanwhile, the RPV+FaPV-GRID scenario records the highest grid sales ratio among the configurations, at 10% without EVs and slightly decreases to 9% with EVs. Figure 10(b) highlights a similar trend in lower-ratio scenarios. In the RPV-GRID configuration, the electricity sales ratio declines from 2% without EVs to 1.50% with EVs. The FaPV-GRID scenario shows minimal values, with 0.10% without EVs, and drops further to 0.05% with EVs. On the other hand, the RPV+FaPV-GRID scenario experiences a decrease from 4% without EVs to 3.60% with EVs. These findings indicated that integrating EVs with systems reduced the surplus energy available for grid sales. This was primarily due to increased energy demand from EVs, which consume a significant portion of the electricity generated by the BIPV system. Despite the declining grid sales ratios, direct utilization of renewable energy for transportation reduced reliance on fossil-based energy, ultimately supporting the efforts of decarbonization on the whole. Therefore, an optimal energy management strategy was recommended to maximize the economic and environmental benefits of the BIPV-EV systems.

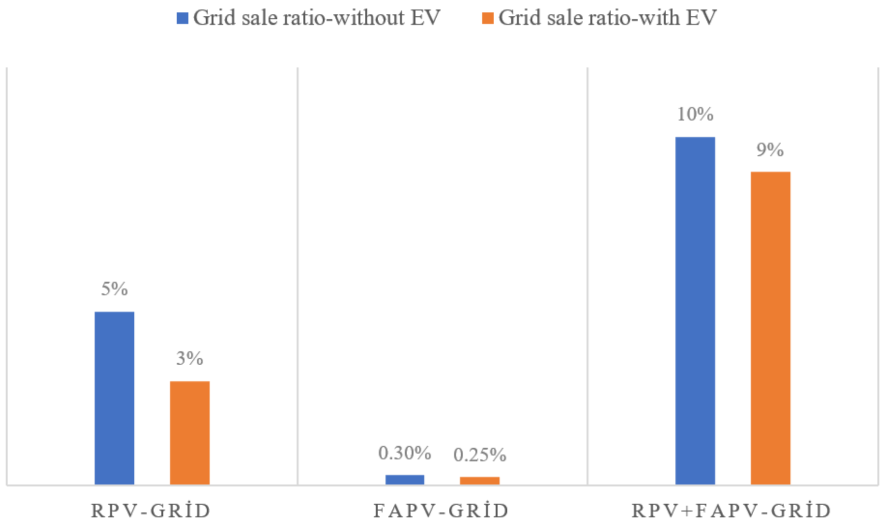


(a)

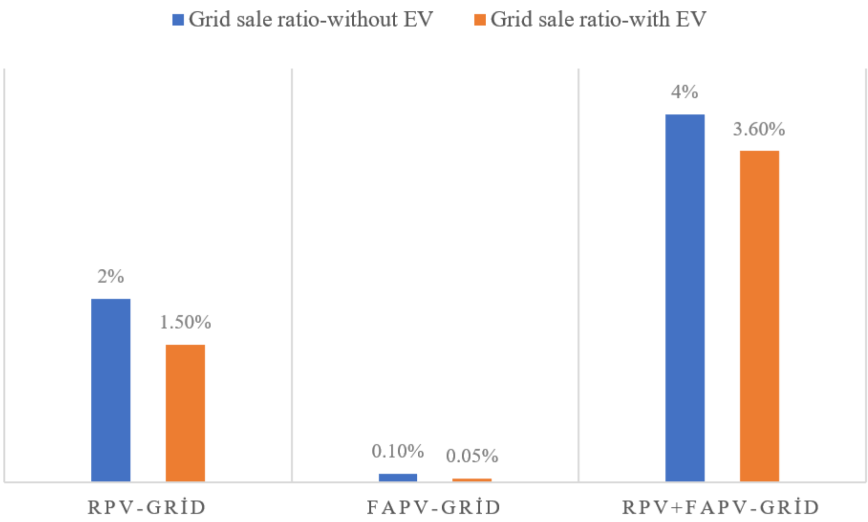


(b)

Figure 9. Evaluation of economic results across different scenarios: (a) Total cost (billion USD) (b) LCOE (USD/kWh)



(a)



(b)

Figure 10. Evaluation of grid sales ratio with or without EVs in (a) 2026, (b) 2026

5. Discussion

5.1 Limitations of Research

This study provided insights into the potential of BIPV systems in supporting the sustainability of energy in Surabaya, in spite of several limitations to be considered as follows. First, the analysis was based on simulations with HOMER Pro and PVsyst software, though providing reasonably accurate estimates, had limitations in capturing dynamic field factors such as changes in the patterns of electricity consumption and PV module degradation over time. The long-term projections presented in this study were subject to several uncertainties. The growth in electricity consumption depended on population dynamics, economic trends, and behavioral changes, which were inherently difficult to predict accurately. Similarly, emission factors might vary depending on the speed of national grid decarbonization, which was influenced by the policies and investments in renewables. The projected rate of EV adoption assumed favorable market conditions and regulatory support, which could change significantly. Second, the lack of spatial data necessitated certain assumptions for determining the areas available for installing RPV and FaPV. Additionally, evolving regulations and policies could affect the results of this study, especially the electricity tariffs, government incentives, and net metering policies in Indonesia. Further research combining empirical data and direct case studies is essential to enhance the accuracy and validity of the findings.

5.2 Potential Role of BIPV

BIPV possesses the potential to support the energy transition in Surabaya by utilizing urban space for renewable energy generation and sustainability promotion. Implementing this system could lead to multiple benefits, including reduced carbon emissions, improved efficiency of building energy, and decreased dependence on fossil fuels. Besides, BIPV offers economic advantages through saving the costs of electricity, enabling the sale of surplus energy to the grid, and creating new revenue opportunities. From a broader perspective, integrating BIPV into electric vehicle (EV) systems could further strengthen the development of a sustainable smart city, where buildings generate and supply energy directly to EV charging. This integration reduces the burden on the primary power grid and enhances the resilience of urban energy, ensuring a more stable and efficient energy supply for the future.

5.3 Challenges in Implementing BIPV Systems in Surabaya

Despite its numerous benefits, implementing BIPV in Surabaya still faces several challenges. Currently, Surabaya adheres to the general renewable energy regulations with the launch of Electricity Supply Business Plan (RUPTL) in Indonesia and Peraturan Menteri ESDM No. 26/2021, which support the installations of RPV. However, the absence of specific local policies to incentivize the integration of FaPV or BIPV into commercial or mixed-use buildings. Limitations also arise from ambiguous net-metering schemes and administrative burdens for grid interconnection. The gaps found in regulatory support hinder investors' confidence and the scale of a project, necessitating more proactive policies at municipal-level. One of the primary challenges is the high initial investment costs, especially for FaPV systems, which require higher installation complexity than RPV. Additionally, regulations and incentive policies for solar energy in Indonesia should be strengthened to encourage the utility of the system. From a technical perspective, limitations in electrical infrastructure and reliance on conventional power grids pose challenges to the stability and reliability of BIPV systems. Another factor is the lack of awareness and understanding among the public and building developers regarding the benefits of BIPV, hence hindering its widespread use. Therefore, an integrated approach involving the government, private sector, and academia is needed to create an ecosystem that supports the development and implementation of BIPV in Surabaya.

6. Conclusions

This study confirmed the potential of BIPV systems in the support of energy transition in Surabaya. The system could, to a great extent, facilitate energy independence and reduce carbon emissions by utilizing the sites of building rooftops and facades for the installation of solar panels. Simulation results showed that the maximum capacity of RPV would be increased from 4.6 GW in 2026 to 6.0 GW in 2036, while the maximum capacity of FaPV would be enlarged from 1.6 GW to 2.0 GW during the same period. The total electricity production from the combination of RPV and FaPV would possibly reach 9.71 GWh per year in 2036 and this could reduce dependence on the grid by 36.6%. The implementation of these systems could lower carbon emissions from 616 tons/year in the grid-based scenario (GRID) to 520 tons/year in the BIPV+EV scenario by 2026, with a drop of carbon emissions intensity to 0.05 kg CO_2/kWh. To assist in the economic consumption of energy, although the BIPV scenario has a relatively high initial investment cost of USD 3.2 billion and USD 4.8 billion in 2026 and 2036 respectively, it provides a viable solution for sustainable urban development in Surabaya and Indonesia with its potential conservation of energy for the next 10 years and the reduced dependence on fossil fuels. Future research should prioritize the empirical validation of BIPV performance across various building types in the cities of Indonesia. Authorities responsible for urban planning should integrate BIPV into zoning laws and building codes to streamline the procedures of relevant policies. Financial mechanisms such as green bonds and solar leasing could reduce financial burden and accelerate deployment. Overall speaking, the success of BIPV-EV systems depends on the coordination of technical, regulatory, and behavioral domains.

Data Availability

The data used to support the research findings are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no conflict of interest.

References

Alhazmi, Y. (2025). Techno-economic design analysis of electric vehicle charging stations powered by photovoltaic technology on the highways of Saudi Arabia. *Energies*, *18*(2), 315. https://doi.org/10.3390/en18020315.

Aminah, S., Susanti, A. H., & Soekartun, R. (2018). Social ecology and the growth machine coalition in the surabaya policy dilemma. *J. Archit. Res. Des. Stud.*, *1*(2), 26–39. https://doi.org/10.20885/jars.vol1.iss2.art7.

Amini Toosi, H. (2025). Life cycle cost optimization of battery energy storage systems for bipv-supported smart buildings: A techno-economic analysis. *Sustainability*, *17*(13), 5820. https://doi.org/10.3390/su17135820.

Amini, K. N., Ridwan, M. K., & Wilopo, W. (2024). Optimization and feasibility analysis of rooftop solar photovoltaic (PV) power generation system design. *IOP Conf. Ser.: Earth Environ. Sci.*, *1381*, 012021. https://doi.org/10.1088/1755-1315/1381/1/012021.

Anang, N., Syd Nur Azman, S. N. A., Muda, W. M. W., Dagang, A. N., & Daud, M. Z. (2021). Performance analysis of a grid-connected rooftop solar PV system in Kuala Terengganu, Malaysia. *Energy Build.*, *248*, 111182. https://doi.org/10.1016/j.enbuild.2021.111182.

Cheng, L., Zhang, F., Li, S., Mao, J., Xu, H., Ju, W., Liu, X., Wu, J., Min, K., Zhang, X., & Li, M. (2020). Solar energy potential of urban buildings in 10 cities of China. *Energy*, *196*, 117038. https://doi.org/10.1016/j.energy.2020.117038.

Dan, Z., Song, A., Zheng, Y., Zhang, X., & Zhou, Y. (2025). City information models for optimal EV charging and energy-resilient renaissance. *Nexus*, *2*(1), 100056. https://doi.org/10.1016/j.ynexs.2025.100056.

Dehkordi, S. R. & Jahangiri, M. (2022). Sensitivity analysis for 3E assessment of BIPV system performance in Abadan in Southwestern Iran. *J. Renew. Energy Environ.*, *9*(1), 1–12. https://doi.org/10.30501/jree.2021.262420.1173.

El Mokhi, C., Choukai, O., Hachimi, H., & Ait Errouhi, A. (2023). Assessment and optimization of photovoltaic systems at the University Ibn Tofail according to the new law on renewable energy in Morocco using HOMER Pro. *Energy Harvest. Syst.*, *10*(1), 55–69. https://doi.org/10.1515/ehs-2022-0035.

Elaouzy, Y. & El Fadar, A. (2022). Energy, economic and environmental benefits of integrating passive design strategies into buildings: A review. *Renew. Sustain. Energy Rev.*, *167*, 112828. https://doi.org/10.1016/j.rser.2022.112828.

Felseghi, R. A., Aşchilean, I., Cobîrzan, N., Bolboacă, A. M., & Raboaca, M. S. (2021). Optimal synergy between photovoltaic panels and hydrogen fuel cells for green power supply of a green building—A case study. *Sustainability*, *13*(11). https://doi.org/10.3390/su13116304.

Fernandez, M. I., Go, Y. I., Wong, D. M. L., & Früh, W. G. (2024). Review of challenges and key enablers in energy systems towards net zero target: Renewables, storage, buildings, & grid technologies. *Heliyon*, *10*(23), e40691. https://doi.org/10.1016/j.heliyon.2024.e40691.

Freitas, B. B., Castro, L. F. C., & Carvalho, P. C. M. (2021). Energy planning tools applied into urban photovoltaic: The importance of compatibilizing with the constructions. *Renew. Energy Power Qual. J.*, *19*(2), 229–234. https://doi.org/10.24084/repqj19.264.

Gamonwet, P. & Dhakal, S. (2023). The assessment of the value of electricity saving and economic benefit to residential solar rooftop PV customer: The case of Thailand. *Energy Strategy Rev.*, *50*, 101203. https://doi.org/10.1016/j.esr.2023.101203.

Ghosh, A. (2025). Solar-powered green hydrogen from electrolyzer (PV-H2): A review. *Solar RRL*, *9*(14), 2500150. https://doi.org/10.1002/solr.202500150.

Grande, L. S. A., Yahyaoui, I., & Gómez, S. A. (2018). Energetic, economic and environmental viability of off-grid PV-BESS for charging electric vehicles: Case study of Spain. *Sustain. Cities Soc.*, *37*, 519–529. https://doi.org/10.1016/j.scs.2017.12.009.

Güven, A. F., Ateş, N., Alotaibi, S., Alzahrani, T., Amsal, A. M., & Elsayed, S. K. (2025). Sustainable hybrid systems for electric vehicle charging infrastructures in regional applications. *Sci. Rep.*, *15*(1), 4199. https://doi.org/10.1038/s41598-025-87985-7.

Güven, A. F. & Yücel, E. (2023). Application of HOMER in assessing and controlling renewable energy-based hybrid EV charging stations across major Turkish cities. *Int. J. Energy Stud.*, *8*(4), 747–780. https://doi.org/10.58559/ijes.1324236.

Hanig, L., Ledna, C., Nock, D., Harper, C. D., Yip, A., Wood, E., & Spurlock, C. A. (2025). Finding gaps in the national electric vehicle charging station coverage of the United States. *Nat. Commun.*, *16*(1). https://doi.org/10.1038/s41467-024-55696-8.

Irshad, A. S., Ludin, G. A., Masrur, H., Ahmadi, M., Yona, A., Mikhaylov, A., Krishnan, N., & Senjyu, T. (2023). Optimization of grid-photovoltaic and battery hybrid system with most technically efficient PV technology after the performance analysis. *Renew. Energy*, *207*, 714–730. https://doi.org/10.1016/j.renene.2023.03.062.

Jahangiri, M., Yousefi, Y., Pishkar, I., Hosseini Dehshiri, S. J., Hosseini Dehshiri, S. S., & Fatemi Vanani, S. M. (2023). Techno-econo-enviro energy analysis, ranking and optimization of various building-integrated photovoltaic (BIPV) types in different climatic regions of Iran. *Energies*, *16*(1), 546. https://doi.org/10.3390/en16010546.

Khan, S., Sudhakar, K., & bin Yusof, M. H. (2023). Building integrated photovoltaics powered electric vehicle charging with energy storage for residential building: Design, simulation, and assessment. *J. Energy Storage*, *63*, 107050. https://doi.org/10.1016/j.est.2023.107050.

Khan, S., Sudhakar, K., Hazwan Yusof, M., & Sundaram, S. (2024). Review of building integrated photovoltaics system for electric vehicle charging. *Chem. Rec.*, *24*(3). https://doi.org/10.1002/tcr.202300308.

Li, H., Qu, H., Tan, X., You, L., Zhu, R., & Fan, W. (2025). UrbanEV: An open benchmark dataset for urban electric vehicle charging demand prediction. *Sci. Data* , *12*(1), 1–10. https://doi.org/10.1038/s41597-025-04874-4.

Liu, J., Li, M., Xue, L., & Kobashi, T. (2022). A framework to evaluate the energy-environment-economic impacts of developing rooftop photovoltaics integrated with electric vehicles at city level. *Renew. Energy*, *200*, 647–657. https://doi.org/10.1016/j.renene.2022.10.011.

Loghmania, N. & Khosravi, A. (2024). A combination of SWHs and PVs mounted on the façade of a building to reduce energy-consuming. *J. Sol. Energy Res.*, *9*(1), 1728–1744. https://doi.org/10.22059/jser.2024.364971.1347.

Mahir, O., Rochd, A., Benazzouz, A., & Ghennioui, H. (2024). Towards decarbonizing large-scale industries: A decision support framework for optimizing grid-connected PV-battery energy systems planning—Case study of an OCP mining site, Morocco, North Africa. *Heliyon*, *10*(20), e39075. https://doi.org/10.1016/j.heliyon.2024.e39075.

Makhmudov, F., Kilichev, D., Giyosov, U., & Akhmedov, F. (2025). Online machine learning for intrusion detection in electric vehicle charging systems. *Mathematics*, *13*(5), 712. https://doi.org/10.3390/math13050712.

Mauludin, M. S., Khairudin, M., Asnawi, R., Trisnoaji, Y., Prasetyo, S. D., Azizah, S. R., & Wiraguna, R. T. (2025). In-depth evaluation and enhancement of a PV-wind combined system: A case study at the Engineering Faculty of Wahid Hasyim University. *Int. J. Power Electron. Drive Syst.*, *16*(2), 1274–1283. https://doi.org/10.11591/ijpeds.v16.i2.pp1274-1283.

Mohammadi, S. A. D. & Gezegin, C. (2022). Design and simulation of grid-connected solar PV system using PVSYST, PVGIS and HOMER software. *Int. J. Pioneering Technol. Eng.*, *1*(1), 36–41. https://doi.org/10.56158/jpte.2022.24.1.01.

Ni, P.;Zheng, H.;Sun, H.;Lei, F.;Wang, Y.;Qin, J.;Wang, W.;Song, J.;Yue, Y.;Yao, S., et al. (2025). Article Building integrated photovoltaics that move beyond rooftops bbuilding integrated photovoltaics. *Cell Rep. Phys. Sci.*, 102725. https://doi.org/10.1016/j.xcrp.2025.102725.

Nishanthy, J., Raja, S. C., & Priya, D. B. (2024). Optimal planning and modelling of the solar roof-top PV system with different incentive policy schemes for residential prosumers: A real-time case study. *Electr. Eng.*, *107*(2), 1617–1641. https://doi.org/10.1007/s00202-024-02581-8.

Nur-E-Alam, M., Zehad Mostofa, K., Kar Yap, B., Khairul Basher, M., Aminul Islam, M., Vasiliev, M., Soudagar, M. E. M., Das, N., & Sieh Kiong, T. (2024). Machine learning-enhanced all-photovoltaic blended systems for energy-efficient sustainable buildings. *Sustain. Energy Technol. Assess.*, *62*, 103636. https://doi.org/10.1016/j.seta.2024.103636.

Nurwidiana, N., Nugroho, D., & Fatmawati, W. (2024). Design of solar home charging for individual electric vehicles: Case study for Indonesian household. *Indones. J. Electr. Eng. Inform.*, *12*(4), 1063–1073. https://doi.org/10.52549/ijeei.v12i4.5078.

Pan, H., Page, J., Shi, R., Cong, C., Cai, Z., Barthel, S., Thollander, P., Colding, J., & Kalantari, Z. (2023). Contribution of prioritized urban nature-based solutions allocation to carbon neutrality. *Nat. Clim. Change*, *13*(8), 862–870. https://doi.org/10.1038/s41558-023-01737-x.

Paradongan, H. T., Hakam, D. F., Wiryono, S. K., Prahastono, I., Aditya, I. A., Banjarnahor, K. M., Sinisuka, N. I., & Asekomeh, A. (2024). Techno-economic feasibility study of solar photovoltaic power plant using RETScreen to achieve Indonesia energy transition. *Heliyon*, *10*(7), e27680. https://doi.org/10.1016/j.heliyon.2024.e27680.

Prasetyo, S. D., Regannanta, F. J., Mauludin, M. S., & Arifin, Z. (2023). Economic feasibility of solar-powered electric vehicle charging stations: A case study in Ngawi, Indonesia. *Mechatron. Intell. Transp. Syst.*, *2*(4), 201–210. https://doi.org/10.56578/mits020402.

Prasetyo, S. D., Rizandy, A. N., Birawa, A. R., Regannanta, F. J., Arifin, Z., Mauludin, M. S., & Sukarman. (2024). Design and economic analysis of a solar-powered charging station for personal electric vehicles in Indonesia. *J. Sustain. Energy*, *3*(2), 65–74. https://doi.org/10.56578/jse030201.

Prasetyo, S. D., Trisnoaji, Y., Arifin, Z., & Mahadi, A. A. (2025). Harnessing unconventional resources for large-scale green hydrogen production: An economic and technological analysis in Indonesia. *Unconv. Resour.*, *6*, 100174. https://doi.org/10.1016/j.uncres.2025.100174.

Purlu, M. & Ozkan, U. (2023). Economic and environmental analysis of grid-connected rooftop photovoltaic system using HOMER. *Turk. J. Electr. Power Energy Syst.*, *3*(1), 39–46. https://doi.org/10.5152/tepes.2023.23002.

Quddus, A. S., Usmani, T., & Hasan, S. H. (2024). Analysis and comparison of energy generation from a 38.4 kWp BIPV system using PVsyst simulation tool. *Indian J. Sci. Technol.*, *17*(48), 5046–5054. https://doi.org/10.17485/IJST/v17i48.3772.

Reddy, M. S. K. & Selvajyothi, K. (2020). Optimal placement of electric vehicle charging station for unbalanced radial distribution systems. *Energy Sour. Part A*, *47*(2), 1–15. https://doi.org/10.1080/15567036.2020.1731017.

Rehman, S., Mohammed, A. B., Alhems, L., & Alsulaiman, F. (2023). Comparative study of regular and smart grids with PV for electrification of an academic campus with EV charging. *Environ. Sci. Pollut. Res.*, *30*(31), 77593–77604. https://doi.org/10.1007/s11356-023-27859-5.

Saez, R., Boer, D., Shobo, A. B., & Vallès, M. (2023). Techno-economic analysis of residential rooftop photovoltaics in Spain. *Renew. Sustain. Energy Rev.*, *188*, 113788. https://doi.org/10.1016/j.rser.2023.113788.

Safitri, D. A., Alina, A. N., Bespalova, L. A., Suprayitno, W. E., & Dhani, N. Q. (2024). The impact of population density, land cover, and spatial patterns on the geoecological evaluation of the Surabaya Coast. *IOP Conf. Ser.: Earth Environ. Sci.*, *1418*, 012040. https://doi.org/10.1088/1755-1315/1418/1/012040.

Schmid, C. V., Ngagoum Ndalloka, Z., & Kośny, J. (2025). Transforming urban energy: Developments and challenges in photovoltaic integration. *Front. Sustain. Cities*, *7*, 1–9. https://doi.org/10.3389/frsc.2025.1584917.

Yu, Z., Lu, Z., Xin, W., Pu, H., Jiang, J., & Ye, B. (2024). Environmental and economic evaluation of urban building-integrated photovoltaic and electric vehicle system. *J. Build. Eng.*, *95*, 110205. https://doi.org/10.1016/j.jobe.2024.110205.

Zhang, Z., Chen, M., Zhong, T., Zhu, R., Qian, Z., Zhang, F., Yang, Y., Zhang, K., Santi, P., Wang, K., et al. (2023). Carbon mitigation potential afforded by rooftop photovoltaic in China. *Nat. Commun.*, *14*(1), 1–12. https://doi.org/10.1038/s41467-023-38079-3.