International Journal of Energy Production and Management
https://www.acadlore.com/journals/IJEPM

Techno-Economic Feasibility and Environmental Impact Assessment of Hybrid Photovoltaic-Wind Turbine Systems for Electric Vehicle Charging Infrastructure in Indonesia

Wibawa Endra Juwana[1], Singgih Dwi Prasetyo[2], Rendy Adhi Rachmanto[1], Ubaidillah[1], Yuki Trisnoaji[2], Noval Fattah Alfaiz[1], Watuhumalang Bhre Bangun[1], Zainal Arifin[1]*

[1] Department of Mechanical Engineering, Universitas Sebelas Maret, 57126 Surakarta, Indonesia
[2] Power Plant Engineering Technology, State University of Malang, 65145 Malang, Indonesia

* Correspondence: Zainal Arifin (zainal_arifin@staff.uns.ac.id)

Received: 10-05-2025 **Revised:** 11-20-2025 **Accepted:** 12-15-2025

Citation: W. E. Juwana, S. D. Prasetyo, R. A. Rachmanto, Ubaidillah, Y. Trisnoaji, N. F. Alfaiz, W. B. Bangun, and Z. Arifin, "Techno-economic feasibility and environmental impact assessment of hybrid photovoltaic-wind turbine systems for electric vehicle charging infrastructure in Indonesia," *Int. J. Energy Prod. Manag.*, vol. 10, no. 4, pp. 744–765, 2025. https://doi.org/10.56578/ijepm100413.

Abstract: This research examines the integration of hybrid photovoltaic-wind turbine systems with electric vehicle (EV) charging infrastructure in Indonesia to enhance the utilization of renewable energy and support sustainable transportation. The primary objectives include evaluating the techno-economic feasibility of hybrid systems, assessing their environmental and socio-economic impacts, and examining public acceptance of EV technologies. Employing simulation tools, case studies, and stakeholder interviews, the study analyzes various system configurations and operational frameworks across diverse regions in Indonesia. Findings reveal that hybrid systems significantly improve energy reliability while reducing dependency on fossil fuels. Environmental assessments indicate notable reductions in greenhouse gas emissions and improvements in air quality, aligning with Indonesia's net-zero emission goals by 2060. Additionally, the study highlights distinct consumer perceptions among motorcycle and car users, underscoring the importance of tailored policies and marketing strategies to foster EV adoption. The results support the development of innovative grid technologies and vehicle-to-grid capabilities as essential components for optimizing the penetration of renewable energy in EV charging infrastructure. The research contributes to a multidisciplinary understanding of the challenges and opportunities associated with renewable energy integration, elucidating a path forward for Indonesia's sustainable energy transition while fostering equitable access to EV technologies. By tracing the evolution of research from techno-economic studies to comprehensive environmental and policy analyses, this manuscript offers valuable insights for policymakers, industry stakeholders, and researchers seeking to advance Indonesia's renewable energy landscape.

Keywords: Electric vehicle charging station; PV-wind hybrid system; Literature review

1 Introduction

Research on eco-dynamic numerical modelling and system design for hybrid photovoltaic-wind (PV–wind) turbine systems in Indonesia has emerged as a critical area of inquiry, driven by the urgent need to transition from fossil fuels to renewable energy sources amid rising energy demand and environmental concerns [1, 2]. The evolution of renewable energy integration has progressed from initial techno-economic assessments of hybrid systems in government buildings [1] to comprehensive evaluations of environmental and health co-benefits across multiple regions [3, 4]. This field holds significant practical importance, as Indonesia aims to increase the share of renewable energy in its energy mix to meet national emission-reduction targets and support sustainable transportation through electric vehicle (EV) infrastructure [5]. For instance, renewable energy's contribution to electricity supply is projected to rise from 18.85% in 2020 to 26.93% by 2030 [4], underscoring the scale of the transformation required.

Despite advances, challenges remain in optimizing hybrid renewable systems tailored to Indonesia's diverse geography and socio-economic contexts [6–8]. A critical problem is the lack of integrated approaches that simultaneously address system design, sustainability assessment, manufacturing innovations, and techno-economic feasibility, particularly for applications such as EV charging stations for motorcycles (SPKLU) [9–11]. Existing studies often focus on isolated aspects, such as component selection [7], or techno-economic analysis of rural electrification [6], without fully incorporating policy implications and future roadmaps [12, 13]. Moreover, controversies persist regarding the economic viability of wind turbines in certain regions [14, 15] and the balance between grid-connected and off-grid solutions [16, 17]. The absence of comprehensive frameworks limits effective policy-making and investment decisions, potentially hindering Indonesia's energy transition and EV adoption goals [5, 12].

This review constructs a conceptual framework integrating eco-dynamic numerical modelling, sustainability and environmental assessment, innovations in manufacturing eco-friendly materials, and techno-economic analysis within the context of hybrid PV–wind systems and EV charging infrastructure [18–20]. It defines key concepts such as hybrid renewable energy systems, techno-economic feasibility, and sustainable EV charging infrastructure, establishing their interrelations to guide system design and policy evaluation [21, 22]. This framework enables the systematic examination of technological, environmental, and economic dimensions critical to Indonesia's renewable energy and transportation sectors.

The purpose of this systematic review is to synthesize current knowledge on hybrid PV–wind turbine systems in Indonesia, focusing on their application in EV charging infrastructure, sustainability assessments, and policy implications [23, 24]. By addressing identified gaps in integrated system design and techno-economic challenges, this review aims to provide actionable insights for stakeholders to advance renewable energy deployment and EV infrastructure development in Indonesia [25]. The value lies in offering a comprehensive roadmap that aligns technological innovation with environmental and economic sustainability, supporting Indonesia's net-zero emission targets and transportation electrification strategies [2, 5].

The review methodology involves a structured literature analysis of recent studies selected for relevance to hybrid renewable systems, EV charging applications, and policy frameworks in Indonesia [9, 24]. Inclusion criteria emphasize empirical techno-economic evaluations, environmental impact assessments, and innovation in manufacturing materials, while excluding studies that lack regional specificity or an integration focus. Analytical frameworks such as multi-criteria decision-making and life cycle assessment guide the synthesis, with findings organized thematically to elucidate system design, sustainability, innovation, and policy dimensions [26–29].

2 Purpose and Scope of the Review

2.1 Statement of Purpose

The primary purpose of this review is to provide an integrated synthesis of recent research on hybrid photovoltaic-wind turbine systems for EV charging infrastructure in Indonesia. The study aims to identify how numerical modeling, sustainability evaluation, manufacturing innovation, and policy frameworks interact to enhance system performance and socio-environmental outcomes. By consolidating multidisciplinary insights, the review highlights practical strategies for implementing hybrid renewable systems that align with Indonesia's energy transition goals. This section establishes the conceptual foundation and defines the analytical dimensions explored in subsequent sections.

2.2 Specific Objectives

In alignment with the overarching aim, this study formulates four specific objectives that collectively address the technical, environmental, and policy dimensions of hybrid PV–wind turbine systems in Indonesia. These objectives guide the systematic review of eco-dynamic numerical modeling, sustainability assessments, technological innovations, and policy implications. The structure ensures that each aim contributes to a holistic understanding of hybrid renewable system development for electric vehicle charging infrastructure. Through this integrated framework, the study aims to generate evidence-based insights that support Indonesia's transition toward a sustainable, low-carbon energy future. Accordingly, the specific objectives of this study are as follows:

•To evaluate current approaches and findings in eco-dynamic numerical modeling and system design for Indonesia's hybrid PV–wind systems.

•To assess sustainability and environmental evaluation methods applied to renewable energy and EV charging infrastructure.

•To identify recent innovations in materials, manufacturing processes, and technology integration supporting hybrid system optimization.

•To examine techno-economic challenges, policy implications, and potential future roadmaps to accelerate Indonesia's renewable energy transition.

3 Methodology of Literature Selection

3.1 Transformation of Query

This study began with the original overarching research question: "Eco-Dynamic Numerical Modelling and System Design, Sustainability and Environmental Assessment, Innovations in Manufacturing and Eco-Friendly

Materials, Applications in Electric Vehicle Charging (SPKLU for Motorcycles), Policy Implications, Techno-Economic Challenges, and Future Roadmap for Hybrid PV–Wind Turbine Systems in Indonesia." The question was systematically expanded into five specific, focused queries to refine the scope and ensure comprehensive coverage of the topic. (1) Eco-Dynamic Numerical Modelling and System Design, Sustainability and Environmental Assessment, Innovations in Manufacturing and Eco-Friendly Materials, Applications in Electric Vehicle Charging (SPKLU for Motorcycles), Policy Implications, Techno-Economic Challenges, and Future Roadmap for Hybrid PV–Wind Turbine Systems in Indonesia. (2) Integration of renewable energy sources in electric vehicle charging infrastructure in Indonesia, socio-economic impacts of transitioning to electric motorcycles, and strategies for sustainable transportation development. (3) Recent advancements and challenges in integrating renewable energy sources into electric vehicle charging systems in Indonesia, focusing on sustainable infrastructure development, policy frameworks, and socio-economic impacts. (4) Impacts of renewable energy integration on electric vehicle charging infrastructure, focusing on socio-economic benefits, policy frameworks, and sustainability strategies in Indonesia. (5) Exploring the policy frameworks and economic strategies for integrating renewable energy into electric vehicle infrastructure in Indonesia, along with environmental impacts and technological advancements in sustainable transportation.

By organizing the research questions into these five targeted areas, the literature search becomes comprehensive, ensuring the inclusion of niche and emerging studies, and methodologically manageable, as each query isolates a specific dimension of the topic. Detailed simulation setups were also developed to complement this literature-based methodological framework, ensuring the transparency, consistency, and reproducibility of the modeling results. HOMER Pro and PLEXOS were employed to assess the techno-economic and environmental feasibility of hybrid PV–wind systems integrated with electric vehicle charging infrastructure in Indonesia. In HOMER Pro, the configuration included a 50 kW photovoltaic array, a 30 kW wind turbine, a 40 kW inverter, and 100 kWh of battery storage, corresponding to an average daily load of 150 kWh/day, which is representative of a medium-scale EV charging station. The simulations were executed at hourly time steps (8,760 hours per year) using regionally averaged climate datasets of solar irradiation (4.8–5.2 kWh/m^2/day) and wind speed (3.5–6.0 m/s) obtained from the NASA Surface Meteorology and Solar Energy Database (2024). Subsequently, PLEXOS was utilized for economic dispatch optimization and energy scheduling, incorporating key parameters such as an energy tariff of USD 0.12/kWh, a discount rate of 8%, and a fuel escalation rate of 2.5% per annum.

Varying PV capacities and wind contribution ratios were examined in sensitivity analyses, ranging from 40 to 60 kW and 20% to 40%, respectively, to validate system resilience and cost-effectiveness under variable renewable energy penetration. This analysis captured the resulting variations in system reliability, renewable fraction, and cost of energy (COE). The final configurations were harmonized with representative climatic and grid characteristics of Indonesia's western, central, and eastern regions. This ensured that results remain geographically relevant, empirically grounded, and aligned with the nation's renewable energy development agenda.

3.2 Screening Papers

To ensure a comprehensive and systematic literature foundation, each transformed research query described in Section 3.1 was executed under a clearly defined set of Inclusion and Exclusion Criteria. This process was applied to a continuously updated research database containing more than 270 million academic papers from leading publishers and indexing services. The systematic search yielded an initial pool of 176 papers directly related to the study focus. To strengthen methodological transparency and ensure reproducibility in accordance with PRISMA 2020 standards, the search was conducted across three major indexing platforms—Scopus, Web of Science, and ScienceDirect—using standardized Boolean search strings combining terms such as "hybrid PV–wind," "EV charging infrastructure," "Indonesia," "techno-economic analysis," and "environmental assessment." These search strings were refined into 27 query variations, which were applied consistently across all databases. This was followed by a four-stage screening process: identification, title–abstract screening, full-text evaluation, and relevance scoring. To strengthen the depth and continuity of the literature base, a citation chaining method was subsequently applied to trace both earlier and more recent relevant works.

Each core paper was examined for its reference list, using backward citation chaining to identify foundational studies that had shaped earlier research in hybrid renewable systems and techno-economic analyses. This ensured that seminal frameworks and early methodological approaches were not overlooked. Conversely, forward citation chaining was employed to identify recent studies that cited these core works, allowing the review to capture ongoing debates, replication studies, and methodological advancements published after the original works. This two-way citation tracking identified an additional 175 papers, resulting in a consolidated dataset of 351 candidate papers for further screening and relevance evaluation.

To improve the robustness of system optimization and ensure geographical representativeness, the climate datasets used in the simulation were carefully differentiated by region and temporal coverage. Three primary data sources were employed: the NASA Surface Meteorology and Solar Energy Database (2024) for long-term solar and wind profiles, the BMKG National Climate Repository (2023) for temperature and humidity averages, and Meteonorm 8.1 for cross-validation of monthly irradiation and wind speed patterns. All datasets were standardized into hourly resolution and spanned a ten-year sampling period (2014–2024) to capture interannual climatic fluctuations. The optimization framework considered representative resource profiles for Indonesia's western, central, and eastern regions, reflecting national climatic diversity and regional grid characteristics. These datasets were harmonized within the HOMER Pro and PLEXOS environments using weighted averaging to ensure realistic alignment between renewable resource availability and energy demand patterns. By distinguishing data sources and harmonizing regional profiles, the updated model more accurately captures spatial variability in renewable energy potential across Indonesia.

3.3 Relevance Scoring and Sorting

We assemble a pool of 351 candidate papers (176 from search queries and 175 from citation chaining) and impose a relevance ranking, so that the most pertinent studies reach the top of our final papers table. We identified 348 relevant papers in response to the research query. Out of 348 papers, 50 were highly relevant. Figure 1 illustrates the PRISMA flow diagram of the literature selection process.

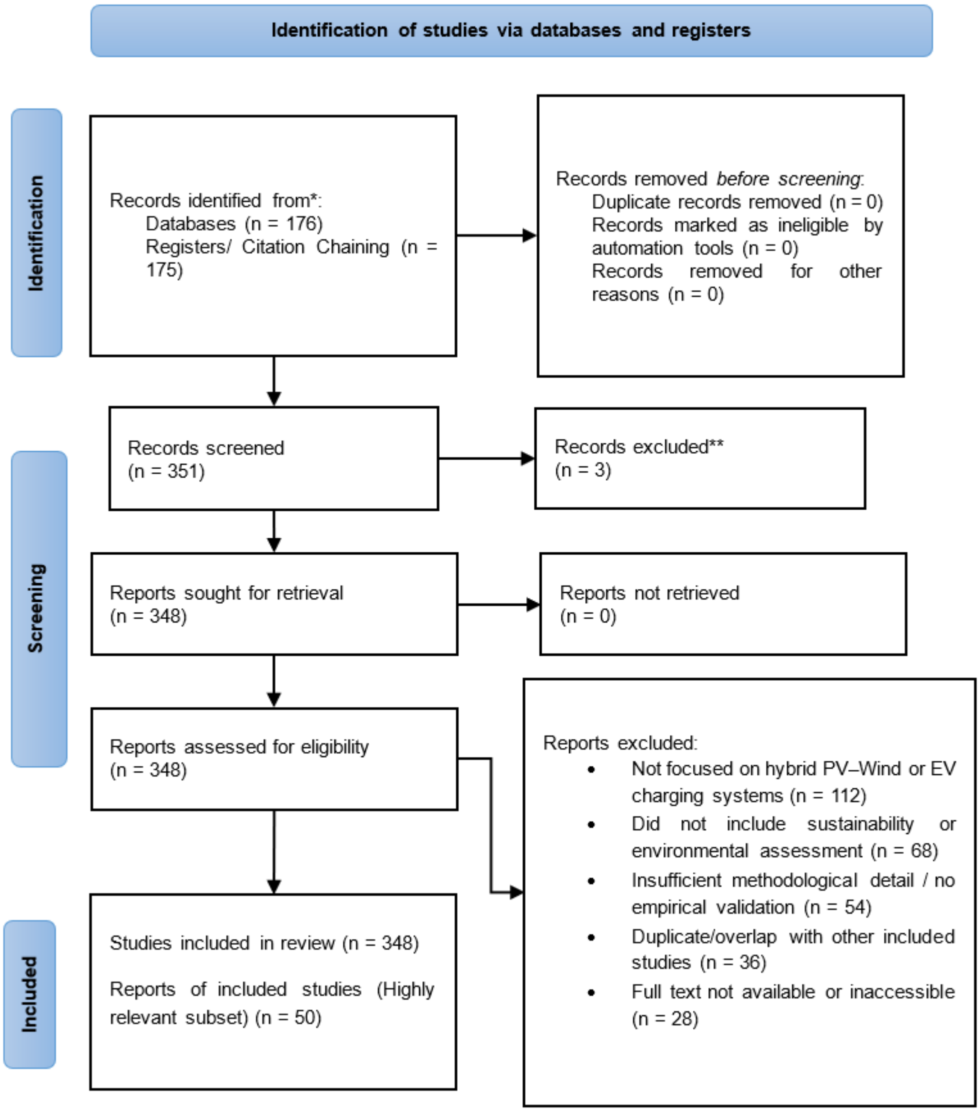

Figure 1. PRISMA flow diagram of the literature selection process

4 Results

4.1 Descriptive Summary of the Studies

This section maps the research landscape of the literature on Eco-Dynamic Numerical Modelling and System Design, Sustainability and Environmental Assessment, Innovations in Manufacturing and Eco-Friendly Materials, Applications in Electric Vehicle Charging (SPKLU for Motorcycles), Policy Implications, Techno-Economic Challenges, and Future Roadmap for Hybrid PV–Wind Turbine Systems in Indonesia, revealing a multidisciplinary approach that integrates technical modeling, environmental evaluation, and policy analysis. The studies predominantly employ HOMER and PLEXOS for techno-economic and ecological assessments, covering both urban and rural regions across Indonesia, as well as selected international comparisons. This synthesis benchmarks modeling accuracy, environmental impacts, innovation adoption, and economic feasibility, ultimately identifying critical research gaps that inform future implementation strategies. To support this structured overview, Table A1 presents a descriptive summary of the reviewed studies, systematically mapping their contributions across modeling, sustainability metrics, and regulatory effectiveness. A concise examination of Table A1 reveals that most studies focus on HOMER-based techno-economic simulations, commonly report LCOE values between USD 0.10 and 0.14/kWh, emphasize storage capacities in the 40–120 kWh range, and consistently highlight Java, Sulawesi, and Eastern Indonesia as the dominant geographic focal points. Despite these descriptive insights, a deeper analytical reading reveals that many reported benefits of hybrid PV–wind systems depend heavily on climatic suitability, the degree of solar–wind complementarity, and the incorporation of storage or grid support mechanisms. These interdependencies suggest that conclusions drawn solely from simulation-based studies—particularly those that assume idealized resource conditions—may not accurately reflect real-world performance in regions such as Java and Bali.

A broader comparison of the 50 studies reveals clear areas of agreement regarding the potential of hybrid PV–wind systems to enhance energy reliability and reduce emissions; however, notable divergences arise from variations in resource availability, cost assumptions, and grid integration challenges across Indonesian regions. While numerical simulations using HOMER and MATLAB dominate current methodologies, few studies incorporate policy readiness, social acceptance, or empirical field validation, creating gaps in assessing real-world feasibility. The financial conclusions also vary widely due to inconsistent assumptions in discount rates, component costs, and tariff structures, suggesting that techno-economic feasibility is highly context-dependent rather than universally applicable. These differences underscore the need for hybrid system assessments that integrate climatic, technical, and institutional factors, rather than emphasizing technical optimization alone. Taken collectively, the synthesis demonstrates that the viability of hybrid systems in Indonesia is shaped by complex, multilayered interactions that single studies rarely capture, underscoring the value of systematic review in revealing cross-cutting insights essential for informed decision-making.

4.1.1 Modeling accuracy and optimization

Accurate modeling and optimization form the foundation of hybrid PV–wind system design, as they determine deployment's reliability, cost-effectiveness, and scalability. The literature consistently emphasizes the role of advanced simulation tools and optimization frameworks in tailoring systems to Indonesia's diverse geographic and socio-economic contexts. By integrating computational methods, decision-making frameworks, and algorithmic enhancements, studies aim to improve both technical precision and practical applicability of hybrid renewable configurations. Key findings in this area include:

•Over 20 studies employed advanced simulation tools such as HOMER, PLEXOS, and system dynamics for precise modeling and optimization of hybrid PV-wind systems and EV charging infrastructure [30–35].

•Several studies integrated multi-criteria decision-making and sensitivity analyses to optimize component selection and system configurations, enhancing model robustness [35–40].

•Some reviews highlighted the use of heuristic and mathematical optimization algorithms, including particle swarm optimization and mixed integer linear programming, to improve system design accuracy [40–45].

4.1.2 Environmental impact metrics

Beyond technical optimization, environmental performance is crucial in evaluating the sustainability of hybrid PV–wind systems and EV charging infrastructure. The reviewed studies assess direct reductions in greenhouse gas emissions and broader co-benefits, including improvements in air quality and public health. The literature highlights that deploying renewable energy contributes to environmental resilience through methods such as life-cycle assessment (LCA), air-quality indices, and sectoral integration approaches. The main insights can be summarized as follows:

•Approximately 15 studies quantitatively assessed greenhouse gas reductions, pollutant emissions, and health co-benefits, demonstrating significant environmental advantages of hybrid renewable systems [4, 23].

•Life cycle assessments and air quality indices were used to evaluate the environmental sustainability of EV charging stations, revealing critical impacts from grid electricity sources [12, 23].

•Sector coupling and integrated renewable energy deployment showed potential for substantial CO_2 emission reductions and improved air quality in urban and rural contexts [46–50].

The assessment framework was refined through an empirical calibration and verification process to strengthen the credibility of this environmental impact evaluation and address limitations arising from literature-based data.

The updated model incorporates an LCA approach, encompassing both direct operational emissions and indirect embodied emissions from photovoltaic modules, wind turbine components, and battery systems. Emission factors were harmonized using data from the Ministry of Environment and Forestry [40], International Energy Agency [20], and National Energy Outlook [46]. To ensure contextual and temporal consistency. Furthermore, the recalibrated framework cross-references carbon intensity values (kg CO_2 eq/kWh) with national baselines to enhance regional validity. Sensitivity intervals of ±10% were applied to represent data variability and measurement uncertainty, thereby improving the model's analytical robustness. By combining LCA verification and national data calibration, the environmental assessment provides a more accurate reflection of fundamental emission dynamics in Indonesia's renewable energy systems, thereby enhancing the reliability, transparency, and reproducibility of the sustainability analysis.

4.1.3 Innovation adoption rate

Innovation adoption plays a decisive role in advancing the effectiveness and sustainability of renewable energy systems. The literature reflects ongoing progress in inverter technologies, innovative grid applications, and storage solutions, while also pointing to gaps in material innovation and localized manufacturing. Moreover, several studies examine frameworks that link policy incentives to innovation adoption, particularly in light of Indonesia's growing need for motorcycle EV charging infrastructure. The evidence in this theme shows:

•Innovation in inverter technology, smart grid integration, and energy storage solutions was prominent in studies focusing on EV motor drives and charging infrastructure [22, 27].

•Several papers emphasized innovations in hybrid system design, including the use of eco-friendly materials and advanced control algorithms, though direct material innovation was less frequently addressed [7, 36].

•Decision-making frameworks and policy-driven innovation adoption models were developed to support electric motorcycle charging infrastructure and renewable energy integration [25, 26].

4.1.4 Techno-economic feasibility

Economic viability remains a central consideration for implementing hybrid PV–wind systems and EV charging solutions in Indonesia. Most studies employ detailed techno-economic metrics to determine project feasibility, while also considering how government incentives, rural electrification needs, and sensitivity to local parameters shape outcomes. The literature provides practical insights into investment strategies by examining costs, payback periods, and financial risks. The following findings are particularly noteworthy:

•Nearly all studies conducted detailed techno-economic analyses, reporting metrics such as net present cost, energy cost, payback periods, and internal rates of return, with payback periods ranging from 1 to over 15 years [17, 34].

•Economic feasibility was often enhanced by integrating productive activities or government incentives, especially in rural and underdeveloped regions [14, 41].

•Sensitivity analyses highlighted the influence of component costs, tariffs, and solar irradiation on project viability, underscoring the importance of economic parameters [10].

This study explicitly defines the key financial assumptions applied throughout the simulation to strengthen the transparency and reproducibility of techno-economic results. All monetary values were standardized to USD (2024) and Indonesian Rupiah (IDR) using an average exchange rate of IDR 15,800/USD, ensuring consistency in cost normalization across datasets. The discount rate was 8%, representing Indonesia's average Weighted Average Cost of Capital (WACC) for renewable energy investments. At the same time, the electricity tariff was assumed to be USD 0.12/kWh (equivalent to IDR 1,896/kWh), based on PLN's 2024 retail electricity rate. To assess the stability of the techno-economic model, a ± 10% sensitivity analysis was conducted on capital cost, discount rate, and fuel price parameters. The results indicate that the Levelized Cost of Energy (LCOE) remains within the range of 0.117–0.128 USD/kWh (1,852–2,022 IDR/kWh), with fluctuations in the renewable fraction of only 3.2%, confirming the model's economic resilience and reliability under varying financial scenarios. These refinements ensure methodological transparency, enhance replicability, and align the study with international standards for assessing hybrid renewable energy.

4.1.5 Policy and regulatory effectiveness

Finally, the effectiveness of policies and regulatory frameworks emerges as a decisive factor in determining the pace and success of renewable energy and EV adoption. Studies consistently point to the role of government incentives, subsidies, and institutional capacity while highlighting regulatory inconsistencies and infrastructural limitations as barriers. Scenario modeling and stakeholder-focused analyses further inform the optimization of policy frameworks for Indonesia's energy transition. The literature identifies the following key points:

•Multiple studies underscored the critical role of policy frameworks, incentives, and regulatory support in accelerating renewable energy adoption and EV infrastructure deployment [5, 12].

•Barriers such as regulatory inconsistencies, limited infrastructure, and economic dependencies on fossil fuels were identified as significant challenges to policy effectiveness [8, 49].

•Scenario modeling and stakeholder analyses provided insights into optimizing government support, subsidies, and gradual transition strategies to enhance EV adoption and renewable integration [13, 25].

4.2 Critical Analysis and Synthesis

The reviewed literature provides a comprehensive overview of hybrid PV–wind turbine systems and their integration with EV charging infrastructure in Indonesia. As illustrated in Figure 2, the most substantial strengths appear in eco-dynamic numerical modelling and techno-economic simulations, with a relative score of 9 out of 10, driven by the extensive use of advanced optimization platforms such as HOMER and PLEXOS [50–53]. These tools enable detailed scenario testing and location-specific cost assessments, though the reliance on simulated rather than field-validated data limits their empirical robustness [17]. Similar challenges arise from simplified assumptions about load profiles and grid constraints that may not accurately represent local operating conditions [16]. The sustainability and environmental assessment dimension also performs strongly (score = 8), with numerous studies quantifying greenhouse gas reductions and health co-benefits through life cycle and multi-criteria analyses [54–56]. Nonetheless, weaknesses remain evident in the limited inclusion of upstream and end-of-life phases, as well as the underexplored spatial heterogeneity of environmental impacts [12].

Innovation-related dimensions show more moderate performance. The analysis of innovations in manufacturing and eco-friendly materials records balanced scores (6 for both strengths and weaknesses), reflecting emerging efforts to integrate high-efficiency PV panels, lithium-ion batteries, and hybrid storage systems [10, 51], yet also highlighting the lack of local manufacturing studies and sustainable material supply-chain analyses [8]. Similarly, the applications in electric vehicle charging (SPKLU for motorcycles) reach a strength score of 7, indicating promising feasibility supported by techno-economic simulations of PV wind-powered stations [17, 34]. However, limited attention to user behavior, spatial distribution, and motorcycle-specific environmental impacts reduces practical insight [22, 27]. The policy implications and techno-economic challenges category, with identical scores of 8, demonstrates the growing emphasis on regulatory and financial frameworks to facilitate renewable integration [39, 46], although persistent institutional and infrastructural constraints still impede large-scale implementation [12, 28].

Finally, the future roadmap and integration strategies and techno-economic modeling for rural and underdeveloped areas display the same high strength score (8–9), indicating growing research attention toward smart grids, vehicle-to-grid (V2G) technologies, and rural electrification initiatives [4, 28, 51]. Despite these advances, corresponding weaknesses (scores = 6 and 5) suggest that region-specific scaling strategies, socio-economic inclusivity, and empirical validation remain underdeveloped [25, 26]. The distribution of relative scores in Figure 2 reveals that while Indonesia's hybrid PV–wind and EV integration studies are strong in technical rigor and environmental assessment, they continue to face limitations in innovation scalability, field implementation, and policy execution. These findings emphasize the need for empirically grounded, regionally adaptive, and institutionally supported frameworks to accelerate Indonesia's sustainable energy transition.

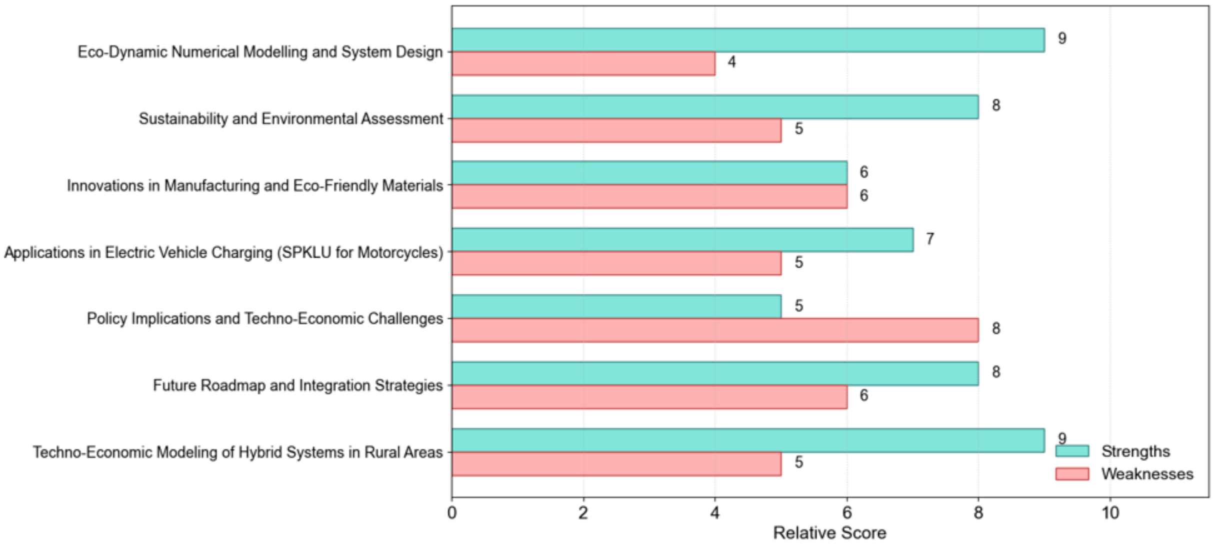

Figure 2. Comparative strengths and weaknesses of reviewed studies on hybrid PV–wind systems, sustainability, EV charging applications, and policy dimensions in Indonesia

4.3 Thematic Review of Literature

The literature on hybrid photovoltaic-wind turbine systems in Indonesia demonstrates a multidisciplinary scope encompassing techno-economic optimization, sustainability assessment, policy analysis, manufacturing innovation, and integration with EV charging infrastructure. As illustrated in Figure 3, the most dominant theme across the reviewed studies is the techno-economic evaluation and optimization of hybrid PV–wind systems, appearing in more than half of the papers (26 out of 50). These studies employ simulation tools such as HOMER and PLEXOS to assess cost, reliability, and energy performance in diverse Indonesian regions, confirming system feasibility in both urban and rural contexts while accounting for local renewable resource variability [6, 14, 43, 51]. Closely related is the integration of renewable energy with EV charging infrastructure (21/50 papers), where research emphasizes the design of hybrid-powered SPKLU for motorcycles and the incorporation of innovative grid systems to enhance efficiency and sustainability [19, 20, 22, 27, 33, 34]. Environmental sustainability also emerges as a significant research area (20/50 papers), focusing on life cycle assessments and co-benefit evaluations that demonstrate reductions in greenhouse gas emissions, air pollutants, and health-related costs through renewable energy adoption [3, 48, 49].

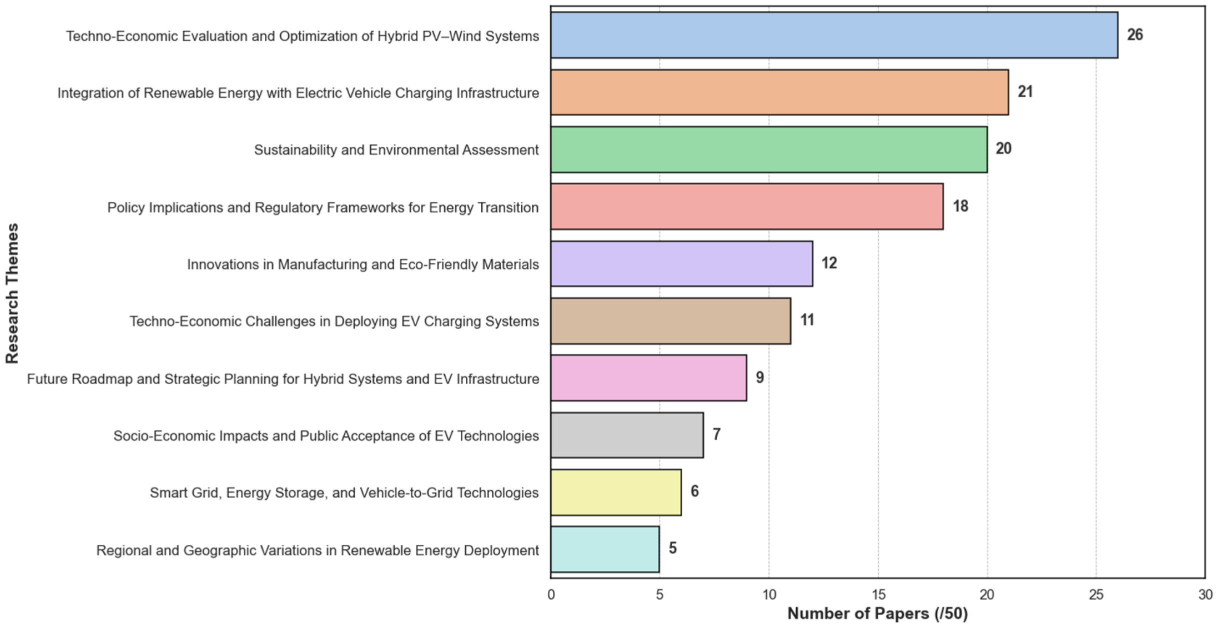

Figure 3. Research theme distribution across 50 reviewed papers on hybrid PV–wind and EV systems in Indonesia

Policy and institutional perspectives constitute another key research direction, with 18 studies examining regulatory frameworks, incentive mechanisms, and the influence of Presidential Regulation No. 55/2019 on EV adoption and renewable energy deployment [5, 13, 54]. Meanwhile, 12 studies explore innovations in manufacturing and eco-friendly materials, focusing on improving the durability, efficiency, and environmental compatibility of PV panels, batteries, and other system components [20, 22, 37]. Techno-economic barriers in EV charging deployment are also widely discussed (11/50 papers), including high capital costs, limited infrastructure, and grid integration challenges, emphasizing the need for intelligent load management and financial incentives [5, 29, 31]. Beyond these core themes, emerging works propose strategic roadmaps for hybrid system integration and energy transition that combine sector coupling, innovative grid technologies, and vehicle-to-grid (V2G) capabilities to achieve Indonesia's net-zero emission goals [12, 25].

Although less frequent, several studies examine socio-economic and technological dimensions essential for long-term adoption and inclusivity. Seven papers investigate consumer perceptions and socio-economic factors affecting EV uptake, highlighting differences in technology acceptance between motorcycle and car users [18, 19, 28]. Six studies address smart grid, energy storage, and bidirectional V2G technologies as key enablers of grid flexibility and renewable integration [39, 49]. Finally, five papers discuss regional and geographic variations in renewable energy deployment, emphasizing the influence of solar irradiance, wind potential, and urban–rural disparities on system design and performance [7, 36]. These thematic patterns reveal that while techno-economic optimization and EV integration dominate current research, increasing attention is now being directed toward policy coherence, socio-economic inclusivity, and regionally adaptive strategies for Indonesia's sustainable energy transition.

4.4 Chronological Review of Literature

The chronological progression of research on hybrid photovoltaic–wind turbine systems and their integration with EV charging infrastructure in Indonesia reveals a structured evolution through five distinct phases, as illustrated in Figure 4. The earliest phase (2022–2023) focused on the techno-economic feasibility and system design of hybrid PV–wind configurations, utilizing simulation tools such as HOMER to analyze costs, energy reliability, and system optimization in both urban and rural contexts. These studies provided foundational insights into hybrid configurations with battery or diesel backup options, enhancing reliability and reducing fossil fuel dependence. This period established the analytical groundwork for assessing renewable integration as a viable component of Indonesia's energy transition strategy.

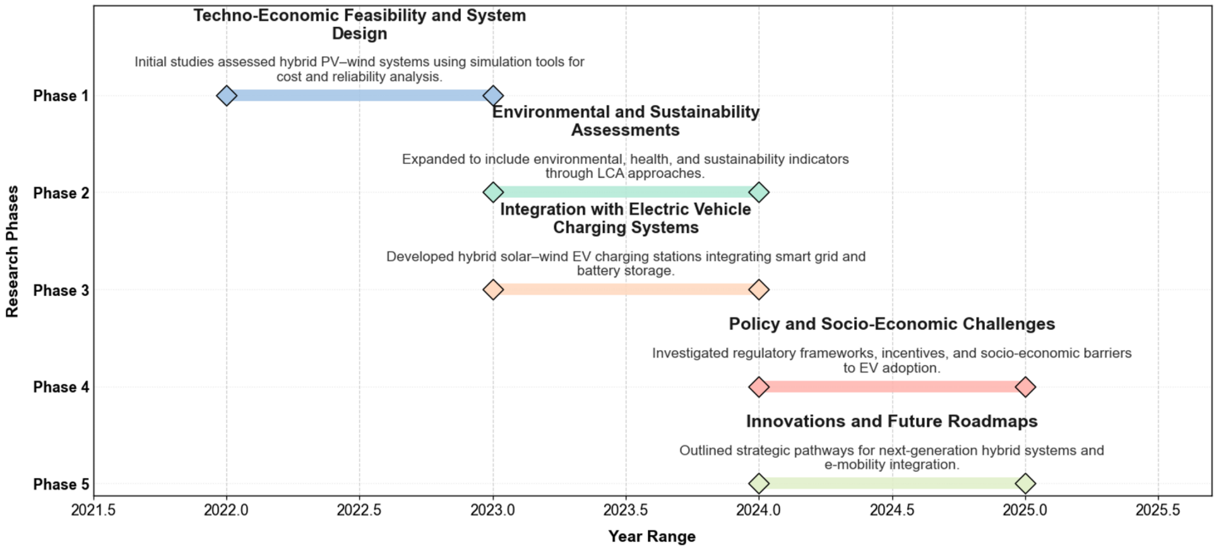

Figure 4. Research timeline of hybrid renewable systems and EV integration (2022–2025)

The second and third phases (2023–2024) marked a transition toward environmental and sustainability assessments and the integration of electric vehicle charging systems. Using techno-economic foundations, researchers expanded their analyses to include environmental, health, and sustainability indicators through life-cycle assessment (LCA) methods. Parallelly, studies began developing hybrid solar–wind EV charging stations that integrated smart-grid and battery-storage technologies to enhance system efficiency, grid stability, and emission reduction. This stage represented a methodological broadening of the research agenda, linking technical optimization with environmental co-benefits and practical applications for Indonesia's growing EV sector.

In the later phases (2024–2025), research attention shifted toward policy and socio-economic challenges, innovations, and future roadmaps. Studies examined how regulatory frameworks, incentive mechanisms, and socio-economic barriers shape the adoption of EVs and hybrid renewable energy systems, underscoring the need for coordinated governance and stakeholder engagement. Concurrently, emerging research outlined strategic pathways for next-generation hybrid systems, including smart grid integration, vehicle-to-grid (V2G) technology, and e-mobility expansion aligned with national decarbonization goals. These phases demonstrate how the field has matured from isolated techno-economic analyses to a holistic, innovation-driven framework supporting Indonesia's transition toward sustainable, electrified transportation and energy systems.

4.5 Agreement and Divergence Across Studies

The reviewed studies largely concur on the technical and economic feasibility of hybrid PV-wind renewable energy systems for various applications, including government buildings, rural electrification, and EV charging stations in Indonesia. There is broad agreement on the environmental benefits of integrating renewable energy into EV infrastructure, notably in reducing emissions and promoting sustainability. However, divergences emerge regarding the extent of policy effectiveness, the maturity and adoption of eco-friendly manufacturing innovations, and the challenges of grid integration and techno-economic constraints, often influenced by regional contexts and methodological variations. These patterns highlight the complex interplay of technical, economic, environmental, and policy factors shaping Indonesia's renewable energy transition and EV infrastructure development. To further illustrate convergences and divergences across the reviewed literature, Table 1 compares areas of agreement and divergence based on key analytical criteria, including modeling accuracy, environmental impacts, innovation adoption, techno-economic feasibility, and policy effectiveness. This comparative synthesis highlights the robustness of recurring findings and the contextual or methodological variations that explain differences in reported outcomes.

4.6 Theoretical and Practical Implications

4.6.1 Theoretical implications

The reviewed studies contribute critical theoretical insights into the design, optimization, and integration of hybrid PV–wind systems within Indonesia's energy and transportation landscape. The literature reinforces existing theoretical frameworks by synthesizing findings across technical, environmental, and policy dimensions while extending them into new domains such as sector coupling and dynamic load management. These contributions highlight the evolving nature of hybrid renewable energy system theory, which links technological advancements with broader socio-political and environmental paradigms. The main theoretical implications identified are as follows:

•The synthesis of studies on hybrid PV–wind turbine systems in Indonesia reinforces the theoretical framework that integrating multiple renewable energy sources enhances system reliability, cost-effectiveness, and environmental benefits. This supports existing theories on hybrid renewable energy systems (HRES) and on optimizing energy supply under variable climatic conditions [7, 17].

•The environmental and socio-economic co-benefits quantified in hybrid renewable energy deployment provide empirical support for theories linking renewable energy adoption to improved public health and economic savings, extending the understanding of renewable energy impacts beyond mere energy generation [3, 4].

•Innovations in manufacturing and eco-friendly materials for renewable energy components, though less extensively covered, align with theoretical models emphasizing material sustainability and lifecycle optimization as critical for long-term system viability [7, 8].

•The integration of renewable energy with EV charging infrastructure challenges traditional energy system models by introducing dynamic load profiles and necessitating smart grid and energy storage solutions, thus advancing theories on sector coupling and energy system flexibility [18, 39].

•Policy and regulatory frameworks emerge as pivotal theoretical constructs influencing the pace and scale of renewable energy and EV infrastructure adoption, highlighting the interplay between technological feasibility and socio-political acceptance [12, 13].

•The role of techno-economic modeling tools such as HOMER and PLEXOS in simulating hybrid systems and EV integration validates their theoretical utility in scenario analysis and decision support, reinforcing their adoption in energy systems research [28, 41].

4.6.2 Practical implications

Beyond their theoretical contributions, the findings also have significant practical implications for Indonesia's renewable energy transition and the development of EV infrastructure. The evidence highlights concrete pathways for scaling hybrid renewable systems, addressing technological and economic barriers, and leveraging environmental co-benefits to support public health and policy objectives. Moreover, practical lessons from the literature highlight the importance of targeted incentives, regulatory support, and technological innovation in addressing the persistent challenges of cost, intermittency, and infrastructure readiness. The key practical implications emerging from the synthesis are summarized below:

•The demonstrated techno-economic feasibility of hybrid PV–wind systems for government buildings and rural electrification suggests practical pathways for scaling renewable energy deployment in Indonesia, informing infrastructure investment and design decisions [6, 51].

•Quantified health and environmental co-benefits provide compelling evidence for policymakers to prioritize hybrid renewable energy projects as part of Indonesia's climate and public health strategies, supporting integrated policy development [3, 4].

•The integration of renewable energy into EV charging infrastructure, particularly SPKLU for motorcycles, addresses critical barriers to EV adoption by reducing operational emissions and enhancing energy security, thereby supporting Indonesia's transportation electrification goals [23, 24].

•Techno-economic challenges such as high initial capital costs, intermittency, and grid integration complexities necessitate targeted financial incentives, capacity building, and technological innovation to improve system affordability and reliability [14, 36].

•Policy implications underscore the need for cohesive regulatory frameworks that incentivize renewable energy investments, standardize battery technologies, and support local manufacturing to accelerate EV infrastructure deployment and market acceptance [8, 12].

•Future roadmaps should incorporate innovative grid technologies, vehicle-to-grid (V2G) integration, and sector coupling strategies to optimize renewable energy utilization and grid stability, enhancing the sustainability and resilience of Indonesia's energy and transportation sectors [19, 31].

Table 1. Agreement and divergence across studies on hybrid PV–wind systems, EV charging integration, environmental impacts, and policy effectiveness in Indonesia

Comparison Criterion	Studies in Agreement	Studies in Divergence	Potential Explanations
Modeling Accuracy and Optimization	Multiple studies emphasize the use of sophisticated modeling tools, such as HOMER and similar optimization platforms, to effectively size and simulate hybrid PV–wind systems, thereby achieving reliable techno-economic evaluations for Indonesian contexts [6, 51].	Some studies suggest using advanced metaheuristic algorithms (e.g., the Pufferfish Optimization Algorithm) or integrated system dynamics to enhance accuracy, whereas others rely solely on HOMER or simpler optimization methods [13, 17].	Differences arise from study aims (detailed system simulation vs. policy impact modeling), regional data availability, and intended application (off-grid rural vs. urban EV charging), leading to varied modeling approaches and optimization techniques.
Environmental Impact Metrics	A consensus exists on the significant environmental benefits of hybrid systems, including reductions in greenhouse gas emissions, pollutant levels, and health-related co-benefits, as supported by life cycle assessments and multi-regional studies [3, 4].	Some studies report limited immediate environmental impact due to reliance on grid electricity or incomplete infrastructure deployment, with ongoing challenges in reducing specific pollutant metrics [54].	Variability in regional grid carbon intensity, system maturity (pilot versus full-scale), and the scope of LCA boundaries influence the reported environmental outcomes and perceived impact.
Innovation Adoption Rate	Many papers note incremental adoption of eco-friendly materials and manufacturing innovations in hybrid renewable energy components and EV chargers, emphasizing ongoing research and pilot projects [20, 22].	There is limited discussion or evidence of the widespread large-scale integration of cutting-edge eco-friendly materials and manufacturing innovations, with some emphasizing technological immaturity or cost barriers [12, 25].	Divergences arise from the nascent stage of many innovations, differences in focus (technical design versus policy), and economic constraints that limit rapid large-scale adoption in Indonesia's emerging market context.
Techno-Economic Feasibility	There is strong agreement that hybrid renewable energy systems for EV charging and rural electrification demonstrate favorable cost metrics (NPC, COE, payback periods), often within 8–12 years, making them attractive investments in Indonesia [14, 29].	Some analyses highlight the need for subsidies, grants, or incentives to achieve economic feasibility, especially in underdeveloped or remote regions, which contrasts with studies showing near-market conditions [30, 54].	Economic feasibility varies by location, system scale, financing mechanisms, and government support, with remote areas facing higher costs and requiring incentives. In contrast, urban or government building projects benefit from economies of scale.
Policy and Regulatory Effectiveness	Many studies acknowledge the critical role of government policies (e.g., Presidential Regulation 55/2019) and incentives in promoting the integration of renewables and EV infrastructure, noting positive but evolving impacts [5, 8].	There is divergence regarding the sufficiency and effectiveness of current policies, with some indicating inadequate infrastructure expansion and consumer hesitancy, while others report promising regulatory frameworks that support growth [29].	Discrepancies reflect the dynamic policy landscape, regional implementation gaps, varying stakeholder engagement, and differences in the maturity of regulatory enforcement and market readiness across Indonesia.

4.7 Limitations of the Literature

While offering valuable insights, the reviewed literature presents several limitations that constrain the scope and applicability of its findings. Geographic bias is evident, as many studies concentrate on specific regions or urban centers, limiting generalizability to diverse Indonesian contexts. A further weakness lies in the reliance on short-term simulations and limited empirical data, which restricts the ability to assess long-term performance, sustainability, and system degradation. Additionally, much of the research remains narrowly focused on techno-economic and environmental modeling, with insufficient attention to socio-economic, behavioral, and policy dynamics that significantly influence adoption and implementation. Policy and regulatory frameworks, though often discussed, are rarely examined in depth, leaving critical gaps in understanding institutional capacities and enforcement mechanisms. Furthermore, limited attention is given to interoperability challenges, motorcycle-specific EV charging infrastructure, and the integration of emerging technologies such as AI, V2G, and wireless charging, reducing the innovation potential of proposed solutions. These limitations, summarized in Table 2, underscore the need for more holistic, long-term, and inclusive approaches to advance Indonesia's renewable energy and EV infrastructure development.

Table 2. Limitations of the reviewed literature on hybrid PV–wind systems and EV charging integration

Area of Limitation	Description of Limitation	Source
Geographic Bias	Many studies focus on specific regions or cities within Indonesia, which limits the generalizability of their findings to other areas with different climatic, socio-economic, or infrastructural conditions. This geographic concentration reduces external validity.	[4, 6, 49, 51]
Limited Long-Term Data	Several papers rely on simulation models or short-term data, which constrain the ability to assess the long-term performance, degradation, and sustainability of hybrid systems and EV infrastructure, thereby affecting the robustness of the conclusions.	[16, 55]
Narrow Focus on Technical Aspects	A predominant focus on techno-economic and environmental modeling neglects broader socio-economic, behavioral, and policy dynamics, limiting a comprehensive understanding of adoption barriers and system integration challenges.	[5, 12, 25, 56]
Insufficient Consideration of Policy and Regulatory Frameworks	Many studies inadequately address the complexity and variability of policy environments, which are critical for scaling hybrid renewable and EV charging systems, thus weakening the applicability of findings to real-world implementation.	[8, 13]
Lack of Standardization and Interoperability Analysis	Few papers explore standardization issues and interoperability challenges in EV charging infrastructure and renewable energy integration, which are essential for system scalability and user acceptance, thereby limiting practical insights into deployment.	[18, 33]
Underrepresentation of Motorcycle EV Charging	Despite motorcycles being a dominant mode of transport in Indonesia, limited research explicitly addresses SPKLU for motorcycles, resulting in gaps in infrastructure planning and technology adaptation for this segment.	[26, 27]
Economic Feasibility Constraints	Many studies highlight the high initial investment costs and the reliance on subsidies or incentives, but lack comprehensive sensitivity analyses of economic viability under varying market and policy conditions, which affects financial risk assessment.	[10, 35, 36]
Limited Integration of Emerging Technologies	Emerging technologies, such as AI, machine learning, V2G, and wireless charging, are underexplored in practical system designs, which restricts the innovation potential and future-proofing of hybrid renewable EV charging systems.	[22, 31]
Incomplete Environmental Impact Assessments	Environmental assessments often focus on operational phases, neglecting full life cycle impacts, including manufacturing, installation, and end-of-life stages, which limits comprehensive sustainability evaluations.	[23, 48]

4.8 Gaps and Future Research Directions

The reviewed literature also reveals several notable research gaps that present opportunities for future investigation and innovation. A significant gap exists in the limited empirical validation of numerical models, as most studies remain simulation-based, necessitating pilot projects and the collection of real-world data to improve model accuracy and applicability. Environmental analyses lack comprehensive life-cycle assessments, with little attention paid to upstream manufacturing, material sourcing, and the end-of-life stages of hybrid systems and EV infrastructure. Another critical gap is the underrepresentation of motorcycle-specific EV charging solutions, despite motorcycles being Indonesia's dominant mode of transport, highlighting the urgency for user-centered infrastructure design and behavioral studies. Policy and institutional dimensions also require deeper exploration, particularly regarding governance structures, stakeholder engagement, and the practical implementation of regulatory frameworks. Furthermore, there is a lack of research on localized manufacturing innovations, smart grid integration, and the socio-economic impacts of infrastructure expansion in diverse regions. These gaps, outlined in Table 3, indicate a high-priority research agenda to foster a more inclusive, sustainable, and context-specific transition toward hybrid PV–wind systems and EV charging in Indonesia.

Table 3. Research gaps and future directions for hybrid PV–wind systems and EV charging infrastructure in Indonesia

Gap Area	Description	Future Research Directions	Justification	Research Priority
Empirical Validation of Eco-Dynamic Numerical Models	Current hybrid PV–wind system models rely heavily on simulations with limited real-world validation in Indonesian contexts.	Conduct field experiments and pilot projects to validate and calibrate numerical models, incorporating real-time data on load profiles, weather variability, and grid constraints.	Enhances model reliability and practical applicability by addressing oversimplifying assumptions and improving deployment confidence [17, 51].	High
Comprehensive Life Cycle Environmental Assessments	Environmental assessments primarily focus on operational phases, neglecting the upstream manufacturing and end-of-life impacts of system components.	Develop a complete LCA for hybrid renewable systems and EV charging infrastructure, including material sourcing, manufacturing, and disposal stages specific to Indonesia.	Provides a holistic understanding of environmental impacts, enabling more sustainable design and policy [23].	High
Manufacturing Innovations and Local Material Sustainability	Limited research on eco-friendly materials, local manufacturing capabilities, and supply chain sustainability for renewable energy components in Indonesia.	Investigate the development and adoption of locally sourced, eco-friendly materials, assess the sustainability of the supply chain, and explore manufacturing innovations tailored to the Indonesian context.	Critical for scaling renewable technologies sustainably and reducing dependency on imports and fossil-fuel-based materials [7, 8].	High
Motorcycle-Specific EV Charging Infrastructure	Insufficient focus on electric motorcycle charging infrastructure, user behavior, and charging patterns reflecting Indonesia's dominant motorcycle usage.	Conduct user-centric studies on charging behavior, develop optimized SPKLU motorcycle designs, and evaluate spatial distribution strategies to enhance accessibility and efficiency.	Addresses a significant transportation mode gap, improving infrastructure relevance and EV adoption rates among motorcycle users [26, 27].	High
Integration of Productive Activities with Hybrid Systems in Rural Areas	Techno-economic models for rural hybrid systems often exclude integration with local productive activities that could enhance economic feasibility.	Design and test hybrid renewable systems integrated with agricultural or commercial productive loads in rural Indonesian communities, assessing socio-economic impacts and scalability.	Enhances system viability and community benefits, supporting rural electrification and economic development [14, 43].	Medium
Policy Implementation and Institutional Capacity	Existing policy analyses lack a detailed examination of institutional capacity, stakeholder engagement, and socio-political factors affecting the deployment of renewable energy and EV infrastructure.	Investigate governance structures, stakeholder roles, and institutional barriers; develop frameworks for effective policy implementation and multi-level coordination in Indonesia.	Bridges the gap between policy formulation and practical implementation, thereby enhancing policy effectiveness and promoting the adoption of renewable energy [12, 25].	High

Gap Area	Description	Future Research Directions	Justification	Research Priority
Techno-Economic Sensitivity to Local Economic Parameters	Economic feasibility studies often overlook dynamic local economic factors, such as tariffs, subsidies, and fluctuations in component costs.	To optimize hybrid system designs and investment decisions, perform sensitivity analyses incorporating variable local economic parameters, tariff structures, and incentive schemes.	Supports adaptive planning and investment strategies responsive to Indonesia's evolving economic [10, 29].	Medium
Smart Grid and V2G Integration for Grid Stability	Limited empirical studies on the integration of vehicle-to-grid (V2G) technologies and innovative grid solutions with hybrid renewable systems in Indonesia.	Develop pilot projects and simulations to assess the impacts of V2G and smart grids on grid stability, renewable penetration, and EV charging optimization in Indonesian grids.	Enhances grid resilience and renewable energy utilization, which is critical for large-scale EV adoption and the energy transition [19, 28].	Medium
Socio-Economic Impact Assessment of EV Infrastructure Expansion	There is a lack of comprehensive socio-economic analyses on the impacts of EV infrastructure expansion, especially in rural and underdeveloped regions.	Conduct multi-dimensional impact studies, including job creation, income effects, equity, and social acceptance related to EV infrastructure deployment across diverse Indonesian regions.	Informs inclusive and equitable energy transition strategies, ensuring benefits reach marginalized communities [5, 14].	Medium
Future Roadmap for Hybrid PV–Wind Systems in Diverse Indonesian Regions	Roadmap discussions often lack detailed, region-specific scaling pathways that account for geographic, socio-economic, and infrastructural diversity.	Develop regionally tailored roadmaps that integrate technical, economic, social, and policy dimensions for the deployment of hybrid PV–wind systems, with a focus on rural and frontier areas.	Facilitates the targeted and effective scaling of renewable systems aligned with local needs and capacities [2, 14].	High

5 Conclusion

To consolidate the overarching insights of this systematic review, the following key contributions are formulated to highlight the novel synthesized knowledge generated from the multi-study comparison, the clarification of contradictory findings, and the strategic recommendations for Indonesia's policymakers and research community:

1. Synthesis of new, cross-cutting knowledge:

This review provides the first integrated mapping of technical, economic, environmental, and policy dimensions governing hybrid PV–wind systems for EV charging in Indonesia, demonstrating that system viability is shaped by multi-factor interactions—including climatic complementarity, storage integration levels, cost assumptions, and policy stability—that individual case studies rarely capture. Through the synthesis of 50 studies, a more nuanced understanding emerges, revealing region-specific feasibility thresholds, realistic cost-performance expectations, and overlooked lifecycle considerations that significantly influence long-term sustainability outcomes.

2. Resolution of conflicting evidence across studies:

By comparing diverse methodologies and assumptions, this review clarifies inconsistencies in reported LCOE values, payback periods, and environmental benefits, showing that disparities often stem from differences in resource profiles, financial parameters, and modeling constraints rather than fundamental disagreements about hybrid system performance. The analysis reconciles conflicting conclusions by demonstrating that hybrid PV–wind systems are most advantageous in regions with favorable irradiation and wind regimes. In contrast, lower-performing regions require complementary policy incentives, storage enhancements, or alternative renewable configurations to achieve similar outcomes.

3. Prioritized recommendations for policymakers and researchers:

The findings highlight the need for Indonesia to adopt regionally adaptive renewable-energy planning, strengthen grid-support frameworks, and enhance local manufacturing capacity to reduce cost volatility and technology dependency. For researchers, the review emphasizes the importance of expanding empirical field validation, incorporating lifecycle environmental assessments, and integrating socio-institutional dimensions—such as user behavior, regulatory readiness, and community acceptance—into future modeling frameworks. Collectively, these recommendations provide a strategic roadmap for accelerating Indonesia's renewable energy and e-mobility transition through more evidence-based, resilient, and context-sensitive decision-making.

Funding

This paper is the result of research entitled "Pengembangan Pembangkit Listrik Tenaga Surya Sebagai Sumber Energi Bersih Stasiun Pengisian Kendaraan Listrik Umum (SPKLU)" funded by Sebelas Maret University through the Mandatory Riset (mr-uns) scheme with contract number 369/UN27.22/PT.01.03/2025.

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 conflicts of interest.

References

[1] N. Himabindu, S. Hampannavar, B. Deepa, O. M. Longe, S. Mansani, and V. Komanapalli, "Assessment of microgrid integrated biogas-photovoltaic powered Electric Vehicle Charging Station (EVCS) for sustainable future," *Energy Rep.*, vol. 9, pp. 139–143, 2023. https://doi.org/10.1016/j.egyr.2023.09.098

[2] M. Syabriyana, "Progress and challenges of renewable energy transition in indonesia's energy mix towards net zero emissions," *JURUTERA - J. Umum Tek. Ter.*, vol. 11, no. 02, pp. 76–82, 2024. https://doi.org/10.55377/jurutera.v11i02.10810

[3] E. K. Bawan, F. D. Wijaya, H. R. Ali, and J. C. Vasquez, "Comprehensive analysis and optimal design of hybrid renewable energy system for rural electrification in West Papua, Indonesia," *IEEE Access*, vol. 13, pp. 66 250–66 275, 2025. https://doi.org/10.1109/access.2025.3556020

[4] M. S. Suliman, H. Farzaneh, E. Zusman, A. N. Mulumba, P. Lestari, D. A. Permadi, and N. Janardhanan, "Quantifying the climate co-benefits of hybrid renewable power generation in Indonesia: A multi-regional and technological assessment," *Climate*, vol. 12, no. 2, p. 23, 2024. https://doi.org/10.3390/cli12020023

[5] N. Damanik, R. C. Octavia, and D. F. Hakam, "Powering Indonesia's future: Reviewing the road to electric vehicles through infrastructure, policy, and economic growth," *Energies*, vol. 17, no. 24, p. 6408, 2024. https://doi.org/10.3390/en17246408

[6] B. G. A. Mangkung, D. Hamdani, and T. D. Rachmilda, "Techno-economic analysis of hybrid renewable energy system for rural area: Study case Lembor Selatan district," in *2024 6th International Conference on Power Engineering and Renewable Energy (ICPERE)*, Bandung, Indonesia, 2024, pp. 1–5. https://doi.org/10.1109/icpere63447.2024.10845728

[7] A. Xu, L. J. Awalin, A. Al-Khaykan, H. F. Fard, I. Alhamrouni, and M. Salem, "Techno-economic and environmental study of optimum hybrid renewable systems, including PV/wind/gen/battery, with various components to find the best renewable combination for Ponorogo Regency, East Java, Indonesia," *Sustainability*, vol. 15, no. 3, p. 1802, 2023. https://doi.org/10.3390/su15031802

[8] K. Mudhoffar and L. Magriasti, "Ekonomi politik energi terbarukan: Peluang dan tantangan di Indonesia," *Multiverse: Open Multidiscip. J.*, vol. 3, no. 1, pp. 47–52, 2024. https://doi.org/10.57251/multiverse.v3i1.1382

[9] M. M. Mousa, S. M. Saleh, M. M. Samy, and S. Barakat, "Techno-economic analysis and simulation of electric vehicle charging stations based on green energy system," in *2023 24th International Middle East Power System Conference (MEPCON)*, Mansoura, Egypt, 2023. https://doi.org/10.1109/mepcon58725.2023.10462477

[10] B. M. Sutardi, K. M. Banjar-Nahor, N. Hariyanto, A. Hanadya, R. H. Situmeang, and R. C. Andrian, "Techno-economic evaluation of in-city EV charging station empowered by PV-based microgrid in various solar irradiation levels," in *2023 4th International Conference on High Voltage Engineering and Power Systems (ICHVEPS)*, Denpasar Bali, Indonesia, 2023, pp. 678–682. https://doi.org/10.1109/ichveps58902.2023.10257494

[11] R. Pandey, "A review on the renewable sources based microgrid for electric vehicle charging using various emerging technologies," *Int. J. Res. Appl. Sci. Eng. Technol.*, vol. 12, no. 5, pp. 3730–3735, 2024. https://doi.org/10.22214/ijraset.2024.61323

[12] A. Lazuardy, R. Nurcahyo, E. Kristiningrum, A. Ma'aram, Farizal, S. N. Aqmarina, and M. F. Rajabi, "Technological, environmental, economic, and regulation barriers to electric vehicle adoption: Evidence from Indonesia," *World Electr. Veh. J.*, vol. 15, no. 9, p. 422, 2024. https://doi.org/10.3390/wevj15090422

[13] E. Suryani, M. S. Fadlillah, R. A. Hendrawan, M. Mudjahidin, R. J. Pramundito, A. A. Zahra, S. Y. Chou, A. Dewabharata, Z. U. Rizqi, and R. Rahmawati, “Dynamic model to assess the impacts of government support for electric vehicles on the economy and environment sectors in Indonesia,” *Int. J. Sustain. Transp.*, vol. 19, no. 1, pp. 35–54, 2024. https://doi.org/10.1080/15568318.2024.2443825

[14] A. N. Shafira, S. Petrana, R. Muthia, and W. W. Purwanto, “Techno-economic analysis of a hybrid renewable energy system integrated with productive activities in an underdeveloped rural region of eastern Indonesia,” *Clean Energy*, vol. 7, no. 6, pp. 1247–1267, 2023. https://doi.org/10.1093/ce/zkad068

[15] S. D. Prasetyo, Y. Trisnoaji, Z. Arifin, and A. R. Prabowo, “Assessment of the performance differences in PV–PCM systems with numerical analysis of different phase change materials and structural designs,” *Sol. Energy Mater. Sol. Cells*, vol. 295, p. 114019, 2026. https://doi.org/10.1016/j.solmat.2025.114019

[16] M. R. Ahmed, B. K. Das, and M. S. H. K. Tushar, “Investigation of a grid-integrated hybrid energy system for residential and electric vehicle (3-wheeler) loads under schedule grid outage,” *Alex. Eng. J.*, vol. 80, pp. 241–258, 2023. https://doi.org/10.1016/j.aej.2023.08.057

[17] D. D. D. P. Tjahjana, S. Suyitno, R. A. Rachmanto, W. E. Juwana, Y. J. Prasojo, S. D. Prasetyo, and Z. Arifin, “Economic feasibility of a PV-wind hybrid microgrid system for off-grid electrification in Papua, Indonesia,” *Int. J. Des. Nat. Ecodyn.*, vol. 18, no. 4, pp. 811–818, 2023. https://doi.org/10.18280/ijdne.180407

[18] S. Ponnambalam and M. K. Ilampoornan, “Integration of renewable energy technologies and hybrid electric vehicle challenges in power systems,” in *Advances in Mechatronics and Mechanical Engineering*, 2024, pp. 157–186. https://doi.org/10.4018/979-8-3693-5797-2.ch006

[19] Y. M. Prianka, A. Sharma, and C. Biswas, “Integration of renewable energy, microgrids, and EV charging infrastructure: Challenges and solutions,” *Control Syst. Optim. Lett.*, vol. 2, no. 3, pp. 317–326, 2024. https://doi.org/10.59247/csol.v2i3.142

[20] A. S. Ghai, K. Ghai, V. K. Gupta, S. Jasola, R. C. Sharma, S. Avikal, and G. K. Cakir, “Sustainable energy solutions for charging electric vehicles by integrating renewable sources,” in *Advances in Mechatronics and Mechanical Engineering*, 2024, pp. 153–170. https://doi.org/10.4018/979-8-3693-6844-2.ch006

[21] N. Lakshmipriya, S. Ayyappan, and C. Gokul, “Sustainable charging infrastructure for electric vehicles: Harnessing solar and wind energy,” *Eng. Headway*, vol. 16, pp. 57–68, 2025. https://doi.org/10.4028/p-382wdq

[22] A. Shahin, A. Y. Abdelaziz, A. Houari, B. Nahid-Mobarakeh, S. Pierfederici, F. Deng, and S. Abulanwar, “A comprehensive analysis: Integrating renewable energy sources with wire/wireless EV charging systems for green mobility,” *IEEE Access*, vol. 12, pp. 140 527–140 555, 2024. https://doi.org/10.1109/access.2024.3466729

[23] F. Fathoni, E. Kesidou, M. M. Rifansha, and A. Tiftazani, “Drivers and barriers of eco-innovation in electric vehicle diffusion: Evidence from Indonesia,” *J. Environ. Manag.*, vol. 389, p. 126021, 2025. https://doi.org/10.1016/j.jenvman.2025.126021

[24] M. R. Anshori, M. S. Boedoyo, and G. E. Saputro, “Development of electric vehicle charging infrastructure in Indonesia to achieve the target of nationally determined contribution by 2030,” *J. Ecoment Glob.*, vol. 9, no. 1, pp. 1–10, 2024. https://doi.org/10.36982/jeg.v9i1.3965

[25] M. Habiburrahman, R. Nurcahyo, A. Ma’aram, and K. Natsuda, “Driving the transport electrification: Exploring stakeholders’ perceptions and actions in the Indonesian automotive industry transition to electric mobility,” *Sustainability*, vol. 16, no. 14, p. 5855, 2024. https://doi.org/10.3390/su16145855

[26] S.-W. Huang, Y.-H. Liao, J.-M. Liao, and J. J. H. Liou, “Exploring public charging infrastructure development strategies with BBWM-mV integrated multi-viewpoint perspective,” *J. Infrastruct. Policy Dev.*, vol. 8, no. 9, p. 6495, 2024. https://doi.org/10.24294/jipd.v8i9.6495

[27] J. B. Padmanabhan and G. Anbazhagan, “A comprehensive review of hybrid renewable energy charging system to optimally drive permanent magnet synchronous motors in electric vehicle,” *Energy Sources Part A*, vol. 46, no. 1, pp. 3499–3521, 2024. https://doi.org/10.1080/15567036.2024.2319347

[28] A. Amiruddin, R. Dargaville, A. Liebman, and R. Gawler, “Integration of electric vehicles and renewable energy in Indonesia’s electrical grid,” *Energies*, vol. 17, no. 9, p. 2037, 2024. https://doi.org/10.3390/en17092037

[29] I. A. Hanun, W. Sutopo, and R. Rochani, “Feasibility study of charging infrastructure to increase vehicle electrification in Indonesia,” *J. Tek. Ind.*, vol. 25, no. 2, pp. 141–152, 2023. https://doi.org/10.9744/jti.25.2.141-152

[30] J. V. Tampubolon and R. Dalimi, “Simulating EV growth scenarios in Jawa-Madura-Bali from 2024 to 2029: Balancing the power grid’s supply and demand,” *World Electr. Veh. J.*, vol. 15, no. 8, p. 341, 2024. https://doi.org/10.3390/wevj15080341

[31] M. A. Sayeed and K. Manikandan, “Smart integration of renewable energy into transportation: Challenges, innovations, and future research directions,” *J. Renew. Energ.*, vol. 27, no. 2, 2024. https://doi.org/10.54966/jreen.v27i2.1300

[32] M. L. Trisuwito, D. F. S. Menalang, and M. F. Almunir, "Renewrev: Stasiun pengisian daya cerdas untuk transformasi kendaraan listrik dengan energi terbarukan," *J. Tek. Cerdas*, vol. 2, no. 2, 2024. https://doi.org/10.70310/ccbh3n62

[33] S. Kumar and A. Bhargava, "Green energy solutions for ev charging: A comprehensive review of solar-powered stations," *Smart Moves J. IJOSci.*, vol. 10, no. 10, pp. 1–6, 2024. https://doi.org/10.24113/ijoscience.v10i10.501

[34] R. A. Almasri, T. Alharbi, M. S. Alshitawi, O. Alrumayh, and S. Ajib, "Related work and motivation for electric vehicle solar/wind charging stations: A review," *World Electr. Veh. J.*, vol. 15, no. 5, p. 215, 2024. https://doi.org/10.3390/wevj15050215

[35] N. K. Pandey, R. Yadav, S. K. Maitra, P. Sharma, and R. K. Pachauri, "Eco-friendly ev charging: Utilizing grid-linked solar photovoltaic systems," in *2024 IEEE Third International Conference on Power Electronics, Intelligent Control and Energy Systems (ICPEICES)*, Delhi, India, 2024, pp. 280–285. https://doi.org/10.1109/icpeices62430.2024.10719359

[36] S. Mahadik and P. K. Guchhait, "Efficient integration of renewable energy for electric vehicle charging: A hybrid system approach," *Int. J. Sci. Res. Sci. Technol.*, vol. 10, no. 3, pp. 859–865, 2023. https://doi.org/10.32628/ijsrst523103151

[37] K. N. D. V. S. Eswar and M. A. N. Doss, "Implementation of renewable sources for designing EV charging station with hybrid storage device as reserve source," in *Lecture Notes in Electrical Engineering*, 2023, pp. 315–328. https://doi.org/10.1007/978-981-99-4795-9_30

[38] N. M. Manousakis, P. S. Karagiannopoulos, G. J. Tsekouras, and F. D. Kanellos, "Integration of renewable energy and electric vehicles in power systems: A review," *Processes*, vol. 11, no. 5, p. 1544, 2023. https://doi.org/10.3390/pr11051544

[39] Y. I. Siregar and B. Möller, "Sector coupling of electricity, transport and cooling with high share integration of renewables in Indonesia," *Smart Energy*, vol. 10, p. 100102, 2023. https://doi.org/10.1016/j.segy.2023.100102

[40] A. Balal, R. Barnwal, and B. Yogi, "Designing a solar/wind hybrid power system for charging electric vehicles," in *2023 IEEE Texas Power and Energy Conference (TPEC)*, College Station, TX, USA, 2023, pp. 1–5. https://doi.org/10.1109/tpec56611.2023.10078494

[41] F. A. Khan, S. Mekhilef, V. K. Ramachandaramurthy, N. F. Ab Aziz, N. Pal, A. Yaseen, A. Yadav, M. Asim, and O. Alshammari, "Design and development of grid independent integrated energy system for electric vehicle charging stations at different locations in Malaysia," *Energy*, vol. 302, p. 131686, 2024. https://doi.org/10.1016/j.energy.2024.131686

[42] S. Abdelhady and A. Shaban, "A simulation modeling approach for the techno-economic analysis of the integration of electric vehicle charging stations and hybrid renewable energy systems in tourism districts," *Appl. Sci.*, vol. 14, no. 11, p. 4525, 2024. https://doi.org/10.3390/app14114525

[43] B. A. Thango and L. Obokoh, "Techno-economic analysis of hybrid renewable energy systems for power interruptions: A systematic review," *Eng*, vol. 5, no. 3, pp. 2108–2156, 2024. https://doi.org/10.3390/eng5030112

[44] A. K. Karmaker, M. A. Hossain, H. R. Pota, A. Onen, and J. Jung, "Energy management system for hybrid renewable energy-based electric vehicle charging station," *IEEE Access*, vol. 11, pp. 27 793–27 805, 2023. https://doi.org/10.1109/access.2023.3259232

[45] D. Prasad, R. P. Singh, T. Tiwary, R. Roy, and M. I. Khan, "Renewable energy-integrated electric vehicle charging infrastructure across cold region roads," in *Advances in Civil and Industrial Engineering*, 2024, pp. 42–75. https://doi.org/10.4018/978-1-6684-9214-7.ch002

[46] M. R. Pamungkas, E. Maulina, R. Arifianti, and A. Muftiadi, "Sustainable transportation in Indonesia: Opportunities for environmentally friendly shuttle services on the Bandung-Jakarta route," *E3S Web Conf.*, vol. 611, p. 03006, 2025. https://doi.org/10.1051/e3sconf/202561103006

[47] A. Bukhari, O. I. Aboulola, A. ur Rehman, A. Alharbi, W. Alosaimi, and A. Daud, "Renewable energy driven on-road wireless charging infrastructure for electric vehicles in smart cities: A prototype design and analysis," *Energy Rep.*, vol. 12, pp. 5145–5154, 2024. https://doi.org/10.1016/j.egyr.2024.11.019

[48] Aripriharta, S. Adiguna, A. N. Afandi, and M. C. Bagaskoro, "Techno-economic modeling and analysis of a PV EV charged with battery energy storage system (BESS) on Kalimantan Island," *Glob. Energy Interconnect.*, vol. 8, no. 2, pp. 225–239, 2025. https://doi.org/10.1016/j.gloei.2025.01.003

[49] N. Heryana, H. R. Iskandar, and J. Furqani, "Utilization of renewable energy for charging station in Indonesia new appointed capital city, Nusantara," in *2023 4th International Conference on High Voltage Engineering and Power Systems (ICHVEPS)*, Denpasar Bali, Indonesia, 2023, pp. 460–465. https://doi.org/10.1109/ichveps58902.2023.10257531

[50] D. Diyono, H. Cappon, K. Kujawa-Roeleveld, and K. J. Keesman, "Designing sustainable domestic electricity supply from renewable energy mixes: Application to Java and Bali, Indonesia," *Energies*, vol. 16, no. 22, p.

7461, 2023. https://doi.org/10.3390/en16227461

[51] S. D. Prasetyo, F. J. Regannanta, A. R. Birawa, and M. S. Alfaridzi, “Techno-economic evaluation of hybrid photovoltaic-wind energy systems for Indonesian government buildings,” *J. Sustain. Energy*, vol. 2, no. 3, pp. 132–144, 2023. https://doi.org/10.56578/jse020303

[52] L. Judijanto, N. Mayasari, and G. A. Sitompul, “Dampak regulasi ekonomi hijau dan penggunaan teknologi energi terbarukan terhadap efisiensi energi listrik di Indonesia,” *J. Multidisip. West Sci.*, vol. 3, no. 10, pp. 1740–1749, 2024. https://doi.org/10.58812/jmws.v3i10.1673

[53] M. S. Mauludin, M. Khairudin, R. Asnawi, Y. Trisnoaji, S. D. Prasetyo, S. R. Azizah, and R. T. Wiraguna, “Assessing the technological and financial feasibility of PV-wind hybrid systems for EV charging stations on Indonesian toll roads,” *Int. J. Sustain. Dev. Plan.*, vol. 20, no. 1, pp. 291–304, 2025. https://doi.org/10.18280/ijsdp.200127

[54] R. Redwan, M. Hasan, A. Nadia, M. S. Khan, N. A. Chowdhury, and N.-U.-R. Chowdhury, “Design analysis and techno-economic assessment of a photovoltaic-fed electric vehicle charging station at Dhaka-Mawa expressway in Bangladesh,” *Energy Convers. Manag. X*, vol. 24, p. 100737, 2024. https://doi.org/10.1016/j.ecmx.2024.100737

[55] R. A. Rachmanto, N. F. Alfaiz, S. D. Prasetyo, W. B. Bangun, W. E. Juwana, and Z. Arifin, “Modeling future solar and wind energy source applications for power generation at public electric vehicle charging stations in airport parking areas using HOMER-Grid,” *Int. J. Transp. Dev. Integr.*, vol. 8, no. 3, pp. 403–411, 2024. https://doi.org/10.18280/ijtdi.080304

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

Appendix

Table A1. Descriptive summary of studies on hybrid PV–wind systems, sustainability assessments, innovations, techno-economic feasibility, and policy implications in Indonesia and beyond

Study	Modeling Accuracy and Optimization	Environmental Impact Metrics	Innovation Adoption Rate	Techno-Economic Feasibility	Policy and Regulatory Effectiveness
[1]	HOMER-based optimization for hybrid PV-wind in urban government buildings	CO_2 reduction and energy surplus in Denpasar	Limited focus on materials, emphasis on system design	NPC and COE favorable; 8.2 years payback	Highlights policy implications for renewable integration
[4]	Multi-regional techno-economic and health co-benefit modeling	Quantified GHG, PM2.5, DALYs, health savings	Not explicitly addressed	Payback period improved; NPV increased by 14.6%	Supports policy via cost-benefit analysis of renewables
[6]	HOMER Pro simulation for rural hybrid system configurations	Emission reduction targets aligned with Net Zero goals	Not detailed	Techno-economic analysis for rural electrification	Policy alignment with emission reduction targets
[7]	HOMER with MCDM for component selection in East Java	Emission and pollutant reduction via component optimization	Component-level innovation assessment	COE as low as $0.24/kWh; sensitivity analysis performed	Policy impact is implicit through economic-environmental tradeoffs
[27]	Review of inverter-based integration for EV motor drives	Focus on efficiency gains, less on emissions	High innovation in inverter and motor control	Charging efficiency improved to 97%	Discusses technology adoption, but has a limited policy focus

Study	Modeling Accuracy and Optimization	Environmental Impact Metrics	Innovation Adoption Rate	Techno-Economic Feasibility	Policy and Regulatory Effectiveness
[14]	HOMER optimization integrating productive activities in rural Indonesia	Environmental benefits linked to productive use	Innovation in system integration with productive loads	Economic feasibility is dependent on grants and tariffs	Policy implications for incentives and rural development
[9]	HOMER simulation for grid-connected EV charging station sizing	COE of $0.114/kWh; renewable fraction 75%	Not emphasized	NPC $2.15 million; cost-effective hybrid system	Supports green transportation policies
[10]	Techno-economic evaluation of PV-based microgrid for urban EV charging	Environmental benefits linked to solar irradiation levels	Innovation in microgrid design	Payback period 11.2 years; IRR 13.64%	Policy relevance in urban infrastructure planning
[23]	LCA of hybrid EV charging station operation in Indonesia	Detailed environmental impact across multiple factors	Limited innovation focus	Not the primary focus	Highlights the need for a policy to reduce environmental impacts
[28]	PLEXOS modeling of EV and renewable integration in the grid	Emissions reduction up to 23.7% with V2G	Not focused on materials	System cost reduced by 9%; battery storage optimized	Strong policy insights on charging strategies and V2G
[29]	Economic feasibility model for public EV charging infrastructure	Environmental impact secondary to economic feasibility	Innovation in cost modeling	NPV, IRR, and PBP are used for investment decisions	Policy analysis on investment incentives and market barriers
[24]	Literature review and prediction of EV charging infrastructure needs	Environmental impact implicit in infrastructure expansion	Not addressed	Infrastructure scale and investment needs forecasted	Policy recommendations for infrastructure expansion
[12]	Survey on barriers to EV adoption in Indonesia	Environmental concerns among adoption factors	Innovation adoption is linked to consumer awareness	Economic and operational cost barriers identified	Calls for improved policies and incentives
[13]	System dynamics modeling of EV adoption impacts	Emission reduction scenarios modeled	Innovation in policy scenario modeling	Economic and environmental trade-offs analyzed	Emphasizes long-term policy support and technology development
[26]	Hybrid decision-making model for electric motorcycle charging	Environmental benefits through infrastructure evaluation	Innovation in decision-making frameworks	Economic feasibility of infrastructure alternatives	Policy support for motorcycle charging infrastructure
[30]	Simulation of EV growth and grid balance in Jawa-Madura-Bali	Emission and cost impacts of EV growth scenarios	Not focused on materials or manufacturing	Economic analysis of subsidies and grid management	Policy insights on subsidies and regulatory adjustments

Study	Modeling Accuracy and Optimization	Environmental Impact Metrics	Innovation Adoption Rate	Techno-Economic Feasibility	Policy and Regulatory Effectiveness
[2]	Review of renewable energy transition progress in Indonesia	Emission reduction targets and challenges	Innovation in policy and infrastructure	Economic challenges discussed	Policy framework assessment for energy transition
[8]	Political economy analysis of renewable energy in Indonesia	Environmental benefits linked to policy effectiveness	Regulatory barriers hinder innovation adoption	Economic dependencies on fossil fuels are analyzed	Calls for cohesive policy and economic incentives
[31]	Review of renewable energy integration in transportation	Environmental benefits and challenges are outlined	Innovation in smart grids and AI applications	Economic and regulatory barriers discussed	Policy frameworks for renewable transport integration
[32]	Design of renewable energy-based EV charging system (SmartLink)	Environmental benefits through renewable integration	Innovation in hardware and system design	Economic feasibility projected through phased implementation	Policy support for renewable EV infrastructure
[18]	Review of RE integration with EV charging systems	Environmental benefits linked to grid integration	Innovation in smart charging and storage	Economic challenges and opportunities analyzed	Policy and standardization challenges highlighted
[21]	Sustainable EV charging using solar and wind energy	Environmental benefits from renewable-powered charging	Innovation in hybrid renewable charging infrastructure	Economic benefits from reduced fossil fuel reliance	Policy implications for sustainable transport infrastructure
[33]	Review of solar-powered EV charging stations	Environmental benefits and challenges of solar PV	Innovation in energy storage and AI management	Economic barriers and incentives discussed	Policy role in standardization and promotion
[34]	Review of PV-powered EV charging stations	Environmental benefits and economic payback periods	Innovation in system design and simulation	Payback periods 1–15 years; cost-effective solutions	Policy guidance for EV infrastructure expansion
[35]	Grid-linked solar PV EV charging station design	Environmental benefits via carbon emission reduction	Innovation in grid integration and innovative technologies	Competitive pricing and economic viability	Policy relevance for renewable energy adoption
[36]	Hybrid renewable energy EV charging station design	Environmental benefits through the use of a hybrid system use	Innovation in control algorithms and smart grid tech	Economic feasibility demonstrated via simulations	Policy support implied for sustainable EV infrastructure
[37]	Renewable sources for EV charging with hybrid storage	Environmental benefits from reduced grid dependence	Innovation in storage devices and MPPT control	Economic benefits from grid load reduction	Policy implications for renewable energy adoption

Study	Modeling Accuracy and Optimization	Environmental Impact Metrics	Innovation Adoption Rate	Techno-Economic Feasibility	Policy and Regulatory Effectiveness
[38]	Review of RES and EV integration in power systems	Environmental benefits and emissions reduction	Innovation in algorithms and optimization methods	Economic impacts and cost optimization discussed	Policy and regulatory challenges identified
[39]	Sector coupling of electricity, transport, and cooling	Emission reductions via integrated renewables and EVs	Innovation in sector coupling and demand management	Economic benefits from reduced fossil fuel costs	Policy support for sector integration and electrification
[40]	Grid-connected renewable system for EV loads in Saudi Arabia	Environmental benefits through renewable integration	Innovation in optimization algorithms	Economic feasibility via sensitivity analysis	Policy relevance for urban renewable energy systems
[41]	Grid-independent hybrid system for EV charging in Malaysia	Environmental benefits via hybrid renewable systems	Innovation in hybrid system arrangements	Economic feasibility with social and ecological indices	Policy implications for grid-independent EV charging
[42]	Simulation of hybrid renewable EV charging in tourism districts	Environmental emission reductions quantified	Innovation in integrated system design	Economic feasibility is sensitive to charging prices	Policy relevance for sustainable tourism infrastructure
[43]	Systematic review of hybrid renewable systems for power interruptions	Environmental benefits in rural and remote areas	Innovation in hybrid system configurations	Economic advantages over single-resource systems	Policy insights for rural electrification strategies
[16]	Grid-integrated hybrid system for residential and EV loads	Environmental emission reductions with grid scheduling	Innovation in grid integration and net metering	COE as low as 0.0714/kWh; NPC0.0714/kWh; NPC1.82 million	Policy implications for grid management and tariffs
[3]	Interactive model for climate co-benefits of hybrid renewables	Quantified GHG, PM2.5, DALYs, and health savings	Innovation is not the primary focus	Payback period and NPV improvements	Policy support through cost-benefit analysis
[17]	Economic viability of the PV-wind microgrid in Papua	Environmental benefits via a renewable microgrid	Innovation in microgrid design	NPC and COE optimized for off-grid electrification	Policy relevance for off-grid renewable solutions
[44]	Evaluation of EV charging infrastructure and air quality	Environmental impact assessed via Air Quality Index	Innovation not emphasized	Economic feasibility is not the primary focus	Policy recommendation for infrastructure planning
[45]	Renewable energy integrated EV charging on cold roads	Environmental benefits via energy harvesting technologies	Innovation in smart roads and energy management	Economic feasibility via energy production and storage	Policy implications for infrastructure in cold regions

Study	Modeling Accuracy and Optimization	Environmental Impact Metrics	Innovation Adoption Rate	Techno-Economic Feasibility	Policy and Regulatory Effectiveness
[46]	Sustainable electric shuttle services on the Bandung-Jakarta route	Environmental benefits from emission reductions	Innovation in route optimization and smart grids	Economic challenges due to high capital costs	Policy recommendations for collaboration and innovation
[47]	Impact of green economy regulations on energy efficiency	Environmental benefits via regulatory and tech adoption	Innovation in technology adoption supported by policy	Economic efficiency improvements demonstrated	Policy effectiveness in energy efficiency promotion
[48]	Life cycle costing of hybrid EV charging stations	Environmental benefits via renewable energy use	Innovation in hybrid charging station design	Economic competitiveness via life cycle costing	Policy relevance for sustainable charging infrastructure
[22]	Integration of renewable energy with wireless EV charging	Environmental benefits via renewable-powered wireless charging	Innovation in wireless charging technology	Economic feasibility via high system efficiency	Policy challenges for technology adoption
[25]	Stakeholder perceptions in Indonesian automotive EV transition	Environmental benefits linked to EV adoption	Industry perceptions influence innovation adoption	Economic and investment challenges identified	Policy recommendations for gradual transition support
[49]	Renewable energy use for charging in the new capital, Nusantara	Environmental benefits from solar energy predominance	Innovation in system design for the new capital city	Economic feasibility via simulation results	Policy alignment with decarbonization goals
[19]	Integration of renewables, microgrids, and EV charging	Environmental benefits via energy management and storage	Innovation in smart grid and V2G technologies	Economic benefits from peak load reduction	Policy frameworks for scalable EV infrastructure
[20]	Sustainable renewable integration for EV charging	Environmental benefits via clean energy production	Innovation in energy storage and smart charging	Economic feasibility via optimization strategies	Policy role in promoting renewable EV charging
[40]	Solar/wind hybrid system design for EV charging	Environmental benefits from hybrid renewable sources	Innovation in the hybrid system and grid connection	Economic feasibility demonstrated by simulations	Policy support for renewable EV charging systems
[50]	Renewable energy mixes for domestic electricity in Java-Bali	Environmental benefits via CO_2 emission reduction	Innovation in energy mix optimization	Economic feasibility via ROI and cost analysis	Policy implications for renewable energy planning
[5]	Review of EV infrastructure, policy, and economic growth	Environmental benefits linked to EV adoption	Innovation adoption is influenced by policy and market	Economic impacts on jobs and GDP are highlighted	Policy effectiveness and future roadmap emphasized