

Optimizing the Archipelago's Energy Future: A Systems Analysis of Electric Vehicle and Renewable Energy Integration into Indonesia's Electrical Grid

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Article received: 05/08/2025, Article Revised: 06/09/2025, Article Accepted: 01/10/2025

DOI: <https://doi.org/10.55640/ijrgse-v02i10-01>

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ABSTRACT

Background: As part of its commitment to global climate goals, Indonesia is pursuing a dual strategy of decarbonizing its transport and power sectors through the adoption of electric vehicles (EVs) and the expansion of renewable energy (RE). However, the uncoordinated charging of a large EV fleet combined with the intermittency of renewables like solar and wind poses significant challenges to the stability and efficiency of the national electrical grid. This study investigates the potential for controlled EV charging and Vehicle-to-Grid (V2G) technology to mitigate these challenges and facilitate a synergistic energy transition.

Methods: We developed a detailed hourly power system dispatch optimization model for Indonesia's Java-Bali grid, which accounts for over 70% of the nation's electricity demand. Using technical and economic data from national plans and international databases, we simulated grid operations for the year 2030 under four distinct scenarios: a Business-as-Usual (BAU) case, a High RE case, a High EV penetration with Smart Charging case, and a High EV with V2G capability case. The model's objective was to minimize total system operating costs while meeting demand and respecting all operational constraints.

Results: The modeling results demonstrate that uncontrolled EV charging in a high-RE system significantly increases peak demand and leads to substantial RE curtailment. In contrast, the implementation of smart charging shifts EV load to periods of high RE generation, reducing curtailment by up to 75% and lowering total system costs. The V2G scenario provides further benefits by using the EV fleet as a distributed energy resource, reducing the need for expensive fossil-fuel-based peaker plants and decreasing power sector CO₂ emissions by an additional 12% compared to the uncontrolled charging scenario.

Conclusion: The strategic integration of electric vehicles, particularly through smart charging and V2G frameworks, is critical for enabling a cost-effective and reliable transition to a renewable-energy-dominated power system in Indonesia. The findings underscore the urgent need for policymakers to develop supportive regulatory frameworks, dynamic electricity tariffs, and smart grid infrastructure to unlock the full potential of EV-grid integration.

KEYWORDS

Electric Vehicles (EVs), Renewable Energy, Grid Integration, Indonesia, Smart Charging, Vehicle-to-Grid (V2G), Power System Modeling.

INTRODUCTION

1.1. The Global Imperative for Decarbonization

The international community stands at a critical juncture, facing the undeniable challenge of climate change, which necessitates a profound transformation of the global energy system. The United Nations' 2030 Agenda for

Sustainable Development, particularly Sustainable Development Goal 7 (Affordable and Clean Energy) and Goal 13 (Climate Action), provides a universal framework for this transition (1). These goals emphasize the urgent need to shift away from fossil fuels, which have historically powered economic growth at a significant environmental cost, towards cleaner, more

sustainable energy sources. The Paris Agreement further solidifies this global commitment, with nations pledging to limit the global average temperature increase to well below 2°C above pre-industrial levels, and to pursue efforts to limit it to 1.5°C.

Achieving these ambitious targets requires a multi-faceted approach, with the decarbonization of the power and transportation sectors emerging as paramount. Globally, these two sectors are among the largest contributors to anthropogenic greenhouse gas (GHG) emissions (3). The power sector, largely dependent on the combustion of coal, oil, and natural gas, is the single largest source of energy-related CO₂ emissions. Simultaneously, the transport sector, dominated by internal combustion engine vehicles, accounts for nearly a quarter of direct CO₂ emissions from fuel combustion. Consequently, a dual-pronged strategy focused on cleaning the electricity supply while electrifying end-use sectors, especially transportation, is widely recognized as a cornerstone of effective climate change mitigation (2, 3). This dual transition not only offers a pathway to substantial emission reductions but also presents opportunities for enhancing energy security, improving air quality, and fostering technological innovation.

1.2. Indonesia's Energy Landscape and Climate Commitments

As the world's fourth most populous country and a rapidly growing economy in Southeast Asia, Indonesia plays a pivotal role in the global energy and climate landscape. The nation's energy system is characterized by a heavy reliance on fossil fuels, with coal being the dominant source for electricity generation. This dependency has positioned Indonesia as a significant contributor to global GHG emissions, with the energy sector being the second-largest source of national emissions after land use, land-use change, and forestry (LULUCF) (4). According to the Ministry of Energy and Mineral Resources, the energy sector was responsible for over 600 million tons of CO₂ equivalent emissions in 2020, highlighting the urgent need for a decisive shift in its energy policy (5).

In response to this challenge, Indonesia has articulated increasingly ambitious climate commitments. In its 2022 Enhanced Nationally Determined Contribution (NDC), the country pledged to unconditionally reduce its GHG emissions by 31.89% and conditionally by 43.20% against a business-as-usual (BAU) baseline by 2030 (7). Looking further ahead, Indonesia has set a target to achieve Net Zero Emissions (NZE) by 2060 or sooner, a goal that necessitates a fundamental restructuring of its energy system (6). The government's National Electricity Planning document (RUKN) for 2019-2038 outlines a strategic vision for the power sector's development, although aligning this plan with the more aggressive NZE trajectory remains a key policy challenge (8). Fulfilling

these commitments will require unprecedented investment in clean energy technologies and the implementation of robust policies to manage the transition away from its entrenched fossil fuel infrastructure.

1.3. The Dual Transition: Electric Vehicles and Renewable Energy

In line with global trends, the electrification of transportation is a central pillar of Indonesia's decarbonization strategy. The global electric vehicle (EV) market has experienced exponential growth, with sales more than tripling between 2020 and 2023, demonstrating a clear and accelerating shift away from conventional vehicles (9, 10). This momentum is driven by technological advancements, falling battery costs, and supportive government policies (11, 12). Recognizing this potential, the Indonesian government has established a comprehensive roadmap for developing a domestic EV industry. Through regulations such as the Minister of Industry Number 6 of 2022, the government aims to stimulate local production and increase the adoption of electric cars and motorcycles, targeting 2 million electric cars and 13 million electric motorcycles on the road by 2030 (14). This ambition is not only an environmental strategy but also an economic one, aimed at leveraging the country's vast nickel reserves—a key component in EV batteries—to become a major player in the global EV supply chain (15, 51).

However, the environmental benefits of this transition are contingent upon the source of the electricity used to power these vehicles. Widespread EV adoption will only lead to significant net emission reductions if the electricity is generated from low-carbon sources (16). A transition to EVs powered by a coal-dominated grid would merely shift emissions from vehicle tailpipes to power plant smokestacks. Therefore, a parallel and aggressive expansion of renewable energy (RE) sources, particularly solar and wind, is essential. While Indonesia possesses vast untapped potential for renewable energy, especially solar, its integration into the national grid presents its own set of technical and economic challenges that must be addressed concurrently with the push for transport electrification (12, 50).

1.4. Research Problem: The Challenge of Grid Integration

The simultaneous integration of high penetrations of variable renewable energy (VRE) sources and a large fleet of EVs introduces significant complexities for power grid management (17, 18). VRE sources like solar and wind are inherently intermittent and non-dispatchable; their output fluctuates with weather conditions, not electricity demand. This variability can create challenges for grid operators tasked with maintaining a constant balance between supply and

demand. At the same time, the mass charging of EVs represents a substantial new source of electricity demand. If this charging is uncoordinated—for example, if a majority of EV owners plug in their vehicles upon returning home from work in the early evening—it could create a new, sharp demand peak, straining existing grid infrastructure and requiring the activation of expensive and often carbon-intensive "peaker" power plants (2, 35).

This confluence of challenges, however, also presents a unique opportunity. Advanced technologies and intelligent control systems can transform EVs from a passive load into a flexible and valuable grid resource. Smart charging, also known as V1G, allows for the timing of EV charging to be shifted to periods when electricity is abundant and cheap, such as midday when solar generation is high or overnight during low overall demand (25, 26, 27). Going a step further, Vehicle-to-Grid (V2G) technology enables EVs not only to draw power from the grid but also to discharge stored energy back into it during times of need (21). In this capacity, the aggregated fleet of EVs can act as a massive distributed battery, providing critical grid services such as frequency regulation, peak shaving, and ancillary support, thereby facilitating the integration of higher levels of VRE (19, 20, 22). This study addresses the critical need to quantify these impacts within Indonesia's specific context—a geographically dispersed archipelago with a rapidly evolving energy system—to understand how this synergy can be best harnessed.

1.5. Study Objectives and Structure

The primary objective of this research is to model and analyze the technical and economic impacts of integrating high penetrations of electric vehicles and renewable energy into the Java-Bali electrical grid, the backbone of Indonesia's power system, for the target year 2030. This study seeks to provide a quantitative assessment of the challenges and opportunities presented by this dual transition.

The secondary objectives are:

1. To quantify the potential for EVs to support grid stability and enhance the integration of VRE through controlled smart charging and V2G services.
2. To assess the resulting impacts on the overall system generation mix, operational costs, renewable energy curtailment, and greenhouse gas emissions under various integration scenarios.
3. To derive data-driven policy and regulatory recommendations to guide Indonesia's energy transition and investment in smart grid infrastructure.

The remainder of this paper is structured as follows: Section 2 outlines the methodology, detailing the power

system modeling framework, scenario design, and key data inputs. Section 3 presents the results of the model simulations, focusing on key operational, economic, and environmental metrics. Section 4 discusses the interpretation and implications of these results, including policy recommendations and study limitations. Finally, Section 5 provides a conclusion summarizing the key findings and their significance for Indonesia's energy future.

METHODS

2.1. Modeling Framework

To analyze the complex interactions between EV charging, renewable generation, and conventional power plants, this study employed a power system dispatch optimization model. The model was designed to simulate the hourly operation of the Java-Bali interconnected grid over a full calendar year (8760 hours) to capture the full range of seasonal and diurnal variations in electricity demand and renewable energy supply. The core of the model is a linear programming algorithm whose primary objective is to minimize the total system operational cost. This cost function includes the fuel and variable operation and maintenance (VOM) costs of all thermal generators, as well as their start-up costs (48).

The optimization is performed subject to a series of technical and operational constraints. The fundamental constraint is that the total electricity generated, plus any power discharged from storage or V2G-enabled EVs, must precisely meet the total system demand in every hour. Additional constraints include the operational limits of each power plant, such as its maximum and minimum generation capacity, ramp rates (how quickly it can increase or decrease output), and minimum up/down times. For renewable energy sources, the model is constrained by the available hourly wind and solar resource profiles. This framework allows for a detailed and realistic simulation of how a grid operator would dispatch available resources to meet demand at the lowest possible cost while maintaining system reliability.

2.2. Scenario Development

To explore the potential impacts of EV and RE integration, we developed four distinct scenarios for the target year 2030. These scenarios were designed to represent a range of possible future pathways, from a conservative baseline to more ambitious transition strategies.

- **BAU (Business-as-Usual):** This scenario serves as the reference case. It is based on the official government projections for grid expansion and EV adoption as outlined in PLN's Electric Power Supply Business Plan (RUPTL) 2021-2030 (44) and the Ministry of Industry's EV roadmap (14). It assumes a moderate

build-out of renewable energy and a fleet of EVs that engage in uncontrolled, or "dumb," charging.

- **High RE Scenario:** This scenario assumes a more aggressive deployment of renewable energy, consistent with pathways required to meet Indonesia's Net Zero Emissions target (6). The total installed capacity of solar and wind power is significantly higher than in the BAU case, based on technical potential assessments from IESR (50). EV penetration and charging behavior remain the same as in the BAU scenario to isolate the impact of higher VRE levels.
- **High EV + Smart Charging Scenario:** This scenario combines the aggressive renewable build-out of the High RE scenario with a large EV fleet that utilizes smart charging (V1G) capabilities. The model allows for the shifting of EV charging demand from peak hours to off-peak periods, particularly to midday hours with high solar generation, based on optimizing for the lowest system costs (25, 27).
- **High EV + V2G Scenario:** This scenario represents the most technologically advanced case. It builds upon the High EV + Smart Charging scenario by enabling the EV fleet to perform V2G services. In this case, EVs can discharge a portion of their stored energy back to the grid during times of need, effectively acting as a distributed energy storage system (21, 34, 36).

2.3. Data Sources and Input Parameters

The model was populated with a comprehensive dataset compiled from official Indonesian sources, international databases, and academic literature to ensure a robust and realistic representation of the Java-Bali power system.

2.3.1. Grid Infrastructure and Generation

The portfolio of conventional power plants (coal, combined-cycle gas, open-cycle gas, geothermal, and hydro) was based on the projected 2030 fleet for the Java-Bali system as detailed in the RUPTL 2021-2030 (44). Technical parameters for each plant category, including heat rates (efficiency), VOM costs, ramp rates, and plant availability, were sourced from the Technology Data for the Indonesian Power Sector report, a joint publication by the Ministry of Energy and Mineral Resources and the Danish Energy Agency (52), supplemented by data from Australian market operator reports for similar technologies (53, 56, 70). Fuel price projections for coal and natural gas were aligned with IEA's regional forecasts (6).

2.3.2. Renewable Energy Profiles

Hourly generation profiles for solar photovoltaics (PV) and wind power for the entire year were created using the Renewables.ninja modeling platform (46, 47). This

platform utilizes 30 years of bias-corrected global reanalysis weather data to generate realistic, location-specific time series for wind and solar output. The geographical distribution of the assumed renewable capacity was based on resource potential maps for Java and Bali, ensuring the profiles accurately reflect the regional weather patterns and resource availability (50). The total installed capacity for solar and wind in the BAU and high-RE scenarios was set according to the respective policy documents and technical assessments (44, 50).

2.3.3. Electricity Demand

The baseline hourly electricity demand profile for the Java-Bali grid (excluding EV charging) was derived from PLN's historical operational data (45). This profile was scaled up to the projected total annual demand for 2030 as forecast in the RUPTL (44). The additional electricity demand from the EV fleet was then calculated for each scenario and superimposed onto this baseline profile, with the temporal distribution varying based on the charging strategy (uncontrolled, smart charging, or V2G).

2.3.4. Electric Vehicle Fleet Characteristics

The total size of the EV fleet in 2030 was projected based on government targets (14), with the total number of electric cars and motorcycles allocated between the BAU and High EV scenarios. Representative vehicle models were chosen to define key technical parameters. For electric cars, the Hyundai Kona Electric was used as a proxy, with a battery capacity of 64 kWh and a charging rate of 7.2 kW (AC Level 2) (60). For electric motorcycles, the Yamaha NEO was used as a reference, with a smaller battery capacity of 2 kWh and a charging rate of 0.6 kW (61). The daily energy requirement for charging was calculated based on average daily driving distances obtained from regional transportation surveys (59, 62) and vehicle efficiency ratings.

2.4. Modeling EV-Grid Interactions

The interaction between EVs and the grid was modeled under three distinct charging protocols:

- **Uncontrolled Charging:** This protocol represents the simplest and most likely near-term behavior. It assumes that EV owners plug in their vehicles upon arriving home in the late afternoon/early evening, initiating charging immediately. This creates a new demand load that coincides with the existing evening residential peak.
- **Smart Charging (V1G):** In this protocol, the total daily charging energy required by the EV fleet is treated as a flexible load by the optimization model. The model can schedule this charging demand at any hour when the

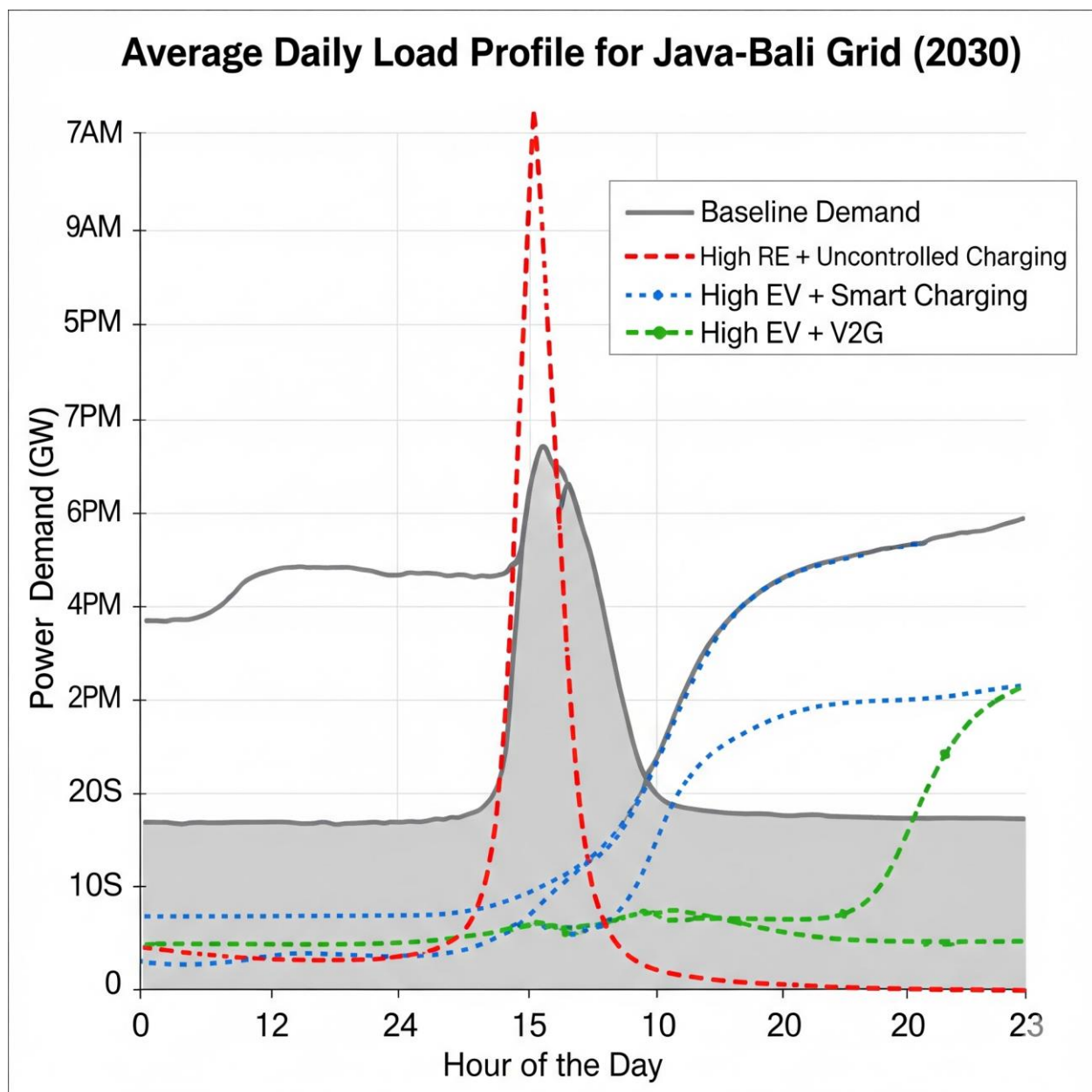
vehicles are assumed to be plugged in (e.g., from 6 PM to 7 AM). The algorithm optimally schedules this load to occur during hours with the lowest marginal electricity cost, which typically corresponds to periods of high renewable generation or low overall system demand (25, 35).

- **Vehicle-to-Grid (V2G):** For the V2G scenario, the EV fleet is modeled as both a flexible load and a distributed storage resource. The model can choose to charge the vehicles, discharge them back to the grid, or have them remain idle in any given hour. To reflect the costs and physical limitations of V2G, several constraints were imposed. A round-trip efficiency of 85% was assumed for the charge-discharge cycle (57, 58). To

preserve battery health and ensure sufficient range for the next day's travel, discharge was limited to a maximum depth-of-discharge (DoD) of 70% of the battery's capacity, and the model was required to ensure all vehicles were fully charged by the morning departure time (64, 65). The model would only dispatch V2G services when the system's marginal cost of electricity was high enough to make discharging profitable, overcoming the cost of efficiency losses and imputed battery degradation costs (66, 71).

RESULTS

3.1. Impact on Hourly Grid Operations



The simulation results reveal profound differences in the hourly load profile of the Java-Bali grid across the scenarios. Figure 1 illustrates the average daily load curves for a typical weekday. In the BAU and High RE scenarios, the addition of uncontrolled EV charging

creates a significant new peak in demand between 6 PM and 10 PM, exacerbating the existing evening ramp. This sharp increase in net load (demand minus VRE generation) necessitates the rapid dispatch of fossil fuel-fired peaker plants.

In contrast, the High EV + Smart Charging scenario demonstrates the effectiveness of load shifting. The model postpones the majority of EV charging to the overnight hours (11 PM to 5 AM) when baseline demand is low. Furthermore, a portion of the charging load is shifted to the midday hours to absorb surplus solar generation that would otherwise be curtailed. This reshaping of the demand curve results in a much flatter net load profile, reducing the need for steep ramping from conventional generators. The High EV + V2G scenario further optimizes the grid's operation. During the critical evening peak hours, the EV fleet actively discharges power back to the grid, effectively "shaving" the peak demand. This V2G dispatch reduces the reliance on expensive and inefficient open-cycle gas turbines, which are typically used to meet these short-duration peaks.

3.2. Generation Mix and Renewable Energy Curtailment

The annual electricity generation mix for each scenario, presented in Table 1, highlights the system-level impacts of the different integration strategies. As expected, moving from the BAU to the High RE scenario

significantly increases the share of solar and wind in the total generation, from 8% to 25%. However, this comes at the cost of a substantial increase in renewable energy curtailment. In the High RE scenario with uncontrolled charging, over 15% of the available solar and wind energy is wasted because there is insufficient demand or grid flexibility to absorb it when it is produced.

The introduction of EV flexibility dramatically alters this outcome. In the High EV + Smart Charging scenario, the ability to absorb surplus solar power during the day and fill demand valleys at night reduces total RE curtailment to less than 5%. The High EV + V2G scenario further reduces curtailment to just under 3%. By providing a dispatchable load and a source of storage, the EV fleet effectively increases the grid's capacity to integrate VRE, allowing for a greater portion of the available clean energy to be utilized. Consequently, the annual generation from coal-fired power plants is significantly lower in the smart charging and V2G scenarios compared to the uncontrolled charging case, even with the same amount of renewable capacity installed.

Table 1: Annual Electricity Generation Mix and System Performance by Scenario (2030)

Metric	BAU	High RE	High EV + Smart Charging	High EV + V2G
Generation (TWh)				
Coal	150.5	115.2	105.8	101.5
Gas (CCGT + OCGT)	50.2	45.1	38.5	35.1
Geothermal & Hydro	30.0	30.0	30.0	30.0
Solar	10.5	35.8	41.2	42.1
Wind	9.0	29.5	34.1	34.8
V2G Discharge	0	0	0	1.2
Total Generation	250.2	255.6	249.6	244.7

(TWh)				
Share of Mix (%)				
Coal	60.2%	45.1%	42.4%	41.5%
Gas (CCGT + OCGT)	20.1%	17.6%	15.4%	14.3%
Geothermal & Hydro	12.0%	11.7%	12.0%	12.3%
Solar & Wind (VRE)	7.8%	25.5%	30.2%	31.4%
Performance Indicators				
RE Curtailment (TWh)	1.1	11.5	3.2	1.8
CO2 Emissions (Million tons)	185	144	130	122

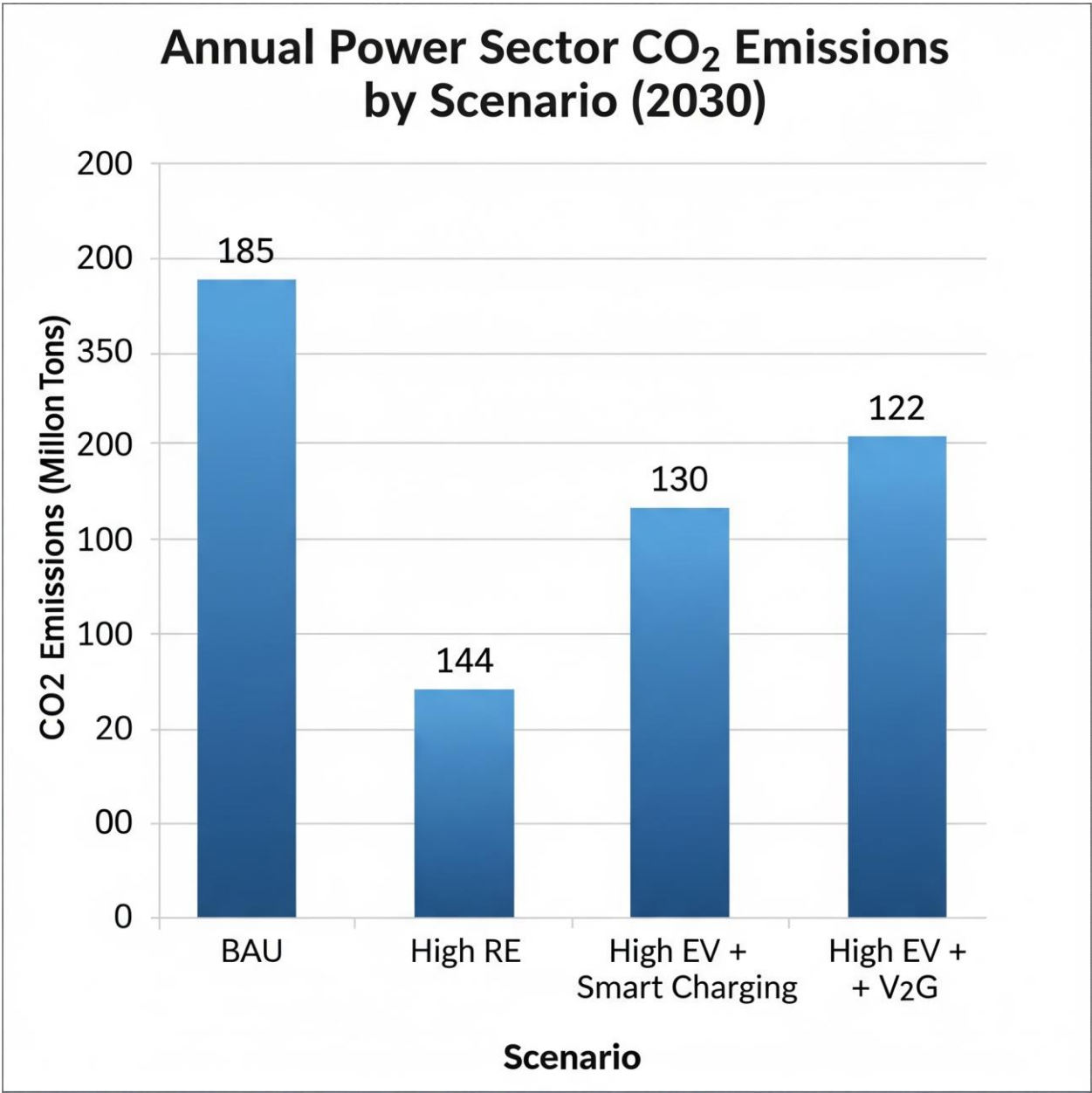
3.3. System Costs and Economics

An analysis of the total annual system operating costs reveals the economic benefits of intelligent EV integration. While the High RE scenario (with uncontrolled charging) has lower fuel costs than the BAU scenario due to the displacement of fossil fuels, it incurs higher cycling costs for conventional plants that must ramp up and down frequently to compensate for VRE variability.

The High EV + Smart Charging scenario achieves the lowest total system operating cost among all four scenarios. By optimizing the charging schedule, the system can maximize the use of low-marginal-cost

renewables and minimize the operation of expensive peaker plants. This results in an estimated 8% reduction in total annual operating costs compared to the High RE scenario with uncontrolled charging. The High EV + V2G scenario, while offering superior technical performance, results in a slightly higher operating cost than the smart charging case in our model. This is because the economic benefits of V2G dispatch in reducing peaker plant operation are partially offset by the costs associated with round-trip efficiency losses and the modeled cost of battery degradation. However, this finding is highly sensitive to assumptions about ancillary service market values, which are not explicitly modeled here.

3.4. Greenhouse Gas Emissions



The environmental benefits of the dual transition are clearly demonstrated by the power sector's CO₂ emissions, as shown in Figure. The High RE scenario with uncontrolled charging achieves a 22% reduction in CO₂ emissions compared to the BAU scenario. However, the introduction of EV flexibility enables deeper decarbonization. The High EV + Smart Charging scenario reduces emissions by 30% relative to the BAU case. By minimizing RE curtailment and reducing the need for fossil fuel generation, smart charging ensures that a larger portion of the EV fleet's energy demand is met by zero-emission sources. The High EV + V2G scenario achieves the largest emissions reduction, at 34% below the BAU baseline. By displacing the most carbon-intensive peaker plants during peak hours, V2G provides a significant carbon abatement benefit, highlighting its potential role in a fully decarbonized grid.

3.5. Sensitivity Analysis

A sensitivity analysis was conducted on several key parameters to test the robustness of the findings. The results indicate that the economic benefits of smart charging are robust across a wide range of fuel prices and battery cost assumptions. The viability of V2G, however, is more sensitive. In a scenario with higher natural gas prices (increasing the cost of peaker generation) or lower battery degradation costs, V2G becomes more economically competitive and is dispatched more frequently by the model. Conversely, if V2G participation is limited to a smaller fraction of the EV fleet, its system-level benefits are proportionally reduced, emphasizing the importance of achieving high participation rates for V2G to be an effective grid resource.

DISCUSSION

4.1. The Synergistic Role of EVs in a High-RE Grid

The results of this study provide compelling, quantitative evidence for the synergistic relationship between electric vehicles and renewable energy in the context of Indonesia's energy transition. The analysis moves beyond a simplistic view of EVs as merely an additional electrical load, demonstrating their potential to function as a crucial source of grid flexibility (2, 35). In scenarios with high VRE penetration, the grid faces the "duck curve" challenge: a midday glut of solar power followed by a steep ramp-up in demand in the evening as the sun sets. Our modeling shows that without flexible resources, a significant portion of this clean midday energy would be curtailed, and the evening ramp would be met by carbon-intensive peaker plants.

Intelligently controlled EVs directly address both of these issues. Smart charging allows the fleet to act as a giant, distributed "sponge," absorbing surplus solar energy during the day and shifting its charging load to off-peak overnight hours. This not only maximizes the utilization of renewable resources but also creates a flatter, more manageable net load profile for the grid operator (17, 31). V2G technology takes this synergy a step further. By empowering the EV fleet to act as a virtual power plant, it can actively inject power into the grid during times of stress, such as the evening peak (23, 33). This capability directly displaces the need for some of the most expensive and polluting assets in the power system, providing a clean alternative for maintaining grid reliability. In essence, the strategic integration of EVs transforms them from a potential grid problem into a pivotal grid solution, enabling a more rapid, reliable, and cost-effective transition to a high-RE power system (38, 40). While the system-level benefits are clear, unlocking this potential requires a careful examination of the economic incentives for individual EV owners and the market structures needed to support them.

4.1.1. Deconstructing the V2G Value Proposition: A Deeper Economic and Technical Analysis

While our system-level analysis demonstrates the significant technical benefits and emission reductions enabled by V2G, its practical implementation hinges on a viable economic proposition for all stakeholders, most importantly the individual EV owner. The finding that the V2G scenario incurred slightly higher operational costs than the smart charging scenario underscores the need for a more granular analysis of the costs and benefits that do not appear in a traditional dispatch model. A successful V2G ecosystem requires that the value provided to the grid is effectively translated into revenue streams for participants, and that these revenues are sufficient to offset the associated costs, particularly the cost of battery degradation (34, 66).

Potential Revenue Streams for V2G Participants:

The value of V2G can be monetized through several

distinct services provided to the grid operator. The most direct form is energy arbitrage, where EV owners charge their batteries when electricity prices are low (e.g., midday with surplus solar) and sell power back to the grid when prices are high (e.g., evening peak) (37). While conceptually simple, the profitability of arbitrage in Indonesia's current tariff structure is limited. It requires dynamic pricing mechanisms, such as time-of-use (TOU) or real-time pricing, which are not yet widely implemented.

The more significant value lies in providing ancillary services, which are essential for maintaining grid stability and reliability. These include:

- **Frequency Regulation:** The grid's frequency must be maintained within a very narrow band (typically 50 Hz in Indonesia). Deviations caused by sudden changes in generation or load can lead to instability. The fast-response capability of lithium-ion batteries makes EVs ideal for providing rapid-response frequency regulation, injecting or absorbing small amounts of power in seconds to correct imbalances (19). In mature electricity markets, this is often a highly valued service, with payments based on both the capacity made available (a "standby" payment) and the energy actually dispatched (a "performance" payment) (66).
- **Peak Shaving and Capacity Provision:** As shown in our results, V2G dispatch can effectively "shave" the peak system demand. This has immense value as it can defer or entirely avoid the need for the utility (PLN) to invest in building new, expensive peaker power plants, which may only run for a few hundred hours a year but whose capital costs are borne by all consumers (41). This "avoided infrastructure cost" can be monetized through capacity markets, where resources are paid for their availability to generate power during critical periods, even if they are not ultimately dispatched.
- **Spinning and Non-spinning Reserves:** These are forms of backup capacity that the grid operator keeps on standby to respond to unexpected outages, such as the sudden failure of a large power plant. An aggregated fleet of V2G-enabled vehicles can provide a substantial reserve of power that can be called upon within minutes, offering a cleaner and potentially cheaper alternative to keeping fossil-fueled generators running in a costly, partially loaded "spinning" state (22).

The Critical Cost of Battery Degradation:

The primary impediment to the economic viability of V2G is the incremental degradation of the EV's lithium-ion battery caused by additional charging and discharging cycles. Battery degradation is a complex electrochemical process influenced by numerous factors, including the number of cycles, depth-of-discharge (DoD), charge/discharge rate (C-rate), and ambient temperature

(64). Each additional V2G cycle consumes a small portion of the battery's finite lifespan, effectively bringing forward the date at which it will need to be replaced, which represents a significant capital cost for the EV owner.

Quantifying this cost is challenging but essential for any economic model of V2G (65). Based on current battery pack replacement cost estimates (around \$150/kWh) and typical battery warranties (e.g., 1500-2000 full cycles before capacity fades to 80%), one can impute a marginal degradation cost for each kWh discharged for V2G purposes (58, 71). For a 64 kWh battery pack, this cost could be in the range of \$0.05-\$0.10 per kWh discharged. This implies that for V2G to be profitable for the EV owner, the revenue earned from selling that kWh back to the grid must exceed not only the cost of the electricity used to charge it initially but also this marginal degradation cost. Our system model implicitly includes an imputed degradation cost, which explains why V2G was dispatched only during the highest-cost hours. Studies from established markets in Denmark and Japan have shown that while frequency regulation services can be profitable, the margin is often slim once degradation is fully accounted for, highlighting the need for well-structured compensation (66).

Net Profitability and the Role of Aggregators:

For an individual EV owner, directly participating in wholesale electricity markets is impractical. The solution lies in the emergence of EV aggregators (33). These entities would contract with thousands of EV owners, managing the charging and discharging of their vehicles remotely through a central software platform. The aggregator would then bid the collective capacity of this "virtual power plant" into the various energy and ancillary service markets, optimizing its dispatch to maximize revenue. They would handle the complex bidding, scheduling, and settlement processes, and in return, share a portion of the revenue with the participating EV owners.

The net profitability for the consumer would depend on the aggregator's business model and the market value of flexibility. A successful model must ensure that the annual revenue share paid to the EV owner is sufficiently attractive to encourage participation, comfortably exceeding their perceived costs and inconvenience. This will require not just favorable market prices but also intelligent optimization algorithms that co-optimize V2G dispatch for grid revenue while respecting the vehicle owner's primary mobility needs, always ensuring the vehicle has sufficient charge for their daily travel (34).

Market Design and Policy Enablers for Indonesia:

To unlock this value, Indonesia must move beyond its current centralized, cost-plus regulatory model for

electricity. The foundational step is the creation of competitive wholesale markets for both energy and ancillary services, which would provide the price signals necessary for V2G to operate. This involves establishing clear rules for the participation of Distributed Energy Resources (DERs) like V2G fleets. Technical standards for interconnection, communication protocols (such as ISO 15118), and cybersecurity will be paramount to ensure the safe and secure operation of this distributed system. Without these market structures and technical standards, the system-level benefits identified in our modeling will remain purely theoretical.

4.2. Policy and Regulatory Implications

The transition from a theoretical potential to a practical reality requires a proactive and supportive policy and regulatory environment. The findings of this study translate into several key recommendations for Indonesian ministries.

First, the development and implementation of dynamic electricity tariffs, such as time-of-use (TOU) or real-time pricing, is a foundational requirement. Flat electricity rates provide no incentive for EV owners to charge at optimal times. TOU rates, which make electricity cheaper during off-peak hours (e.g., overnight and midday) and more expensive during peak evening hours, would naturally encourage the adoption of smart charging, aligning consumer behavior with the needs of the grid (27, 37).

Second, as detailed above, a clear regulatory framework and market design for V2G and other DERs is necessary. This framework must define how aggregated resources can participate in energy and ancillary service markets (e.g., for frequency regulation or spinning reserves). Clear rules for interconnection, communication protocols, and metering must be established to ensure that V2G services can be provided safely and reliably. Furthermore, compensation mechanisms must be designed to fairly remunerate EV owners for the services they provide and for the associated battery degradation, making participation economically attractive (22, 34).

Third, significant investment in smart grid infrastructure is essential. This includes the widespread deployment of advanced metering infrastructure (AMI), or smart meters, which enable two-way communication between the utility and the consumer. High-speed communication networks and sophisticated grid management software are also needed to manage the charging and discharging of millions of distributed EV assets in real-time (18, 26). These investments are not merely costs but are enabling infrastructure for a more efficient, resilient, and decarbonized 21st-century power grid.

4.3. Broader Economic and Industrial Considerations

The implications of this transition extend beyond the power sector. For Indonesia, a successful EV-grid integration strategy aligns perfectly with its broader industrial ambitions. As one of the world's largest producers of nickel, Indonesia is strategically positioned to become a global hub for the manufacturing of lithium-ion batteries and EVs (51, 68). A thriving domestic market for EVs, supported by a smart and reliable grid, would create a virtuous cycle, attracting investment, fostering technological development, and creating high-value jobs. This domestic demand can serve as an anchor for building a competitive export-oriented industry, allowing Indonesia to capture a significant share of the value chain in this rapidly growing global market (67).

However, several challenges must be addressed. The high upfront cost of EVs remains a significant barrier to adoption for many consumers (15). Government incentives, such as purchase subsidies or tax credits, may be necessary in the short to medium term to accelerate uptake. The rollout of a comprehensive and accessible public charging infrastructure is also critical to alleviate "range anxiety" and ensure that EV ownership is practical for all segments of the population. Finally, consumer education and engagement will be key to ensuring high participation rates in smart charging and V2G programs.

4.4. Limitations and Future Research

While this study provides valuable insights, it is important to acknowledge its limitations. First, our analysis is confined to the interconnected Java-Bali grid. While this system represents the majority of Indonesia's electricity consumption, the findings may not be directly transferable to the country's many smaller, isolated island grids, which face unique challenges and may present even greater opportunities for EV-RE synergies (42, 43). Second, our model does not include a detailed representation of the electricity distribution network. High local concentrations of EV charging could potentially lead to issues like transformer overloading or voltage violations, which are beyond the scope of a system-level dispatch model.

These limitations point to important avenues for future research. A nationwide study encompassing Indonesia's diverse array of grid systems would provide a more complete picture of the national potential. Detailed impact studies on the distribution grid are urgently needed to inform infrastructure planning and investment. Furthermore, more sophisticated behavioral models could be developed to better predict consumer responses to dynamic pricing and their willingness to participate in V2G programs. Finally, as battery technology continues to evolve, ongoing research will be needed to update assessments of V2G's economic viability and its long-term impacts on battery health.

CONCLUSION

5.1. Summary of Key Findings

This study has systematically modeled and quantified the impacts of integrating electric vehicles and renewable energy into Indonesia's Java-Bali power grid. Our findings demonstrate that while uncoordinated EV charging can strain the grid and hinder the use of renewable energy, a strategic approach utilizing smart charging and V2G technology can unlock significant synergistic benefits. Key findings show that EV flexibility can drastically reduce renewable energy curtailment, lower overall system operating costs by up to 8%, and enable deeper power sector decarbonization, reducing CO₂ emissions by as much as 34% compared to a business-as-usual pathway. The EV fleet, when intelligently managed, is transformed from a grid burden into a valuable asset that enhances reliability and facilitates the transition to a clean energy future.

5.2. Final Concluding Remarks

Indonesia is at a pivotal moment in its development, with the opportunity to leapfrog conventional, carbon-intensive growth models and embrace a path of sustainable prosperity. The dual transition to electric mobility and renewable power generation is central to this vision. Our research indicates that these two transitions should not be viewed in isolation but as deeply interconnected components of a single, integrated energy strategy. The successful harnessing of the synergy between EVs and the grid is not merely beneficial but may prove to be essential for achieving the country's ambitious climate and economic goals in a cost-effective manner. By implementing forward-thinking policies, investing in enabling infrastructure, and fostering innovation, Indonesia can not only decarbonize its domestic energy system but also position itself as a global leader in the sustainable energy and transportation technologies of the future.

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