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UNLOCKING THE NEXUS OF SUPPLY CHAIN EFFICIENCY IN ELECTRIC VEHICLE MARKETS: A SYSTEM THINKING APPROACH

Abstract

Electric vehicles (EVs) present a promising pathway to reduce carbon emissions, yet their adoption in developing markets remains constrained by high production costs, infrastructure gaps, and supply chain inefficiencies. This study investigates the Indonesian EV market using a mixed-method approach, combining techno-economic analysis with a system thinking framework. Primary data were collected through interviews and FGDs with eight stakeholders, while secondary data from 2020-2024 supported trend analysis. The study employs a Causal Loop Diagram (CLD) to map systemic interactions among policy, technology, and market forces. The results suggest that a 25% increase in subsidies and a 40% infrastructure expansion could lead to a 60% rise in EV adoption, assuming battery prices remain stable. Policy and marketing strategies, such as targeted incentives and circular economy practices like localized battery recycling, emerge as key leverage points for building a sustainable and resilient EV supply chain. The findings offer actionable insights for developing markets to design integrated policies that align economic incentives with clean mobility goals.

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INTRODUCTION

The worsening climate crisis, driven largely by carbon dioxide emissions from fossil fuel-powered vehicles, necessitates an urgent transition to sustainable transportation solutions. Contributing nearly one-quarter of global greenhouse gas emissions, the transportation sector underscores the pivotal role of electric vehicles (EVs) in mitigating environmental damage (Guzek et al., 2024). Beyond their potential to reduce emissions, EVs offer an opportunity to redefine the transportation landscape through cleaner and more efficient technologies. However, widespread adoption of EVs remains a formidable challenge, particularly in developing nations, where infrastructure is underdeveloped, and costs are prohibitive. These barriers highlight the gap between the promise of EV technology and its practical implementation on a global scale.

This challenge is compounded by the inherent complexities of the EV supply chain. A heavy reliance on critical raw materials such as lithium and cobalt, coupled with inadequate battery recycling systems, undermines both environmental sustainability and market resilience (Bhanu et al., 2024; Wu et al., 2023). Furthermore, the extraction and supply chain logistics of these materials often result in significant ecological and social consequences, calling into question the long-term viability of current practices. Adding to this complexity is the inadequate availability of charging infra-

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structure, particularly outside urban centers, which further constrains EV adoption. As such, the interplay between supply chain vulnerabilities and technological limitations amplifies the urgency to develop comprehensive solutions.

Global efforts to promote EVs through fiscal incentives, tax reductions, and infrastructure investments are promising but remain insufficient to address these multifaceted challenges. Existing strategies often focus on isolated interventions, such as subsidies or innovations in battery technology, without fully accounting for the interconnected nature of supply chain dynamics, market behaviors, and policy impacts. This fragmented approach risks creating inefficiencies and bottlenecks that may undermine progress, particularly in emerging economies. Consequently, the need for holistic and systemic frameworks becomes increasingly evident.

Recognizing these complexities, this study emphasizes the need for an integrated framework to optimize the efficiency of EV supply chains. By leveraging a systems thinking approach, which views the EV ecosystem as an interconnected set of components influenced by policy, technology, and market behavior, the research explores the dynamic relationships between raw material supply, technological innovation, and regulatory interventions. This holistic perspective enables the identification of strategic leverage points within the system, offering practical and policy-relevant insights for stakeholders. Ultimately, the findings aim to accelerate EV adoption while promoting both environmental sustainability and economic resilience, particularly in emerging markets where systemic challenges are most pronounced.

1. LITERATURE REVIEW

The transition to electric vehicles (EVs) represents a pivotal shift in addressing the global climate crisis. However, this shift is fraught with challenges stemming from supply chain inefficiencies, high production costs, and infrastructure gaps (Ehsan et al., 2024; Gong et al., 2024). Existing literature underscores the importance of understanding the interconnected nature of these challenges to design effective solutions. Using system thinking and techno-economic perspectives, this review analyzes key barriers and identifies pathways for optimizing EV supply chains (Bhanu et al., 2024; Guzek et al., 2024).

Demand for EVs has surged globally, driven by rising awareness of environmental issues and proactive government policies. Subsidies, tax incentives, and infrastructure investments in countries such as Norway and China have significantly boosted adoption rates (Ribeiro et al., 2023; Schulz-Mönninghoff et al., 2023). However, in developing nations, limited purchasing power and infrastructure inadequacies continue to hinder progress (Michaelides et al., 2023; Wu et al., 2023). These disparities highlight the need for localized policies and collaborative efforts to address affordability and infrastructure gaps effectively (Nimesh et al., 2024). A systems thinking approach becomes vital here as it integrates economic, social, and environmental factors to evaluate the effectiveness of interventions (Saputra & Andajani, 2023).

One significant challenge lies in the production and cost of EV batteries. Lithium-ion batteries dominate the market, yet they face issues such as raw material scarcity and price volatility (Bhanu et al., 2024; Corradi et al., 2023). Recycling technologies offer potential solutions but remain limited in scalability due to technological and infrastructural barriers (Rönkkö et al., 2024). System thinking emphasizes the interdependencies between raw material availability, recycling advancements, and geopolitical factors, while techno-economic analysis quantifies the trade-offs between cost reductions through recycling and the initial investment required for these systems (Lal & You, 2023).

Charging infrastructure represents another critical barrier to EV adoption, particularly in regions with underdeveloped energy grids (Touhs et al., 2023). Innovations like Vehicle-to-Grid (V2G) technology and renewable energy integration have emerged as potential solutions to enhance accessibility and grid stability (Nazari et al., 2024; Michaelides et al., 2023). However, the uneven distribution of charging stations and high installa-

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tion costs persist as challenges (Demartini et al., 2023). A system thinking framework helps uncover the feedback loops linking infrastructure investment, consumer confidence, and electric vehicle adoption. By integrating this perspective with techno-economic insights, stakeholders can identify cost-effective, scalable charging models tailored to regional conditions, supporting both infrastructure planning and consumer marketing strategies (Peng et al., 2024; Asgarian et al., 2023).

The EV industry's sustainability also faces challenges stemming from the environmental and social costs of mining raw materials like lithium and cobalt. Circular economy practices, including battery recycling, reduce dependency on new materials and mitigate ecological harm (Jose et al., 2024; Rönkkö et al., 2024). However, these practices encounter barriers such as high costs and regulatory inconsistencies (Demartini et al., 2023). Systems thinking identifies leverage points to harmonize policy, technology, and market dynamics, while techno-economic analysis evaluates the financial viability of these solutions in achieving sustainability goals (Alanazi, 2023; Jose et al., 2024).

Moreover, EV adoption entails complex socio-economic trade-offs. While EVs significantly reduce carbon emissions and improve air quality, the transition poses risks such as job losses in traditional automotive industries (Corradi et al., 2023; Schulz-Mönninghoff et al., 2023). Systems thinking provides a holistic view of these trade-offs, enabling strategies that maximize net benefits across economic and environmental dimensions. Techno-economic approaches further quantify the impacts of subsidies, infrastructure investments, and regulatory frameworks, offering actionable insights for policymakers (Demartini et al., 2023; Ahuchogu et al., 2024).

2. METHODOLOGY

2.1. Research framework and CLD approach

This study adopts a systems thinking approach to understand the complexity and dynamics of the factors influencing the electric vehicle (EV) market. Systems thinking allows researchers to view a system as a whole, consisting of interrelated components that influence each other, rather than analyzing each element in isolation. This approach is highly relevant in the context of the EV market, as it is influenced by a variety of technical, economic, policy, and social factors that are interconnected and dynamic (Tamakloe & Caesar, 2024; Tavana et al., 2024; Waseem et al., 2023).

One of the key tools used in systems thinking is the Causal Loop Diagram (CLD), which helps to illustrate cause-and-effect relationships between variables within a system. CLD enables the identification of feedback loops, showing how changes in one variable can affect others directly or indirectly within the system (Meszaros et al., 2020; Rey et al., 2024). By mapping these relationships, CLD provides deeper insights into the mechanisms that drive or hinder EV adoption. In this study, CLD is used to visually depict the interactions between key factors influencing EV adoption and market efficiency.

Figure 1 illustrates a simple CLD showing the interactions between technical aspects (such as battery efficiency and production costs) and economic factors (such as incentives and market prices). Each variable in this CLD is connected by arrows indicating the direction of influence, with feedback loops demonstrating how changes in one factor can either amplify or mitigate changes in another. In this diagram, feedback loops are labeled as either R (Reinforcing) or B (Balancing). Reinforcing loops (R) indicate self-reinforcing dynamics, where an initial change leads to further change in the same direction, potentially accelerating growth or decline. Balancing loops (B), conversely, represent stabilizing mechanisms in the system, which resist change and promote equilibrium.

Through this CLD, the study aims to provide a clearer picture of how diverse factors, from technology to public policy, interact to shape the future of the EV market. This process will enable stakeholders to better understand the impact of implemented policies and predict how the system will react to specific changes.

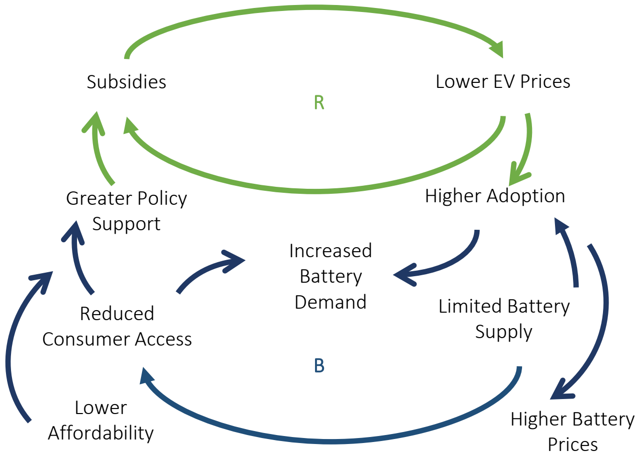

Figure 1. Simple causal loop diagram for the electric vehicle market

2.2. CLD construction process

The construction of the primary Causal Loop Diagram (CLD) in this study began with a comprehensive data collection process involving structured interviews and focus group discussions (FGDs) with key stakeholders in the electric vehicle (EV) ecosystem. Experts were selected from various sectors, logistics, policy, production, and technology, to ensure a wide range of perspectives. A structured questionnaire guided the discussions, focusing on identifying critical variables that influence EV adoption, as well as exploring the interconnections and feedback mechanisms between them.

The interviews were conducted in a structured format, allowing participants to elaborate on the causal relationships they observed within the system. Their responses were analyzed to identify both direct and indirect relationships among variables. These were then categorized into reinforcing and balancing loops, capturing how certain changes could either amplify or stabilize dynamics within the EV market.

To provide a visual overview of the process, Figure 2 illustrates the research workflow, from questionnaire development to the refinement of the final CLD. This workflow reflects an iterative process where expert feedback was incorporated at each stage to improve accuracy and relevance. The resulting CLD serves as a robust analytical tool for understanding system behavior and simulating the potential impact of various policy and market interventions.

2.3. Data collection and triangulation

Data collection for this study was conducted through a mix of primary and secondary sources to ensure a comprehensive understanding of the electric vehicle (EV) market. Primary data were gathered through focus group discussions (FGDs) and structured interviews with industry experts, while secondary data were obtained from industry reports, government publications, and other relevant market studies. This combination provided diverse perspectives, which were crucial for constructing the Causal Loop Diagram (CLD) and ensuring the robustness of the findings.

Triangulation was employed to validate the CLD and enhance the credibility of the results. Triangulation involves comparing and cross-checking data from various sources to identify consistencies and discrepancies, which helps to verify the accuracy and reliability of the findings (Sarasi et al., 2025). This approach strengthened the validity of the relationships identified in the CLD and ensured that the model accurately reflected the underlying system (Sarasi et al., 2024). To further validate the CLD, the study used regression analysis and scenario testing. Regression analysis was conducted to assess the statistical relationships between the key variables identified in the CLD, providing a quantitative measure of the strength and significance of these relationships. Scenario testing involved applying different policy scenarios to assess their potential impact on the EV market and determine how changes in key variables could influence adoption rates and market outcomes.

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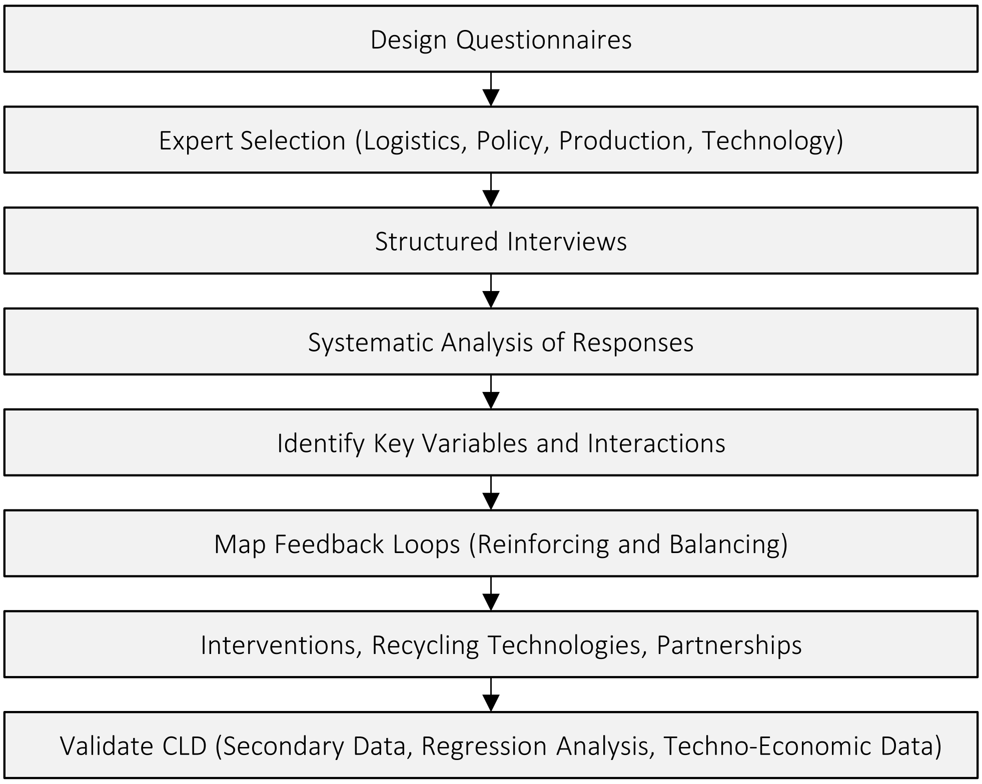

Figure 2. Research design workflow and CLD construction process

Table 1 presents the techno-economic data used for the regression analysis and scenario testing. This table includes detailed information on the technical and economic factors that affect EV adoption, such as battery efficiency, production costs, market prices, and government incentives. By analyzing this data, the study was able to quantify the impact of these factors and integrate them into the CLD for a more precise understanding of the market dynamics.

Table 2 provides the profiles of the participants involved in the FGDs. This table includes information about each participant's background, area of expertise, and role in the EV ecosystem. Understanding the diversity of the participants is important for interpreting the qualitative data collected, as it highlights the different perspectives that informed the construction of the CLD. The table shows the range of expertise represented, from technical experts to policy analysts, ensuring that the CLD captures a holistic view of the EV market.

Finally, Table 3 presents the results of the triangulation process. This table summarizes how data from multiple sources were integrated and cross-checked, showing how expert insights, industry reports, and secondary data were used to refine and validate the CLD. The table highlights the consistency between different data sources, which increases the confidence in the accuracy of the identified relationships and feedback loops in the system.

Table 1. Techno-economic data for CLD validation

	Year	Subsidies (%)	Battery price (USD/kWh)	EV adoption (million)	Infrastructure investment (USD million)	CO2 Reduction (million tons)
1	2020	10	200	0.2	500	2
2	2021	15	180	0.4	700	4
3	2022	20	160	0.6	900	6
4	2023	15	140	0.8	1200	8
5	2024	30	120	1.0	1500	10

Table 2. Experience and expertise of FGD participants

Respondent	Expertise	Age (years)	Experience (years)
Raw material supplier 1	Logistic and raw material distribution	45	20
Raw material supplier 2	Global raw material procurement	38	15
Battery manufacturer 1	Battery technology and capacity development	40	18
Battery manufacturer 2	Battery production and supply chain	35	12
Vehicle manufacturer 1	Electric vehicle design and production	37	14
Vehicle manufacturer 2	Project management and electric vehicle development	48	22
Government official 1	Renewable energy regulations and policies	50	25
Government official 2	Transportation infrastructure policy	44	20

Table 3. Triangulated data processing results

No.	Topics	Alternatives	Opinion	Conclusion	Connection to CLD	Policy
1	Demand for electric vehicles through government incentives	Electric vehicle tax incentives are a key factor in increasing demand. Purchase subsidies for electric vehicles are effective in accelerating adoption. Policies for free parking and charging exemptions provide additional appeal. Leasing and loan incentive programs for electric vehicles help drive demand. Government incentives are still insufficient to significantly boost demand.	a = 1 b = 2 c = 1 d = 2 e = 2	Most respondents highlight the need for stronger government incentives, such as subsidies, tax breaks, leasing support, and parking fee exemptions, to boost electric vehicle adoption effectively.	Macro: subsidies Micro: tax incentives Interface: policy efficiency	Strengthen government incentives with a focus on leasing and parking exemptions to address policy gaps and boost adoption.
2	Battery production and supply and its impact on price	Limitations in battery raw materials keep battery prices high. An unstable battery supply makes it difficult for electric vehicle prices to decrease. Domestic battery production is not yet sufficient to meet demand, leading to higher costs due to import dependency. The development of new battery technologies, such as solid-state, could lower prices in the long term. International agreements for battery raw material supply have helped reduce prices.	a = 2 b = 2 c = 2 d = 1 e = 1	Respondents agree that unstable battery supply, limited raw materials, and import reliance drive up EV costs, but advancements like solid-state batteries and international agreements may lower prices.	Macro: raw material supply Micro: solid-state batteries Interface: technology agreements	Focus on domestic battery production and solid-state technology to reduce costs and dependency on imports.
3	Charging infrastructure and charging technology	Currently, charging infrastructure is unevenly distributed, especially outside major cities. Fast charging technology increasingly supports charging efficiency, but is still not widely available. The high cost of building charging stations slows down infrastructure expansion. Solar-powered charging technology could be a sustainable solution in the future. Home charging with government support greatly aids in increasing electric vehicle adoption.	a = 2 b = 2 c = 1 d = 2 e = 1	Respondents note uneven charging infrastructure, high station costs, and limited fast-charging availability. They highlight solar-powered and home charging, with government support, as key future solutions.	Macro: infrastructure expansion Micro: charging stations Interface: accessibility	Prioritize fast-charging and solar-powered infrastructure development to address accessibility challenges.

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Table 3 (cont.). Triangulated data processing results

No.	Topics	Alternatives	Opinion	Conclusion	Connection to CLD	Policy
4	Supply chain sustainability and battery recycling	Battery recycling programs are still in development and need strengthening. The battery supply chain needs to be more transparent to ensure sustainability and environmental preservation. The use of environmentally friendly raw materials for batteries is becoming a major concern. Investment in battery recycling technology can reduce the environmental impact of electric vehicles. Collaboration between government and private sectors is necessary to accelerate the development of a sustainable supply chain.	a = 3 b = 2 c = 1 d = 1 e = 1	Most respondents emphasize the need to strengthen battery recycling and supply chain sustainability through transparency, eco-friendly materials, and government-private sector collaboration.	Macro: recycling programs Micro: supply chain transparency Interface: collaboration	Enhance battery recycling programs and supply chain transparency to reduce environmental impacts and ensure sustainability.
5	Economic and environmental impact of electric vehicles	Electric vehicles will create new jobs in the renewable energy and battery manufacturing sectors. The reduction in electric vehicle emissions can help Indonesia achieve its carbon emission targets. Electric vehicles could reduce healthcare costs due to cleaner air in major cities. Short-term economic impacts may be severe because the transition requires significant investment. Electric vehicles could accelerate the reliance on more environmentally friendly renewable energy.	a = 2 b = 2 c = 1 d = 1 e = 2	Respondents highlight EVs' benefits: lower emissions, job creation, and reduced healthcare costs, despite investment challenges.	Macro: emission reduction, Micro: job creation Interface: economic impacts	Leverage the environmental and economic benefits of EVs while addressing short-term investment challenges through public-private partnerships.

2.4. Techno-economic analysis

To strengthen the validity of the Causal Loop Diagram (CLD) and derive practical insights, this study incorporated a techno-economic analysis that bridges technological feasibility with economic viability. This analytical approach is particularly relevant in the context of the Indonesian electric vehicle (EV) market, where adoption is shaped by a complex interplay of cost structures, policy interventions, infrastructure availability, and technological readiness. By integrating technical indicators, such as battery efficiency, charging infrastructure, and raw material availability, with economic variables, such as subsidies, production costs, and market uptake, this analysis offers a holistic understanding of system performance and potential leverage points.

Techno-economic analysis in this study serves two main purposes. First, it validates the feedback loops captured in the CLD by providing quantitative data that reflect actual trends in the EV ecosystem. Second, it supports scenario testing by showing how changes in policy or technology can influence market outcomes. This method complements the system thinking framework by reinforcing data-driven insights with empirical trends observed in the real world.

Table 4 presents the techno-economic data used in this analysis, covering the period from 2020 to 2024. As the table illustrates, increasing government subsidies are associated with a steady decline in battery prices – from USD 200/kWh in 2020 to USD 120/kWh in 2024. This, in turn, is correlated with a significant rise in EV adoption, from 0.2 million to 1 million units over the same period. Infrastructure investment also grew from USD 500 million to USD 1.5 billion, contributing to a cumulative CO_2 reduction of 10 million tons by 2024. These figures underscore the systemic impact of coordinated fiscal and technological interventions.

Table 4. Techno-economic data for CLD validation

	Year	Subsidies (%)	Battery price (USD/kWh)	EV adoption (million)	Infrastructure investment (USD million)	CO2 reduction (million tons)
1	2020	10	200	0.2	500	2
2	2021	15	180	0.4	700	4
3	2022	20	160	0.6	900	6
4	2023	15	140	0.8	1200	8
5	2024	30	120	1.0	1500	10

These trends validate the reinforcing feedback loops in the CLD, where increases in subsidies and infrastructure investment reduce battery prices and enhance market accessibility. This dynamic accelerates EV adoption and contributes to broader environmental benefits. While this study does not employ mathematical modeling or simulations, the analysis of historical patterns provides strong support for the system model and highlights actionable leverage points.

Insights from focus group discussions (FGDs) further enriched the techno-economic analysis by adding real-world perspectives to the data-driven model. These discussions revealed operational bottlenecks, regulatory limitations, and challenges in innovation readiness, which are not fully captured through quantitative analysis alone. Participants from key sectors, including raw material supply, battery manufacturing, vehicle production, and public policy, provided practical insights that contextualized the techno-economic findings. Their input helped refine the CLD to better reflect the actual complexities and interdependencies within Indonesia's evolving EV ecosystem.

The integration of techno-economic data and qualitative stakeholder insights enables a nuanced understanding of the EV supply chain. This combination enhances the depth and accuracy of the CLD, allowing for more comprehensive modeling of systemic interactions. It not only validates the feedback loops identified in the CLD but also supports the development of targeted, evidence-based strategies for scaling up EV adoption in Indonesia.

The FGDs revealed several key stakeholder perspectives on the development of electric vehicles in Indonesia. Raw material suppliers expressed that government incentives are still inadequate, with limited domestic raw material supply remaining a major constraint to battery price reduction. The high cost and uneven distribution of charging infrastructure were also raised as persistent challenges, alongside the need to accelerate battery recycling programs.

Battery manufacturers and vehicle makers emphasized that while subsidies have been effective in stimulating adoption, reliance on imported battery components continues to pose risks to cost stability and supply continuity. They pointed to solar-powered charging systems and advancements in solid-state batteries as long-term solutions, although both require substantial investment and policy support to reach full implementation.

Government officials underlined the critical role of public-private partnerships in advancing a sustainable and localized EV supply chain. They supported the use of policy incentives beyond subsidies, such as leasing, credit support, and charging

Table 5. Experience and expertise of FGD participants

Respondent	Expertise	Age (years)	Experience (years)
Raw material supplier 1	Logistic and raw material distribution	45	20
Raw material supplier 2	Global raw material procurement	38	15
Battery manufacturer 1	Battery technology and capacity development	40	18
Battery manufacturer 2	Battery production and supply chain	35	12
Vehicle manufacturer 1	Electric vehicle design and production	37	14
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Government official 1	Renewable energy regulations and policies	50	25
Government official 2	Transportation infrastructure policy	44	20

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exemptions, to further encourage consumer adoption. However, they also acknowledged that structural issues, such as limited domestic battery production and technological dependency, remain substantial barriers.

To synthesize these findings, triangulation analysis was conducted by integrating FGD responses, in-depth interviews, and secondary data. This comprehensive approach allowed for the identification of recurring patterns and cross-validation of insights from various stakeholder groups. Table 6 presents a summary of the triangulated themes, highlighting the convergence of expert opinions, implications for the CLD structure, and actionable policy considerations that can inform strategic decision-making in the EV sector.

Based on Table 6, most respondents agree that government incentives, such as purchase subsidies and tax reductions, are essential for accelerating EV adoption. However, current policies are still perceived as insufficient. The main challenges identified include unstable battery supply, limited raw material availability, and reliance on imports, all of which contribute to high production costs. In addition, the uneven distribution of charging infrastructure, particularly outside urban centers, and the high cost of its development remain significant barriers.

Table 6. Triangulated data processing results

No.	Topics	Alternatives	Opinion	Conclusion	Connection to CLD	Policy
1	Demand for electric vehicles through government incentives	Electric vehicle tax incentives are a key factor in increasing demand. Purchase subsidies for electric vehicles are effective in accelerating adoption. Policies for free parking and charging exemptions provide additional appeal. Leasing and loan incentive programs for electric vehicles help drive demand. Government incentives are still insufficient to significantly boost demand.	a = 1 b = 2 c = 1 d = 2 e = 2	Most respondents highlight the need for stronger government incentives, such as subsidies, tax breaks, leasing support, and parking fee exemptions, to boost electric vehicle adoption effectively.	Macro: subsidies Micro: tax incentives Interface: policy efficiency	Strengthen government incentives with a focus on leasing and parking exemptions to address policy gaps and boost adoption.
2	Battery production and supply and its impact on price	Limitations in battery raw materials keep battery prices high. An unstable battery supply makes it difficult for electric vehicle prices to decrease. Domestic battery production is not yet sufficient to meet demand, leading to higher costs due to import dependency. The development of new battery technologies, such as solid-state, could lower prices in the long term. International agreements for battery raw material supply have helped reduce prices.	a = 2 b = 2 c = 2 d = 1 e = 1	Respondents agree that unstable battery supply, limited raw materials, and import reliance drive up EV costs, but advancements like solid-state batteries and international agreements may lower prices.	Macro: raw material supply Micro: solid-state batteries Interface: technology agreements	Focus on domestic battery production and solid-state technology to reduce costs and dependency on imports.
3	Charging infrastructure and charging technology	Currently, charging infrastructure is unevenly distributed, especially outside major cities. Fast charging technology increasingly supports charging efficiency, but is still not widely available. The high cost of building charging stations slows down infrastructure expansion. Solar-powered charging technology could be a sustainable solution in the future. Home charging with government support greatly aids in increasing electric vehicle adoption..	a = 2 b = 2 c = 1 d = 2 e = 1	Respondents note uneven charging infrastructure, high station costs, and limited fast-charging availability. They highlight solar-powered and home charging, with government support, as key future solutions.	Macro: infrastructure expansion Micro: charging stations Interface: accessibility	Prioritize fast-charging and solar-powered infrastructure development to address accessibility challenges.

Table 6 (cont.). Triangulated data processing results

No.	Topics	Alternatives	Opinion	Conclusion	Connection to CLD	Policy
4	Supply chain sustainability and battery recycling	Battery recycling programs are still in development and need strengthening. The battery supply chain needs to be more transparent to ensure sustainability and environmental preservation. The use of environmentally friendly raw materials for batteries is becoming a major concern. Investment in battery recycling technology can reduce the environmental impact of electric vehicles. Collaboration between government and private sectors is necessary to accelerate the development of a sustainable supply chain.	a = 3 b = 2 c = 1 d = 1 e = 1	Most respondents emphasize the need to strengthen battery recycling and supply chain sustainability through transparency, eco-friendly materials, and government-private sector collaboration.	Macro: recycling programs Micro: supply chain transparency Interface: collaboration	Enhance battery recycling programs and supply chain transparency to reduce environmental impacts and ensure sustainability.
5	Economic and environmental impact of electric vehicles	Electric vehicles will create new jobs in the renewable energy and battery manufacturing sectors. The reduction in electric vehicle emissions can help Indonesia achieve its carbon emission targets. Electric vehicles could reduce healthcare costs due to cleaner air in major cities. Short-term economic impacts may be severe because the transition requires significant investment. Electric vehicles could accelerate the reliance on more environmentally friendly renewable energy.	a = 2 b = 2 c = 1 d = 1 e = 2	Respondents highlight EVs' benefits: lower emissions, job creation, and reduced healthcare costs, despite investment challenges.	Macro: emission reduction Micro: job creation Interface: economic impacts	Leverage the environmental and economic benefits of EVs while addressing short-term investment challenges through public-private partnerships.

The triangulated results further highlight the differing priorities across stakeholder groups. Raw material suppliers prioritize upstream challenges, including resource scarcity and recycling constraints. Manufacturers and vehicle producers focus on technological advancement and supply chain resilience, while government actors emphasize policy innovation and environmental targets. These perspectives converge on the need for an integrated strategy that aligns fiscal policy, infrastructure development, and technological support.

The analysis of techno-economic trends and systemic interactions reinforces the findings from stakeholder consultations. For instance, the decline in battery prices closely mirrors the increase in government subsidies, illustrating the reinforcing feedback loops captured in the CLD. Likewise, infrastructure investments correlate with CO_2 reduction, validating the system model's representation of policy leverage points.

Moreover, innovations like solar-powered charging and solid-state battery technology are aligned with long-term sustainability goals. These technologies offer promising pathways for reducing emissions and enhancing energy efficiency in transportation. However, their adoption depends heavily on coordinated investment, localized implementation, and institutional readiness. In particular, underserved regions would benefit from decentralized energy solutions to overcome infrastructure disparities and ensure equitable access to clean mobility.

In conclusion, the triangulated findings support the study's systemic approach. They demonstrate that understanding complex interdependencies is critical to designing effective interventions in the EV ecosystem. Cross-sector collaboration and targeted intervention are essential to achieving scalable and sustainable EV adoption in Indonesia. These insights offer a pathway for policymakers to harmonize economic, techno-

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logical, and environmental objectives in the national transition toward clean mobility.

3. RESULTS

The CLD analysis complements these insights by illustrating the feedback loops that drive or constrain system dynamics. Reinforcing loops, such as those linked to subsidies and infrastructure expansion, amplify growth, while balancing loops, such as limited raw material supply, highlight systemic bottlenecks that require targeted intervention. The graphs vividly depict how aligning fiscal policies with technological innovations can address these bottlenecks and support sustained growth. By contextualizing these trends within Indonesia's unique market conditions, the study provides actionable recommendations for policymakers and industry stakeholders to accelerate the transition to electric vehicles.

Figure 3 illustrates the complex dynamics of electric vehicle adoption using color-coded nodes that enhance interpretability. Yellow nodes represent technology-related variables such as fast charging technology and collaboration, acting as key drivers of innovation. Pink nodes indicate policy instruments, including government subsidies, tax incentives, and parking fee exemptions. Green nodes highlight supply chain and infrastructure components such as battery supply, charging infrastructure, and battery recycling. Purple nodes represent renewable energy support through solar-powered charging. Blue nodes capture interface-level variables including government incentives, leasing support, and economic impacts. Finally, the central orange node reflects the system's core outcome: electric vehicle adoption.

The reinforcing loops (R1-R5) demonstrate mechanisms that amplify systemic growth. R1 (Subsidies Loop) shows how government subsidies reduce EV prices, boosting adoption and justifying further subsidies through reduced emissions. R2 (Tax Incentives Loop) connects fiscal incentives to increased consumer uptake and policy expansion. R3 (Leasing Loop) highlights how leasing programs lower entry barriers, increasing adoption and policy reinforcement. R4 (Infrastructure Loop) links infrastructure investments to broader accessibility and economic growth. R5 (Solid-State Technology Loop) emphasizes how innovation improves battery supply and affordability, further accelerating adoption.

In contrast, the balancing loops (B1-B3) identify constraints that limit growth. B1 (Battery Supply Loop) reveals how raw material shortages cap pro-

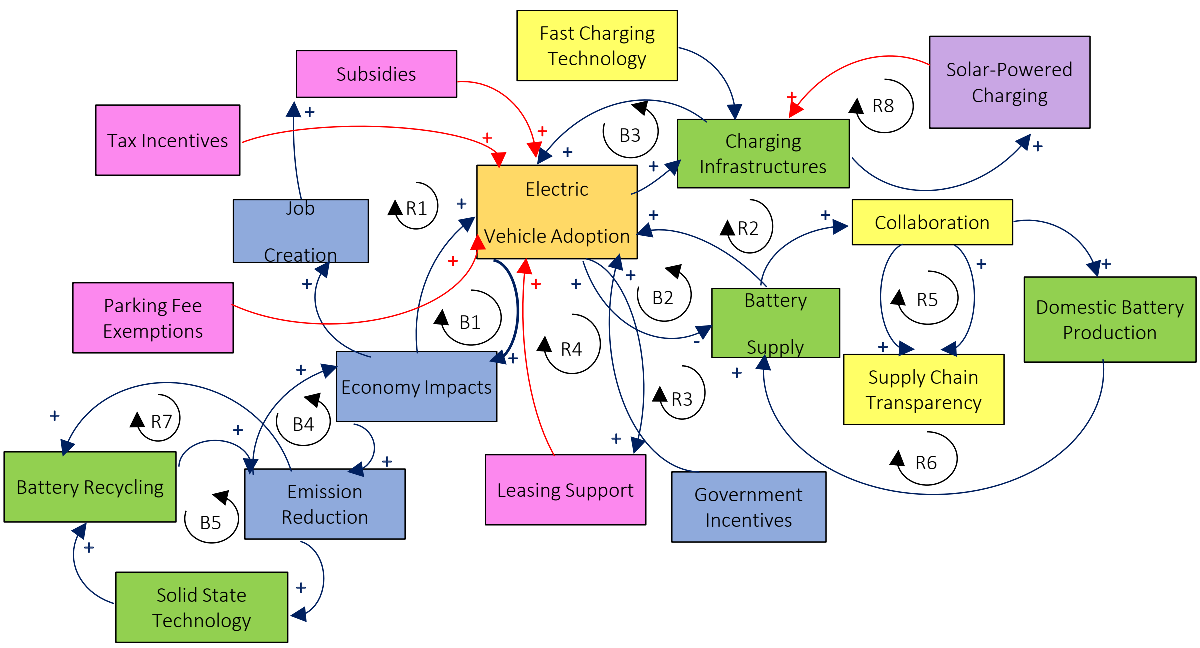

Figure 3. Integrated CLD macro, micro, interface and policies

duction capacity. B2 (Transparency Loop) shows how lack of supply chain transparency slows development. B3 (Economic Pressure Loop) demonstrates how financial constraints and high initial costs can dampen the effects of subsidies.

These dynamics align with the journal's emphasis on systems thinking, particularly the role of policy in shaping technological and economic outcomes. The CLD shows that effective policy design must not only initiate reinforcing loops but also mitigate the effects of balancing loops to ensure sustained momentum. The model supports integrated interventions targeting macro, micro, and interface levels to overcome existing constraints.

The graphs derived from the techno-economic analysis further validate these relationships. The first graph depicts the relationship between subsidies, battery prices, and EV adoption from 2020 to 2024. As subsidies increase, battery prices decline significantly, resulting in an exponential rise in EV adoption. This trend corresponds directly with loops R1 and R2 in the CLD, showing how financial policies can drive technological adoption.

The second graph illustrates the correlation between infrastructure investments and CO_2 reduction. Investments in charging networks correlate with declining emissions, reinforcing the relationship between accessibility, usage, and environmental impact. This supports loop R4 and highlights how infrastructure growth is essential to achieving climate goals.

The dual-axis chart in Figure 4 emphasizes the interplay among key variables over time. Battery prices drop steadily from USD 200/kWh to USD 120/kWh, while infrastructure investments rise from USD 500 million to USD 1.5 billion. Meanwhile, EV adoption increases from 0.2 to 1 million units, aligned with growing subsidies from 10% to 30%. CO_2 reductions follow suit, increasing from 2 to 10 million tons. These trends confirm the validity of the reinforcing loops and the system's responsiveness to strategic interventions.

This analysis shows that synchronized policy and technology development can produce compounding benefits. It emphasizes the importance of continued government commitment and innovation investment to sustain momentum. The findings suggest that a 25% increase in subsidies and a 40% boost

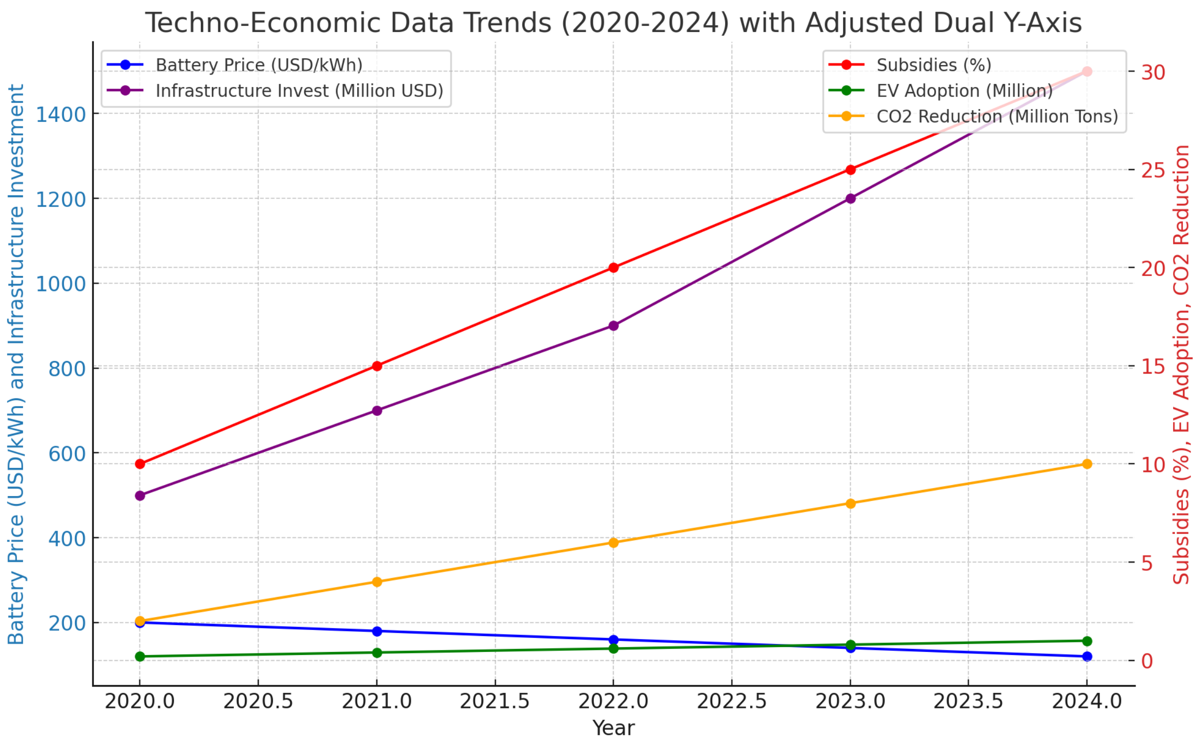

Figure 4. Techno-economic data trends (2020-2024)

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in infrastructure could raise EV adoption by 60%, aligning with estimates by Schulz-Mönninghoff et al. (2023).

Moreover, the study extends beyond existing literature by proposing circular economy strategies to address battery waste. This aligns with Corradi et al. (2023), who highlight the importance of recycling in EV sustainability. It also affirms concerns from Bhanu et al. (2024) about raw material dependencies. Localized recycling, solar charging, and eco-innovation emerge as viable solutions for Indonesia's EV supply chain resilience.

By integrating these findings, this study offers a systemic approach that connects fiscal, technological, and environmental strategies. It reinforces the argument that EV adoption in emerging markets requires tailored, cross-sector solutions. These results contribute both to academic discourse and to practical policymaking aimed at advancing sustainable mobility transitions.

4. DISCUSSION

The findings of this study align with and extend the existing body of literature on electric vehicle adoption and supply chain dynamics. Prior studies, such as Schulz-Mönninghoff et al. (2023), emphasize the role of fiscal policy in shaping EV market growth. The results reaffirm this by showing that sustained subsidies and tax incentives create a reinforcing loop that accelerates adoption, particularly when coupled with infrastructure expansion and technological innovation.

Besides, this study builds on the observations of Corradi et al. (2023) who highlight the importance of sustainability measures like battery recycling in ensuring long-term viability. The integration of red nodes in the CLD, representing supply chain transparency and recycling, demonstrates how environmental strategies can be incorporated into broader system models. This complements circular economy perspectives by showing how environmental goals can be systemically embedded in policy and technological frameworks.

Furthermore, the challenges identified by Bhanu et al. (2024) regarding raw material dependencies are also reflected in the balancing loops of our CLD. Specifically, B1 and B2 emphasize how limited raw material supply and low transparency hinder adoption, pointing to the need for upstream innovation and stronger governance. Unlike studies that treat these constraints as isolated issues, this research frames them within the dynamic feedback system that governs the EV market.

The proposed systemic strategy provides a comprehensive framework for policymakers. Rather than relying on fragmented initiatives, this model shows how integrated interventions across fiscal, technological, infrastructural, and environmental domains can work together to shift the system toward sustainability. It also suggests that policy effectiveness depends not only on scale but also on timing and coordination across feedback structures.

Importantly, the study contributes to the literature by introducing a multilayered CLD that reflects macro, micro, and interface-level dynamics. This helps bridge the gap between high-level policy discourse and on-the-ground technological implementation. The color-coded visualization of variables adds clarity to stakeholder communication and enhances the usability of the model in both academic and practical settings.

In summary, this research validates the critical role of subsidies, infrastructure, and technology in driving EV adoption, while also identifying systemic constraints that must be addressed for long-term success. It provides a novel contribution by integrating sustainability and circular economy considerations into a systemic model that can guide targeted and holistic interventions.

CONCLUSION

This study concludes that the adoption of electric vehicles (EVs) in Indonesia is influenced by a complex interplay of technological, economic, and policy-driven factors. Through a techno-economic analysis supported by focus group discussions and systemic modeling via a Causal Loop Diagram (CLD), this research reveals how government subsidies, infrastructure investment, and innovation in battery technologies significantly enhance EV adoption. The presence of reinforcing loops demonstrates the compounding effect of well-designed policies, while the balancing loops underscore the persistent challenges of raw material dependency, lack of transparency, and initial cost barriers.

The integration of macro, micro, and interface-level dynamics within the CLD provides a holistic understanding of the EV ecosystem. By identifying leverage points and feedback structures, the study emphasizes the importance of aligning policy interventions with infrastructure development and technological readiness. The dual role of fiscal policy and eco-innovation emerges as a strategic pathway not only for increasing EV penetration but also for achieving environmental and economic sustainability.

For policymakers, the findings underscore the need for consistent and scalable support in the form of subsidies, tax incentives, and public-private partnerships to expand infrastructure and reduce cost barriers. Industry stakeholders are encouraged to invest in circular economy approaches, such as battery recycling and domestic production of key materials, to strengthen supply chain resilience. For future researchers, this study offers a foundation for conducting longitudinal analyses and behavioral studies, particularly in emerging markets where systemic readiness varies regionally.

Ultimately, this research contributes to the broader discourse on sustainable mobility by offering a practical and visually communicative model that can guide policy design and stakeholder collaboration. While this study provides a comprehensive framework using secondary data, future research should incorporate primary data collection to capture region-specific market behavior and test emerging battery technologies. Such efforts would further refine the strategic pathways identified here and strengthen the applicability of systemic models in diverse local contexts. The systemic approach presented here affirms that achieving Indonesia's clean energy transition goals requires not only innovation and investment but also strategic coordination across sectors, supported by evidence-based policymaking.

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Validation: Vita Sarasi.
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