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Assessing the Effectiveness of Policy Measures to Accelerate Mining Dump Truck Electrification: A System Dynamics Approach

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ABSTRACT

Global pressure to reduce greenhouse gas (GHG) emissions through the Net Zero Emissions commitment is accelerating the transition from traditional diesel-powered equipment to electric machinery, including in Indonesia's mining sector. Despite progress in adopting diesel-powered dump trucks in mining operations, electrification efforts have largely focused on passenger vehicles, leaving a regulatory gap for heavy mining equipment. This study develops a system dynamics model integrated with Bass diffusion theory to simulate the adoption of electric mining dump trucks in Indonesian mining from 2025 to 2060. Five scenarios were constructed by varying the promotion rate and market growth, and two policy instruments were tested: import duty exemption and a preferential electricity tariff for charging facilities. Results indicate that import duty exemption consistently outperformed the electricity tariff discount across all configurations. These findings suggest that the government should prioritize promotional and regulatory signaling programs.

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1. INTRODUCTION

The development of electric battery-powered machines and equipment is accelerating, triggering a transition from internal combustion engine (ICE)-driven equipment to electric equipment, including in the mining sector. Demand for this transition is driven by the decarbonization agenda, which is rising as international awareness of global climate action grows. As a signatory to the Paris Agreement, Indonesia has committed to achieving Net Zero Emissions (NZE) by 2060 or earlier, as stipulated in the country's Enhanced Nationally Determined Contribution (NDC) and the Long-Term Strategy for Low Carbon and Climate Resilience (LTS-LCCR 2050). As a major contributor to emissions, Indonesia's mining and quarrying industries emitted around 9.5

million metric tons of CO_2 equivalent in 2021 [1]. This is equivalent to the use of diesel-powered heavy equipment, especially haul trucks, in open-pit mining operations, as transportation costs represent 50-60% of total operating costs in open-pit mines [1], while haul truck fuel consumption alone can represent up to 30% of total energy used at a mine site[2]. This combination of high emission intensity and economic importance makes dump truck operations a crucial leverage point and a transformational step for mining decarbonization. Dump trucks' fuel consumption accounts for roughly 56% of total consumption in open-pit mining operations [3]. The trend toward electric dump trucks results in considerable operational cost savings of 40%-62%, mainly due to the absence of diesel fuel expenses and lower maintenance [3].

While the benefits are promising, several barriers remain to electrification in Indonesian mining. First, the initial investment remains considerable. The capital cost of BEMDT units is higher than that of comparable diesel units, and developing the required charging infrastructure adds complexity, particularly in remote locations [4]. Second, electricity supply reliability and grid access differ between mining sites, so hybrid solutions or on-site renewable systems are required [4], [5].

Before major original equipment manufacturers (OEMs) drove the commercialization of electric mining dump trucks globally, Canada pioneered the introduction of battery-powered electric vehicles for underground mining as early as 2012 [6]. Several mining sites in North America, South America, and Europe now operate fully electric haul truck fleets [6]. Moreover, the Norwegian Government's Mineral Strategy, published in June 2023, has set a policy benchmark by targeting all new mining machinery to be zero-emission by 2030 [7]. Collectively, these developments suggest that electric dump truck technology is moving from research to early commercial feasibility, creating an opportunity for nations to secure a position in this technological transition.

Despite this global momentum, Indonesia's adoption of electric mining dump trucks remains in an early stage. Although electric mining dump trucks were introduced at the 2023 Indonesia Mining Expo and electrification initiatives have been introduced at selected gold, coal, and mineral mining operations, only a small number of mining sites have commenced using electric dump trucks to date. This slow uptake is attributable to a structural policy gap: Indonesia's existing electric vehicle policy framework, anchored by Presidential Regulation (Perpres) No. 55/2019 on the Acceleration of Battery Electric Vehicle Programs and Government Regulation (PP) No. 79/2014 on National Energy Policy, focuses predominantly on passenger vehicles and two-wheelers, creating a regulatory vacuum for heavy mining equipment electrification. The Ministry of Energy and Mineral Resources (ESDM) has begun drafting strategies to speed up the electrification of heavy equipment in mining areas, as part of a wider green and smart mining agenda that also covers energy efficiency, carbon footprint reduction, and clean energy use. However, the lack of specific policy tools such as purchase subsidies for electric dump trucks, carbon pricing mechanisms for mining diesel consumption, phase-out mandates, or dedicated infrastructure investment for mine-site charging means that the transition is currently driven by voluntary market adoption with limited institutional support.

The shift from conventional diesel dump trucks to battery-electric dump trucks is not a simple technology substitution, but a complex system change. The adoption of electric mining dump truck as the substitution of the conservative are shaped by the difference in energy costs between fuel and electricity, the availability of infrastructure such as charging stations and the mine-site grid's capacity, the availability of human resources with the skills to operate and maintain electric equipment, changes in operational patterns and mine planning, the required capital investment and total cost of ownership considerations, regulatory frameworks and incentive structures, and the overall trend of digitalization in the mining industry [4]. The complexity requires analytical accommodation of feedback loops, time delays, nonlinear interactions and the dynamic interaction between policy interventions and market responses. System dynamics (SD) modeling, pioneered by Forrester (1961) and widely used in energy transition studies (Sterman, 2000; Struben and Sterman, 2008), offers this capability. When combined with the Bass diffusion model (Bass, 1969), which models the S-curve adoption pattern with the coefficients of innovation (p) and imitation (q), the SD framework can be used to simulate how policy levers could accelerate or decelerate technology adoption over time, making it an ideal methodology to analyze the electrification trajectory of mining dump trucks from 2025 to 2060, in line with Indonesia's NZE pledge.

A variety of factors across the economic, technical, infrastructural, and institutional domains are driving the decision to adopt electric mining dump trucks [8], [9]. The key economic barrier to adoption is the difference in capital expenditure (CAPEX) of electric vs. conventional diesel dump trucks. Electric trucks offer significant operational expenditure (OPEX) benefits by eliminating fuel costs and reducing maintenance, but the higher capital expenditure (CAPEX) remains a financial challenge that many mining operators, especially mid-sized operators, find difficult to overcome.

A comparative analysis of operating and investment costs for diesel and electric trucks in coal haulage found that although operational and total costs are statistically similar for diesel trucks over the life of the equipment, the problem is cash flow being front-loaded by the investment cost [10]. Another highlight is the need for infrastructure development and policy support to enable wider adoption [10].

Beyond economics, technical and infrastructure barriers also shape adoption acceptance. Some areas have shown that electric machines are less preferred than conventional hydraulic machines due to operational confidence, perceptions of technology maturity, and cost [11]. For underground mining applications, electric trucks offer safety benefits over diesel-powered ones, reducing air quality problems and ventilation costs, a significant operational cost in confined spaces [12]. However, the situation differs for open-pit operations. Installing charging infrastructure at remote mining sites involves significant upfront capital expenditure. Electricity supply reliability and grid availability vary by mine location, potentially requiring hybrid energy systems or on-site renewable energy generation [4]. Also, the switch to electric equipment creates a need for new technical skills (battery management, high-voltage systems, diagnostics for electric drivetrains, etc.) that require structured training programs that mining companies may not be prepared to deliver at scale [4].

A distinct set of influences on adoption are institutional and policy factors. Indonesia's current electric vehicle policy frameworks are mainly based on Presidential Regulation No. 55/2019 on the Acceleration of Battery Electric Vehicle Programs and Government Regulation No. 79/2014 on National Energy Policy, which focus on passenger vehicles and two-wheelers [13], thereby creating a regulatory vacuum for the electrification of heavy mining equipment.

More generally, introducing electric equipment in haulage systems requires a comprehensive analysis of interrelated economic and environmental aspects at the planning stage, as these factors strongly influence the project's feasibility [3]. Collectively, the studies show that the decision to adopt electric mining dump trucks is not attributable to a single variable but results from the dynamic interaction of cost structures, technological readiness, infrastructure availability, workforce capabilities, and regulatory frameworks, which requires systematic analytical approaches.

To boost the adoption of new technology as a strategic program, government interventions are crucial, whether fiscal or non-fiscal. For example, in electrification programs for electric vehicle adoption, government interventions may reduce barriers to EV adoption and increase EV attractiveness relative to internal combustion engine (ICE) vehicles, as long as EVs are not cost-competitive with ICE vehicles [14], [15]. The same barriers also apply to the adoption of electric mining dump trucks. Although the study shows that the transition to electric mining dump trucks is feasible and can support cost-efficient, low-emission operations, government interventions are crucial for policy formulation and accelerating electric mining dump truck adoption [8] [16].

Government interventions can accelerate electric mining dump truck adoption. In studies on electric vehicle adoption, subsidies for EV purchase, technology promotion, tax incentives, purchasing incentives, and a carbon tax are effective interventions [15], [17], [18], [19], [20]. In a study on electric truck adoption in Indonesia, Wangsa et al. (2023) found that Tax incentives of 36.5%-40% combined with subsidies ($1,000 - $25,000) effectively accelerate electric truck adoption. Another study on government interventions in Indonesia found that fiscal and non-fiscal policies to encourage EV adoption, along with reducing EV taxes and improving EV technology, are key factors in increasing EV adoption [18]. Fiscal policies, such as purchase tax and value-added tax (VAT) exemptions, have enabled EVs to gain a large market share in Norway [14]. For electric mining dump truck adoption, Prihasta et al. (2026) found that successful electrification cannot rely solely on favorable financial indicators but requires a collaborative business model between electric providers and mining industry stakeholders to balance investment efficiency, system reliability, and operational continuity.

This study aims to fill the gap in policy-oriented studies on the electrification of mining dump trucks by incorporating a system dynamics simulation model based on Bass diffusion theory. The model is expected to replicate the causal relationship structure among factors in Indonesia's mining dump truck electrification ecosystem and explore the effects of policy interventions that can drive the electrification transition of mining heavy equipment. This paper adds to the energy policy discussion by offering a quantitative, scenario-based framework to assess the effectiveness, cost, and timing of various policy instruments to accelerate the decarbonization of a critical yet largely overlooked segment of the mining industry that is relevant not only for Indonesia but also for other mineral-rich developing economies that face similar electrification challenges. The critical indicator used to evaluate policy effectiveness under different scenarios is electric dump truck mining volume.

2. METHOD

Research Design

To understand how electric mining dump trucks, as an innovative technology, diffuse through social and economic systems, this study is anchored in the Bass Diffusion Model. Bass (1969) introduced a mathematical diffusion model that captures the S-curve adoption pattern through the equation $dN(t)/dt = [p + q \cdot N(t)/M] \cdot [M - N(t)]$, where p represents the coefficient of innovation (external influence from advertising, policy, and mandates), q represents the coefficient of imitation (internal influence from word-of-mouth and demonstrated success), and M represents the total market potential. The model captures the growth behaviour of a new product's initial purchases and sales forecast [21]. Integrating Bass diffusion theory within system dynamics models offers a powerful analytical approach for policy-oriented adoption studies. Several studies on the adoption of new technologies, such as alternative energy and EVs, commonly describe adoption using the Bass diffusion model and integrate it with a system dynamics framework [13] [22] [23] [24]. Embedding the Bass diffusion equation within an SD framework makes these parameters endogenous variables modified by feedback loops.

This study employs a system dynamics (SD) approach integrated with the policy analysis framework [25] to model the adoption dynamics of electric dump trucks in Indonesia's mining sector and to investigate the effectiveness of policy interventions in accelerating the electrification transition. System dynamics, originally developed by Forrester (1961) and systematized by Sterman (2000), is a methodology for studying complex systems characterized by feedback loops, stocks and flows, time delays, and nonlinear relationships. The SD approach has been widely used to address the complexity and transition dynamics of technology adoption mechanisms, and it has been integrated with policy analysis frameworks to investigate the robustness of specific policy mixes for technology adoption. This adoption mechanism is modelled using the Bass diffusion model (Bass, 1969), which captures the growth behaviour of innovative technology adoption through the interplay of innovation effects (external policy influence) and imitation effects (word-of-mouth and demonstrated operational success). This integrated SD-Bass-policy analysis approach enables the study to simulate how different policy configurations affect adoption trajectories over the 2025–2060 time horizon, aligned with Indonesia's Net Zero Emissions commitment.

The research follows a sequential five-phase process adapted from Sterman (2000) and the policy analysis framework (Walker, 2000). Phase 1 (Problem Analysis) involves actor analysis to identify stakeholders, their problem perceptions, objectives, and resources, and defining the system boundary to delineate endogenous, exogenous, and excluded elements. Phase 2 (Model Conceptualization) translates the problem owner's

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objectives into system outputs of interest (key performance indicators), identifies policy intervention variables, and constructs a causal loop diagram (CLD) capturing the feedback structure governing adoption dynamics. Phase 3 (Model Development) translates the conceptual CLD into a quantitative stock-and-flow diagram (SFD) using Vensim simulation software, with the Bass diffusion model embedded as the core adoption module. Phase 4 (Model Validation) applies a battery of structural and behavioural tests following the validation taxonomy proposed by Barlas (1996), including boundary adequacy, dimensional consistency, extreme condition, and sensitivity analysis tests. Phase 5 (Policy Simulation and Evaluation) uses the validated model to assess policy interventions under multiple scenarios, comparing adoption trajectories, emission-reduction outcomes, and cost-effectiveness across alternative policy configurations.

Actor analysis

In actor analysis within System Dynamics, each actor in the table plays a distinct role in shaping system behavior, particularly the adoption of electric heavy equipment in mining. These roles reflect how each stakeholder influences feedback loops, either reinforcing or slowing down the transition.

The Government of Indonesia acts as the system regulator and catalyst. It defines direction through policies, regulations, and incentives aligned with NZE targets. By introducing policy interventions—such as subsidies, emission standards, or infrastructure programs- the government can activate a reinforcing loop that increases adoption of electric equipment. It holds the strongest leverage in the system because it controls institutional resources and can reduce uncertainty for other actors. Essentially, the government's role is to unlock the system and shift it from a fossil-fuel-based equilibrium toward electrification.

The Mining Contractor Companies function as the primary adopters and decision-makers. Their role is operational—they decide whether to purchase and use electric heavy equipment in mining activities. However, their behavior is highly sensitive to cost, efficiency, and infrastructure availability. Currently, they act as a gatekeeper with a balancing effect, meaning their hesitation slows down adoption due to perceived risks and high investment costs. In system dynamics terms, they are a critical node where policy signals and market conditions are translated into actual demand.

Heavy equipment manufacturers act as technology providers and supply enablers. They develop, produce, and improve electric heavy equipment to meet industry needs. However, their actions depend heavily on market demand and policy support. With low demand and limited incentives, they remain in a passive "waiting" position, which creates a supply-side constraint. In SD terms, they influence the system through innovation and cost reduction, which can eventually create a reinforcing loop—where better technology leads to higher adoption, which in turn encourages further production and improvement.

Table 1. Actor analysis of electric dump truck adoption in Indonesia

Actor	Problem Perception	Cause of Problem	Objective	Interest	Resource	Position
Government of Indonesia	Complying with the NZE commitment requires efforts to reduce emissions from mining operations. Currently, mining equipment uses fossil fuels extensively.	Carbon emission reduction has not yet used equipment electrification strategies, so far it has only used a mixture of biofuels.	Encourage the shift to electric dump truck, thereby reducing fuel imports and moving towards a smart mining program.	The development of electric dump truck adoption	Making policy interventions for energy and mining	Developing and delivering policy interventions
Mining Contractor Company	So far, we have been using conventional mining dump trucks, and we see that electric dump trucks require additional infrastructure.	Currently, the price of electric dump truck equipment is still expensive, and not all mines have direct access to electric charging infrastructure.	Can use more efficient mining equipment and support emission reduction	Reliable and efficient mining equipment	You can choose to buy electric dump truck or conventional mining dump truck.	Waiting for developments
Heavy Equipment Manufacturing	Demand for electric dump trucks is limited, with some buyers still in the trial phase.	There is no incentive for purchasing electric dump trucks so there is no sales attraction.	There is tech innovation so that electric heavy equipment is more reliable	There is technological development so that electric heavy equipment is more reliable	Providing more reliable and economical electric heavy equipment	Conducting innovation but still waiting for any market development

Defining system boundary

Since this study follows a system dynamics framework, the system boundary must be set to delineate what is included and excluded. This study discusses the market for electric mining dump trucks, framed as the adoption of electric mining dump trucks as a new technology. The simulation is limited to battery-powered electric dump trucks as the research object, and at this time of study, the only heavy equipment that is already commercialized is the electric dump truck. Consumer choice is limited to switching from diesel-powered internal combustion engine (ICE) dump trucks to battery-powered electric mining dump trucks for mining operations. Therefore, the study did not consider other heavy equipment, new technologies such as hybrid and hydrogen technology, or other kinds of heavy equipment such as wheel loaders and excavators. The model is run from 2025 to 2060, in line with Indonesia's NZE target timeline.

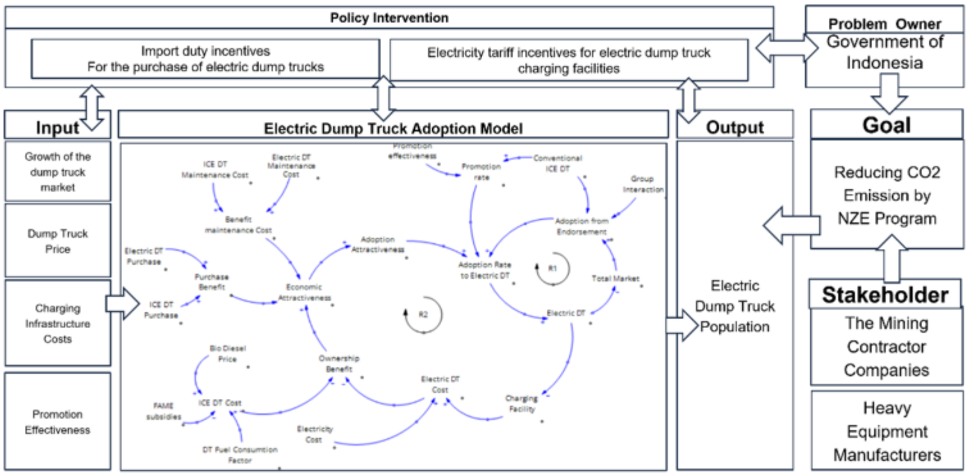

Figure 1: System Diagram

Model Conceptualization

This research describes the conceptual model using a system diagram that includes the problem owner and their goal, output of interest or indicator, system inputs, policy interventions, stakeholders, and a causal loop diagram (CLD) that illustrates the dynamics of the electric mining dump truck adoption model. The causal loop diagram (CLD) was developed based on actor analysis, a literature review, and the Bass diffusion model structure to capture the feedback mechanisms governing electric dump truck adoption in Indonesia's mining sector. The CLD identifies two main reinforcing loops (R1 and R2) and integrates an infrastructure linkage mechanism that connects adoption stock to infrastructure development.

Loop R1 (Social Influence and Adoption Loop) explains how promotion, demonstration effects, and inter-firm interaction accelerate electric mining dump truck adoption. This loop corresponds to the imitation coefficient (q) in the Bass diffusion model. As the promotion rate and group interaction among mining actors increase, adoption from endorsement rises, raising the electric mining dump truck adoption rate and increasing the total stock of electric dump trucks in operation. As more mining companies adopt electric mining dump trucks, visibility increases, operational confidence builds, and industry acceptance strengthens, further reinforcing social influence and encouraging additional adoption. This mechanism is consistent with the word-of-mouth and market diffusion effect described in the Bass diffusion model (Bass, 1969) and its application to vehicle technology transitions (Struben and Sterman, 2008).

Loop R2 (Economic Attractiveness Loop) describes how cost-related factors drive the adoption decision. Economic attractiveness is a composite variable shaped by three benefit categories: purchase benefits (electric mining dump truck cost vs. ICE dump truck cost, adjusted for subsidies), operating benefits (electricity price vs. biodiesel/diesel price, fuel consumption differences, FAME subsidy effects), and maintenance cost benefits (reduced mechanical complexity of electric drivetrains). When the total cost of ownership (TCO) of electric mining dump trucks becomes more favourable than that of ICE dump trucks, adoption attractiveness increases, leading to a higher adoption rate. Increased adoption further strengthens market confidence and, through learning effects and economies of scale, can drive cost reductions over time, reinforcing the loop. This loop corresponds to the economic dimension of the innovation coefficient (p) in the Bass diffusion model, as policy instruments such as purchase subsidies and carbon pricing directly modify the cost parameters that feed into this loop.

Infrastructure Linkage: The CLD additionally incorporates the relationship between electric mining dump truck adoption stock and charging infrastructure development. More operational electric dump trucks drive demand for mine-site charging facilities. Expanding charging infrastructure reduces operational barriers (range limitations, charging downtime) and improves the feasibility of electric mining dump truck deployment, indirectly reinforcing both R1 (by increasing observability and confidence) and R2 (by reducing effective operating costs). This mechanism represents supply-side feedback that can either accelerate or constrain adoption depending on the pace of infrastructure investment.

Overall, the CLD shows that electric dump truck adoption is governed by reinforcing mechanisms driven by social influence and economic feasibility, supported by policy interventions and infrastructure development. The absence of explicit balancing loops in the CLD does not imply that constraints are absent; rather, the balancing dynamics are captured implicitly through the Bass diffusion model's market saturation term [M – N(t)], which naturally decelerates adoption as the fleet approaches full electrification, and through the exogenous constraints (battery price floors, grid capacity limits) that bound the system's behaviour.

Model Development

The conceptualization from the Causal Loop Diagram was translated into a stock-and-flow diagram (SFD) developed in Vensim simulation software. The qualitative CLD is then translated into a quantitative model structure. The SFD architecture is adapted from the EV adoption module developed by Setiawan et al. (2022) as the base model and modified to reflect the specific characteristics of the mining dump truck market. The core adoption module identifies the factors and relationships that influence potential adopters' decision to transition from conventional ICE dump trucks to electric dump trucks. Annual electric mining dump truck sales are driven by two primary factors: the willingness to adopt (shaped by the social influence and promotion loop, R1) and electric mining dump truck attractiveness (shaped by the economic attractiveness loop, R2).

The willingness-to-adopt component uses Bass diffusion theory, capturing both the innovation effect (p) and the imitation effect (q). The innovation effect represents adoption driven by external influences—policy signals, promotional activities, and regulatory mandates—that motivate early adopters independently of the existing installed base. The imitation effect represents adoption driven by social interaction, demonstration effects, and industry benchmarking, consistent with the formulation used by Struben and Sterman (2008) and Yu et al. (2018). Unlike the standard Bass model, where p and q are static parameters, the SD integration allows these coefficients to respond dynamically to changes in system state: p increases when policy interventions (subsidies, mandates) are activated, and q increases as the installed base of operational electric mining dump trucks grows and generates observable performance evidence.

The electric mining dump truck attractiveness component aggregates the economic comparison between electric and conventional dump trucks across three cost dimensions: purchase cost (including any subsidies or tax incentives), operating cost (electricity vs. diesel/biodiesel fuel cost, adjusted for consumption rates), and maintenance cost (reflecting the reduced mechanical complexity of electric drivetrains). These cost inputs are calculated as time-varying functions reflecting expected price trajectories: battery costs follow a learning-curve decline based on cumulative global production; diesel and biodiesel prices follow projections from Indonesia's energy price scenarios; and electricity tariffs follow PLN's industrial rate trajectories. The model uses these dynamic costs to compute a TCO attractiveness ratio that feeds into the adoption rate equation.

Model Testing

Model validation follows the taxonomy proposed by Barlas (1996), which distinguishes between direct structure tests and structure-oriented behavior tests. For a policy-oriented SD model examining a future technology transition, structural validation takes precedence over behavioral reproduction, especially where historical adoption data for electric mining dump trucks in Indonesian mining does not yet exist. The following validation tests are applied:

Boundary adequacy test: Assesses whether all variables and feedback structures essential to the research question are included within the model boundary. This is evaluated through expert review and comparison with the literature on mining electrification adoption factors[3], [4].

Dimensional consistency test: Verifies that all equations in the model are dimensionally consistent, using Vensim's built-in units checking function.

Extreme condition test: Tests whether the model behaves plausibly under extreme parameter values (e.g., zero growth ICE dump trucks, zero initial ICE dump trucks). Dynamic Hypothesis: There is no additional Electric Dump Truck due to the adoption of ICE Dump Trucks when the ICE market growth parameter is set to an extreme condition of zero. As a result, the Electric Dump Truck Population remains at its initial value and does not increase, the Number of ICE Dump Trucks is zero, and the extreme-condition verification shows no growth when the growth input is zero.

Scenario Development and Policy Design

This study constructed five scenarios to examine how the adoption of electric mining dump trucks responds to varying levels of promotional effort and market expansion over the 2025–2060 simulation period. Two parameters were selected for variation. The first is the promotion rate, which captures the intensity of government awareness campaigns, demonstration projects, and regulatory signaling directed at mining companies. In the Bass diffusion formulation used in this model, the promotion rate corresponds to external influences on the innovation coefficient (p); a higher value means more potential adopters are reached through channels other than peer interaction. The second parameter is the market growth rate, which reflects the pace at which the total dump truck fleet in Indonesian mining expands due to production growth and fleet replacement. This rate determines the trajectory of the market potential (M) over time. Each parameter was set at a high (H) or low (L) level relative to the baseline, producing four scenario variants alongside the baseline.

The baseline assumes a promotion rate of 1% and a market growth rate of 2%, consistent with the present situation in which mining electrification receives limited promotional attention and the dump truck fleet grows at a pace that follows recent production trends. Scenario 1 (Accelerated Transition) sets both parameters at high levels (3% promotion, 5% growth), reflecting a condition where active government promotion coincides with strong commodity-driven fleet expansion. Scenario 2 (Electrification Support) retains the high promotion rate but pairs it with low market growth (1%), representing a situation where the government pushes electrification even as the mining sector contracts or stagnates. Scenario 3 (Weakened Electrification Support) reverses this combination: the mining market grows rapidly at 5%, but the government provides little promotional support (0.5%). This scenario is useful for testing whether market expansion alone, without deliberate policy effort, is enough to drive the transition. Scenario 4 (Market Weakening) sets both parameters at their lowest values (0.5% promotion, 1% growth), serving as the pessimistic bound in which neither government policy nor market conditions favor adoption.

Two policy instruments are introduced as levers that the government can apply on top of any scenario configuration. Policy 1 is a 10% fiscal incentive on the purchase of electric dump truck units, delivered through an import duty exemption on electric mining dump trucks and their principal components, such as battery packs and electric drivetrain assemblies. In the model, this reduces the capital expenditure (CAPEX) of electric dump trucks by 10%, shifting the total cost of ownership comparison in favor of electric units and feeding directly into the economic attractiveness variable within the R2 loop. Policy 2 establishes a preferential electricity tariff by granting a 20% discount on industrial electricity rates applied to electric mining dump truck charging facilities at mine sites. This lowers the operating expenditure (OPEX) of electric trucks by reducing the per-kilowatt-hour charging cost, widening the running-cost gap between electric and diesel equipment. Both instruments target the R2 (Economic Attractiveness) loop but act on different cost components: Policy 1 on upfront purchase cost and Policy 2 on recurring energy cost.

Each of the five scenario configurations is simulated under four policy conditions: no intervention, Policy 1 alone, Policy 2 alone, and both policies combined, producing a total of twenty simulation runs. The results are evaluated using three indicators: the cumulative number of BEDT units adopted by 2060.

3. RESULTS AND DISCUSSION

Table 2 presents the electric dump truck population at the end of the simulation period (t = 2060) for each scenario-policy combination. Under baseline conditions, the model projects a fleet of 873.16 electric dump truck units by 2060. The results are divided into two distinct groups based on the promotion rate setting.

Table 2. Results and impact table of each scenario and policy

Policy Instrument	Baseline	S1: Accelerated Transition	S2: Electrification Support	S3: Weakened Electrif. Support	S4: Market Weakening
Policy 1: Import duty exemption	873.16	5,323.93	2,506.41	805.81	484.15
Policy 2: Preferential electricity tariff	873.16	4,943.54	2,340.44	771.48	468.17
Difference (Policy 1 – Policy 2)	—	+380.39	+165.97	+34.33	+15.98
Policy 1: change vs. baseline	—	+509.8%	+187.0%	−7.7%	−44.5%
Policy 2: change vs. baseline	—	+466.2%	+168.0%	−11.6%	−46.4%

The two scenarios with a high promotion rate produced fleet sizes substantially above the baseline. Under S1 (Accelerated Transition), the electric dump truck population reached 5,323.93 units with Policy 1 and 4,943.54 units with Policy 2, an increase of 509.8% and 466.2% over the baseline. Under S2 (Electrification Support), which maintains high promotion but assumes low market growth, the population reached 2,506.41 units with Policy 1 and 2,340.44 units with Policy 2, or 187.0% and 168.0% above the baseline. Despite the low market growth rate in S2, the fleet size remained roughly three times larger than the baseline under both policy instruments.

The two scenarios with a low promotion rate produced fleet sizes below the baseline. Under S3 (Weakened Electrification Support), the population fell to 805.81 units under Policy 1 and 771.48 units under Policy 2, a decline of 7.7% and 11.6% from the baseline. Under S4 (Market Weakening), the population dropped further to 484.15 units with Policy 1 and 468.17 units with Policy 2, or 44.5% and 46.4% below the baseline. In both S3 and S4, neither policy instrument was sufficient to bring the fleet size back to the baseline level.

Across all scenarios, Policy 1 (import duty exemption) produced a larger electric dump truck fleet than Policy 2 (preferential electricity tariff). The gap between the two instruments was widest in S1, where Policy 1 yielded 380.39 more units than Policy 2, and in S2, where the difference was 165.97 units. In S3 and S4, the gap narrowed to 34.33 and 15.98 units, respectively.

The simulation results reveal a clear asymmetry in how promotion rate and market growth rate influence BEDT adoption. Comparing S2 and S3 isolates this effect: S2 has high promotion with low market growth, and S3 has low promotion with high market growth. Under Policy 1, S2 produced 2,506.41 units while S3 produced only 805.81. The same pattern holds under Policy 2. This means that a government that actively promotes electrification can generate a fleet three times larger than one that relies on market expansion alone. Within the Bass diffusion framework, this result is consistent with the role of the innovation coefficient (p): in the early phase of a technology transition, when the installed base is small and imitation effects are weak, adoption is driven primarily by external influence. The promotion rate directly amplifies this coefficient, whereas market growth expands the denominator (M) without accelerating the rate at which individual firms decide to adopt. The practical consequence is that, at this stage of the transition, the government's most effective lever is not market size but the intensity and consistency of its promotional and regulatory effort.

The comparison between the two policy instruments also carries a practical interpretation. Policy 1 outperformed Policy 2 in every scenario, and the margin was largest when conditions were favorable (S1 and S2). The import duty exemption affects the upfront purchase cost, which mining companies evaluate at the investment decision stage. A 10% reduction in purchase price is visible and immediate: it appears in the procurement budget and in the capital approval process. The electricity tariff discount, by contrast, acts on operating costs that accumulate over the equipment's lifetime. Although the cumulative savings from a 20% tariff reduction may be substantial over 15–20 years of operation, they are spread across future periods and subject to uncertainty about tariff policy continuity. For a mining contractor deciding whether to order an electric dump truck, the purchase price reduction is a more tangible and certain incentive than a promise of lower electricity bills over the next two decades. This difference in salience at the decision point explains Policy 1's consistent advantage over Policy 2 in the simulation.

The failure of both policy instruments to lift adoption above the baseline in S3 and S4 deserves particular attention. Even in S3, where the mining market grows at 5% and creates ample opportunity for fleet turnover, a promotion rate of 0.5% leaves the innovation coefficient too low to trigger adoption at a meaningful rate. The fiscal incentives tested here, a 10% CAPEX reduction and a 20% OPEX reduction, modify the economic attractiveness of electric dump trucks but do not address the awareness, confidence, and information gaps that prevent mining companies from considering the technology in the first place. This finding aligns with the broader technology adoption literature, where Rogers (2003) found that awareness and knowledge are prerequisites for the adoption decision, and that economic advantage alone does not drive diffusion if potential adopters are not aware of or confident in the innovation. In system dynamics terms, fiscal instruments operate through the R2 (Economic Attractiveness) loop, but if low promotional input starves the R1 (Social Influence and Adoption) loop, the overall adoption rate remains suppressed regardless of how attractive economics become. The policy implication is that fiscal incentives should be treated as complementary to, not substitutes for, active promotional and regulatory programs.

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These findings suggest a sequenced policy approach for the Government of Indonesia. In the near term (2025–2035), the priority should be on promotional intensity: demonstration projects at major mining sites, regulatory signals such as electrification targets in mining permits (IUP/IUPK), and industry awareness programs that build operational confidence. During this same period, a CAPEX-oriented incentive such as import duty exemption should accompany the promotional effort, because it addresses the most immediate barrier at the investment decision point. In the medium term (2035–2045), as the installed base of electric dump trucks grows and the imitation coefficient (q) contributes more to adoption, the government can gradually shift its fiscal support toward OPEX-oriented instruments such as preferential electricity tariffs. At this stage, a larger operational fleet generates more peer evidence and word-of-mouth influence, reducing the dependence on external promotion. The tariff discount then reinforces the economic case for operators already aware of and open to the technology, rather than serving as the initial trigger for adoption. This phased approach aligns the policy mix with the natural dynamics of Bass diffusion, where early adoption is driven by p and later adoption increasingly by q.

Several limitations should be noted. The model treats the mining sector as a single aggregate market and does not differentiate between coal, gold, nickel, and other mineral operations, which may have different fleet sizes, operating profiles, and economic conditions. The two policy instruments tested are relatively modest in scale (10% and 20% reductions), and this simulation round did not explore stronger interventions or combinations with regulatory mandates. The Bass diffusion parameters used in this study are estimated from analogous EV adoption studies rather than calibrated against historical BEDT adoption data in Indonesia, which does not yet exist in sufficient volume. Future research should extend the model to incorporate differentiated mining sub-sectors, test a wider range of policy instrument intensities including regulatory mandates and carbon pricing, and update the Bass parameters as empirical adoption data becomes available from early BEDT deployments in Indonesian mining operations.

4. CONCLUSION

This paper developed a system dynamics model integrated with Bass diffusion theory to explore policy strategies to accelerate the adoption of battery-electric dump trucks in Indonesia's mining sector over 2025–2060. The study made several contributions. First, it constructed a causal loop diagram that identified two reinforcing feedback loops governing adoption: the social influence and adoption loop (R1), corresponding to the Bass imitation coefficient, and the economic attractiveness loop (R2), corresponding to the innovation coefficient as modified by policy instruments. Second, using a 2×2 factorial scenario design that varies the promotion rate and market growth rate, the simulation showed that the promotion rate is the dominant driver of adoption. Scenarios with high promotional effort (S1 and S2) produced electric dump truck populations of 2,340 to 5,324 units by 2060, far exceeding the baseline of 873 units, while scenarios with low promotional effort (S3 and S4) fell below the baseline even with fiscal incentives. Third, comparing two policy instruments, the study found that a 10% import duty exemption on electric dump truck purchases consistently outperformed a 20% preferential electricity tariff for charging facilities across all scenario configurations. The CAPEX-oriented instrument produced 16 to 380 more units than the OPEX-oriented instrument depending on the scenario, confirming that upfront cost reduction carries greater weight at the investment decision point during the early phase of a technology transition.

Based on these findings, this paper proposes the following recommendations for mining dump truck electrification policies in Indonesia:

1. The government should focus on promotional and regulatory signaling programs as the main policy lever in the short term (2025–2035) rather than fiscal incentives. The simulation also showed that fiscal incentives alone cannot compensate for low promotional effort. Such projects at large mining sites, inclusion of electrification targets in mining permits (IUP/IUPK), and organized industry awareness campaigns would increase the innovation coefficient (p) in the Bass diffusion process and provide the awareness and confidence conditions that precede adoption decisions. Without these programs, even generous fiscal incentives are being deployed in a context where most mining companies do not yet consider electric dump trucks a viable option.
2. In the early transition phase, when fiscal support is provided, the government should favour CAPEX-oriented instruments such as import duty exemption rather than OPEX-oriented instruments such as electricity tariff discounts. The 10% import duty exemption was always more widely taken up than the 20% electricity tariff discount, as purchase price reduction is both visible and certain at the time of the investment decision, while operating cost savings are spread over the 15–20-year lifecycle of the equipment and subject to the risk of policy continuity. As the installed fleet grows and operational evidence accumulates, OPEX-oriented instruments can be introduced to further the economic case for operators that have already passed the initial awareness hurdle.
3. The government should design the policy instruments as a bundle rather than in isolation. The scenario analysis showed that neither market growth nor fiscal incentives alone can beat the baseline under weak promotional effort. A package of coordinated measures, including promotional programs, import duty exemption, and preparatory infrastructure investment, would address multiple barriers simultaneously. As the transition process matures, the Bass imitation coefficient (q) becomes more important as the installed base grows. The policy mix can then shift from promotion-heavy to incentive-heavy, in line with the stage of the diffusion process.
4. The government should develop mine-site charging infrastructure and grid capacity alongside demand-side policies. The causal loop diagram identified infrastructure availability as a mechanism that reinforces the social influence loop (R1) and the economic attractiveness loop (R2). However, the absence of charging infrastructure will impose operational constraints and limit the use of electric dump trucks in practice, weakening the demonstration effects that drive the imitation coefficient. Coordination among the Ministry of Energy and Mineral Resources (ESDM), PLN, and mining concession holders will be required to develop charging infrastructure plans that are consistent with the projected adoption trajectory under the selected policy configuration.

5. Future research should extend the model in several directions. The present model treats the mining sector as one aggregate market. Disaggregating by mineral type (coal, nickel, gold, copper) would capture differences in fleet composition, haul distances, and economic conditions that affect adoption feasibility. The range of policy instruments tested should be broadened to include regulatory mandates, such as phase-out dates for new diesel dump truck purchases, carbon pricing on mining diesel consumption, and green financing mechanisms. The parameters used in this study were estimated based on similar studies on EV adoption. The model should be recalibrated when empirical data from early deployments of electric mining dump trucks in Indonesian mining become available. Finally, the environmental benefit of electrification depends on the carbon intensity of the electricity grid supplying the mines. Combining this model with an energy system model that accounts for Indonesia's changing generation mix would provide a more complete evaluation of the net emission reduction potential

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