Carbon Policy Effectiveness in Indonesia's Electricity Generation Subsector

Tasya Dwi Farlian Putri[1]*, Arie Dipareza Syafei[2]

[1,2]Departement of Environmental Engineering, Institut Teknologi Sepuluh Nopember, Sukolilo, Surabaya 60111, Indonesia

*Corresponding author:
Email: farliantasya@gmail.com

Abstract.

Climate change has increased the urgency of strengthening greenhouse gas (GHG) mitigation policies in energy systems. In Indonesia, the electricity generation subsector is strategically important because it remains closely linked to fossil fuel use while also becoming a central arena of national energy transition policy. This study aims to develop a system dynamics model for simulating the effect of carbon policy on GHG emissions in Indonesia's electricity generation subsector, evaluating the effectiveness of existing carbon policy pathways, and formulating policy directions based on scenario results and policy lessons from selected countries. The study applies a quantitative system dynamics approach using Causal Loop Diagram and Stock and Flow Diagram modelling in Vensim. The model represents interactions among demographic drivers, electricity demand, fossil and renewable generation capacity, fossil fuel consumption, carbon policy variables, and GHG emissions. Three scenarios were simulated: a baseline scenario, a 2030 medium-term target scenario, and a 2060 Net Zero Emission scenario. Model validation using MAPE indicated acceptable historical fit for population and power-generation emission variables. The results show that the baseline follows a high-emission pathway under weak policy pressure. The 2030 scenario reduces emissions to 196.42 MtCO2, below the 250 MtCO2 target. However, the 2060 scenario still leaves 127 MtCO2e of residual emissions, indicating that the Net Zero target is not fully achieved. The findings suggest that carbon policy is effective in the medium term but requires stronger integration with coal phase-down, renewable expansion, MRV, enforcement, and transition finance for long-term mitigation.

Keywords: *Carbon policy; electricity generation; greenhouse gas emissions; Net Zero Emission and system dynamics.*

I. INTRODUCTION

Climate change has become a central challenge for environmental governance because it affects ecological stability, economic development, and social welfare simultaneously [1, 2]. The global mitigation agenda requires deep emission reductions, particularly in energy systems that continue to depend on fossil fuels [1, 2]. The literature and policy documents reviewed in this study emphasize that limiting global warming requires rapid reductions in greenhouse gas emissions and a shift toward low-carbon energy supply [1, 2]. Within this context, the electricity generation subsector is a strategic intervention point because it connects economic activity, public electricity demand, fuel choices, generation technology, and national decarbonization policy [3]. Changes in electricity demand and generation mix can therefore alter the national emission trajectory more directly than many other policy domains [3].

Indonesia is a relevant case because its national mitigation commitment is closely linked to the transformation of the energy sector [4, 5]. Indonesia has committed to reducing greenhouse gas emissions through its Nationally Determined Contribution and has reaffirmed the direction toward Net Zero Emission by 2060 or earlier [4, 5]. The Second Nationally Determined Contribution identifies the energy sector as a major source of national emissions [5]. The electricity generation subsector is therefore not only a technical source of emissions but also a policy arena where national targets, electricity planning, investment decisions, and transition finance intersect [5, 7, 19].

The focus on electricity generation is also justified by the structure of Indonesia's power system [6, 7]. Fossil fuels, particularly coal and natural gas, remain central in electricity supply, while national electricity planning increasingly emphasizes renewable energy and storage [6, 7]. This creates a policy tension: electricity demand is expected to grow with population and economic activity, but the system must simultaneously reduce emission intensity and fossil fuel dependence [5, 7]. The RUPTL PLN 2025-2034 is

positioned as an important planning instrument for future power-system development, including new renewable generation and storage [7]. Consequently, carbon policy must be assessed together with the dynamics of electricity demand, fossil capacity, renewable capacity, and technology transition [7, 10].
Carbon pricing has become one of the most visible policy instruments for climate mitigation [10]. Previous studies and policy references indicate that carbon tax, emissions trading, and mixed-policy approaches depend on policy design, coverage, compliance, and economic context [10, 11, 12, 13]. Indonesia has begun to implement carbon economic value instruments, including carbon trading in the electricity generation subsector and the development of a national carbon exchange [8, 9]. However, the presence of a carbon price does not automatically guarantee emission reduction [10, 12]. A carbon price may be weakened by limited coverage, weak monitoring, reporting, and verification, low compliance, free allocation, or fossil energy subsidies that reduce the net economic signal received by power producers [9, 10].

Existing evaluations of carbon policy are often dominated by econometric or ex-post approaches [12, 13]. Such approaches are useful for measuring observed policy effects, but they may be limited in explaining how feedback loops, time delays, stock accumulation, and non-linear relationships shape long-term emission pathways [11]. System dynamics is therefore relevant because it allows policy analysis to represent interactions among population, economic activity, electricity demand, generation capacity, fuel consumption, renewable substitution, carbon price, compliance, and emissions. This methodological gap is important for Indonesia because current carbon policy must be evaluated not only for short-term emission reduction, but also for its ability to redirect the structure of the electricity generation system toward long-term decarbonization.

The novelty of this research lies in the use of a system dynamics model to evaluate the effectiveness of carbon policy in Indonesia's electricity generation subsector while linking simulation results with policy lessons from Germany, the United Kingdom, Norway, and China [14, 16, 18, 20]. These countries are not treated as direct comparative modelling objects, but as references for identifying policy principles that may be adapted to Indonesia. The research objective is therefore to develop a model that explains the causal structure of emissions, evaluate the effectiveness of existing carbon policy pathways, and synthesize policy recommendations for the electricity generation subsector.

II. METHODS

This study uses a quantitative system dynamics design. The unit of analysis is Indonesia's electricity generation subsector, not the entire national emission inventory. The model is designed to explain how annual GHG emissions from electricity generation are shaped by macroeconomic, demographic, technical, and policy variables. The main output variable is annual GHG emissions from the electricity generation subsector. The main explanatory variables include population, electricity demand, fossil generation capacity, renewable generation capacity, fossil fuel consumption, emission factors, carbon price variables, fossil energy subsidy, coverage rate, MRV compliance, obligation fulfilment, and compliance rate. The research hypothesis is implicit in the model structure: stronger and more credible carbon policy, when combined with renewable expansion and fossil-capacity control, is expected to reduce emissions compared with the baseline trajectory.

The model boundary is limited to the energy sector, specifically electricity generation. It does not explicitly model emissions from transport, industry energy use, buildings, oil and gas production, fugitive emissions, agriculture, waste, IPPU, or FOLU. This boundary was selected to keep the model operational and consistent with the research focus on carbon policy implementation in the electricity generation subsector. Countries such as Germany, the United Kingdom, Norway, and China are used as policy references rather than as parallel modelled systems. Their experience is included in the discussion stage to support recommendation synthesis, particularly for ETS design, carbon taxation, coal phase-out, CCUS, MRV, and gradual cap tightening.

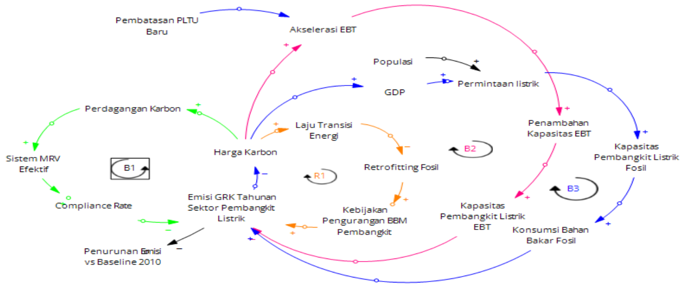
Data collection relies on secondary data and official policy documents already identified in this study [4, 5, 7, 8, 9, 10]. Quantitative data are used to formulate model equations, calibrate parameters, and run simulations. These data include GHG emissions from electricity generation, power generation capacity by energy type, electricity generation and demand, GDP, population, generation mix, emission factors, plant efficiency, carbon price, emission cap, benchmark, and policy targets. Qualitative data are used to interpret policy context, regulatory design, national targets, and lessons from reference countries [14, 16, 18, 20].

Table 1. Core Variables in the System Dynamics Model [5, 7, 9, 10]

Variable group	Main variables	Function in the model
Emission output	Annual GHG emissions from electricity generation	Represents the main outcome used to assess carbon policy effectiveness.
Demand drivers	Population, GDP, electricity demand	Explain pressure on electricity supply and fossil fuel use.
Carbon policy	Carbon tax policy, net effective carbon rate, subsidy, coverage rate, MRV compliance, obligation fulfilment	Determines whether carbon policy produces an effective economic and compliance signal.

The modelling process begins with problem formulation and literature review, followed by variable identification and system boundary setting. The first model representation is a Causal Loop Diagram (CLD), which is used to map causal relationships and feedback mechanisms among variables. The second representation is a Stock and Flow Diagram (SFD), which translates the conceptual structure into a quantitative simulation model in Vensim. In the SFD, stocks include key accumulations such as fossil generation capacity, renewable generation capacity, population, electricity demand, and net effective carbon rate. Flows include additions or reductions to these stocks, such as new power plant development, decommissioning, renewable expansion, birth, death, new electricity demand, efficiency saving, carbon tax policy, and fossil subsidy effects.

Fig. 1. Early Assumption Causal Structure of the Model



The model uses several conceptual equations derived from the model structure. Annual GHG emissions from electricity generation are represented as a function of fossil fuel consumption and fossil capacity additions, reduced by compliance with carbon policy, emission reduction measures, and substitution by renewable capacity. Fossil fuel consumption is formed by coal, natural gas, and oil-based fuel components. Fossil generation capacity is modelled as a stock that increases through new coal and gas power capacity and decreases through decommissioning and conversion toward renewable generation. Renewable generation capacity is also modelled as a stock that increases through new renewable power projects and capacity upgrades and decreases through degradation, retirement, and operational disturbances.

Carbon policy is represented through net effective carbon rate rather than nominal carbon price alone [10]. The model defines net effective carbon rate as carbon tax policy minus fossil energy subsidy. This formulation reflects the idea that a nominal carbon price may not fully work if fossil subsidies, weak compliance, or limited coverage reduce the actual economic pressure on fossil generation [9, 10]. Compliance rate is represented as a function of coverage rate, MRV compliance, and obligation fulfilment [9]. This structure is important because it treats carbon policy effectiveness as an institutional and economic outcome rather than merely a stated tariff.

Three scenarios are simulated. Scenario 1 is the baseline or business-as-usual reference mode, representing a system without strong carbon policy pressure. Scenario 2 is the medium-term target scenario for 2030, designed to evaluate whether existing carbon policy and energy-transition measures are sufficient to keep emissions below the 2030 benchmark used in this study [5]. Scenario 3 is the long-term scenario toward Net Zero Emission by 2060, designed to test whether stronger policy and transition assumptions are sufficient to move emissions toward zero [5].

Model validation is conducted using Mean Absolute Percentage Error (MAPE) by comparing historical simulation outputs with available actual data. This study validates two variables: population and annual GHG emissions from electricity generation. Population is validated because it represents a demographic driver of electricity demand. Annual GHG emissions are validated because they represent the main output variable used to assess policy effectiveness. The validation is not intended to prove perfect forecasting ability, but to assess whether the model is sufficiently representative for scenario comparison and long-term policy analysis.

Table 2. Scenario Design and Evaluation Logic

Scenario	Function	Evaluation logic
Scenario 1: Baseline	Reference mode representing weak carbon policy pressure and fossil-dependent electricity supply.	Used to observe the high-emission behaviour of the system under business-as-usual conditions.
Scenario 2: 2030 Target	Medium-term test of existing carbon policy and transition measures.	Successful if 2030 emissions are below the 250 MtCO2 target and lower than baseline.
Scenario 3: 2060 NZE	Long-term test of strengthened carbon policy, renewable transition, and fossil reduction.	Successful if emissions approach zero and show a consistent decline toward the NZE pathway.

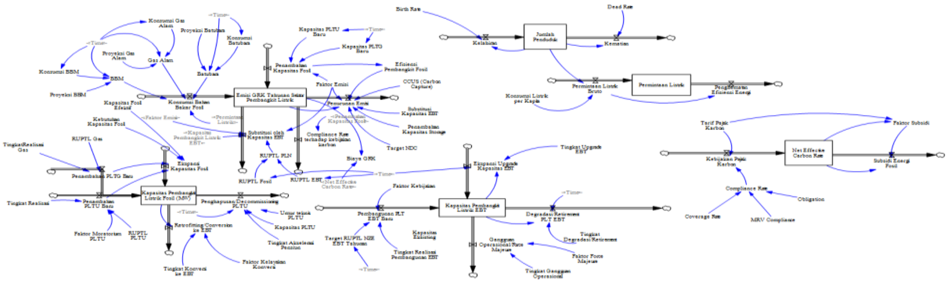
III. RESULTS AND DISCUSSION

The system dynamics model shows that emissions in the electricity generation subsector are not produced by a single cause. They emerge from interactions among electricity demand, fossil capacity, fossil fuel consumption, renewable energy capacity, energy efficiency, carbon pricing, fossil energy subsidy, and compliance. In the CLD, the CLD identifies reinforcing and balancing mechanisms. A reinforcing mechanism appears when economic and demographic growth increases electricity demand, which then increases fossil generation and fossil fuel consumption when the system remains fossil-dependent. This mechanism pushes annual GHG emissions upward in the absence of effective counteracting policy.

The balancing mechanisms are created by carbon policy and energy transition variables. Carbon trading, MRV, and compliance form a balancing loop because stronger MRV improves emission data accuracy, supports compliance, and increases emission reduction relative to the baseline. Carbon price also forms a balancing loop when it increases the economic pressure on fossil generation, supports transition toward renewable energy, encourages fossil retrofitting or efficiency, and reduces fossil fuel consumption. Renewable energy capacity acts as a substitution mechanism because it can reduce the need for fossil generation when it grows sufficiently and is supported by storage, grid readiness, and investment certainty.

The SFD translates these relationships into a quantitative model. Annual emissions are increased by fossil fuel consumption and fossil capacity additions, but reduced by compliance rate, emission reduction measures, and renewable substitution. This structure is important because it captures both the persistence of fossil capacity and the gradual effect of policy interventions. Fossil power capacity behaves as a stock: it does not disappear immediately when policy changes, but declines only through decommissioning or conversion. Renewable capacity also behaves as a stock: it grows only when new projects, upgrades, and realization rates are sufficient. This stock-flow logic explains why long-term decarbonization requires more than a carbon price; it requires structural changes in the power system.

Fig. 2. Stock and Flow Diagram



Model validation indicates that the simulation is acceptable for scenario analysis. The population variable obtains a MAPE value of 6.43%, which falls within the very accurate category used in the thesis. The emission variable obtains a MAPE value of 14.01%, which falls within the accurate category. The thesis notes that the population simulation tends to overestimate actual population, but the validation is still useful because population is treated as a driver for reading system behaviour rather than as a precise demographic forecast. The emission validation is more central because annual GHG emissions from electricity generation are the main output for evaluating carbon policy effectiveness. These validation results support the use of the model for comparing scenarios, while also requiring caution in interpreting the absolute numbers as exact predictions.

Table 3. Validation and Scenario Results

Assessment item	Result in the thesis model	Interpretation
Population validation	MAPE = 6.43%	Very accurate category; useful for reading demographic pressure on electricity demand.
Emission validation	MAPE = 14.01%	Accurate category; acceptable for scenario comparison.
Scenario 1	High-emission baseline pathway under weak policy pressure	Shows the reinforcing effect of electricity demand, fossil capacity, and fossil fuel consumption.
Scenario 2	2030 emissions = 196.42 MtCO2; target = 250 MtCO2; gap = -53.58 MtCO2	Meets the medium-term target and reduces emissions against the baseline reference.
Scenario 3	2060 residual emissions = 127 MtCO2e	Does not fully achieve NZE because residual emissions remain.

Scenario 1 functions as the reference mode. Its purpose is not to achieve mitigation targets, but to show the behaviour of the system when carbon policy pressure is weak. The simulation indicates that baseline emissions increase consistently when the system is dominated by electricity demand growth and fossil fuel consumption. In this scenario, net effective carbon rate is close to zero after the initial period, which means that power generation does not receive a meaningful economic signal to reduce fossil fuel use. The result demonstrates a classic reinforcing pattern: electricity demand encourages additional generation, fossil supply remains dominant, fossil fuel consumption increases, and emissions continue to rise. The baseline therefore confirms that carbon policy intervention is necessary to shift the electricity system away from a high-emission pathway.

Scenario 2 evaluates the medium-term effectiveness of carbon policy and energy transition measures. The simulation reports that emissions in 2030 reach 196.42 MtCO2 under Scenario 2, while the target is 250 MtCO2. The resulting gap is negative, which indicates that the scenario meets the medium-term target. This means that, in the model, current carbon policy and transition measures are able to reduce emissions below the 2030 benchmark when compliance and renewable substitution are included.

The effectiveness of Scenario 2 is not primarily caused by a reduction in electricity demand. The simulation shows that population and electricity demand remain important pressures on the system. The difference emerges from the supply-side and policy-side balancing mechanisms. Net effective carbon rate becomes stronger than in the baseline, compliance improves, and renewable capacity begins to substitute part of fossil generation. The policy signal increases the cost pressure on fossil generation, while renewable expansion reduces dependence on fossil fuel consumption. This finding is important because it indicates that carbon policy can work when it is embedded in a broader policy package rather than treated as an isolated price instrument.

Scenario 3 evaluates the long-term direction toward Net Zero Emission by 2060 [5]. It represents a stronger policy setting in which carbon policy, renewable transition, and fossil-fuel reduction are reinforced. However, the simulation reports that the scenario still leaves residual emissions of 127 MtCO2e in 2060. This residual emission means that the scenario has not yet achieved full net zero in the electricity generation subsector.

The residual emission under Scenario 3 is explained by the persistence of fossil generation capacity and fossil fuel use. Even when renewable capacity expands substantially, the model indicates that fossil capacity does not fall toward zero by the end of the simulation period. As long as fossil capacity remains available and continues to contribute to electricity supply, residual emissions will remain. This finding clarifies why long-term decarbonization cannot rely on carbon price and renewable capacity alone. It must also address the retirement, conversion, or operational reduction of fossil assets, supported by grid readiness, storage, flexible generation, and financing mechanisms that make accelerated transition feasible.

The comparison across scenarios provides the central finding of the research. Current carbon policy pathways can be effective in the medium term, especially when policy compliance and renewable substitution are strengthened. However, the same structure is not sufficient for achieving long-term NZE if fossil capacity remains structurally embedded in the system. The model therefore distinguishes between medium-term effectiveness and long-term sufficiency. A policy package may meet a 2030 emission target, but still fail to generate the continuous decline required for 2060. This distinction is one of the main contributions of the system dynamics approach because it exposes time delays and stock persistence in the power system.

Table 4. Policy Lessons and Adaptation Directions for Indonesia [14, 15, 16, 17, 18, 20]

Reference country	Key lesson	Adaptation direction for Indonesia
Germany / EU	ETS effectiveness depends on declining cap, MRV, compliance, auctioning, and revenue recycling.	Tighten PTBAE, expand coverage, strengthen MRV, reduce excessive free allocation, and use carbon revenue for transition assets.
United Kingdom	Carbon price works better when combined with coal phase-out and renewable investment certainty.	Integrate carbon pricing with early coal retirement and renewable procurement mechanisms such as CfD or feed-in premium.
Norway	Carbon tax and CCUS require strong governance and financing; CCUS should not create carbon lock-in.	Use CCUS selectively for hard-to-retire assets and prioritize fossil capacity reduction.
China	Benchmark-based ETS can be a starting point, but must gradually move toward absolute caps.	Begin with realistic benchmarks, then strengthen toward absolute caps, broader coverage, digital MRV, and limited offsets.

The SWOT-based policy learning used in this study strengthens the interpretation of the simulation results. Germany provides lessons on cap-and-trade design through the EU Emissions Trading System [14]. The important lesson is not merely the existence of an emissions trading system, but the presence of a declining cap, annual MRV obligation, compliance enforcement, auctioning, and the use of auction revenue for transition finance [14, 15]. For Indonesia, this means that carbon trading should not remain a low-price and narrow-coverage instrument. It should gradually move toward a tighter cap, broader coverage of fossil generation, stronger MRV, and more strategic use of carbon revenue.

The United Kingdom provides a different lesson because its experience combines carbon price support with coal phase-out and renewable investment support [16, 17]. Carbon price becomes more effective when it is supported by a clear schedule for reducing coal generation and by investment certainty for renewable energy [16, 17]. For Indonesia, the relevant adaptation is not simply to copy the United Kingdom's policy design, but to integrate carbon price signals with a credible coal-retirement roadmap and an investment mechanism that improves the bankability of renewable-energy projects.

Norway contributes lessons on carbon tax and CCUS [18]. This study does not recommend that Indonesia apply CCUS broadly to all fossil power plants. Instead, it emphasizes selective use based on feasibility and the risk of carbon lock-in. CCUS can be relevant for assets that are difficult to retire in the short term, but it should not become a justification for extending fossil dependence. This lesson supports the model finding that residual emissions cannot be solved by one instrument alone.

China provides a lesson that is particularly relevant to countries with large electricity systems and continued fossil dependence [20]. The analysis describes China's gradual ETS pathway, beginning with benchmark-based allocation and moving toward stricter absolute caps. For Indonesia, a phased approach may be realistic because the national carbon market is still developing. However, the model also warns that if benchmark-based allocation and free permits remain too loose for too long, absolute emissions may continue to rise when electricity demand grows.

The policy synthesis from this study can be grouped into five directions. First, Indonesia should tighten the emission cap and PTBAE gradually so that carbon policy creates a stronger long-term signal [14, 20]. Second, ETS coverage should be expanded to all fossil-based power generation so that emission leakage within the power subsector is reduced [14, 20]. Third, MRV and enforcement should be strengthened through digital reporting, periodic verification, and credible obligation fulfilment [9, 14]. Fourth, fossil energy subsidies should be reviewed because they weaken the net effective carbon rate and reduce the behavioural impact of carbon policy [10]. Fifth, carbon revenue should be recycled into renewable energy, grid modernization, storage, flexible generation, and coal retirement so that the price signal is converted into structural change [15, 16, 19].

From an academic perspective, the study demonstrates that system dynamics is useful for evaluating policy effectiveness in a complex energy transition setting. The model does not treat carbon policy as a simple independent variable with a direct linear effect. Instead, it places policy inside a feedback structure where carbon price, coverage, MRV, compliance, subsidy, renewable capacity, fossil capacity, and demand interact. This helps explain why policy can appear effective in one time horizon but insufficient in another. The study therefore contributes to the literature by showing that policy effectiveness should be assessed not only by short-term emission reduction, but also by its ability to alter the underlying structure of the electricity system.

For policy practice, the results imply that Indonesia's carbon policy should be designed as part of a transition package [10, 19]. If policy makers only increase the nominal carbon price without expanding coverage, improving MRV, reducing fossil subsidies, and financing low-carbon alternatives, the net policy signal may remain weak [9, 10]. Conversely, if carbon revenue and compliance mechanisms are used to accelerate renewable development, storage, transmission, and fossil asset retirement, carbon policy can become a structural driver of decarbonization [15, 19]. The key message is that long-term mitigation requires alignment between carbon market design and electricity planning [7, 10].

Several methodological limitations must be considered when interpreting the findings. First, the model is built for national-level behaviour rather than detailed spatial dispatch analysis. It does not represent the physical differences among Indonesian electricity systems, island grids, transmission bottlenecks, reserve margins, or plant-level dispatch order. This limitation is consistent with the research boundary, which aims to explain the interaction between carbon policy and electricity-generation emissions at an aggregate subsector level. Therefore, the model is useful for reading structural tendencies and policy direction, but it should not be interpreted as a replacement for detailed power-system planning or unit-level operational modelling.

Second, the model uses secondary public data and policy assumptions. This is appropriate for a study-based policy simulation, but it also means that some variables are represented through simplified relationships. For example, compliance, MRV quality, obligation fulfilment, and subsidy effects are modelled as policy variables that influence net effectiveness rather than as institution-by-institution behavioural data. Similarly, renewable capacity growth and fossil decommissioning are represented through stock-flow relationships, not through project-level financial closure or grid-connection schedules. These simplifications are necessary to keep the model transparent and operational, but they also explain why the results should be read as scenario-based policy evidence rather than deterministic prediction.

Third, the comparison with Germany, the United Kingdom, Norway, and China should be understood as selective policy learning. This study treats those countries as policy-learning references rather than modelled comparative systems. Their role is to provide lessons on policy design that may be adapted to Indonesia, such as cap tightening, carbon price support, coal phase-out planning, renewable investment certainty, CCUS governance, and gradual movement from intensity benchmarks to absolute caps. This distinction matters because direct policy transfer is rarely possible. Indonesia's electricity demand growth, fossil dependence, tariff sensitivity, financing needs, and archipelagic grid structure require adaptation rather than replication of foreign models.

These limitations also point to future research directions. A more advanced model could include investment cost, electricity tariff impacts, storage requirements, transmission readiness, renewable intermittency, and electricity reliability indicators. It could also compare alternative policy packages, such as low, medium, and high carbon price pathways; accelerated renewable deployment; fossil subsidy reform; or combined ETS, carbon tax, and transition-finance scenarios. Such extensions would strengthen the ability of system dynamics modelling to support policy design, especially for assessing not only emission outcomes but also economic feasibility, reliability, and social acceptance of the power-sector transition.

IV. CONCLUSION

The study concludes that the system dynamics model developed in the research is able to represent the interaction among economic and demographic drivers, electricity demand, fossil and renewable generation capacity, fossil fuel consumption, carbon policy, compliance, and power-sector emissions in Indonesia. The simulation shows that the existing carbon policy pathway can support medium-term emission reduction when supported by compliance and renewable substitution, but it is not yet sufficient to ensure a full long-term transition toward net zero because fossil capacity and residual emissions remain embedded in the system. The research contributes by demonstrating that carbon policy effectiveness should be assessed through feedback structure, stock persistence, policy coverage, MRV, compliance, subsidy effects, and power-system transition readiness. Accordingly, Indonesia needs an integrated policy package that combines stronger carbon pricing, tighter emission caps, broader ETS coverage, robust MRV and enforcement, gradual fossil subsidy reform, accelerated renewable energy development, storage and grid investment, and a credible pathway for coal retirement, so that carbon policy can shift the electricity generation subsector from medium-term mitigation performance toward sustained structural decarbonization.

REFERENCES

[1] Intergovernmental Panel on Climate Change. (2018). Global warming of 1.5°C. Special Report on Global Warming of 1.5°C.

[2] Intergovernmental Panel on Climate Change. (2023). Climate change 2023: Synthesis report. IPCC.

[3] World Resources Institute. (2023). 4 charts explain greenhouse gas emissions by countries and sectors. World Resources Institute.

[4] Republic of Indonesia. (2015). Enhanced Nationally Determined Contribution of Republic Indonesia.

[5] United Nations Framework Convention on Climate Change. (2025). Second nationally determined contribution of the Republic of Indonesia.

[6] International Energy Agency. (2023). CO2 emissions 2022. In Encyclopedia of Sustainable Management. https://doi.org/10.1007/978-3-031-25984-5_300288

[7] PT Perusahaan Listrik Negara. (2025). Bahan paparan Direktur Utama PLN.

[8] Ministry of Energy and Mineral Resources of the Republic of Indonesia. (2023, September 26). Menteri ESDM luncurkan perdagangan karbon subsektor pembangkit listrik.

[9] Directorate General of Electricity, Ministry of Energy and Mineral Resources. (2024). Kementerian ESDM terbitkan aturan acuan nilai ekonomi karbon subsektor listrik.

[10] World Bank Group. (2025). State and trends of carbon pricing. https://doi.org/10.1596/978-1-4648-2255-1

[11] Borissov, K., & Bretschger, L. (2018). Optimal carbon policies in a dynamic heterogenous world. Economics Working Paper Series 18/297, ETH Zürich. https://doi.org/10.3929/ethz-b-000294528

[12] Kohlscheen, E., Moessner, R., & Takats, E. (2021). Effects of carbon pricing and other climate policies on CO2 emissions. CESifo Working Papers, No. 9347.

[13] Stechemesser, A., et al. (2022). Climate policies that achieved major emission reductions: Global evidence from two decades. Nature Climate Change.

[14] European Commission Climate Action. (2026a). About the EU emissions trading system (EU ETS).

[15] European Commission Climate Action. (2026b). Auctioning allowances under the EU emissions trading system (EU ETS).

[16] Twidale, S. (2024, September 29). Britain to become first G7 country to end coal power as last plant closes. Reuters.

[17] Twidale, S. (2026, April 16). Britain to scrap carbon tax on electricity generation from April 2028. Reuters.

[18] Buli, N. (2025, August 25). Norway's Northern Lights CCS project starts operations with first CO2 injected. Reuters.

[19] United Nations Development Programme. (2026). Indonesia Just Energy Transition Partnership (JETP).

[20] Owojori, O. M., & Anwana, E. (2025). Climate governance in the BRICS: Pathways toward net-zero emissions. Discover Sustainability.