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A System Dynamics Approach to Analyze Biodiesel Production and Oil Import Dependency in Indonesia

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ABSTRACT - Indonesia's persistent dependence on imported diesel fuel poses significant challenges to national energy security, fiscal stability, and exposure to global market volatility. In response, the government plans to implement a mandatory B50 biodiesel blending policy starting in 2026 to reduce diesel imports by leveraging domestic bioenergy resources. While higher blending mandates are often assumed to directly lower imports, existing studies largely rely on static or deterministic approaches that inadequately capture feedback dynamics and long-term uncertainty. This study addresses this gap by integrating system dynamics modelling with Monte Carlo simulation to analyze the impact of biodiesel blending policies on diesel import dependency under structural and parametric uncertainty. The model incorporates biodiesel production growth, domestic allocation after exports, diesel demand growth, and blending effectiveness within a feedback-based framework calibrated using historical data from 2013 to 2024. Simulation results indicate that the B50 policy consistently reduces diesel import requirements relative to the baseline; however, absolute imports may continue to rise without sufficient domestic supply expansion. Cumulative results show that by 2035, the B50 policy achieves import reductions of approximately 55–58 million kiloliters, increasing to around 60 million kiloliters when combined with accelerated biodiesel production growth. Monte Carlo analysis reveals robust medium-term outcomes by 2030 but increasing uncertainty by 2035. The findings highlight that blending mandates must be accompanied by sustained supply-side development to ensure long-term effectiveness and resilience.

Keywords: biodiesel blending policy, crude import dependency, system dynamics, monte carlo simulation, energy security

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INTRODUCTION

Indonesia's energy system continues to face structural challenges due to its high dependence on imported diesel fuel, most notably in the transportation and industrial sectors (Fischer & Meyer 2020). Although Indonesia has made significant progress in developing biodiesel based on domestic palm oil resources, overall diesel demand has surged, resulting in persistent import dependency and exposure to international price volatility, supply disruptions, and fiscal pressures (PASPI 2024). Diesel imports not only affect energy security but also have broader macroeconomic implications through foreign exchange outflows and subsidy burdens. Addressing this dependency has therefore become a central objective of national energy policy (Wirawan et al., 2024).

In response to these challenges, the government of Indonesia has progressively strengthened biodiesel blending mandates as a strategic instrument to substitute imported fossil diesel with domestically produced biofuel (ESDM 2025). According to an official statement by the Ministry of Energy and Mineral Resources, the government plans to implement a mandatory B50 biodiesel blending policy starting in 2026 as part of a broader strategy to stop diesel imports and enhance national energy security (Pambudi et al., 2019; Veza et al., 2021; Widrian et al., 2022). This policy represents a significant escalation from previous blending levels and reflects strong political commitment to leveraging domestic bioenergy resources. However, while higher blending mandates are often assumed to directly reduce diesel imports, their actual effectiveness depends on complex interactions among biodiesel production capacity, domestic allocation versus export behaviour , and ongoing growth in diesel demand (Dharmawan et al., 2020). Existing policy debates and analytical studies frequently treat biodiesel blending targets as a linear substitution mechanism, implicitly assuming that higher blending rates will proportionally reduce diesel imports. In practice, biodiesel policy outcomes are shaped by dynamic feedback mechanisms, capacity constraints, and time-dependent system behavior (Silalahi et al., 2019). If domestic biodiesel production growth does not keep pace with diesel demand expansion, or if a significant share of biodiesel output is diverted to exports, the import substitution effect of blending mandates may weaken over time. These dynamics highlight the need for an analytical framework capable of capturing feedback-driven behavior and structural constraints rather than relying solely on static or short-term assessments.

Previous studies on biodiesel and biofuel policy impacts have predominantly employed econometric approaches, partial equilibrium models, or scenario -based accounting analyses. While these methods provide valuable insights into historical relationships and short-term policy effects, they often lack the ability to represent nonlinear interactions, feedback loops, and delays that characterize real-world energy systems (Ismukurnianto 2022; Jumardi et al., 2025; Rahman 2022; Usman & Haans 2017). More recent research has applied system dynamics modeling to energy policy analysis, recognizing its suitability for capturing endogenous system behavior (Anggoro et al., 2023). Meanwhile, Monte Carlo simulations have been widely used to quantify uncertainty in energy demand forecasts and policy outcomes (Wicaksono et al., 2019). However, studies that integrate system dynamics modeling with probabilistic Monte Carlo analysis in the context of biodiesel blending and diesel import dependency remain limited, particularly for emerging economies such as Indonesia.

This study addresses these gaps by developing an integrated modeling framework that combines system dynamics and Monte Carlo simulation to analyze the impacts of biodiesel blending policies on diesel import dependency under uncertainty. The analysis explicitly incorporates biodiesel production growth, domestic allocation after exports, diesel demand growth, and policy blending effectiveness within a feedback-based structure. By focusing not only on annual outcomes but also on cumulative import reductions and probabilistic risk profiles, the study provides a more comprehensive assessment of long-term policy performance. The framework is explicitly aligned with Indonesia's planned B50 mandate starting in 2026, ensuring strong policy relevance and timeliness (Nuva et al., 2019).

The findings of this study are intended to inform multiple stakeholders. For policymakers and government agencies, the results provide evidence-based insights into the conditions under which biodiesel blending mandates can effectively reduce diesel import dependency and mitigate long-term risk. For energy planners and regulators, the modeling framework offers a practical tool to evaluate alternative policy and supply-side strategies under uncertainty. For industry stakeholders, particularly biodiesel producers and feedstock suppliers, the study highlights the importance of sustained production capacity expansion and domestic market allocation. For the academic community, this research contributes to the literature by demonstrating the value of integrating system dynamics and probabilistic simulation for policy-oriented energy system analysis in developing and emerging economies.

METHODOLOGY

This study adopts a mixed-method modeling approach that integrates system dynamics modeling with probabilistic Monte Carlo simulation to analyze the impact of biodiesel blending policies on diesel import dependency in Indonesia (Jiao et al., 2014; Nemeth & Fearnhead 2021). The methodological framework is designed to capture both the structural behavior of the energy system and the uncertainty associated with long-term policy implementation. The analysis is conducted through a sequence of interrelated stages, beginning with conceptual modeling and followed by quantitative simulation and uncertainty assessment.

Research framework and data sources

The research framework is grounded in a system dynamics perspective, which is particularly suitable for analyzing energy systems characterized by feedback loops, nonlinearity, and time delays. The model focuses on the interaction between diesel demand, biodiesel production, domestic biodiesel allocation, exports, and diesel imports as a residual component.

The primary data source for the supply-side calibration is historical biodiesel data for Indonesia spanning 2013–2024, including biodiesel production, domestic utilization, diesel fuel demand (B0) and exports (ESDM, 2024). These data are compiled from the national biodiesel dataset and cross-referenced with the 2024 Handbook of Energy & Economic Statistics of Indonesia. The data are used to establish baseline trends and parameter ranges rather than to perform direct econometric estimation, consistent with the exploratory and policy-oriented nature of system dynamics modeling.

Conceptual model development: causal loop diagram

The first stage of model development involves the construction of a causal loop diagram (CLD) to identify the dominant feedback structures governing biodiesel production and diesel import dependency (Crabolu et al., 2023). The CLD captures reinforcing and balancing feedback loops linking biodiesel production growth, domestic biodiesel availability, blending mandates, diesel demand, and diesel imports. Export allocation is explicitly incorporated as a leakage mechanism that reduces the volume of biodiesel available for domestic substitution.

The CLD serves two key purposes. First, it provides a transparent conceptual representation of policy-relevant system behavior. Second, it guides the selection of state variables, flows, and auxiliary relationships in the subsequent quantitative model. Particular attention is given to identifying capacity constraints and feedback dominance under different policy scenarios, which later inform scenario design and interpretation.

Quantitative system dynamics model

Based on the CLD, a simplified stock-flow system dynamics model is developed to simulate diesel import requirements over the study horizon. Diesel demand is modeled as an exogenous growth process, while biodiesel production follows a growth trajectory calibrated to historical trends and scenario assumptions, following commonly adopted approaches in energy system dynamics modeling (Prima et al., 2026). Domestic biodiesel availability is calculated as total production minus exports, and diesel imports are determined residually after accounting for biodiesel substitution under specified blending mandates.

Two main deterministic scenarios are simulated. The baseline scenario assumes the continuation of existing blending levels throughout the simulation horizon. The policy scenario implements a B50 biodiesel blending mandate scheduled to take effect in 2026, consistent with current government plans. An additional enhanced supply scenario combines the B50 mandate with accelerated biodiesel production growth to assess the role of supply-side readiness. Simulation outputs include annual diesel import requirements, import dependency indicators, and cumulative import reductions relative to the baseline.

Uncertainty and Monte Carlo Simulation

To account for uncertainty in long-term projections, the deterministic system dynamics model is extended using Monte Carlo simulation. Key uncertain parameters include diesel demand growth rates, biodiesel production growth rates, export shares, and blending effectiveness. Probability distributions are assigned to these parameters based on historical variability and plausible policy ranges.

Thousands of Monte Carlo iterations are conducted to generate probabilistic distributions of outcomes for selected target years, specifically 2030 and 2035. The results are analyzed using histograms, cumulative distribution functions (CDFs), boxplots, and fan charts to assess not only expected policy impacts but also the associated uncertainty and risk profiles. This probabilistic approach enables a more robust evaluation of policy performance under structural and parametric uncertainty.

Visualization and scenario interpretation

Model outputs are visualized using a combination of time-series plots, cumulative impact curves, probabilistic distributions, and uncertainty envelopes.

These visualizations support comparative interpretation across scenarios and time horizons, highlighting both central tendencies and variability (Ridaliani et al., 2025; Samura et al., 2025; Satiyawira et al., 2025). The integrated use of deterministic and probabilistic visual tools ensures that policy conclusions are informed by both expected outcomes and uncertainty considerations. This is illustrated in Figure 1.

RESULT AND DISCUSSION

The findings derived from the CLD and descriptive data analysis are highly relevant to recent policy developments in Indonesia's energy sector. According to an official statement released by the Ministry of Energy and Mineral Resources, the Indonesian government plans to implement a mandatory B50 biodiesel blending policy by 2026

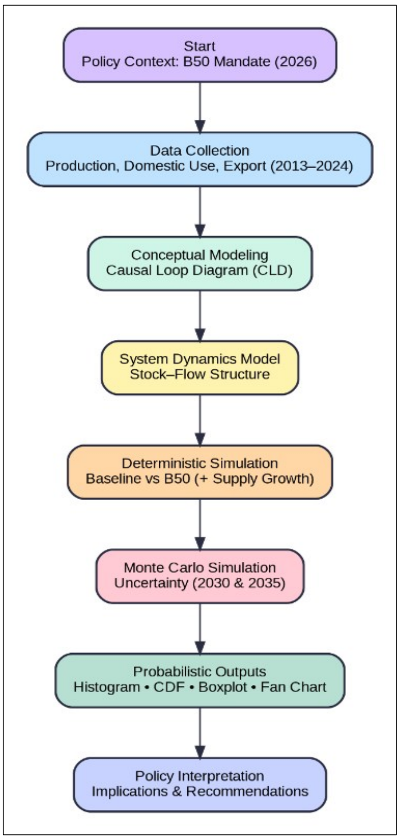


Figure 1. Flow of chart. Research framework integrating system dynamics modelling and Monte Carlo simulation for evaluating biodiesel policy impacts on diesel import dependency.

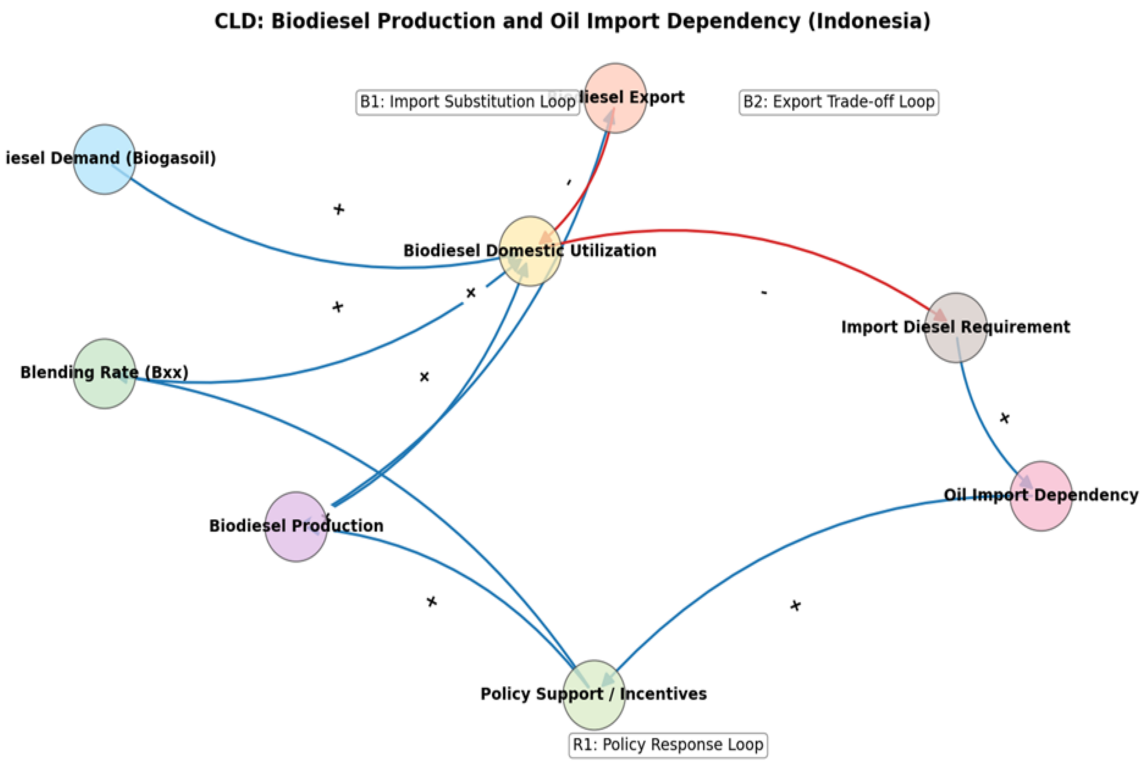


Figure 2. Causal loop diagram illustrating feedback relationships among biodiesel production, domestic allocation, diesel demand, blending policy, and diesel import dependency.

as part of a broader strategy to stop diesel imports and strengthen national energy security (ESDM, 2025). This policy direction provides an important real-world context for interpreting the dynamic relationships identified in this study (Figure 2).

The CLD illustrates the fundamental feedback mechanisms governing biodiesel production and diesel import dependency. An increase in biodiesel production enhances the availability of domestic biodiesel supply, which in turn increases the volume of biodiesel absorbed into the diesel fuel mix in accordance with mandatory blending targets. Higher biodiesel utilization directly reduces the demand for fossil diesel, thereby lowering diesel import volumes and import dependency. This reduction in imports contributes positively to national energy security and reinforces policy justification for higher blending mandates. At the same time, the CLD explicitly captures a counteracting mechanism through biodiesel exports. Rising export volumes reduce the biodiesel supply available for domestic blending, constraining the import substitution effect. Consequently, the CLD emphasizes that the effectiveness of biodiesel blending policies is not determined solely by the blending target, but also by the dynamics of biodiesel production growth, diesel demand growth, and export allocation.

The CLD is translated into a simplified quantitative system dynamics model that retains the core structure relevant to the research objective. The model links diesel demand, biodiesel production, domestic biodiesel availability after exports, and diesel imports as a residual variable after biodiesel substitution. Historical biodiesel data from the dataset (2013–2024) are used to anchor the supply side of the model.

Table 1 presents the historical series of biodiesel production, domestic utilization, and exports over this period. It also highlights why export share is explicitly modelled, since exports represent a non-negligible leakage that can weaken the effectiveness of domestic blending policies. Moreover, the observed fluctuations in export volumes suggest that external market dynamics and price differentials play a significant role in shaping supply allocation decisions.

Simulation results are presented through a series of figures. Figure 2 compares diesel import requirements under the baseline and the B50 policy scenario. The baseline represents a continuation of existing blending levels. The policy scenario incorporates the actual policy trajectory implemented in Indonesia, consisting of B35 up to 2023, B40 during 2024–2025, and B50 starting in 2026, which are in line with government plans to gradually eliminate diesel imports through higher biodiesel mandates. The policy curve consistently lies below the baseline curve, indicating reduced import requirements. The vertical gap between the two curves represents the magnitude of import substitution achieved by the policy. From a system dynamics perspective, this reduction reflects not only the higher blending target but also the system's capacity to supply sufficient biodiesel domestically.

Table 1. Biodiesel production, domestic utilization, and export in Indonesia (2013–2024) Source: Processed from national biodiesel statistics (Excel dataset) and handbook of energy & economic statistics of Indonesia 2024.

Year	Biodiesel production (Thousand KL)	Domestic utilization (Thousand KL)	Biodiesel export (Thousand KL)
2013	2,8	1.1	1.7
2014	3,4	1.6	1.8
2015	3,7	1.9	1.8
2016	4,1	3.1	1.0
2017	6,5	4.7	1.8
2018	7,6	6.1	1.5
2019	8,4	6.4	2.0
2020	8,8	7.2	1.6
2021	9,3	8.2	1.1
2022	10,4	9.6	0.8
2023	12,2	11.3	0.9
2024	13,9	13.1	0.8

Figure 3 displays the import dependency indicator, approximated as the ratio of diesel imports to total diesel demand. This indicator is particularly relevant for energy policy analysis, as it captures relative dependence rather than absolute volumes. Under the B50 policy scenario, import dependency declines compared to the baseline. However, the reduction is not strictly proportional to the increase in blending rates, as the system is constrained by biodiesel supply availability. If biodiesel production growth does not keep pace with diesel demand growth, import dependency may stabilize or even increase despite higher blending targets. This outcome is consistent with the CLD logic, which highlights capacity constraints and export leakage as limiting factors.

Figure 4. Diesel import dependency ratio under baseline and biodiesel blending policy scenarios. This graph presents the ratio of diesel imports to total diesel demand. The decline under the B50 scenario indicates the impact of the blending policy, but changes are not strictly proportional due to supply limitations and export allocations.

This outcome is consistent with the CLD logic, which highlights capacity constraints and export leakage as limiting factors. In particular, the effectiveness of higher blending mandates is strongly moderated by the ability of the domestic biodiesel sector to expand production capacity and allocate sufficient volumes to the domestic market. When production growth lags behind demand expansion, the balancing effect of biodiesel substitution weakens over time, allowing reinforcing demand-driven dynamics to dominate the system. As a result, import dependency becomes increasingly sensitive to structural conditions on the supply side rather than policy ambition alone. These findings suggest that blending mandates must be accompanied by coordinated measures aimed at strengthening biodiesel feedstock availability, processing capacity, and domestic allocation mechanisms in order to achieve sustained reductions in diesel import dependency.

Figure 4 illustrates the cumulative reduction in diesel imports relative to the baseline scenario under the two policy-oriented cases, namely the implementation of the B50 mandate from 2026 and the B50 mandate combined with accelerated biodiesel production growth. The accelerated growth assumption is derived from historical

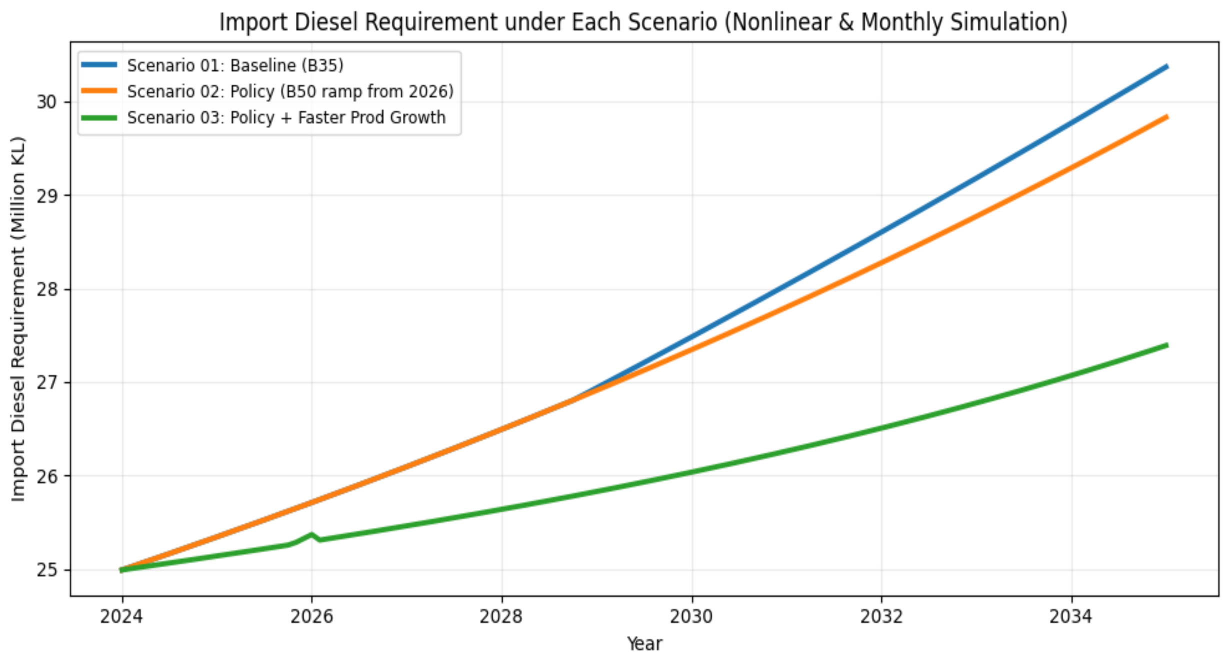
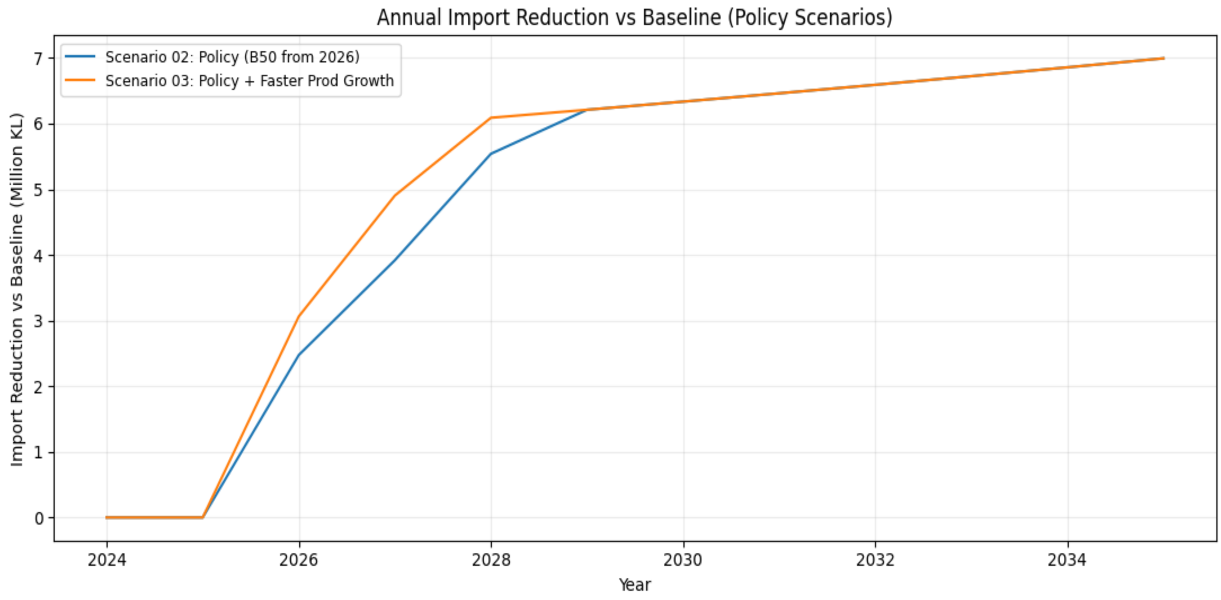


Figure 3. Projected diesel import requirements under baseline and biodiesel policy scenarios.
The curve shows annual diesel import requirements under the baseline and B50 scenarios. The vertical gap between the curves represents import reduction achieved by the B50 policy, emphasizing that the effectiveness depends on domestic biodiesel supply capacity.



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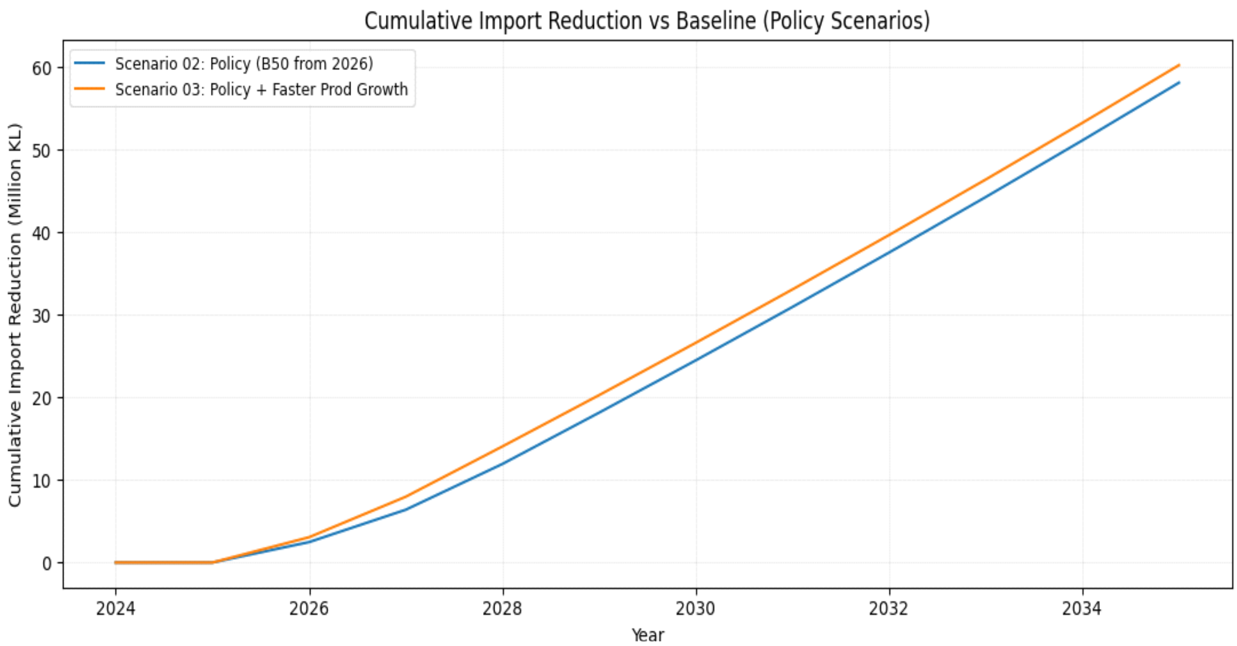

Figure 5.Cumulative diesel import reduction under B50 and enhanced biodiesel production scenarios.
This figure highlights cumulative diesel import reduction relative to the baseline for two scenarios. The widening difference between standard B50 and B50 with accelerated biodiesel production underscores the cumulative benefits of domestic supply capacity development.

production trends, national biodiesel expansion targets reported by ESDM, and projections from previous studies on biofuel capacity development. This scenario represents a policy-consistent upper-bound trajectory of supply-side readiness. The cumulative representation highlights the long-term impact of policy interventions by aggregating annual import savings over time, thereby providing a clearer indication of structural change in import dependence. Following the introduction of the B50 policy, cumulative import reductions increase steadily in both scenarios, indicating that the benefits of higher blending mandates are not instantaneous but accumulate progressively as the system adjusts to new production and consumption patterns.

Figure 5.Cumulative diesel import reduction under B50 and enhanced biodiesel production scenarios. This figure highlights cumulative diesel import reduction relative to the baseline for two scenarios. The widening difference between standard B50 and B50 with accelerated biodiesel production underscores the cumulative benefits of domestic supply capacity development.

The cumulative simulation results (Figures 2–4) further emphasize the long-term and path-dependent nature of biodiesel policy impacts. By 2035, the B50 policy scenario achieves cumulative diesel import reductions of approximately 55–58 million kiloliters relative to the baseline trajectory. When the blending mandate is combined with accelerated biodiesel production growth, cumulative import savings increase further to around 60 million kiloliters. The widening gap between these two scenarios illustrates the compounding benefits of early and sustained supply-side expansion, whereby relatively modest annual reductions in diesel imports translate into substantially larger cumulative gains over time. These results confirm that the long-term effectiveness of biodiesel policy is shaped less by the nominal blending target itself and more by the trajectory of domestic supply capacity development and retention for domestic use.

Beyond deterministic outcomes, the Monte Carlo simulation provides critical insight into the uncertainty and risk associated with these policy impacts. For 2030, the distribution of diesel import reduction is centered around a median value of approximately 5.2 million kiloliters, with relatively

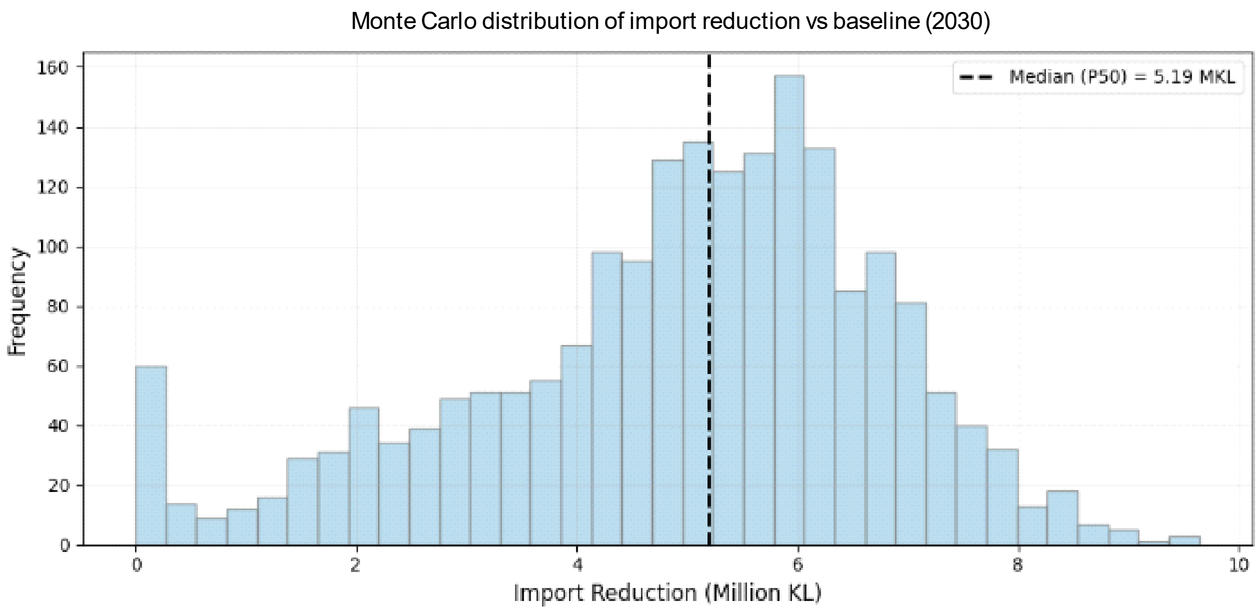

Figure 6. Probability distribution of diesel import reduction from Monte Carlo simulation in 2030.
The histogram shows the probabilistic distribution of diesel import reduction in 2030 from Monte Carlo simulation. The unimodal distribution around a median of ~5.2 million kL indicates a stable medium-term outcome with relatively low variability.

limited dispersion (Figure 5). This indicates that medium-term policy outcomes under the B50 mandate are comparatively robust to uncertainty in key parameters such as diesel demand growth, biodiesel production expansion, export share, and blending effectiveness. In contrast, the 2035 distribution shifts to a higher median import reduction of approximately 6.8 million kiloliters and exhibits substantially wider dispersion. This widening uncertainty reflects the cumulative propagation of structural and parameter uncertainty over longer time horizons, as reinforcing feedback mechanisms increasingly amplify differences in biodiesel production growth trajectories and domestic allocation performance (Figure 6).

The divergence between the two policy curves becomes increasingly pronounced over time, with the scenario incorporating faster biodiesel production growth consistently achieving higher cumulative import reductions. This widening gap illustrates the compounding effect of supply-side readiness, whereby incremental annual reductions in diesel imports translate into substantially larger cumulative savings in the long run. In contrast, the policy-only scenario exhibits a more moderate accumulation of import reductions, reflecting limitations imposed by production capacity and export allocation. From a system dynamics perspective, this behavior reflects the strengthening of balancing feedback loops in the presence of enhanced production growth, which progressively suppress the reinforcing demand-driven forces that otherwise sustain import dependency.

Overall, the figure underscores that the long-term effectiveness of biodiesel blending policies is determined not only by the level of the blending mandate itself, but also by the trajectory of domestic biodiesel supply expansion. The cumulative nature of the results further emphasizes the strategic importance of early and sustained investments in production capacity, as delays in supply-side development can result in permanently lower cumulative import savings even when ambitious blending targets are eventually achieved.

Given the increasing uncertainty associated with longer-term projections, the study complements deterministic scenario analysis with Monte Carlo simulation. Monte Carlo methods are applied to key uncertain parameters, including diesel demand growth, biodiesel production growth, export share, and policy blending effectiveness. A total of 10,000 simulation iterations are performed to ensure statistical robustness of the results with key uncertain parameters that include diesel demand growth rates, biodiesel production growth rates, export shares, and blending effectiveness. By running thousands of iterations, the model generates probabilistic distributions of outcomes such as diesel import reduction and import dependency for 2030 and 2035. This probabilistic framework allows policy impacts to be assessed not only in terms of expected values but also in terms of risk and uncertainty.

For 2030, the Monte Carlo simulation projects a probability distribution of diesel import reduction relative to the baseline scenario. The distribution exhibits a unimodal shape centred around a median value of approximately 5.2 million kiloliters, indicating the most likely magnitude of import reduction under the assumed uncertainty ranges. The relatively moderate spread of the distribution suggests that, in the medium term, the effectiveness of the biodiesel policy remains comparatively stable despite variability in demand growth, production expansion, export allocation, and blending performance. Most simulation outcomes cluster within a narrow band around the median, implying that the policy impact by 2030 is reasonably robust and less sensitive to extreme parameter realizations. This pattern reflects the dominance of structural policy effects during the early implementation phase, when system inertia and shorter accumulation periods limit the amplification of uncertainty.

In contrast, the Monte Carlo distribution for 2035 displays a noticeably wider spread and a rightward shift in the median value to approximately 6.8 million kiloliters. This indicates that the potential magnitude of diesel import reduction increases over the longer term, but is accompanied by substantially higher uncertainty. The broader distribution reflects the cumulative effect of uncertainty propagation over time, as small deviations in growth rates, export shares, and blending effectiveness compound across successive years. While higher import reductions become increasingly probable, the dispersion of outcomes highlights that long-term policy performance is more vulnerable to structural constraints and supply side variability. From a system dynamics perspective, this behavior is consistent with reinforcing feedback mechanisms, whereby differences in biodiesel production growth trajectories and domestic allocation increasingly shape the system's evolution as the time horizon extends.

To further explore the probabilistic characteristics of diesel import reduction beyond central tendency and dispersion, the analysis extends from frequency-based representations to cumulative probability assessment. While histogram distributions provide insight into the range and likelihood of outcomes, they do not directly convey the probability of achieving a specific level of import reduction. To address this limitation, the cumulative distribution function (CDF) is employed to evaluate policy performance in probabilistic terms, enabling a more explicit interpretation of risk, confidence levels, and threshold-based outcomes under uncertainty.

Figure 7 depicts the cumulative distribution functions of diesel import reduction relative to the baseline scenario for the years 2030 and 2035 under the B50 policy. The CDF curves reveal a clear rightward shift from 2030 to 2035, indicating an increasing probability of achieving larger import reductions as the policy effects accumulate over time. The 2030 curve rises more steeply and reaches higher cumulative probabilities at lower reduction levels, reflecting comparatively lower uncertainty in medium-term outcomes. In contrast, the 2035 curve exhibits a more gradual ascent, signifying a wider dispersion of possible outcomes and greater long-term uncertainty. This divergence highlights the compounding effect of uncertainty propagation within the system dynamics framework, where variations in biodiesel production growth, export allocation, and demand trajectories increasingly influence outcomes over longer horizons. Importantly, the separation between the two curves illustrates that although higher import reductions become more attainable by 2035, the probability of achieving any given reduction level depends critically on sustained supply-side performance and policy consistency. Ultimately, the CDF analysis confirms that long-term reductions in diesel import dependency require combining ambitious blending mandates with adaptive and resilient supply-side strategies capable of mitigating uncertainty and maintaining policy effectiveness over time.

While CDF provides a clear probabilistic perspective on the likelihood of achieving specific levels of diesel import reduction, it does not explicitly summarize the central tendency and dispersion of outcomes in a compact comparative form. To complement the CDF analysis, the results are further examined using boxplot representations, which allow direct comparison of median outcomes, interquartile ranges, and extreme values across different target years. This approach facilitates a more intuitive assessment of how uncertainty and risk evolve over time under the same policy framework. Figure 8 illustrates the boxplot comparison of Monte Carlo simulation results for diesel import reduction relative to the baseline scenario in 2030 and 2035. The boxplot for 2030 exhibits a relatively narrower interquartile range with a median centered around moderate import reduction levels, indicating that medium-term policy outcomes are comparatively stable and clustered within a limited range of variability. In contrast, the 2035 boxplot shows a higher median value accompanied by a substantially wider interquartile range and a greater number of extreme observations. This pattern confirms that, although the expected magnitude of import reduction increases over the longer term, the associated uncertainty also expands significantly. The presence of wider whiskers and more pronounced outliers in 2035 reflects the cumulative amplification of uncertainty inherent in long-term system dynamics, where variations in biodiesel production growth, export behavior, and demand trajectories progressively diverge. The CDF results and the boxplot analysis show that long-term reductions in diesel import dependency offer greater potential benefits but are inherently subject to higher risk, underscoring the importance of adaptive policy mechanisms and continuous monitoring of supply-side performance.

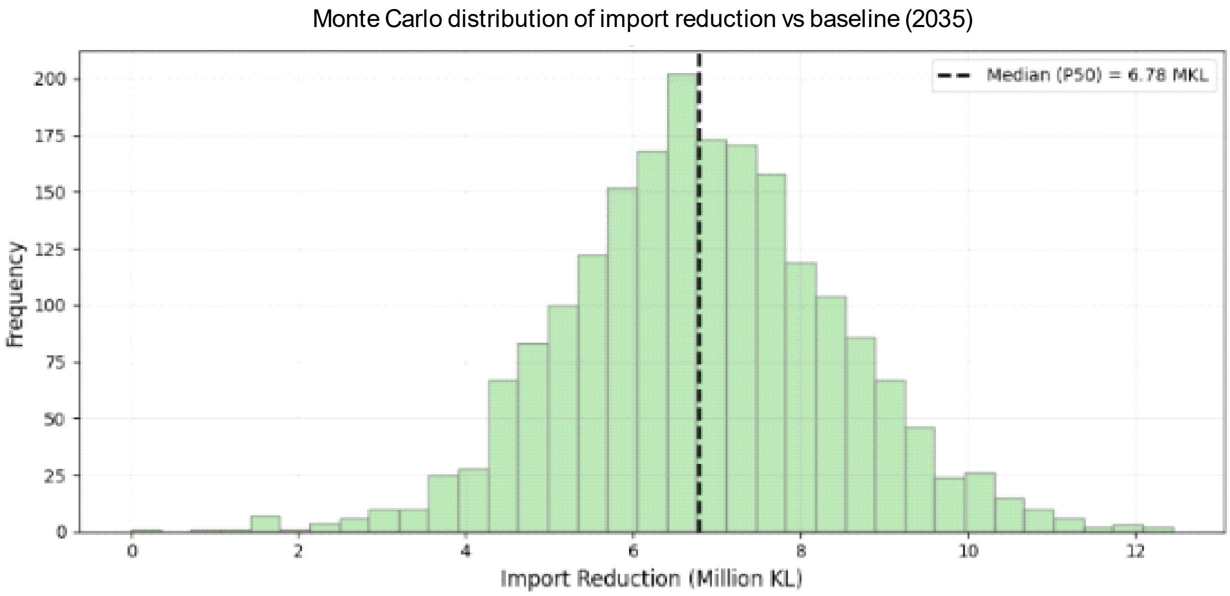

Figure 7. Probability distribution of diesel import reduction from Monte Carlo simulation in 2035.
The 2035 distribution shows a median of ~6.8 million kL with a wider spread, reflecting higher long-term uncertainty due to cumulative variability in supply, demand, and blending effectiveness.

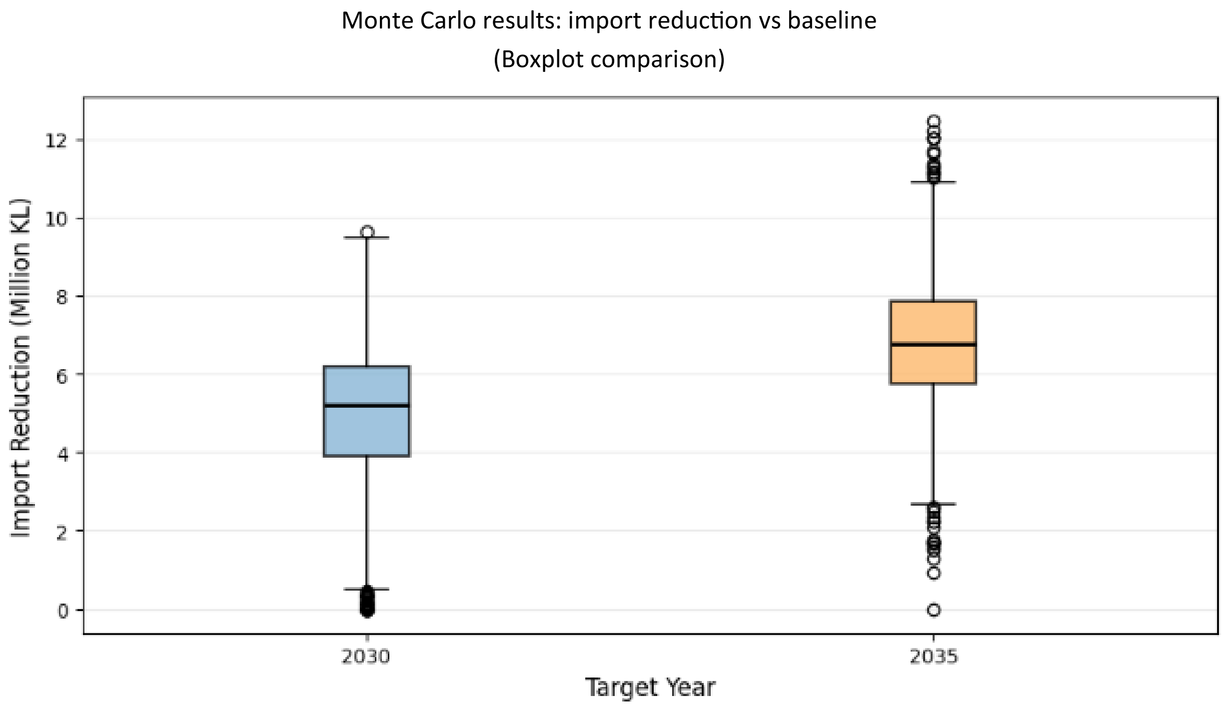

Figure 9. Boxplot comparison of Monte Carlo simulation results for diesel import reduction in 2030 and 2035.
The boxplot compares median, interquartile range, and outliers between 2030 and 2035. The wider interquartile range and whiskers in 2035 highlight increasing risk and uncertainty over the long term.

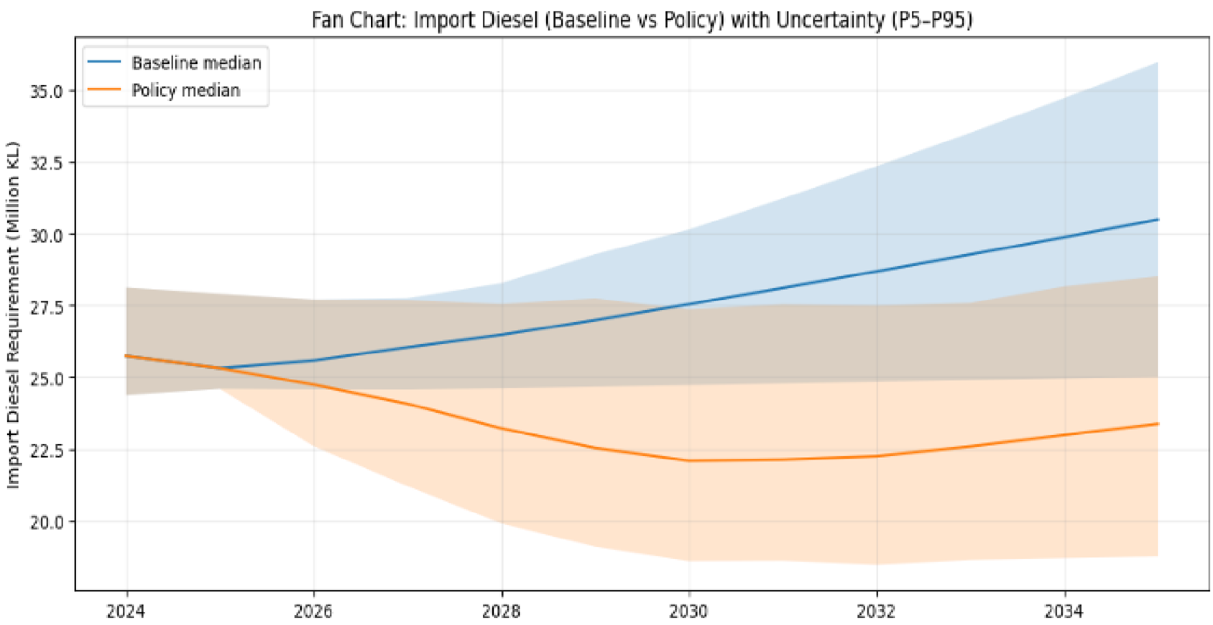

Figure 10. Fan chart of diesel import requirements under baseline and B50 policy scenarios with P5–P95 uncertainty intervals. The fan chart illustrates how uncertainty evolves over time. The B50 scenario shows a lower median and narrower uncertainty band than the baseline,highlighting the stabilizing effect of biodiesel substitution on the energy system.

Although the boxplot analysis effectively summarizes differences in central tendency and variability at selected target years, it does not adequately represent the dynamic evolution of uncertainty across the simulation period.

To overcome this limitation, the analysis uses a fan chart to explicitly illustrate how uncertainty propagates over time under both baseline and policy scenarios. By integrating median trajectories with percentile-based uncertainty intervals, the fan chart offers a more holistic depiction of the temporal development of diesel import requirements and the associated risk profile throughout the modeling horizon.

Figure 9 shows the fan chart of diesel import requirements under the baseline and B50 policy scenarios, incorporating uncertainty bounds defined by the P5–P95 percentile range. The baseline trajectory exhibits a steadily increasing median import requirement over time, accompanied by an expanding uncertainty envelope. This widening fan reflects the compounding effect of uncertainty in demand growth and structural system dynamics, indicating that reliance on imports becomes increasingly exposed to risk in the absence of stronger substitution mechanisms. In contrast, the policy scenario displays a markedly lower median import trajectory, particularly after the implementation of the B50 mandate, demonstrating the stabilizing influence of biodiesel substitution on diesel import needs. Although the uncertainty band under the policy scenario also widens over time, its overall range remains consistently lower than that of the baseline case, suggesting a risk-mitigating effect of the policy intervention.

The increasing separation between the baseline and policy fan charts highlights the dual function of biodiesel policy in reducing both the expected level of diesel imports and the degree of long-term uncertainty. From a system dynamics standpoint, the policy scenario reinforces balancing feedback mechanisms associated with domestic fuel substitution, thereby attenuating the reinforcing effects of demand growth that characterize the baseline trajectory. The partial overlap of uncertainty bands in the early years indicates that short-term outcomes remain sensitive to structural and parameter variability, whereas more pronounced divergence in later years underscores the cumulative advantages of sustained policy implementation. Overall, these findings demonstrate that biodiesel blending mandates play a critical role not only in lowering anticipated diesel import volumes but also in enhancing the resilience of the energy system to long-term uncertainty, supporting the need for integrated policy approaches that align demand-side mandates with continous development of domestic supply capacity.

CONCLUSION

This study applies a system dynamics framework combined with probabilistic Monte Carlo simulation to examine the impact of biodiesel blending policies on diesel import dependency in Indonesia. The results demonstrate that increasing biodiesel blending mandates, as represented by the B50 policy scenario implemented from 2026, can significantly reduce diesel import requirements relative to the baseline scenario. However, the analysis also reveals that the effectiveness of blending mandates is fundamentally conditioned by domestic biodiesel supply growth and allocation to the domestic market. Under the policy-only scenario, diesel imports decline relative to the baseline but may continue to increase in absolute terms due to persistent growth in diesel demand, indicating that blending mandates alone are insufficient to fully counter demand-driven pressures.

The cumulative system dynamics results highlight the long-term and path-dependent nature of policy impacts. By 2035, the B50 policy scenario achieves cumulative diesel import reductions of approximately 55–58 million kiloliters relative to the baseline trajectory. When the blending mandate is complemented by accelerated biodiesel production growth, cumulative import savings increase further to around 60 million kiloliters. This divergence illustrates the compounding benefits of early and sustained supply-side expansion, where relatively modest annual reductions translate into substantially larger cumulative gains over time. These findings confirm that the long-term effectiveness of biodiesel policy is shaped more by the trajectory of domestic supply capacity development than by the blending target itself.

The Monte Carlo simulation further reveals the risk and uncertainty profile associated with these policy outcomes. For 2030, the distribution of diesel import reduction is centered around a median of approximately 5.2 million kiloliters, with relatively limited dispersion, indicating that medium-term policy impacts are comparatively robust to uncertainty in diesel demand growth, biodiesel production expansion, export share, and blending effectiveness. In contrast, the 2035 results exhibit a higher median import reduction of approximately 6.8 million kiloliters accompanied by substantially wider dispersion. This widening uncertainty reflects the cumulative propagation of structural and parameter uncertainty over longer time horizons, as reinforcing feedback mechanisms amplify differences in production growth and domestic allocation performance.

The probabilistic analyses using cumulative distribution functions, boxplots, and fan charts consistently show that while larger import reductions become increasingly attainable over time, long-term outcomes are inherently subject to higher variability. Importantly, the fan chart analysis demonstrates that the B50 policy scenario not only lowers the median trajectory of diesel imports relative to the baseline but also maintains a narrower uncertainty envelope, indicating a stabilizing effect of biodiesel substitution on the energy system. Nevertheless, partial overlap of uncertainty bands in the early years suggests that short-term outcomes remain sensitive to structural conditions and implementation dynamics.

From a policy perspective, these results imply that the B50 blending mandate should be regarded as a necessary but not sufficient instrument for achieving sustained reductions in diesel import dependency. To maximize policy effectiveness and reduce long-term risk exposure, blending mandates must be accompanied by coordinated measures that expand biodiesel feedstock availability, strengthen processing capacity, and manage export leakage to ensure sufficient domestic supply. Consequently, an integrated policy strategy that aligns demand-side blending mandates with continuous supply-side development and adaptive monitoring mechanisms is essential to enhance national energy security, reduce vulnerability to import shocks, and improve the resilience of Indonesia's fuel system under long-term uncertainty.

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DECLARATIONS

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Author contribution

Andry Prima contributed to conceptualization, methodology development, supervision, and manuscript review. Bayu Satiyawira, Havidh Pramadika, and Daud Asrun Nauw contributed to data analysis, system dynamics modeling, and simulation. Lisa Samura, Mustamina Maulani, and Cahaya Rosyidan contributed to literature review, data interpretation, and manuscript preparation. Maman Djumantara and Djunaedi Agus Wibowo contributed to validation and technical review. Wiwik Dahani contributed to data verification and visualization. Osama Jawaid Butt contributed to manuscript editing, language refinement, and academic review. All authors have read and approved the final manuscript.

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Competing interest

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GLOSSARY OF TERMS AND SYMBOLS

Terms & Symbols	Definition	Unit
B50	Mandatory biodiesel blending of 50% biodiesel with diesel fuel	% (v/v)
B35	Mandatory biodiesel blending of 35% biodiesel with diesel fuel	% (v/v)
Biodiesel	Renewable fuel derived from biological sources used as diesel substitute	–
CLD	Causal loop diagram	–
Diesel Demand	Total domestic demand for diesel fuel	kiloliters (kL)
Diesel Import	Volume of diesel fuel imported to meet domestic demand	kiloliters (kL)

Import Dependency	Ratio of diesel imports to total diesel demand	–
Monte Carlo Simulation	Probabilistic simulation method using random sampling	–
System Dynamics	Modeling approach for analyzing feedback-driven systems	–
Domestic Utilization	Biodiesel volume absorbed by the domestic market	kiloliters (kL)
Biodiesel Production	Total annual production of biodiesel	kiloliters (kL)
Biodiesel Export	Biodiesel volume allocated for export markets	kiloliters (kL)
Baseline Scenario	Scenario assuming continuation of existing policies	–
Policy Scenario	Scenario reflecting implementation of new policy (B50)	–
Feedstock	Raw material used for biodiesel production	–
Energy Security	Ability of a nation to ensure reliable energy supply	–
Import Substitution	Replacement of imported fuel with domestic alternatives	–
CDF	Cumulative distribution function	–
Fan Chart	Graphical representation of uncertainty over time	–

REFERENCES

Anggoro, P. W., Yuniarto, T., Bawono, B., Setyohadi, D. B., Murdapa, P. S., & Jamari, J., (2023), System dynamics modelling for calculation of carbon footprint on a non-homogeneous production system: A case in a ceramic studio. Results in Engineering, 17. https://doi.org/10.1016/j.rineng.2022.100812.

Crabolu, G., Font, X., & Eker, S., (2023), Evaluating policy complexity with Causal Loop Diagrams. Annals of Tourism Research, 100. https://doi.org/10.1016/j.annals.2023.103572.

Dharmawan, A. H., Fauzi, A., Putri, E. I. K., Pacheco, P., Dermawan, A., Nuva, N., Amalia, R., & Sudaryanti, D. A., (2020), Bioenergy policy: The biodiesel sustainability dilemma in Indonesia. International Journal of Sustainable Development and Planning, 15(4). https://doi.org/10.18280/ijsdp.150414.

ESDM, (2024), The Handbook of Energy and Economic Statistics of Indonesia 2024. the Ministry of Energy and Mineral Resources (MEMR). www.esdm.go.id/assets/media/content/content-handbook-of-energy-and-economic-statistics-of-indonesia-2024.pdf.

ESDM, (2025 December 23), Kementerian ESDM RI - Media Center - Arsip Berita - Pemerintah Tetapkan Alokasi Biodiesel Tahun 2026 sebesar 15,65 juta kL. Direktorat Jenderal Minyak Dan Gas Bumi Kementerian ESDM Republik Indonesia. https://www.esdm.go.id/id/media-center/arsip-berita/pemerintah-tetapkan-alokasi-biodiesel-tahun-2026-sebesar-1565-juta-kl.

Fischer, C., & Meyer, T., (2020), Baptists and Bootleggers in the Biodiesel Trade: EU-Biodiesel (Indonesia). World Trade Review, 19 (2). https://doi.org/10.1017/S1474745620000075.

Ismukurnianto, D. A, (2022), Mitigation Of Carbon Dioxide And Green House Gas Emission From Oil And Gas Industry In Indonesia. *Scientific Contributions Oil and Gas*, 31(1). https://doi.org/10.29017/scog.31.1.856.

Jiao, J.-L., Han, K.-Y., Wu, G., Li, L.-L., & Wei, Y.-M, (2014). The effect of an SPR n the oil price in China: A system dynamics approach. Applied Energy, 133, 363–373. https://doi.org/10.1016/j.apenergy.2014.07.103.

Jumardi, A., Yusgiantoro, P., & Siagian, U., (2025), Development of Energy System Modeling to Forecast 2060 Oil and Gas Demand in The Household Sector of East Kalimantan Using Bottom-Up Method. *Scientific Contributions Oil and Gas*, 48(1), 159–177. https://doi.org/10.29017/scog.v48i1.1732.

Nemeth, C., & Fearnhead, P., (2021), Stochastic Gradient Markov Chain Monte Carlo. In Journal of the American Statistical Association (Vol. 116, Number 533). https://

doi.org/10.1080/01621459.2020.1847120.

Nuva, N., Fauzi, A., Dharmawan, A. H., & Kumala Putri, E. I., (2019), Political Economy of Renewable Energy and Regional Development: Understanding Social and Economic Problems of Biodiesel Development in Indonesia. Sodality: Jurnal Sosiologi Pedesaan, 7(2). https://doi.org/10.22500/sodality.v7i2.19727.

Pambudi, A., Puspitawati, E., & Nursechafia, N., (2019), The Determinants of Biodiesel Export in Indonesia. Signifikan: Jurnal Ilmu Ekonomi, 8(2). https://doi.org/10.15408/sjie.v8i2.10961.

PASPI (2024, March 15), Biodiesel Indonesia: Produksi, Konsumsi dan Ekspor (2024). Palm Oil Agribusiness Strategic Policy Institute.

Prima, A., Moengin, P., Astuti, P., Sari, E., Nugrahanti, A., & Jawaid Butt, O., (2026), Determining The Dynamics of The Petroleum Buffer Reserve of Indonesia. *Scientific Contributions Oil and Gas*, 49(1), 65–81. https://doi.org/10.29017/scog.v49i1.1987.

Rahman, M., (2022), Cadangan Strategis Minyak untuk Keamanan Energi Indonesia. *Lembaran Publikasi Minyak Dan Gas Bumi*, 45(1), 47–53. https://doi.org/10.29017/lpmgb.45.1.681.

Silalahi, M., Santoso, A., & Hidayat, D., (2019), A Scientometric Study on Biodiesel Development in Indonesia. STI Policy and Management Journal, 4(1). https://doi.org/10.14203/stipm.2019.148.

Usman, & Haans, A., (2017), Mengoptimalkan Perolehan Minyak pada Lahan Terbatas Menggunakan Sumur Berarah dan Pendesakan Air. (Optimizing Oil Recovery on Limited Land Area using Directional Wells and Waterflooding). *Lembaran Publikasi Minyak dan Gas Bumi*, 51(1), 1–12. http://www.journal.lemigas.esdm.go.id. https://doi.org/10.29017/LPMGB.51.1.9

Veza, I., Said, M. F. M., Djamari, D. W., Abas, M. A., Latiff, Z. A., & Perang, M. R. M., (2021), Future Direction of Microalgae Biodiesel in Indonesia. Journal of Advanced Research in Applied Sciences and Engineering Technology, 25(1). https://doi.org/10.37934/araset.25.1.16.

Wicaksono, F. D., Bin Arshad, Y., & Sihombing, H., (2019), Monte Carlo net present value for techno-economic analysis of oil and gas production sharing contract. International Journal of Technology, 10(4). https://doi.org/10.14716/ijtech.v10i4.2051.

Widrian, A. F., Arifianto, B. S., Nurbaiti, & Sasongko, N. A., (2022), Review of Biodiesel Policy in Indonesia. IOP Conference Series: Earth and Environmental Science, 1034(1). https://doi.org/10.1088/1755-1315/1034/1/012062.

Wirawan, S. S., Solikhah, M. D., Setiapraja, H., & Sugiyono, A., (2024), Biodiesel implementation in Indonesia: Experiences and future perspectives. In Renewable and Sustainable Energy Reviews (Vol. 189). https://doi.org/10.1016/j.rser.2023.113911.