Policy Scenario Analysis of a Sugarcane-Based Alcohol-to-Jet Sustainable Aviation Fuel Supply Chain

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Abstract

Sustainable aviation fuel (SAF) is expected to play an important role in aviation decarbonization, but its expansion remains constrained by limited feedstock availability and high production costs. This study develops a system dynamics model to represent a sugarcane-based alcohol-to-jet (ATJ) supply chain and evaluates policy scenarios that affect the feasibility of SAF industry development. The model includes upstream sugarcane production, midstream ethanol allocation and ATJ conversion, downstream blending with fossil jet fuel, and an environmental and techno-economic assessment of project performance. Two groups of policies were examined: policies to increase feedstock availability and policies to improve project economics. Feedstock-oriented policies were evaluated using ethanol availability for SAF production, while economic policies were assessed using the SAF minimum selling price (SAF MSP) and net present value (NPV). Results show that increasing farmer adoption and improving crop yield expand ethanol availability and raise SAF production potential, although ethanol competition with gasoline blending limits long-term supply. Stacked economic policies reduced SAF MSP, with feedstock subsidy producing the largest reduction, while market-based measures improved project profitability but remain dependent on carbon prices. These results show the value of system dynamics for examining interactions across the supply chain and for testing policy strategies to support SAF development.

Keywords: System dynamics, sustainable aviation fuel, alcohol-to-jet, supply chain modeling, policy analysis, techno-economic analysis.

1. Introduction

The aviation sector is growing rapidly, but so is the challenge of reducing its climate impact (IATA, 2024a). Aviation currently contributes to about 2.5 % of global energy-related CO2 emissions (IEA, 2025). If no action is taken, these emissions could double over the next 25 years (Federal Aviation Administration, 2021). Since aviation emissions are largely driven by the carbon intensity of the fuel, replacing fossil jet fuel with sustainable aviation fuels (SAF) is one of the most promising near-term mitigation options, especially because it can be used within existing aircraft and infrastructure (Rosales Calderon et al., 2024). Yet, despite numerous announced projects, SAF deployment remains far below what is needed. In 2024, SAF supplied only about 0.3% of global jet fuel demand, well below projected targets (IATA, 2024b). Its large-scale adoption continues to be constrained mainly by its higher cost compared with fossil jet fuel, which is associated with high feedstock costs, expensive conversion processes, and relatively low conversion efficiencies (Martulli et al., 2025; U.S. Department of Energy, 2024).

The feasibility of a SAF production cannot be assessed solely at the conversion stage, but must be examined across the full supply chain, from feedstock cultivation and processing to fuel conversion, blending, and end use (Martinez-Valencia et al., 2021; Raman et al., 2024). SAF's long-term development is influenced by a broad set of interrelated factors, including land use, potential trade-offs with food production, environmental impacts, economic viability, competition with other biofuel uses, market opportunities, and policy support (Ismael et al., 2025; Ng et al., 2021; Wandelt et al., 2025; Wang et al., 2024; Zhang et al., 2020). The emergence of a competitive SAF industry further depends on stable regulation, supporting infrastructure, and coordination among key actors (López Gómez et al., 2023; Rosales Calderon et al., 2024). Beyond SAF's role in reducing up to 90% of aviation emissions (Prussi, 2025; U.S. Department of Energy, 2024), the industry may also generate wider benefits through rural development and domestic industrial activity, and enhance energy security (Capaz et al., 2021). A comprehensive assessment of an SAF supply chain, therefore, requires an integrated, system-level perspective.

System dynamics studies of the biofuel industry at the national level have largely examined how policies and strategies affect food security, sustainability, land use, and production outcomes, often with the goal of reducing biofuel costs. In contrast, its application to SAF assessment remains limited (Espinoza et al., 2017; Jin et al., 2019; Jonker et al., 2017; Kuo et al., 2019; López Gómez et al., 2023; Mahate et al., 2023; Martínez-Jaramillo et al., 2019; Soares De Carvalho Freitas et al., 2022; Taheri et al., 2024). This study develops a system dynamics model of a sugarcane-based alcohol-to-jet (ATJ) supply chain for SAF production, in which ethanol derived from sugarcane is converted into jet fuel. The model is used to test policy scenarios that affect the feasibility of industry development, considering feedstock production and project economic viability.

2. Methodology

This study extends the work in progress, "Modeling the Feasibility of an Alcohol-to-Jet Industry Based on Sugarcane in Ecuador," presented at the 2025 International System Dynamics Conference (Echeverria-Paredes, 2025).

The methodology consisted of two main stages: model development and policy testing. Model development included defining the system boundaries, constructing the causal loop diagram, translating it into a stock-and-flow model in Stella Architect, and validating the model structure. Policy testing then involved defining a base case and evaluating alternative policy scenarios.

2.1. Model development

Model development began by identifying the main stages of the sugarcane-based ATJ-SAF supply chain and selecting the key processes to represent. The model was then organized into upstream, midstream, and downstream stages (Figure 1). Upstream processes include sugarcane cultivation, processing, and ethanol production. Midstream activities allocate ethanol between gasoline blending and SAF production; a techno-economic analysis was used to estimate the SAF minimum selling price (SAF MSP). Downstream processes include fossil jet fuel production and blending with SAF; the potential emissions reductions were also calculated. Technological development, financing opportunities, energy and water use, and climate-related events were excluded.

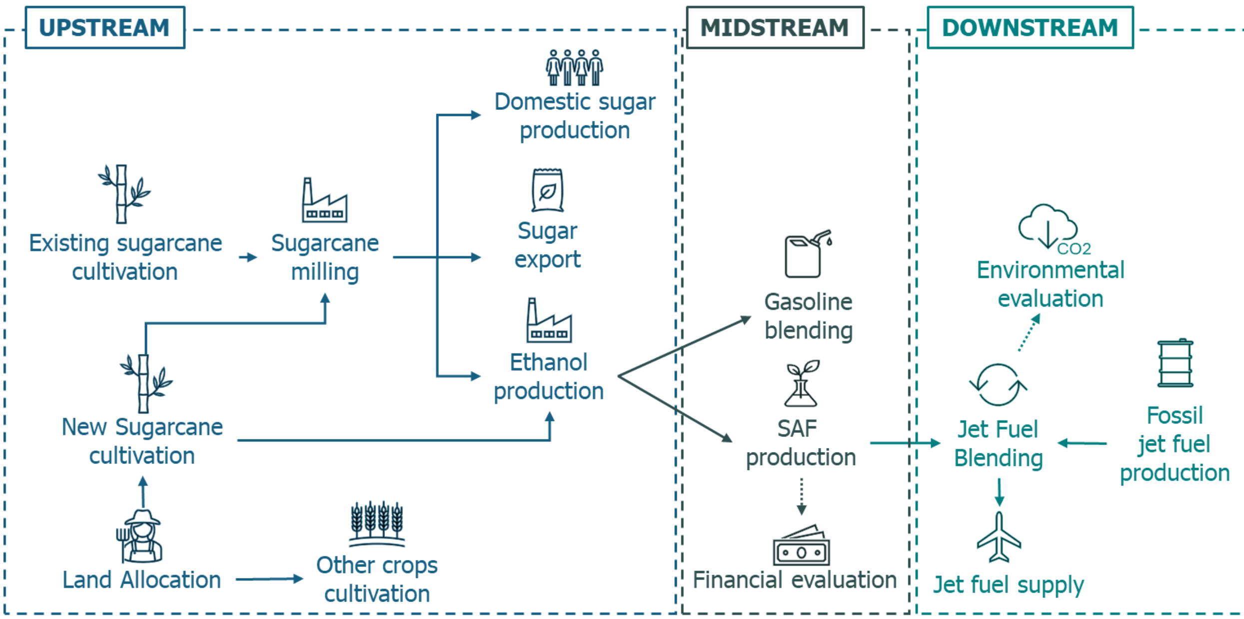


Figure 1 Supply chain for SAF production via ATJ pathway using sugarcane as feedstock

Based on the supply chain structure, a causal loop diagram was developed to represent the key feedback mechanisms influencing system behavior over time. The dynamic interactions in the system are presented in Figure 2.

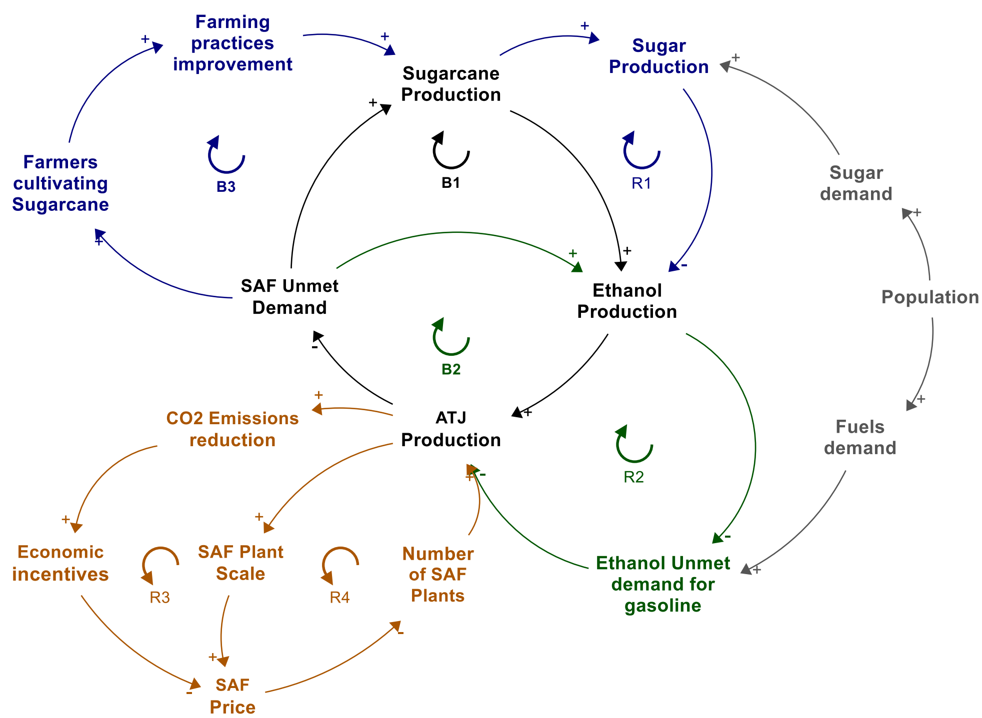


Figure 2 Causal Loop Diagram for a sugarcane-based ATJ supply chain. In the figure, blue arrows indicate upstream dynamics; green arrows represent midstream and downstream interactions; orange arrows denote financial relationships; and gray arrows show single-link relationships

The causal loop diagram presents three balancing loops and 4 reinforcing loops, described as:

- **B1:** If SAF unmet demand increases, sugarcane production increases, which leads to higher ethanol production and therefore higher ATJ production. The rise in ATJ production reduces the unmet demand for SAF.
- **B2:** If SAF unmet demand increases, ethanol production increases, which raises ATJ production and consequently reduces the unmet demand for SAF.
- **B3:** If SAF unmet demand increases, more farmers choose to cultivate sugarcane. This improves farming practices and increases sugarcane production, which then boosts ethanol production and ATJ production, ultimately reducing SAF unmet demand.
- **R1:** If SAF unmet demand increases, sugarcane production increases, leading to more sugar or to more ethanol production. However, if more sugarcane is destined for sugar production, less feedstock would be available for ethanol production, resulting in lower ATJ production and, therefore, higher SAF unmet demand.
- **R2:** If SAF unmet demand increases, ethanol production increases, reducing the unmet demand for ethanol in gasoline blending. However, if the unmet demand for ethanol in gasoline

blending decreases (because more ethanol is diverted to gasoline rather than ATJ), ATJ production decreases, thereby increasing the unmet demand for SAF.

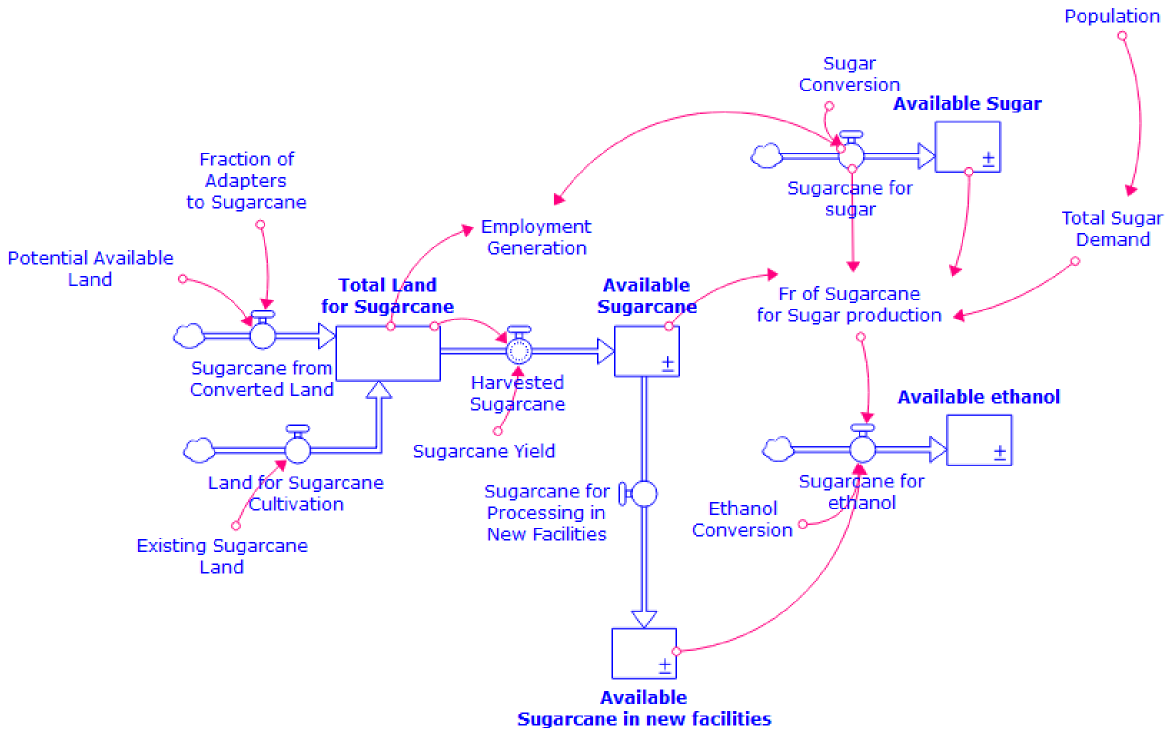
- **R3:** If ATJ production increases, CO_2 emissions reductions increase. If this environmental benefit is monetized, it increases the economic incentives to produce SAF, lowering its price. A lower SAF price increases the number of SAF plants that can be built over time, further increasing ATJ production.
- **R4:** If ATJ production increases, plant scale increases, which decreases the SAF price. A lower SAF price increases the number of SAF plants that can be built over time, thereby increasing ATJ production.

After defining the supply chain structure and developing the causal loop diagram, the model was translated into a stock-and-flow model using Stella Architect® software. In the model, year zero represents 2025, and the model is run 10 years earlier to represent an existing sugarcane industry. A simplified version of the sub-models for each stage of the supply chain is shown in Figure 3. The figure presents major stocks, key flows, and main outputs in the upstream, midstream, and downstream sub-models.

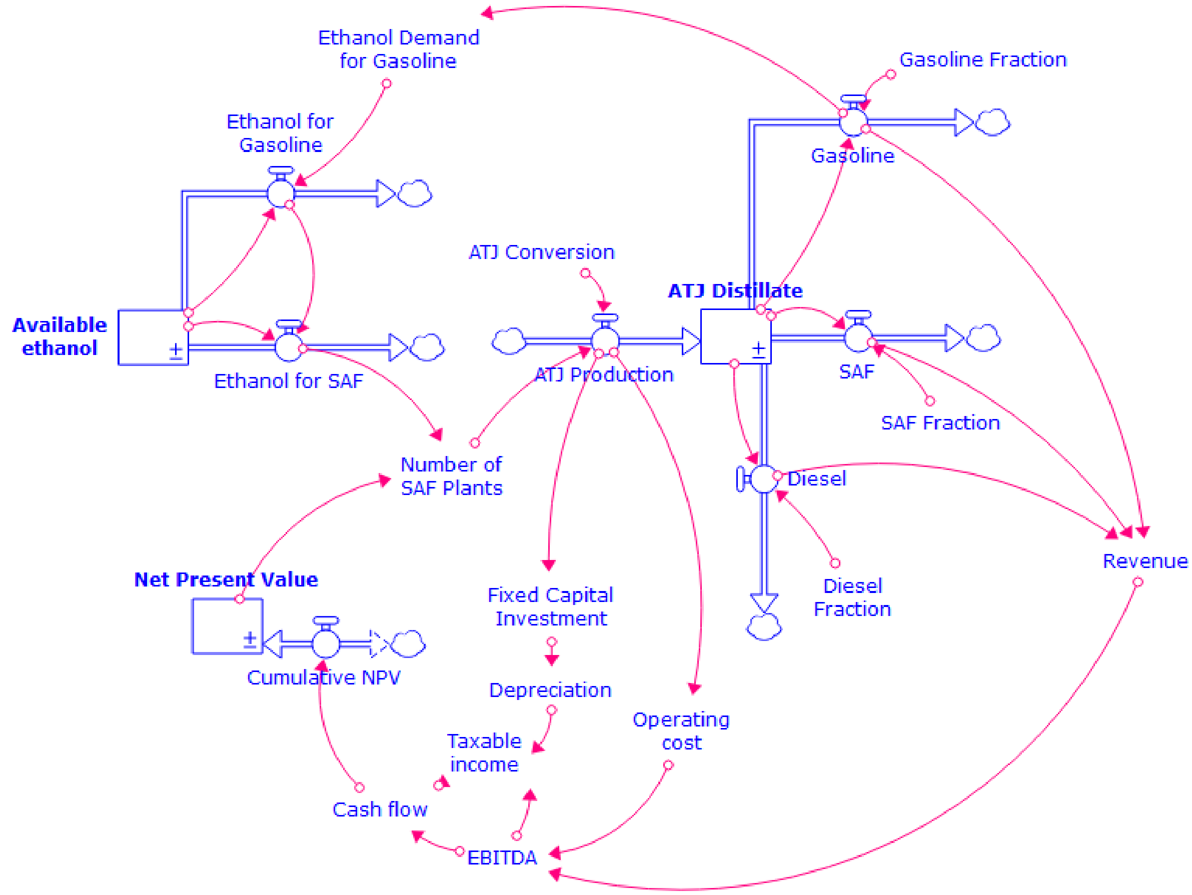
In the upstream sector, total sugarcane land includes both existing cultivated area supplying current sugar mills and potential land that can be converted to sugarcane if farmers adopt the crop. Based on crop yield, this land generates the available sugarcane supply. Sugarcane is first processed in existing mills up to their capacity; when supply exceeds that capacity, new facilities are added to convert sugarcane directly into ethanol. To protect food security, the model prioritizes sugar production, allocating only surplus sugarcane to ethanol production once sugar demand is met.

In the midstream sector, ethanol from upstream operations can be allocated either to gasoline blending or to SAF production, with gasoline demand prioritized before ethanol is diverted to SAF. Ethanol directed to the ATJ pathway is converted into SAF, gasoline, and diesel, and this gasoline can reduce the ethanol required for blending with fossil gasoline. This sector also includes a techno-economic assessment in which fixed capital investment, operating costs, and NPV are estimated as a function of ATJ production capacity. ATJ-SAF production occurs only when ethanol availability is sufficient and the project is economically viable. Stella's optimization tool was used to calculate the SAF MSP.

In the downstream sector, SAF is blended with fossil jet fuel. National jet fuel demand defines the required quantities of SAF and fossil jet fuel in the final blend. The model then estimates the resulting CO_2 emissions reductions based on the lifecycle emissions of SAF, including emissions from the conversion pathway and indirect land-use change.


Population
Sugar Conversion
Available Sugar
Fraction of Adapters to Sugarcane
Sugarcane for sugar
Total Sugar Demand
Employment Generation
Potential Available Land
Total Land for Sugarcane
Available Sugarcane
Fr of Sugarcane for Sugar production
Sugarcane from Converted Land
Harvested Sugarcane
Available ethanol
Sugarcane Yield
Land for Sugarcane Cultivation
Sugarcane for Processing in New Facilities
Ethanol Conversion
Sugarcane for ethanol
Existing Sugarcane Land
Available Sugarcane in new facilities

a)



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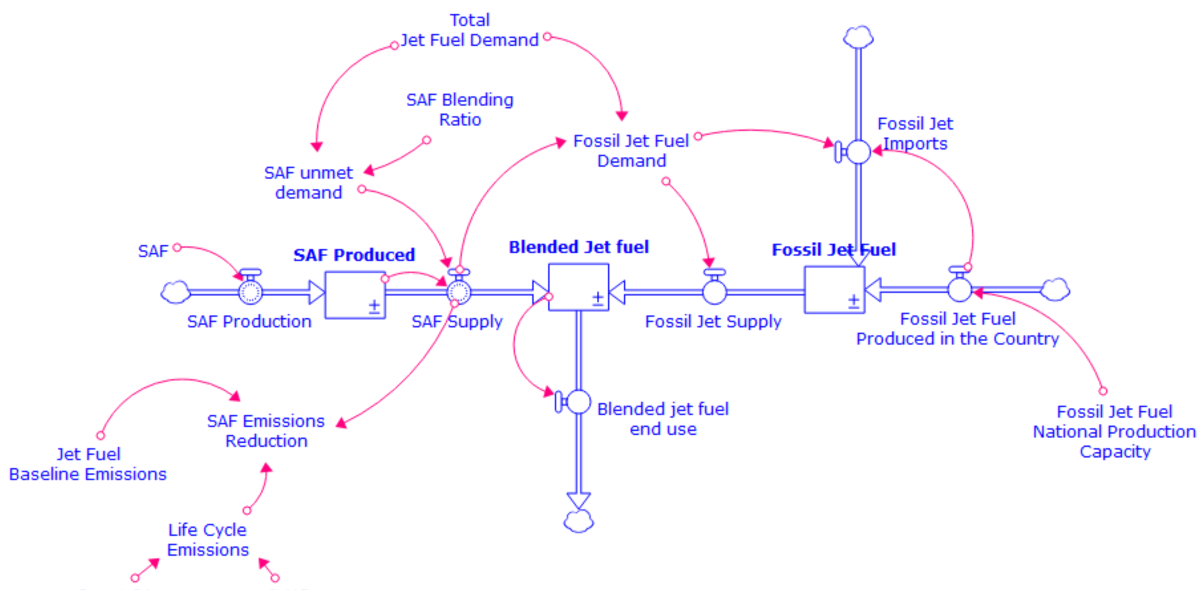

c)

Figure 3 Summarized stock and flow diagram to represent a) upstream, b) midstream, and c) downstream operations in a sugarcane-based ATJ supply chain

The model structure and behavior were validated with stakeholders across different stages of the supply chain in Colombia, Ecuador, and the Dominican Republic. Extreme-condition tests showed that the model reproduced expected behavior under limiting assumptions. Robustness was also evaluated by varying the simulation time step, with results changing by less than 1%. In addition, optimization runs with multiple initial conditions converged, with no meaningful differences in the results. Table 1 summarizes the model's main endogenous and exogenous parameters and outcomes.

Table 1 Main exogenous and endogenous parameters in the model, and the main outcomes for evaluation

Category	Variables
Exogenous	Sugarcane land, processing capacities, crop yield, process conversions, population, sugar consumption per capita, gasoline and jet fuel demand, prices, financial assumptions, lifecycle assessment data, policy incentives
Endogenous	Sugar demand, ethanol production, ethanol demand for gasoline, SAF demand, fossil jet fuel demand, SAF production, gasoline production, diesel production, emission reduction, equipment cost, and input material's cost
Main outcomes	Ethanol availability, SAF MSP, NPV

2.2. Policy scenarios evaluation

2.2.1. Base case description

A base-case scenario was established as the reference condition for assessing how policy interventions affect feedstock production and the economic viability of a SAF production project. The corresponding parameters are summarized in Table 2. The aim of the model is to be used in any sugar-producing country or region. Therefore, rather than representing a specific site, the base case reflects the conditions of a small sugarcane-producing country, with Ecuador used as the main reference context for land use, population, gasoline and jet fuel demand, and sugarcane and ethanol production capacity (Azucarera Valdez, n.d.; Coazucar, 2013; CODANA, 2025; INEC, 2025a, 2025b; Ministerio de Energía y Minas, 2024; Sociedad Agrícola e Industrial San Carlos, 2023; SODERAL S.A., 2025). The base case assumes that 50% of farmers with potential land are interested in converting their land to sugarcane. The maximum SAF blending ratio was defined according to ASTM (ASTM, 2024). Key outputs evaluated under this scenario include ethanol availability, SAF production potential, and emissions reduction. The model was simulated for 40 years to evaluate the system's long-term response. In the absence of additional policy support, this scenario serves as the benchmark against which alternative policy cases are compared.

Table 2 Parameters to define the base case scenario

Parameter	Value	Units
Existing land cultivated with sugarcane	90,000	ha/year
Potential available land	60,000	ha/year
Fraction of adapters to sugarcane	0.5	Dimensionless
Sugarcane yield	75	Ton/ha
SAF maximum blending ratio	0.5	Dimensionless

Gasoline demand	Graphic input	L/year
Jet fuel demand	Graphic input	L/year
Population	Graphic input	People/year
Sugarcane processing capacity in existing facilities	7,000,000	t/year
Ethanol production capacity in existing facilities	150,000,000	L/year
New ethanol facilities production capacity	2,000,000	t/year

The techno-economic analysis was based on the ATJ ethanol pathway assessment developed by (Brandt et al., 2021). Because that study reflects U.S.-specific conditions, its financial assumptions were adopted here as reference values and are presented in Table 3. These parameters were used to estimate project economic behavior in the model, but they do not represent country-specific financing conditions. These parameters were used to calculate the project's economic viability through the SAF MSP and the NPV of the ATJ project.

Table 3 Economic parameter assumptions for the technoeconomic evaluation (Brandt et al., 2021)

Parameter	Assumed value
Cost year	2021
Plant financing	Loan 70% and equity share 30%
Loan rate	8%
Loan term	10 years
Plant life	3 years of building and 20 years of operation
Income tax	17.3%
Working capital	20%
Nominal financial discount rate	12.2%
Inflation	2%
Operational days/year	329

The economic assumptions for prices and costs were based on (Brandt et al., 2021), with the exception of ethanol price, which was set to the average market price of sugarcane-derived ethanol in Brazil (CEPEA - ESALQ, 2026). The main values are presented in Table 4.

Table 4 Parameters to define the financial base case scenario (Brandt et al., 2021)

Parameter	Value	Units
Ethanol price	0.51	USD/L
Natural Gas price	4.02	USD/MMBtu
Hydrogen price	1,753	USD/t
Electricity rate	0.089	USD/kWh
Cooling water rate	0.017	USD/t
Refrigeration cost	15.88	USD/MMBtu

2.2.2. Policy scenarios

Policy scenarios were grouped by their primary objective: increasing feedstock availability for SAF production or improving the economic feasibility of an SAF project. Because these two groups address different mechanisms, they were evaluated using different approaches. Feedstock-oriented policies were assessed through one-at-a-time sensitivity analysis, in which individual input parameters were varied while all others were held constant (Geleynse et al., 2018). Their effects were measured through the amount of ethanol available for SAF production. In contrast, economic policies were evaluated as a sequential set of stacked interventions, with each policy applied on top of the results of the previous one. Their effects were assessed through changes in SAF MSP and, for the final market-based policy, NPV.

- **Production policies**

The first group of policies was designed to increase ethanol availability for SAF production. The first policy scenario, referred to as the sugarcane grower's policy, focuses on farmers and aims to increase feedstock availability by encouraging sugarcane cultivation. It represents measures that provide more favorable conditions for growers, including a stable market and fair prices for sugarcane. Depending on policy effectiveness, a greater or smaller proportion of farmers may shift eligible land into sugarcane production. This scenario would test how ethanol availability changes when 25%, 50%, or 75% of the land is converted to sugarcane.

The second policy scenario, the crop yield improvement policy, aims to increase ethanol availability for SAF production by boosting sugarcane yields. It represents support measures for farmers, such as incentives or credit programs that improve cultivation and harvesting practices. In the model, policy effectiveness is reflected in higher crop yields. Three yield levels are evaluated: the base-case value of 75 t/ha, 85 t/ha, which is commonly reported in countries such as the United States, and 95 t/ha, which represents higher-yield conditions such as those observed in Nicaragua or El Salvador (Food and Agriculture Organization of the United Nations, 2025).

- **Economic policies**

The second group of policies aimed to improve the economic feasibility of SAF production, such as mandates, cost-reduction measures, and market-based incentives (Malina et al., 2022). The policies were applied sequentially to evaluate their cumulative effect on project economics. This study assumes a blending mandate that allows the maximum SAF blend with fossil jet fuel, thereby creating a stable market for SAF. The first scenario, the feedstock subsidy policy, applies a 0.10 USD/L subsidy to ethanol for SAF production, reflecting the high contribution of feedstock to operating costs. The resulting SAF MSP was then used as the basis for the second scenario, the capital grant policy, which was represented as a 20% reduction in the total delivered equipment cost. A third scenario, the emissions-based SAF incentive policy, was subsequently applied as a producer's incentive, based on a modified version of the U.S. Clean Fuel Production Credit, considering a 1.75 USD per gallon of SAF multiplied by the emissions factor of the fuel; it is treated as taxable income in the model (IRS, 2025).

The final economic policy scenario is a book-and-claim policy in which the emissions reduction attributes of SAF are monetized. In the model, this policy is represented as additional revenue based on the carbon price applied to the CO_2 emissions avoided by replacing fossil jet fuel with SAF. Sugarcane-based SAF can reduce emissions by up to 42% compared to conventional jet fuel.

Three carbon price levels are evaluated: 25, 50, and 75 USD per ton of CO_2. Its effect is assessed by changes in the project's net present value (NPV).

3. Results and Discussion

This section presents the results of the base-case scenario, followed by the effects of feedstock-related and economic policy scenarios.

3.1. Base case scenario results

The base-case scenario represents a small sugarcane-producing country with 90,000 ha already under sugarcane cultivation and 50% adoption among farmers with eligible land. This results in a total of 135,000 ha by year 9 (Figure 4a). Harvested sugarcane is first allocated to sugar production. Figure 4b shows that, although the share of sugarcane used for sugar increases over time as demand grows, production remains sufficient to satisfy sugar demand throughout the simulation.

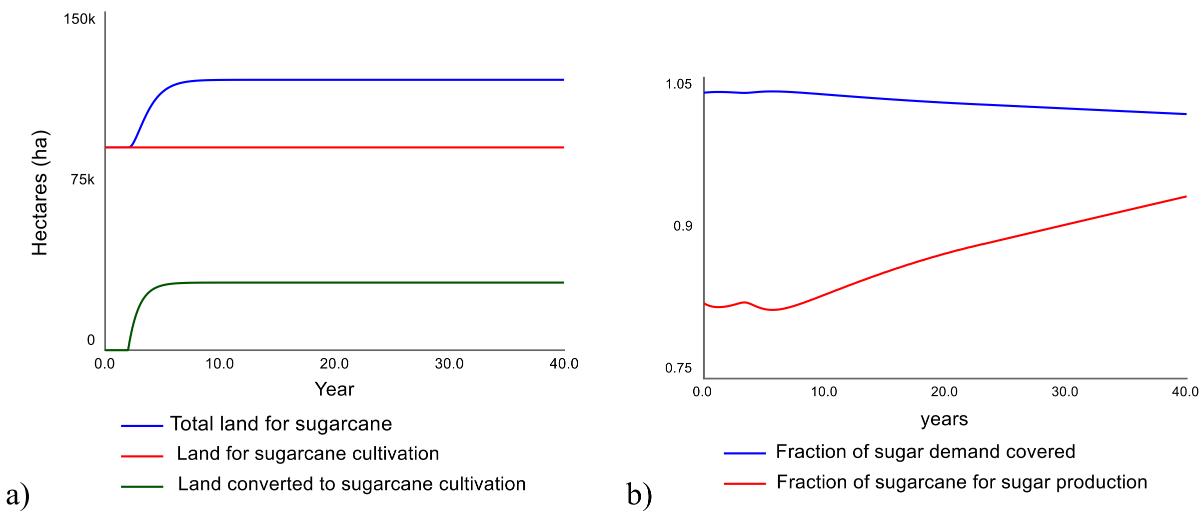

Figure 4 Base case model results a) land and b) sugar dynamics

Under base-case conditions, sugarcane production exceeds the processing capacity of existing facilities, necessitating the construction of a new plant to convert sugarcane directly into ethanol. The addition of this facility increases ethanol availability by year 10 (Figure 5a). This ethanol is then allocated between gasoline blending and SAF production. Because gasoline blending represents an existing market, the model prioritizes meeting ethanol demand for gasoline before diverting the remaining volume to SAF production. Figure 5b shows that the ethanol supply is sufficient to meet gasoline-blending demand throughout the simulation. Figure 5c presents the ethanol available for SAF production. During the first ten years, ethanol production remains too low to sustain SAF production. After year 10, however, the new ethanol facility begins operation and ethanol availability increases substantially. Nevertheless, as ethanol demand for gasoline blending continues to rise, the amount available for SAF gradually declines. Under these conditions, the system can support the production of 25 million liters of SAF.

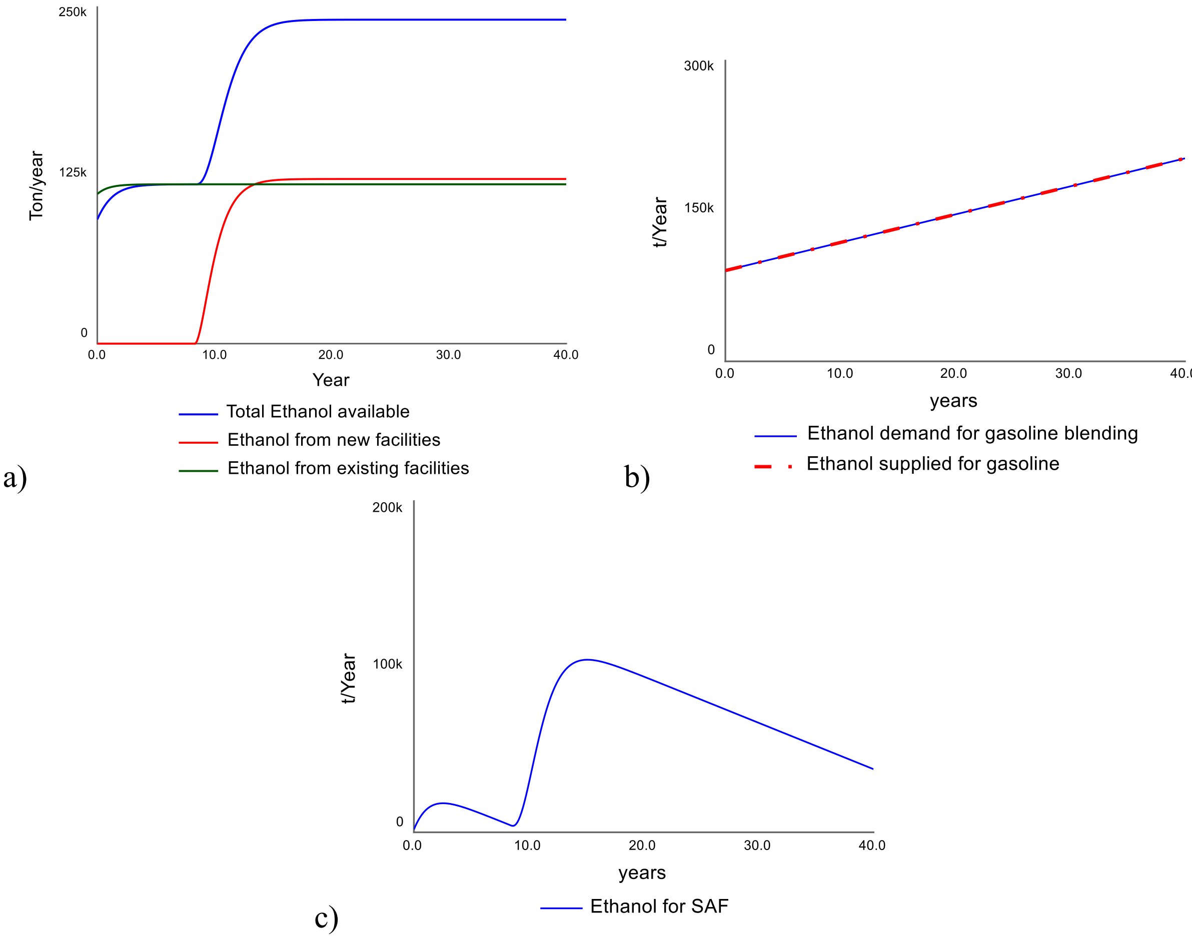

Figure 5 Midstream results for the base case scenario. a) Total ethanol available, b) ethanol demand for gasoline, and c) ethanol available for SAF production

3.2. Policy scenarios

This section presents the effects of feedstock-oriented policies on ethanol availability for SAF production. Followed by the effects of stacked economic policies on the SAF MSP and the NPV.

3.2.1. Production policies

- Sugarcane growers' policy

The sugarcane grower incentive policy shows that increasing farmer adoption can substantially improve ethanol availability for SAF production. Three adoption levels were evaluated: 25%, 50%, and 75% of farmers with eligible land converting to sugarcane cultivation. At 25% adoption, feedstock supply is insufficient to support SAF production, and after year 11, ethanol availability also becomes inadequate to meet gasoline blending demand (Figure 6). In contrast, the 50% and 75% cases produce similar results. In both cases, feedstock availability is sufficient to justify the construction of one new ethanol facility but not enough to support a second, so ethanol availability remains similar. Under these conditions, ethanol available for SAF decreases over time as demand for gasoline blending continues to grow. This suggests that the allocation of ethanol between gasoline and SAF should be further examined to ensure a more stable SAF supply. Overall, these scenarios suggest that SAF production in the range of 25 to 50 million liters could be achieved under moderate to high farmer adoption.

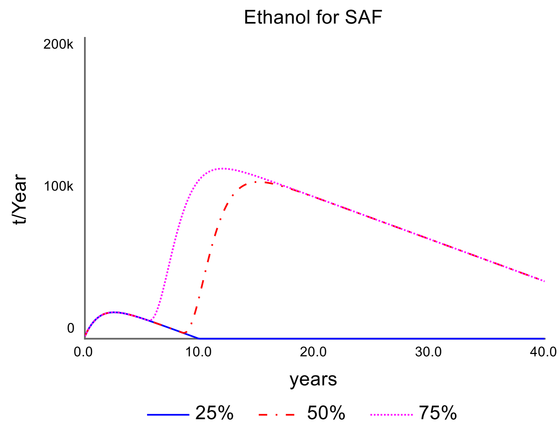

Figure 6 Ethanol available for SAF considering that 25%, 50%, and 75% of farmers with potential land adopt sugarcane cultivation

- Crop yield improvement policy

Assuming that 50% of farmers convert their available land to sugarcane cultivation, three crop-yield levels were evaluated: 75, 85, and 95 t/ha. The results show similar ethanol availability under yields of 75 and 85 t/ha (Figure 7). As with the farmer adoption scenarios, both cases can support only one new ethanol production facility. Under these conditions, ethanol supply is sufficient to meet gasoline blending demand, but only about 25 million liters of SAF can be produced. In contrast, a yield of 95 t/ha substantially increases ethanol availability for SAF, exceeding 150,000t and supporting approximately 75 million liters of SAF production.

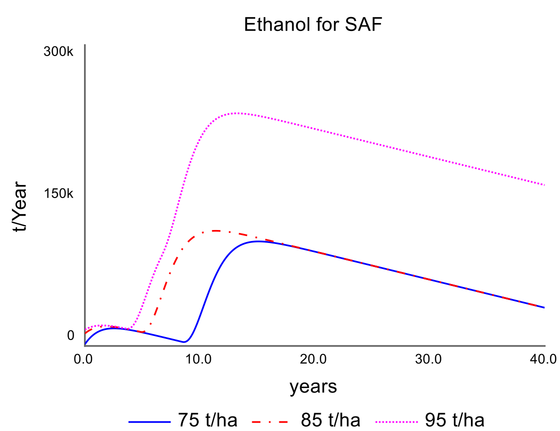

Figure 7 Ethanol availability considering a sugarcane crop yield of 75, 85, and 95 t/ha

These trade-offs should be evaluated further in relation to rural development, economic growth, and broader national benefits. This will be explored in future work by applying the model to a country-specific context.

3.2.2. Economic policies

Economic policies were evaluated under the scenario with the highest ethanol availability for SAF production. As described in the previous section, this case assumes that 50% of farmers convert eligible land to sugarcane cultivation and that crop yield increases to 95 t/ha. Under these conditions, the economic analysis considered an ATJ-SAF plant capacity of 75 million liters per year. Figure 8 shows the reduction in the SAF MSP as each policy was applied sequentially. The largest reduction was achieved through the ethanol subsidy, which is consistent with feedstock accounting for about 80% of total operating costs. The 20% capital grant reduced SAF MSP by about 2%. Although larger grants could produce greater reductions, their feasibility would need to be assessed. The emissions-based incentive produced only a limited reduction because the lifecycle emissions of a standalone ATJ facility were estimated at 52.9 g CO_2e/MJ, while the baseline used for the incentive calculation was 47.4 g CO_2e/MJ (ICAO, 2024; IRS, 2025). This baseline was taken from the U.S. Clean Fuel Production Credit, but because it does not differentiate among fuel types, a jet-fuel-specific baseline would be more appropriate. Overall, the results indicate that no single policy is sufficient to make SAF cost-competitive and that a combination of measures is needed to reduce production costs (Brandt et al., 2022; Martinez-Valencia et al., 2023). Even after all stacked policy scenarios, SAF MSP remained above the fossil jet fuel reference price of 0.58 USD/L (EIA, 2024), indicating that additional incentives would still be required to achieve economic feasibility.

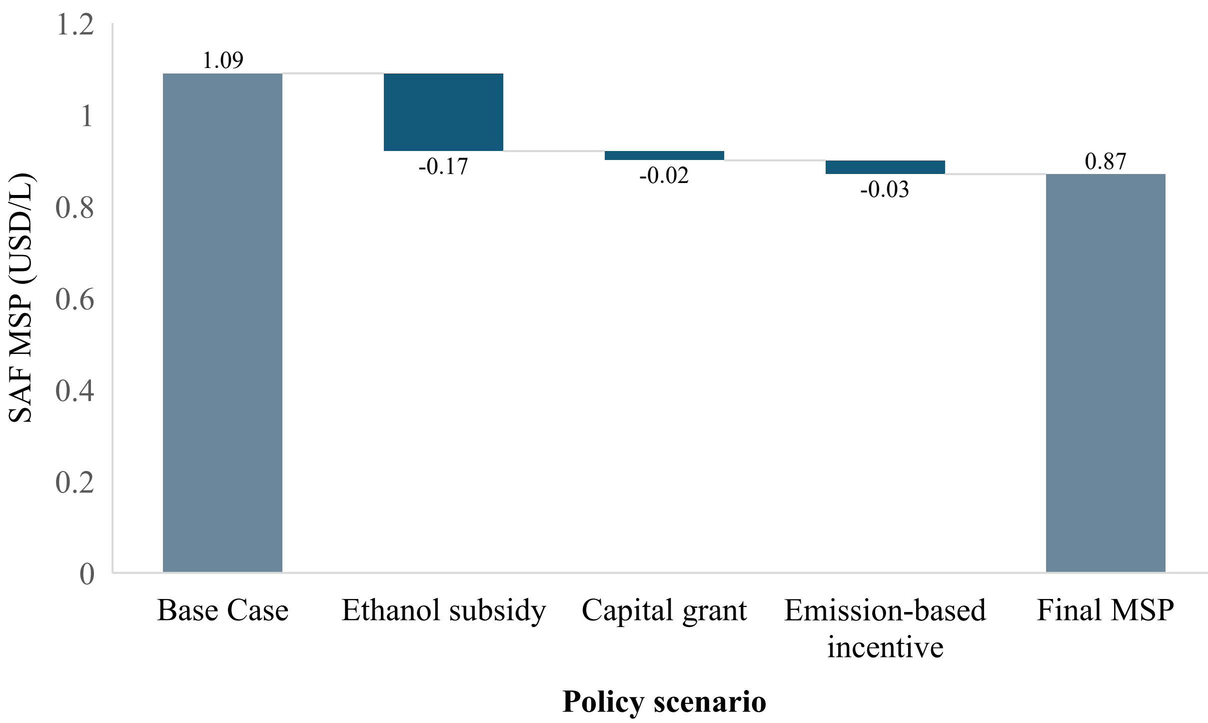

Figure 8 Effect of policy scenarios on the SAF MSP

Market-based measures such as book-and-claim may represent an important strategy for improving SAF competitiveness. These policies assume that the emissions reductions achieved by replacing fossil jet fuel with SAF can be monetized through carbon markets at different carbon price levels. As shown in Figure 9, the project reaches an NPV of zero by the end of the project horizon before these incentives are applied. Once carbon revenues are included, the project achieves a positive NPV, and higher carbon prices shorten the time required to reach profitability. For example, under the highest carbon price, the project becomes profitable after 13 years, compared with 16 years under the second-highest price. Although carbon markets are still evolving and remain subject to regulatory uncertainty, ongoing compliance and voluntary market efforts suggest that this could become a feasible mechanism for supporting SAF projects (Clean Skies for Tomorrow, 2022; Prussi, 2025; SABA, 2024). Taken together, the results indicate that developing a sugarcane-based ATJ-SAF industry requires both sufficient feedstock supply and stacked policy support to improve project feasibility.

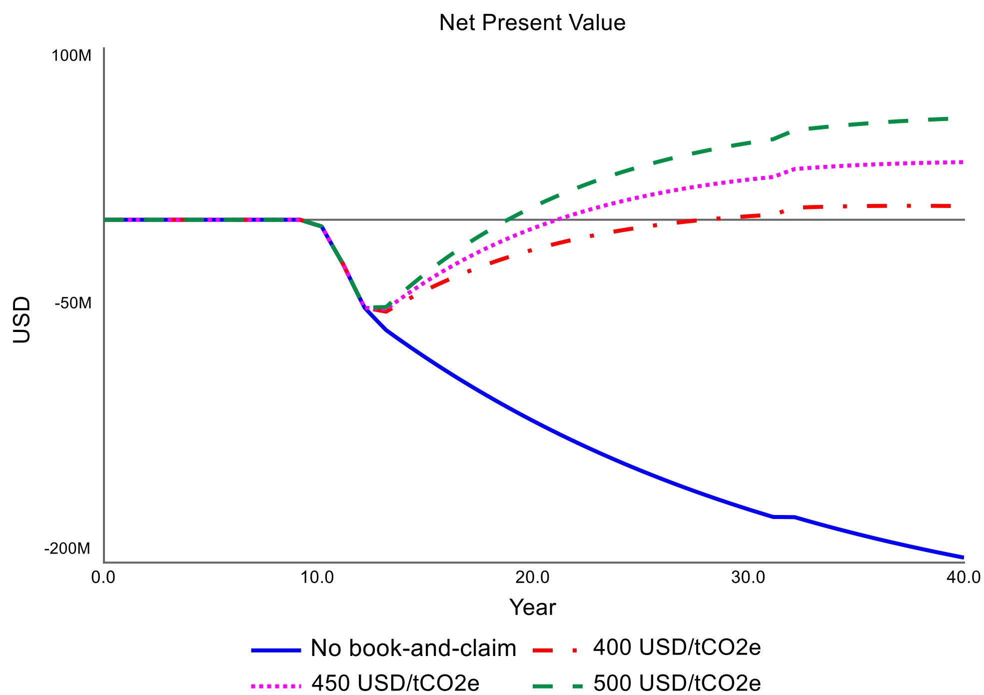

Figure 9 Effect of the carbon market price on the NPV of the project

4. Conclusions

A system dynamics model of a sugarcane-based alcohol-to-jet (ATJ) supply chain captured the main feedback loops linking land conversion, sugarcane production, ethanol availability, SAF production and blending, and project economics. By capturing these interactions over time, the model helps explain how feedstock conditions and policy support together shape the development of a potential SAF industry.

The results show that feedstock availability is a fundamental requirement for industry emergence. Higher farmer adoption and improved sugarcane yields increase ethanol availability, increasing the potential for SAF output. However, these gains do not automatically translate into sustained SAF supply, since ethanol is first used to cover gasoline blending demand. This highlights the importance of understanding allocation trade-offs within different biofuels. On the economic side, the results indicate that single policy measures are not sufficient to make SAF competitive with fossil jet fuel. Although feedstock support produced the largest reduction in SAF minimum selling price, stacked policy measures were needed to achieve more meaningful improvements. In addition, market-based mechanisms showed potential to improve profitability by monetizing SAF's emissions-reduction attributes. Overall, the findings suggest that the long-term development of a sugarcane-based ATJ-SAF industry depends on the combined effect of feedstock expansion and coordinated policy support. While the current model simplifies some factors, including detailed spatial conditions, water and energy requirements, and technology developments, it provides a useful framework for future country-specific applications.

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