



TECHNOECONOMIC ASSESSMENT FOR THE PRODUCTION OF RENEWABLE AVIATION FUEL FROM AN INTEGRATED ETHANOL PLANT

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ABSTRACT

The growing global demand for decarbonization of the transportation sector, especially in commercial aviation, is promoting the development of Sustainable Aviation Fuels as a short-term and medium-term alternative to fossil fuels. This study presents a technical-economic assessment for the production of Sustainable Aviation Fuel from an integrated sugarcane ethanol biorefinery (1G+2G) in Brazil, using an Integrated Linear Programming model implemented in LINGO v.20. The model integrates physical, economic, and logistics submodels, optimizing material and energy flows, plant location, costs, and revenues. The results demonstrate that SAF demand is fully covered in all cases, with a constant production of 5.24 Mtons/year, confirming the viability of the proposed configurations. The production of renewable electricity, diesel, and gasoline varies between scenarios, while the valorization of vinasse into biomethane (scenarios 2 and 4) maximizes energy use and soil productivity. The area needed to grow sugarcane exclusively for SAF would be 2.68 million hectares, which entails environmental challenges and competition with other uses. Minimum selling prices (USD 1.69–1.75/L) are highly competitive compared to international alternatives. Revenues depend primarily on SAF (79–84%), while raw material costs represent the largest component (64–72%).

Keywords: biomass, biofuels, SAF, ethanol, biogas.

1 INTRODUCTION

The transition to a low-carbon economy has become one of the greatest global challenges of the 21st century (Dong; Liu; Yang, 2024). Greenhouse gas (GHG) emissions, responsible for climate change, come largely from the massive use of fossil fuels in the transportation, energy and industrial sectors (Doliente et al., 2020). In this context, the search for renewable and sustainable energy sources has intensified in recent decades, with special attention to the sectors that are most difficult to decarbonize, such as commercial aviation (Aghaei et al., 2022; Bhatt et al., 2023). Given the technical and operational nature of air transport, which requires high energy density and specific physical and chemical characteristics in fuels, alternatives such as electrification or the direct use of hydrogen remain unviable in the short term (Ansell, 2023; Eyberg et al., 2024). In this scenario, Sustainable Aviation Fuels (SAF) emerge as a realistic intermediate solution to achieve a substantial reduction in the sector's emissions without requiring a radical transformation of existing airport infrastructure and aircraft (Liang et al., 2025; Teixeira et al., 2024; Walter et al., 2021).

Among the different SAF production routes, one of the most promising is that based on the conversion of ethanol into hydrocarbons through the Alcohol-to-Jet (ATJ) route (Doliente et al., 2020; Shahriar; Khanal, 2022). This technology allows the transformation of ethanol, a light and renewable alcohol, into a hydrocarbon mixture that meets the specifications of Jet-A1 fuel, used in commercial aviation (Julio et al., 2021; Tiwari et al., 2023).



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The development of advanced biofuels, such as second-generation SAF, involves a complex interplay of technical, economic, and environmental factors (Karimi; Simsek; Kheiralipour, 2025). Given this complexity, the use of mathematical models and optimization tools has become a fundamental component for the design, evaluation and operation of advanced biorefineries (Liang et al., 2025; Vickram et al., 2025). Applied to the production of SAF from 2G ethanol, a MILP model can, for example, help determine the optimal location of conversion plants, the volume of feedstock required, the necessary infrastructure investments, and the best allocation of resources to maximize profitability or minimize emissions (Lim; Luckert; Qiu, 2023). These models also allow for the simulation of different economic scenarios. Furthermore, factors such as the use of renewable energy in the biorefinery, the use of biogenic CO₂, or the energy integration between units can have a decisive impact on net emissions reduction (Neag et al., 2023). In this sense, the integration of cogeneration systems with biomass, the valorization of by-products (such as residual lignin or vinasse) and the use of renewable sources of electrical energy can substantially improve the overall efficiency of the system and reduce its environmental footprint (Negi et al., 2023).

Finally, the development of a sustainable value chain for the production of SAF from cellulosic ethanol requires a systemic approach, integrating technical, economic, environmental and social aspects (Leila; Whalen; Bergthorson, 2018). The generation of scientific and technological knowledge, as well as the training of qualified human resources, will be crucial to accelerating the adoption of these technologies in countries like Brazil, where there is a solid agro-industrial base, but there is still a lack of greater integration between sectors.

In this context, this study aims to comprehensively analyze the production of SAF from first and second generation ethanol derived from sugarcane, incorporating mathematical modeling tools to assess its technical and economic viability. By formulating and solving an MILP-based optimization model, the objective is to identify the optimal conditions for implementing this technology in a realistic environment, considering biomass availability and SAF demand. This research contributes to the body of knowledge on integrated biorefineries and energy transition strategies, offering relevant insights for decision-making in the scientific, industrial, and governmental spheres.

2 CASE STUDY

The optimization model was developed for Brazil, a world leader in sugarcane production and with extensive experience in biofuels. Sugarcane is used as a feedstock for ethanol production, obtained through two routes: first-generation ethanol (1G) and second-generation ethanol (2G). These routes are integrated with a biorefinery, allowing for more efficient use of biomass and higher yields per ton of sugarcane. Ethanol (1G and 2G) serves as an input in the Alcohol-to-Jet (ATJ) technological route, which converts it into SAF. The study considered six Brazilian states with sugarcane availability in 2023: São Paulo, Goiás, Minas Gerais, Mato Grosso, Mato Grosso do Sul, and Paraná (IBGE, 2025). Demand for SAF was estimated based on major aviation fuel distribution centers for 2024 (ANP, 2025). Four technological scenarios were analyzed:

1. Production of SAF and byproducts from an integrated ethanol biorefinery. Buying green H₂ for hydrotreating.
2. Production of SAF and byproducts from an integrated ethanol biorefinery, with valorization of vinasse for the production of biomethane. Buying green H₂ for hydrotreating.
3. Production of SAF and byproducts from an integrated ethanol biorefinery. Producing green H₂ using a proton exchange membrane (PEM) for hydrotreatment.



4. Production of SAF and byproducts from an integrated ethanol biorefinery, with valorization of vinasse for the production of biomethane. Producing green H₂ using a proton exchange membrane (PEM) for hydrotreatment.

3 METHODOLOGY

This study presents a model of Integer Linear Programming (MILP) developed to optimize the production of sustainable aviation fuels (SAF). The model is based on a superstructure that integrates different technological layers and is represented by an optimized work flow. All processes considered are modeled from mass and energy balances, using data obtained from literature and technical estimates. The mathematical formulation was implemented in the LINGO v.20 software and was built from three interrelated submodels: (I) a physical model; (II) an economic model and (III) a regional logistics model, which considers the location of two resources, their distribution and the modal transport involved.

The integration of these components allows the analysis of different system configurations and the selection of the ideal alternative from a technical, economic and logistical perspective. The methodology used is based on previous studies (Garcia; Palacios; Ensinas, 2024; Infante Cuan et al., 2025; Khalid et al., 2025).

The physical model reveals the mass and energy balances of each stage of the process. The proposed economic model structures the investment costs of the technological units, as well as the costs of purchasing, selling, and transporting resources. Investments were updated to 2024 using the CEPCI index and adjusted by a scale factor for different capacities. The prices of inputs and outputs, such as sugarcane, hydrogen, electricity, enzymes, water and biofuels, were defined based on recent references and assumptions. Road transportation was considered the main mode, with costs calculated by (Agência Nacional de Transportes Terrestres, 2025) for different resources and truck types. The feasibility analysis uses economic indicators such as Internal Rate of Return (IRR), Payback Period, and Net Present Value (NPV). A SAF price of 2,500 USD/tons, a 20-year horizon, and Minimum Attractive Rate of Return (MARR) of 8% were adopted. The minimum selling price (MSP) was defined as the price that zeroes the NPV. The regional logistics model developed seeks to optimize resource allocation, reduce transportation costs, and increase the efficiency of the SAF supply chain in Brazil. To achieve this, it considers three main variables: regional demand, resource availability by state, and transportation distances. Optimal plant locations and conversion stages were determined by an optimization algorithm, balancing economic and logistical criteria. Since future biorefineries are not precisely defined, distances were estimated from state capitals (Google Maps, 2025) and adjusted to 90% of each state's average radius (Weisstein, 2025), better representing territorial dispersion. This data allowed us to define optimal production and distribution configurations, maximizing economic and operational viability.

The objective function of the model is to maximize the Net Present Value (NPV) of the system, incorporating all projected cash flows over the planning horizon and discounting them to a previously defined attractiveness taxa. The NPV is obtained by the difference between soma two annual liquid profits, duly updated for the present value, and the amount of the initial investment. This economic criterion, expressed mathematically in the equation (1), allows us to evaluate the financial viability of the system, privileging configurations that generate the greatest economic return over time.

$$NPV = -\text{Investment} + \sum_t \frac{\text{Cash flow}}{(1+\text{MARR})^t} \quad (1)$$



4 RESULTS AND DISCUSSION

The evaluation of the four scenarios analyzed shows that SAF demand was fully met in all cases, achieving a constant production of 5.24 Mtons/year. This confirms that the proposed configurations are viable for ensuring the supply of sustainable aviation fuels (SAF), although they differ in energy performance, land use efficiency, and economic profitability. Table 1 shows consumption and production of each resource.

Table 1 - Resource consumption and production

Consumption	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Sugarcane (Tons)	208,455,200	208,455,200	208,455,200	208,455,200
Water (Tons)	381,431	381,431	387,927	387,927
Enzymes (Tons)	1,229,886	1,229,886	1,229,886	1,229,886
H ₂ green (Tons)	213,678	213,678		
Production	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Electricity (MW)	14,109,540	13,567,410	4,630,414	4,088,290
SAF (Tons)	5,235,112	5,235,112	5,235,112	5,235,112
Renewable Diesel (Tons)	427,356	427,356	427,356	427,356
Renewable Gasoline (Tons)	2,457,297	2,457,297	2,457,297	2,457,297
Biomethane (Tons)		725,747		725,747

The amount of sugarcane consumed was the same in all scenarios: 208,5 Mtons/year, with an average agricultural yield of 77,749 t/ha, the required area is estimated at 2,68 million hectares. For context, Brazilian production in 2023 reached 782,59 Mt of sugarcane (IBGE, 2025), equivalent to approximately 10,07 million hectares of cultivated land. This implies that expansion dedicated exclusively to SAF would represent approximately 26,6% of the current sugarcane area in Brazil. Such a magnitude poses significant challenges: territorial expansion into environmentally sensitive areas, competition with food and sugar/ethanol, and potential tensions in energy security and the international competitiveness of the sugar and alcohol sector. The results show clear differences between the technological configurations. Comparing the scenarios also allows us to identify the amount of energy produced per ton of processed sugarcane. Scenario 2 achieves the highest production, with 2,115.67 MJ/tons, suggesting better energy utilization of the resource. At the other extreme, Scenario 3 generates 1,793.35 MJ/tons, showing the lowest performance. Scenarios 1 and 4 present similar values, with 1,957.05 MJ/tons and 1,951.97 MJ/tons, respectively, demonstrating an intermediate balance in energy conversion. These results demonstrate that differences in technology and system configuration directly impact the energy yield per unit of processed sugarcane.

When evaluating the investment scenarios considered, the results show significant differences in terms of profitability and financial viability. The comparison of the four scenarios highlights relevant differences in economic performance. Scenario 2 (IRR 19.7%) presents the most attractive return, followed by Scenario 4 (18.5%), both indicating higher competitiveness compared to Scenarios 1 (18.2%) and 3 (17.2%). The latter shows the lowest return, suggesting greater sensitivity to market fluctuations and increased risk in capital recovery. The discounted payback period reinforces this interpretation, ranging from 6.55 years (Scenario 2) to 7.65 years (Scenario 3). In general, scenarios with lower IRRs are also associated with longer payback



periods, confirming a less favorable investment profile. Scenario 2 thus stands out as the most balanced alternative, combining a high return with a relatively short payback time. The Net Present Value (NPV), derived from discounted cash flows, further supports these conclusions. The highest NPV is obtained in Scenario 4 (MUSD 20,059.91), followed by Scenario 2 (MUSD 18,674.01). In contrast, Scenario 1 (MUSD 15,614.10) and Scenario 3 (MUSD 16,955.10) present lower values, indicating comparatively reduced wealth creation for investors. The Minimum Selling Price (MSP) adds another perspective: Scenario 4 offers the lowest MSP (1.69 USD/L), which increases its attractiveness in competitive markets. Scenario 1, on the other hand, shows the highest MSP (1.75 USD/L), which could represent a disadvantage in price-sensitive environments. These results position the company in a position of high competitiveness when compared to various alternatives reported in international literature. For example, mill-based crops present the highest costs, with feed values of 4.09 USD/L (Tanzil et al., 2021), reflecting the high expenses related to the cultivation and processing of biomass. Similarly, second-generation lignocellulosic biomass conversion processes present high MSP, in the order of 2.74 USD/L (Diederichs et al., 2016), due to technological complexity and the need for specialized infrastructure. On the other hand, the most competitive results are associated with sugarcane, with values reported between 0.96 USD/L (Yao et al., 2017) and 2.05 USD/L (Teixeira et al., 2024), demonstrating the potential of this raw material in function of its high agricultural productivity and lower cost of processing. In the context of this spectrum of results, the values obtained in this study (1.69–1.75 USD/L) stand out as highly competitive. They are situated below the majority of the lignocellulosic processes and do so, just as they will be close to the best of the first-generation sugarcane crops reported in previous studies. Nearby two results such as the MSP of 1.17 USD/L reported by Klein et al., (2018) for the integration of 1G and 2G processes shows that the efficient utilization strategy of cane biomass, including the waste utilization, represents a viable and promising solution for SAF production.

As Figure 1 illustrates in all scenarios, revenues depend primarily on SAF, which represents between 79% and 84% of total revenue. Renewable gasoline (11–14%) and renewable diesel (2%) provide complementary revenues, while biomethane accounts for 2–3% in the scenarios with anaerobic digestion of vinasse. Electricity generation has a small share (2–6%), indicating that the majority of the economic value comes from liquid fuels. Similarly, raw material costs (RMC) also indicate that all scenarios are heavily dependent on sugarcane, making them vulnerable to price fluctuations (Figure 2).

Figure 1 – Distribution of revenues

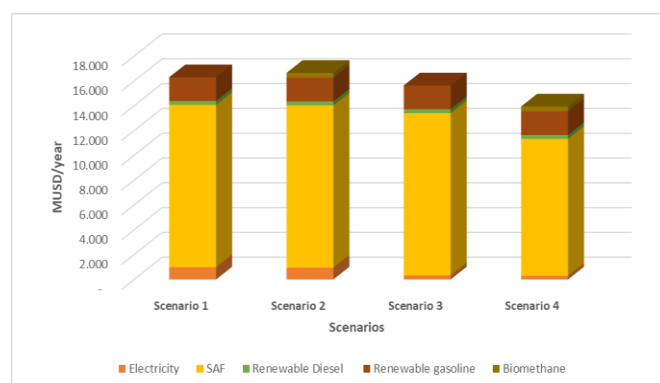
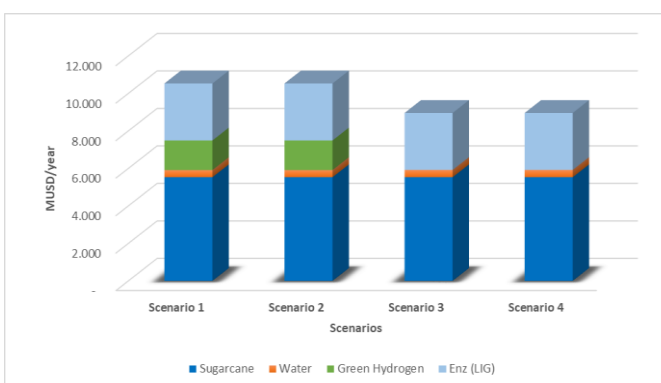


Figure 2 – Distribution of raw material cost



Annual feedstock costs are the most significant component, with shares of 64–72%, followed by operating costs (12–16%) and transportation costs (3–4%). A decisive factor is the source of green hydrogen. In the scenarios with external purchase

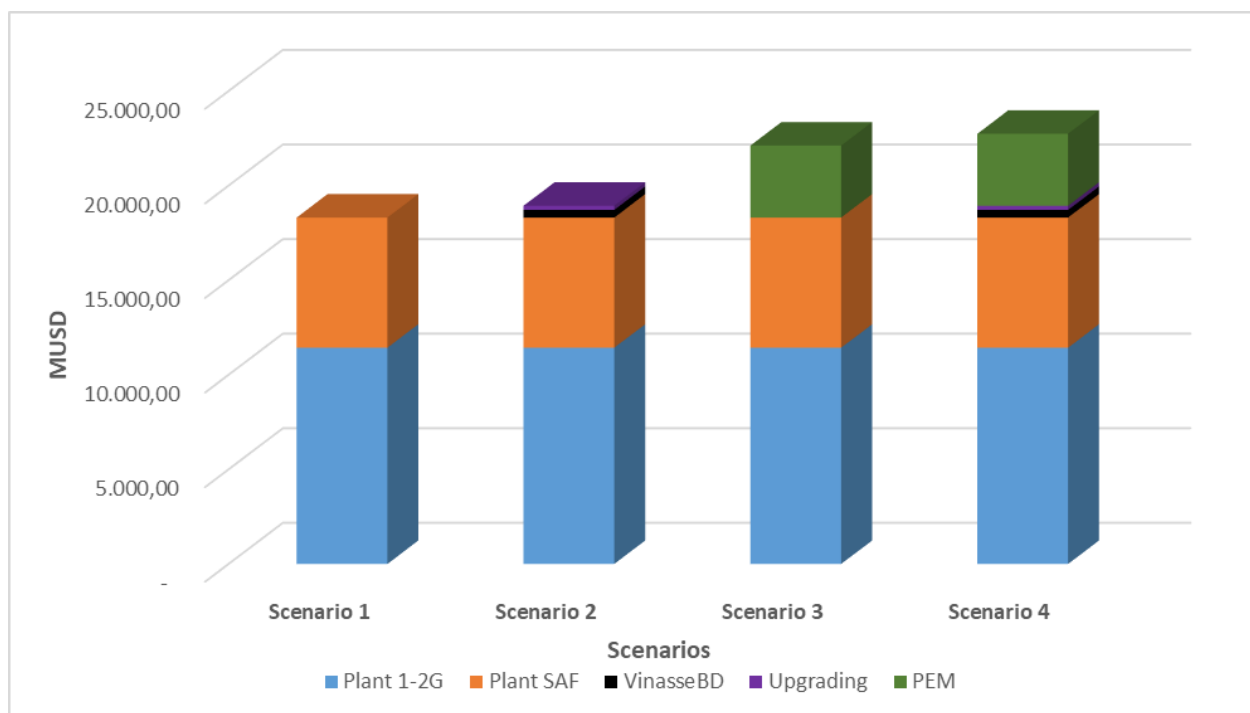


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(scenario 1 and scenario 2), the acquisition cost was USD 7,390/t; this value corresponds to ~15% of the feedstock, reinforcing the strong dependence on market conditions for green hydrogen. In the PEM electrolysis scenarios (scenario 3 and scenario 4), this expense disappears, but is offset by higher CAPEX: the PEM plant accounts for 17% of the plant's cost, in addition to an increase in operating costs. Thus, the trade-off is between exposure to H₂ prices versus increased capital investment. The figure 3 indicates how investments are divided into all scenarios. It is important to highlight that for scenarios 2 and 4, the set of green hydrogen production plants through the decomposition of vinasse are responsible for only 3% of the total investment.

Figure 3 – Distribution of investment costs by units



5 CONCLUSIONS

This study evaluated different technological configurations for the production of sustainable aviation fuels (SAF) from sugarcane, integrating energy performance, land use, and economic viability. In all scenarios, the proposed demand was met with a constant production of 5.24 million tons of SAF per year, confirming the technical feasibility of the proposed model. However, the magnitude of biomass consumption represents a considerable challenge: the use of 208.5 Mtons of sugarcane per year requires approximately 2.68 million hectares, equivalent to 26.6% of the area currently cultivated in Brazil. This result highlights the importance of considering the impacts on food security, competition with the sugar-ethanol sector, and pressure on sensitive ecosystems in the event of territorial expansion. In terms of land-use efficiency, significant differences were observed between configurations. Energy production per ton of processed sugarcane ranges from 1,793.35 to 2,115.67 MJ/ton, with Scenario 2 being the most efficient and Scenario 3 the least favorable, while Scenarios 1 and 4 remain in the intermediate range. Byproduct valorization, particularly the anaerobic digestion of vinasse for biomethane production (scenarios 2 and 4),



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was shown to be a key strategy for maximizing energy utilization and increasing system profitability. The analysis of the minimum sales price (MSP) placed the results between USD 1.69 and USD 1.75/L, positioning the sugarcane SAF at a highly competitive level compared to alternatives reported in the literature.

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