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Incentivizing Sustainable Aviation Fuel: Supply Chain and Policy Insights from Brazil

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Abstract

Sustainable aviation fuel (SAF) plays a central role in decarbonizing the aviation sector. Brazil is positioned to become a leader in SAF production and consumption from sugarcane-based ethanol. However, integrating SAF into the Brazilian sugarcane industry is challenging due to high production costs, an undeveloped SAF supply chain, and ethanol competition between ground and aviation transportation. The present study uses mixed-integer linear optimization to design SAF supply chains in Brazil under various blend requirements and design scenarios. Three sugarcane mills in São Paulo are identified for strategic SAF investments, with a recommended premium of 2.6 R\$ L⁻¹ (0.5 US\$ L⁻¹). Furthermore, SAF production increases net CO₂ emissions by up to 2.7 Mt year⁻¹ (relative to a 0% baseline) due to ethanol displacement. Sensitivity analysis reveals SAF conversion and emission targets for net-zero system emissions. These results provide several key insights to guide SAF supply chain growth, technology development, and policy design in Brazil. Finally, the general optimization framework provides a template for SAF capacity expansion worldwide.

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1 Introduction

2 Aviation currently contributes approximately 2.5% of global energy-
3 related CO₂ emissions, with significant growth anticipated in the coming
4 years.¹ The sector faces global pressure to decarbonize, with the Inter-
5 national Civil Aviation Organization (ICAO) proposing a 5% emissions
6 reduction goal by 2030.² Sustainable aviation fuel (SAF), i.e., biomass- and
7 biomaterials-derived synthesized paraffinic kerosene (SPK), is expected to
8 play a significant role in achieving the net-zero emissions scenario by 2050,
9 contributing up to 65% of emission reductions.³ However, currently, SAF
10 represents only ~0.2% of global jet fuel consumption, hindered by high
11 production costs, immature technologies, and undeveloped supply chains.^{3,4}

12 Brazil possesses a unique opportunity to become a global leader in SAF
13 production and consumption from sugarcane ethanol. As the world's second-
14 largest bioethanol producer and the largest producer from sugarcane (33.6
15 million (M) m³ in 2023–2024⁵), Brazil has well-established biomass infras-
16 tructure that can support the rapid development of a structured SAF supply
17 chain. Sugarcane ethanol exhibits low carbon intensity⁴ and is expected
18 to become a key feedstock for SAF production via the alcohol-to-jet (ATJ)
19 technology, converting alcohol to SAF through the basic steps of dehydra-
20 tion, oligomerization, and hydrogenation.⁶ We estimate that, with current
21 ATJ technologies, sugarcane ethanol in Brazil has the potential to contribute
22 approximately 36% of the global SAF capacity increase required to meet pro-
23 jected demand for 2030 under a net-zero emissions by 2050 scenario (~46
24 Mm³⁴). Furthermore, the coproduction of SAF in sugarcane bio-refineries
25 may significantly reduce capital and operational costs.⁷

26 Designing a SAF supply chain in Brazil requires decisions regarding where
27 to locate new production facilities, how much SAF to produce, and how feed-
28 stocks and products should be transported throughout the network. Facility

siting decisions are inherently discrete,⁸ while production and transportation decisions are continuous. Additionally, as the associated costs, material balances, capacity limits, and transportation requirements can be represented using linear relationships, the resulting optimization problem can be formulated as a mixed-integer linear program (MILP). MILPs are powerful modeling approaches to optimize large-scale problems with well-established commercial solvers, which can prove global optimality of solutions.⁹

For example, MILPs have been employed for optimal SAF supply chain design in the U.S.,^{10–12} Mexico,^{13,14} Germany,¹⁵ India,¹⁶ and SAF produced from microalgae cultivated from sugarcane vinasse in Brazil.¹⁷ These studies focus on optimal facility location and SAF technology selection; however, the integration of a SAF supply chain into the Brazilian sugarcane industry presents complex, interdependent, and multiscale optimization problems, including a strong dependence on sustainable energy policy and individual government decisions, competition between ground and air transportation for ethanol use, and differing objectives between supply chain managers and individual mill owners. MILP has also been used to design biofuel supply chains under various policy mechanisms. Hombach et al.¹⁸ used MILP to design a biodiesel supply chain in Germany, considering six instruments of European biofuel regulations. Ebrahimi et al.¹⁹ used MILP to evaluate different incentive structures on a carinata-based SAF supply chain in Florida. Additionally, methods such as market equilibrium and Nash equilibrium optimization have been employed to determine the optimal design of biofuel supply chains under various policies, such as producer credits,^{20,21} interest rate reduction,²² investment subsidies,²³ and emissions penalties.²⁴

The present study employs MILP to optimize a realistic scenario of integrating SAF production from sugarcane ethanol into the Brazilian sugarcane industry. This unique framework explores optimal facility location, ATJ technology development, policy implications, and the broader market impacts of SAF integration. We consider the optimal supply chain design across various SAF adoption scenarios, including SAF blend levels ranging from 0% to 50%, two categories of SAF production locations (sugarcane mills and oil refineries), and two decision-making paradigms: a central planner aiming to minimize supply chain costs and an investor aiming to maximize profits. The results highlight the optimal number of SAF suppliers and their locations, recommend necessary incentives for attractive SAF investments, and capture secondary effects of a SAF market in Brazil.

The remainder of this article is organized as follows. We first review the

relevant background on the sugarcane industry, ethanol upgrading to SAF, and existing SAF policy mechanisms. We then present the supply chain design problem statement, mathematical model, data sources, and analysis methods, followed by the results of our analysis. We close with concluding remarks and open research directions. All results are distilled into three key insights to inform SAF policy-makers and technology developers.

Background: SAF Potential in Brazil

We begin by contextualizing the challenges of SAF integration into the Brazilian sugarcane industry and the assumptions underlying the analysis.

Ethanol Supply Chain and Logistics in Brazil

Brazil is the world’s second-largest producer of ethanol with approximately 396 operational ethanol mills: 373 that process sugarcane, 13 that process corn, and 10 that are flexible mills capable of processing both sugarcane and corn.²⁵ The total ethanol production (both anhydrous and hydrated) reached 33.6 Mm³ in the 2023–2024 harvest, containing 81% of ethanol derived from sugarcane and the remaining 19% from corn.⁵ Sugarcane ethanol production was the largest between May and December, reaching a mean biweekly production of 1.88 Mm³. In the remaining months, the mean biweekly production was reduced to 0.431 Mm³. From the same harvest, Brazil exported 1.77 Mm³ of ethanol, mainly to South Korea (0.845 Mm³) and the U.S. (0.3 Mm³), and imported 250,000 m³ of ethanol from the U.S. (58%), Paraguay (25%), and Argentina (15%) to compensate for seasonal production variations.⁵

The bioethanol infrastructure in Brazil is the result of decades of public policies that promote the production and consumption of ethanol, dating back to the 1970s, when the Brazilian government launched the Proálcool program (a national alcohol program aimed at developing innovative biofuel technologies).²⁶ Ethanol distilleries that process sugarcane are mainly located in São Paulo, the midwestern states of Mato Grosso do Sul and Goiás, and along the northeastern coast of Brazil. Figure 1a and 1d show the sugarcane processing capacity in each Brazilian state and the location of each sugarcane mill, respectively. All sugarcane mills in Figure 1d are separated by annexed operation (produces sugar and ethanol) and ethanol production only.

Most sugarcane mills in Brazil (66% of those considered) operate under an annexed distillery configuration, producing both sugar and ethanol.²⁷

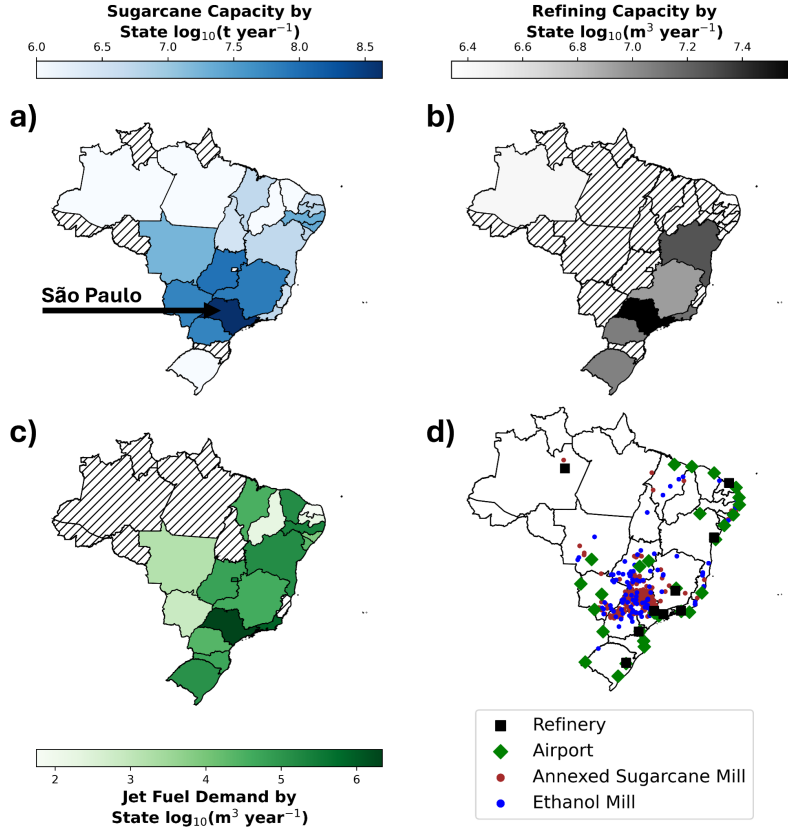


Figure 1: Four maps of Brazil showing a) sugarcane capacity, b) refining capacity, and c) jet fuel (airport) demand by state alongside d) locations of airports, refineries, ethanol distilleries (produce ethanol only), and annexed mills (produce sugar and ethanol) considered in the optimization analysis. The state of São Paulo is emphasized as it has the highest sugarcane capacity, refining capacity, and jet fuel demand in the country. Patterned states have no capacity or demand in our dataset.

102 With an annexed distillery configuration, sugarcane mills typically allocate
 103 about half of their harvest to sugar production and the other half to ethanol
 104 production, depending on which market offers better prices for producers.⁵
 105 During the ethanol expansion phase that began in 2004, several autonomous
 106 distilleries (producing only ethanol) were built to meet projected domestic
 107 and international ethanol demand.²⁸ For many years, sugarcane was the sole
 108 raw material used for ethanol production in Brazil, fulfilling nearly all do-
 109 mestic demand. However, starting in 2012, corn mills began to operate, and

110 by 2020, flexible mills were introduced. Corn is often planted as a mid-
111 harvest crop,²⁹ and flexible mills have increased the ethanol supply in Brazil,
112 contributing 6 Mm³ in 2023.³⁰

113 The current ethanol distribution system in Brazil involves sugarcane mills
114 sending anhydrous and hydrated ethanol to refineries or distribution depots
115 (usually installed near refineries). Figure 1b shows the refining capacity in
116 each Brazilian state. At the distribution depots, anhydrous ethanol (approx-
117 imately 60% of total ethanol production) is blended with gasoline at a ratio
118 of 22% to 35% by volume, nominally 27%, per regulations set by the National
119 Petroleum Agency (ANP). The percentage of the Brazilian automotive fleet
120 using hydrated ethanol varies significantly with ethanol and gasoline prices.
121 Ethanol prices have been historically volatile due to seasonal supply fluc-
122 tuations. Between April 2023 and February 2024, approximately 21% of
123 combustion engine cars used ethanol,⁵ despite 70% of the Brazilian automo-
124 tive fleet comprising flex-fuel vehicles.³¹ Increasing the supply of corn ethanol
125 from flexible mills presents an opportunity to boost biofuel consumption by
126 providing a less seasonal supply, helping ensure more stable prices.

127 The Brazilian biofuel supply chain is primarily connected through road
128 transport (80%). Rail, duct, and cabotage transportation modes have limited
129 capacity in the Brazilian ethanol supply chain,³² accounting for 14%, 3%, and
130 3% of the total transportation, respectively.³³ A duct system has operated
131 since 2013, connecting the sugarcane production region of Uberaba (Minas
132 Gerais) and Ribeirão Preto (São Paulo) to the Petrobras refinery region of
133 Paulínia (São Paulo). The system is expanding to the Logum System (a
134 private initiative led by ethanol producers and Petrobras) that connects other
135 ethanol-producing cities in São Paulo to oil refineries.³⁴ The duct system
136 today has approximately 1,100 km of pipeline delivering approximately 6
137 Mm³ of ethanol in 2023. It is projected to increase to 1,400 km of pipeline
138 delivering approximately 9 Mm³ of ethanol per year.³⁵

139 *SAF Production in Brazil: the ATJ Technology*

140 Brazil is the world’s sixth-largest aviation market,³⁶ consuming ~5 Mm³
141 of jet fuel per year. Figure 1c shows the jet fuel demand for each Brazilian
142 state. To support energy transition goals, the Brazilian government launched
143 the National Program for Sustainable Aviation Fuel (ProBioQAV) to incen-
144 tivize research, production, and the use of sustainable aviation fuels. The
145 ProBioQAV program implements a blending mandate for SAF over the com-
146 ing years, from 1% greenhouse-gas emissions reductions in 2027 to 10% in

2037, but it still needs to be fully implemented.³⁷

The ATJ technology is a natural choice for SAF production in Brazil, given the installed sugarcane ethanol capacity, as it converts alcohol into jet fuel.⁶ Furthermore, with recent public policies incentivizing electric car production in Brazil, the electrification of the Brazilian fleet may lead to an ethanol surplus that could be diverted to SAF production via the ATJ technology. However, Brazil has historically prioritized transportation decarbonization through sugarcane ethanol and flex-fuel vehicles. Consequently, electrification policies and market deployment have lagged behind those of China, the United States, and Europe, with automakers continuing to focus primarily on flex-fuel and hybrid-flex vehicle technologies.³⁸ The electrification process in Brazil is expected to progress slowly in the coming years, with less than 0.5% of the Brazilian fleet containing electric engines,³⁹ and approximately half of which are hybrids.⁴⁰

Watson et al.⁴ reported, on average, SAF produced by the ATJ technology reduces CO₂ emissions by 57% based on an analysis of the literature. The ICAO's Carbon Offset and Reduction Scheme for International Aviation (CORSIA) reported the midpoint emissions for SAF from sugarcane as 24.1 gCO₂eq MJ⁻¹ compared to 89 gCO₂eq MJ⁻¹ for fossil-based jet fuel (a 73% reduction).⁴¹ Furthermore, Watson et al.⁴ reported, on average, SAF produced by the ATJ technology costs 240% more than fossil-based jet fuel. Geleynse et al.⁴² performed a techno-economic analysis of the conventional ATJ process from an ethanol feedstock and reported a nominal minimum jet fuel selling price (MJSP) of more than 4 \$ gal⁻¹ (~ 1 \$ L⁻¹) with the cost of the ethanol feedstock making up 79% of the MJSP.

In January 2024, LanzaJet opened the world's first ethanol-to-SAF production facility in Georgia, U.S., producing 9 M gallons ($\sim 34,000$ m³) of SAF per year and 1 M gallons of renewable diesel per year.⁴³ While there are currently no operational SAF facilities in Brazil, five commercial-scale facilities (one using ATJ technology) and two pilot-scale facilities (one using ATJ technology) are in the conceptualization or planning phase.⁴⁴ Petrobras (an oil and gas company) announced a commercial-scale ATJ facility in São Paulo; however, the production capacity and project start date are not publicly available.⁴⁴ Additionally, Raízen (an ethanol production company) announced a pilot-scale ATJ facility also in São Paulo, with a project start date of 2030 and an unspecified production capacity.⁴⁴

183 Methods

184 This paper proposes an optimization framework for designing SAF supply
 185 chains in the Brazilian sugarcane industry.

186 *Optimization Problem Statement*

187 The optimization framework is derived from the classic facility location
 188 problem.⁸ The sites for new facilities (ATJ capacity) are selected from a finite
 189 set of candidate locations (existing sugarcane mills or refineries) organized
 190 across the supply chain stages (Figure 2).

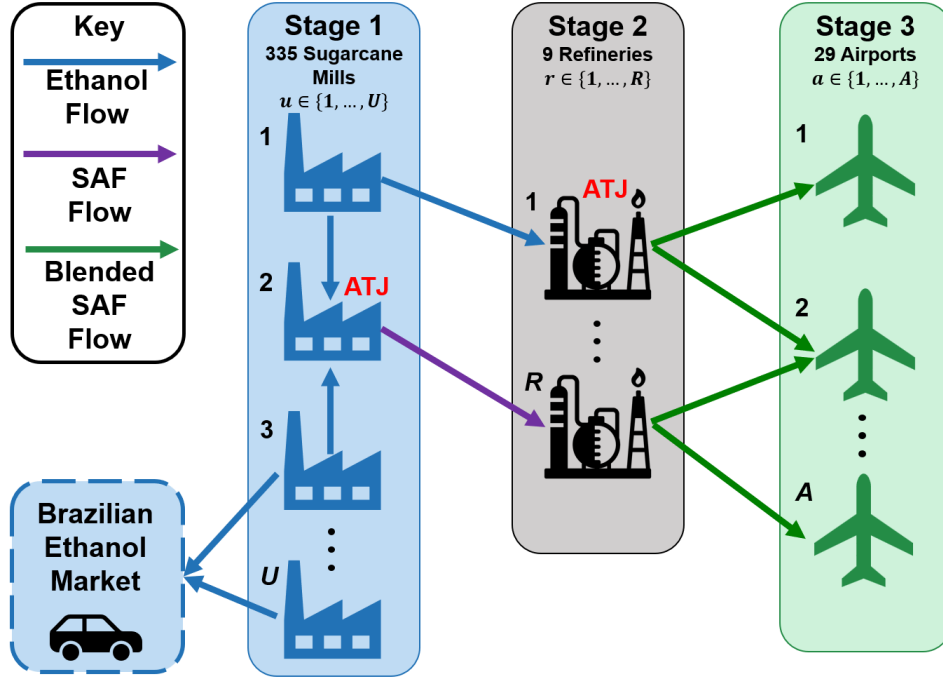


Figure 2: Visual representation of a potential three-stage SAF supply chain design containing mills (blue), refineries (black), and airports (green). In this representation, sugarcane mill 2 and refinery 1 invest in the ATJ technology (red) and produce SAF (purple arrows) or produce and blend SAF (green arrows), respectively. To increase the total ATJ capacity, sugarcane mill 2 purchases additional ethanol from mills 1 and 3 (blue arrows). SAF produced in mill 2 is trucked to refinery R to produce blended SAF (a blend of SAF and conventional jet fuel, green arrows) and then supplied to airports 2 through A . Similarly, refinery 1 purchases ethanol from mill 1 to produce and blend SAF to supply airports 1 and 2. The remaining mills, 3 through U , supply ethanol to the Brazilian ground transportation market, which is assumed to be distributed to consumers by refineries.

Supply chain Stage 1 contains 335 sugarcane mills (processing capacities ranging from 1 to 5.5 Mt year⁻¹) operational in 2024, excluding corn mills and flexible mills that process both sugarcane and corn.²⁵ The mills produce sugar, ethanol (or only ethanol in the case of distilleries), and electricity from waste (non-competing with the other products). Stage 2 includes nine refineries in Brazil that can blend SAF with conventional fossil-based jet fuel and certify the resulting fuel for use in passenger flights.⁴⁵ Finally, Stage 3 includes 29 international airports, excluding those in the Amazon region, as transportation would incur additional costs with limited data available. Each stage is connected by the transportation of fuels via trucks. Figure 1d shows the locations of the supply chain infrastructure. The supply chain is constrained to meet a fraction (0% to 50%) of Brazil’s jet fuel demand while satisfying domestic sugar and ground transportation fuel (light-duty vehicles) demand.

Investments in ATJ capacity are considered either as brownfield expansions integrated into existing sugarcane mills in Stage 1 or as greenfield facilities co-located with refineries in Stage 2. Brownfield integration leverages existing feedstock handling, utilities, storage, and transportation infrastructure, reducing capital requirements and enabling rapid deployment. In contrast, greenfield facilities located near refineries facilitate access to blending infrastructure and established fuel distribution networks, potentially reducing downstream logistics costs and simplifying SAF integration into existing jet fuel supply chains. Both configurations have been proposed as viable pathways for scaling commercial SAF production.^{42,46,47} Mixed mill-refinery configurations were not considered as this study focuses on comparing distinct brownfield and greenfield deployment pathways, and the lower capital cost of brownfield investments would likely dominate the optimization.

Table 1 summarizes the key components of the three optimization formulations considered. The full mathematical model is explained in the Input Data and Constraints section. The **first formulation** adopts a classic central planner perspective and minimizes total supply chain cost while satisfying three concomitant markets: sugar, light-duty vehicle fuel, and aviation fuel. In this case, SAF production is enforced through the blending requirement, and no explicit SAF incentives are considered. This formulation serves to achieve SAF deployment targets at the lowest overall system cost.

The **second formulation** also adopts a central planner perspective but shifts the objective from minimizing system costs to maximizing total sugarcane mill profits, emulating an investor’s perspective. While investment

229 decisions remain centrally coordinated and SAF production is mandated,
 230 this formulation more closely reflects real-world deployment by incorporat-
 231 ing profitability into the objective function. Aggregate profit maximization
 232 is used as a simplifying assumption to identify economically attractive infras-
 233 tructure configurations, implicitly assuming a competitive market in which
 234 mills face similar cost structures and individually lack sufficient market power
 235 to influence market conditions. Consequently, this formulation provides in-
 236 sight into how profitability considerations influence SAF supply chain design
 237 and investment allocation under mandated SAF deployment. This is consis-
 238 tent with other supply chain design studies.^{48–51}

239 The **third formulation** removes the SAF blend mandate, setting the
 240 required blend to zero, and treats the SAF premium as a policy parameter.
 241 The per-facility bounds on ATJ investment size remain. By incrementally
 242 increasing the premium until SAF production becomes economically favor-
 243 able, this formulation identifies the minimum incentive required to induce
 244 market-driven SAF adoption. Unlike the first two formulations, which as-
 245 sume SAF deployment is mandated, this case directly evaluates the level of
 246 policy support necessary to stimulate investment in SAF production. Addi-
 247 tionally, as refinery profitability is not explicitly represented in the model,
 248 only investments integrated with sugarcane mills are considered.

249 In total, we consider five case studies defined by the decision-making
 250 paradigm, investment location, and the inclusion of incentives: (1) central
 251 planner without (w/o) incentives, with ATJ investments at sugarcane mills;
 252 (2) central planner without incentives, with investments at refineries; (3)
 253 investor without incentives, with investments at sugarcane mills; (4) investor
 254 without incentives, with investments at refineries; and (5) investor with (w)
 255 incentives, with investments at sugarcane mills. Cases 1 through 4 were
 256 solved, considering SAF blend requirements from 0% (reference case) to 50%
 257 in increments of 10%, resulting in (4×6) 24 model instances. Case 5 considers
 258 no SAF blend requirement.

259 *Input Data and Constraints*

260 We now present the input data and mathematical constraints that define
 261 each stage of the supply chain. The full model and nomenclature table are
 262 presented in SI Section S2.

Table 1: Summary of the three optimization formulations (columns) considered in this analysis. The **Objective** rows describe the two optimization objectives considered, and the **Constraint** rows describe all the possible constraints of the mathematical optimization formulation. A checkmark (✓) indicates that the corresponding objective or constraint is included in the mathematical optimization formulation. The SAF blend requirement is enforced in the SAF Demand Fulfillment constraint. The reference case is considered for each optimization formulation with a 0% SAF blend requirement and no incentives.

	Central Planner w/o Incentives	Investor w/o Incentives	Investor w/ Incentives
Objectives			
Minimize Total Supply Chain Cost	✓		
Maximize Total Mill Profits		✓	✓
Constraints			
Mass Balances	✓	✓	✓
Capacity/Production Restrictions	✓	✓	✓
Purchase/Sale Restrictions	✓	✓	✓
Positive Mill Profits	✓	✓	✓
Demand Fulfillment (Sugar, Ground, and SAF)	✓	✓	
Demand Fulfillment (Sugar and Ground)			✓
Case Studies	1 & 2	3 & 4	5

263 *Stage 1: Sugarcane Mills*

264 We consider 335 sugarcane processing mills in Brazil, 220 annexed (pro-
265 ducing ethanol and sugar), and 115 producing only ethanol. Figure 3 illus-
266 trates a process flow diagram for an annexed sugarcane mill u with integrated
267 SAF production.

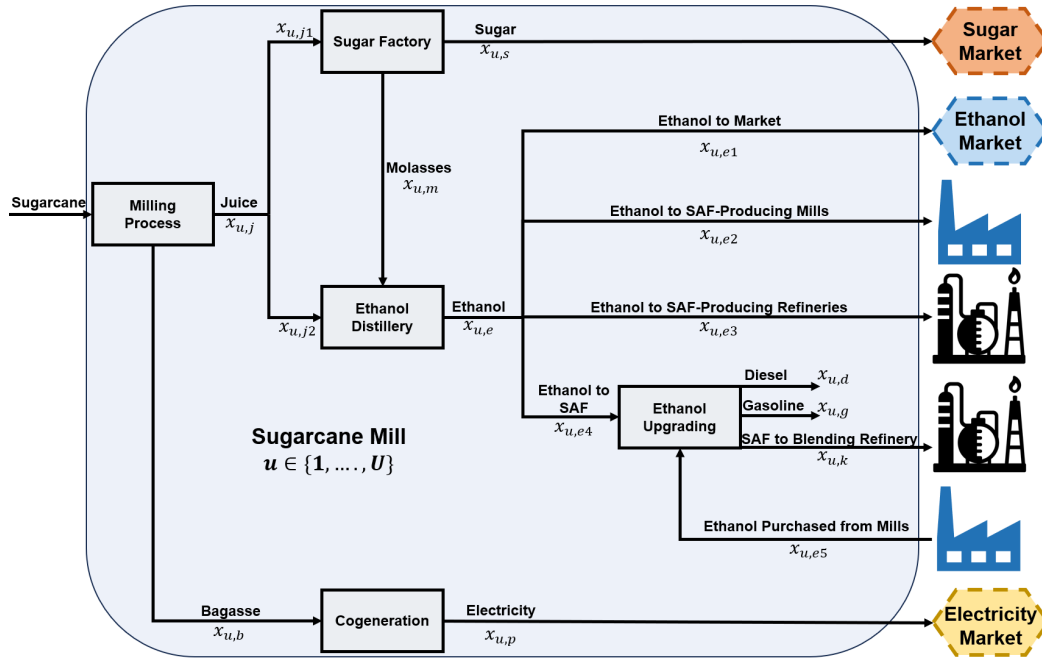


Figure 3: Process flow diagram for sugarcane mill u . Rectangles represent process units and the variables $x_{u,i}$ refer to the production of product i at a given mill u .

268 The ethanol produced at sugarcane mill u has four potential destinations:
 269 the market, SAF-producing mills, SAF-producing refineries, and onsite in-
 270 tegrated SAF production. Additionally, each sugarcane mill u can invest in
 271 SAF capacity, and each SAF-producing mill can purchase ethanol from non-
 272 SAF-producing mills nearby to increase the total ATJ capacity (individual
 273 ATJ capacity investments are limited to 700,000 m³ of SAF per year). SAF-
 274 producing mills include integrated aviation fuel production from internally
 275 produced and purchased ethanol, considering an ATJ process that produces
 276 a mixture of gasoline, diesel, and bio-jet fuel. The distribution of ethanol to
 277 the market for ground transportation is approximated to occur via refineries,
 278 which handle further distribution to consumers. This configuration is based
 279 on Brazil’s current ethanol distribution system, in which sugarcane mills de-
 280 liver ethanol to refineries or distribution depots (which are usually located
 281 alongside refineries).

282 Supporting Information (SI) Section S2.1 defines the mathematical con-
 283 straints that model each sugarcane mill. Equations S4-S14 represent the
 284 linear mass balances of each mill.⁵² Mill productivity is represented by in-
 285 stalled processing capacity rather than historical utilization rates. Conse-
 286 quently, the model assumes a total of 816 Mt year⁻¹ of sugarcane processing
 287 across all mills in the supply chain, representing an overestimation of roughly
 288 23% relative to the 661 Mt historical production for the 2023/2024 harvest
 289 season.⁵³

290 Equations S15-S17 impose lower bounds on sugar and ethanol production
 291 at each annexed mill, modeling the typical ethanol-to-sugar ratio range of
 292 40% to 60%. Equations S18 and S19 represent the linear mass balances on
 293 ethanol transportation between mills. Equations S20 and S21 represent the
 294 restrictions on ethanol purchasing and selling to produce SAF.

295 The yes/no decision to invest in SAF capacity is represented by a binary
 296 decision variable, y_u , where $y_u = 1$ is yes and $y_u = 0$ is no for mill u . The
 297 binary variable is used to bound the production of SAF (represented by the
 298 subscript k) at mill u , $x_{u,k}$, using a big-M constraint (Equation 1):

$$\underline{M} y_u \leq x_{u,k} \leq \overline{M} y_u, \quad \forall u \in \mathcal{U} \quad (\text{Mill SAF Capacity Investment}) \quad (1)$$

299 The upper bound of $\overline{M} = 700,000$ m³ of SAF per year reflects the largest
 300 single-facility ATJ capacity considered in the literature.¹⁹ The lower bound
 301 of $\underline{M} = 28,000$ m³ per year represents a minimum economic plant size, ob-
 302 tained as the smallest mill in our dataset (1,000,000 t of sugarcane per year)
 303 converting all of its ethanol to SAF.

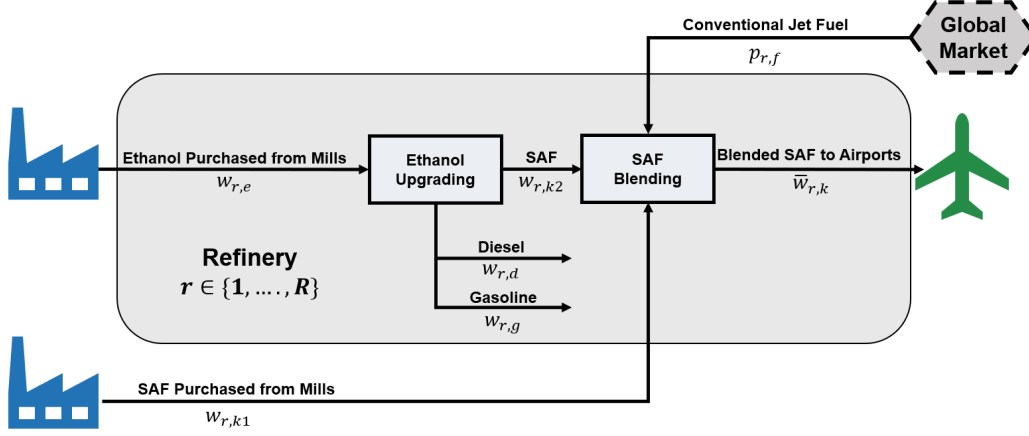


Figure 4: Process flow diagram for refinery r . Rectangles represent process units, the variables $w_{r,i}$ represent the total volume in refinery r of species i , variables $p_{r,f}$ represent the volume of conventional jet fuel blended with SAF at refinery r , and the variables $\bar{w}_{r,k}$ represent the volume of blended SAF produced at refinery r .

304 Furthermore, because SAF costs are not competitive with fossil-based
 305 jet fuel, requiring mills to invest in SAF without subsidies could result in
 306 negative profits. Equation 2 avoids this by ensuring each mill has a positive
 307 annual profit (Θ_u). The mill profit calculation is defined with the investor
 308 formulation below.

$$\Theta_u \geq 0, \quad \forall u \in \mathcal{U} \quad (\text{Positive Mill Profits}) \quad (2)$$

309 Stage 2: Refineries

310 Refineries blend SAF with conventional fossil-based jet fuel to a specified
 311 SAF fraction (η), with a maximum blend volume of 50% SAF. Each refinery,
 312 r (Figure 4), can purchase SAF from SAF-producing mills in Stage 1 to
 313 blend with fossil-based jet fuel produced onsite. Additionally, each refinery
 314 can invest in ATJ capacity and purchase ethanol from non-SAF-producing
 315 sugarcane mills in Stage 1 to produce SAF in Stage 2.

316 SI Section S2.2 defines the mathematical constraints that model each
 317 refinery. Equations S23 to S26 represent the material balances between Stage
 318 1 and Stage 2 for ethanol and SAF transactions. Equation S22 restricts
 319 ethanol sales from SAF-producing mills. Equations S27 to S31 represent the
 320 linear mass balances of each refinery.

321 The yes/no decision to invest in SAF capacity is represented by the binary

322 decision variable z_r , where $z_r = 1$ is yes and $z_r = 0$ is no for refinery r . The
 323 binary variable is used to bound the production of SAF at refinery r , $w_{r,k}$,
 324 using a big-M constraint (Equation 3):

$$\underline{M} z_r \leq w_{r,k} \leq \overline{M} z_r, \quad \forall r \in \mathcal{R} \quad (\text{Refinery SAF Capacity Investment}) \quad (3)$$

325 *Stage 3: Demand Fulfillment*

326 All blended SAF from Stage 2 is transported to each airport in Stage 3.
 327 The supply of blended SAF, $\overline{w}_{r,k}$, leaving each refinery r , is constrained to
 328 meet the mandated SAF blend requirement, in which a fraction (η) of the
 329 aviation fuel delivered to each airport (up to 50% by volume) must be SAF.
 330 Equation 4 represents the volume of blended SAF, $\chi_{r,a}$, sold from refinery
 331 r to airport a . Equation 5 represents the demand fulfillment, D_a^k , for each
 332 airport a in Stage 3.

$$\overline{w}_{r,k} = \sum_{a \in \mathcal{A}} \chi_{r,a}, \quad \forall r \in \mathcal{R} \quad (\text{Blended SAF to Airports Sum}) \quad (4)$$

333

$$D_a^k = \sum_{r \in \mathcal{R}} \chi_{r,a}, \quad \forall a \in \mathcal{A} \quad (\text{SAF Demand Fulfillment}) \quad (5)$$

334 Equation 6 ensures that the sum over sugar produced, $x_{u,s}$, at each mill u
 335 meets a minimum demand, D^s , of 44 Mt (based on 2023 production levels⁵³).
 336 Additionally, we assume that the sugar quantity can be supplemented by
 337 sugar purchased from the global market (imports), p_s .

$$\sum_{u \in \mathcal{U}} x_{u,s} + p_s \geq D^s \quad (\text{Sugar Demand Fulfillment}) \quad (6)$$

338 Furthermore, we ensure that total ground transportation demand is met,
 339 as gasoline is required to replace the ethanol that would otherwise have been
 340 destined for the Brazilian fleet and is now converted into SAF. The total
 341 ground transportation demand, D^t , is estimated as a total energy demand
 342 (1.74 billion (B) GJ) using the total volume of hydrous ethanol and gasoline
 343 C (a 75% gasoline and 25% anhydrous ethanol blend) consumed in Brazil in
 344 2023, 16 and 46 Mm³, respectively³⁰ and the energy densities of ethanol (γ_e)
 345 and gasoline C (γ_g), 21,200 and 29,520 MJ m⁻³, respectively.⁵⁴ Throughout
 346 this work γ_e and the ATJ conversion $\theta_{e,k}$ are expressed on a *hydrous* ethanol
 347 basis (SI Section S4.9.1). The ground transportation demand can be fulfilled

by ethanol sent to the market (represented by subscript $e1$), $x_{u,e1}$, from mills; domestic corn ethanol, p_e ; gasoline produced as a byproduct of SAF in mills, $x_{u,g}$, and refineries, $w_{r,g}$; and gasoline from the global market, p_g (Equation 7). The domestic corn ethanol is constrained to 2023 production levels (τ_e), estimated as 6 Mm³³⁰ (Equation 8).

$$(p_e + \sum_{u \in \mathcal{U}} x_{u,e1})\gamma_e + (p_g + \sum_{u \in \mathcal{U}} x_{u,g} + \sum_{r \in \mathcal{R}} w_{r,g})\gamma_g \geq D^t \quad (7)$$

(Ground Transportation Demand Fulfillment)

$$p_e \leq \tau_e \quad (\text{Upper Bound on Ethanol Available for Purchase}) \quad (8)$$

Objectives for Decision-Making Perspectives

For the optimal design of the supply chain, we consider three optimization formulations: a central planner without incentives, an investor without incentives, and an investor with incentives (Table 1).

Central Planner: Minimize Total System Cost.

Cases 1 and 2 minimize the total supply chain cost. The costs considered in our supply chain network include operating costs (OPEX), capital costs (CAPEX), logistics costs (transportation), and additional costs incurred when sourcing products from global markets to ensure demand is met. We consider a piece-wise linear approximation of the CAPEX scaling equation to estimate the total CAPEX for mill u , Ω_u^U , and refinery r , Ω_r^R (Equations S32-S41). ATJ capacity investments at sugarcane mills are assumed to be brownfield using a reference CAPEX of 167 M R\$ estimated by Geleynse et al.⁴² considering a reference SAF capacity of 35,000 m³. ATJ capacity investments at refineries are considered greenfield, estimated using a 50% larger reference CAPEX (251 M R\$).

The total supply chain OPEX, Λ , is calculated as the sum of the total sugarcane mill OPEX contribution (Λ^U) and the total refinery OPEX contribution (Λ^R). The sugarcane mill OPEX contribution (Equation 9) considers the yearly cost to produce sugar, ethanol, SAF, and electricity. The refinery OPEX contribution (Equation 10) considers only the yearly cost to produce SAF. The parameters λ_i refer to the production cost of product i . Table 2 lists the nominal production cost parameter values.

$$\Lambda^U = \sum_{u \in \mathcal{U}} [\lambda_s x_{u,s} + \lambda_e x_{u,e} + \lambda_k^{brown} x_{u,k} + \lambda_p x_{u,p}] \quad (\text{Mill OPEX}) \quad (9)$$

Table 2: Nominal production cost parameter values. Data from Mutran et al.⁵⁵ except λ_k^{brown} and λ_k^{green} , which are from Geleynse et al.⁴²

Symbol	Description	Nominal Value
λ_s	Sugar production cost	1,150 $\frac{\text{R\$}}{\text{t s}}$
λ_e	Ethanol production cost	1,800 $\frac{\text{R\$}}{\text{m}^3 \text{ e}}$
λ_k^{brown}	Integrated SAF production cost	870 $\frac{\text{R\$}}{\text{m}^3 \text{ k}}$
λ_k^{green}	SAF production cost	1,130 $\frac{\text{R\$}}{\text{m}^3 \text{ k}}$
λ_p	Electricity production cost	7 $\frac{\text{R\$}}{\text{MWh}}$

377

$$\Lambda^R = \sum_{r \in \mathcal{R}} \lambda_k^{green} w_{r,k} \quad (\text{Refinery OPEX}) \quad (10)$$

378 The supply chain total logistics cost, Φ , is calculated as the sum of Stage
379 1, Φ_1 (mills to refineries), and Stage 2, Φ_2 (refineries to airports), transporta-
380 tion costs. The Stage 1 logistic cost (Equation 11) consists of transportation
381 of ethanol from mill u to SAF-producing mill j ($\omega_{u,j}$), transportation of
382 ethanol to refineries ($\nu_{u,r}$), and transportation of SAF to refineries ($\rho_{u,r}$).
383 The parameters $d_{u,j}$ and $d_{u,r}$ represent the distance between mill u and mill
384 j and the distance between mill u and refinery r , respectively. The Stage
385 2 logistic cost (Equation 12) consists of the transportation of blended SAF
386 from refineries to airports. The parameters $d_{r,a}$ represent the distance from
387 refinery r to airport a , the parameter δ ($0.16 \text{ R\$ km}^{-1} \text{ m}^{-3}$) represents the
388 variable transportation cost of SAF and ethanol, and the parameter ψ (17.82
389 $\text{R\$ m}^{-3}$) represents the fixed transportation cost of ethanol and SAF. These
390 average transportation costs are taken from the appendix of the Brazilian
391 Resolution for Freight Prices⁵⁶ and reflect shipment distance and volume;
392 regional variations in road quality, terrain, and transportation infrastruc-
393 ture are not explicitly represented. The distances between each stage were
394 estimated using the Haversine distance formula (see SI Section S1), which
395 calculates the distance between two points on a sphere from their longitude
396 and latitude.

$$\begin{aligned}
\Phi_1 = & \underbrace{\sum_{u \in \mathcal{U}} \sum_{j \in \mathcal{U}} \delta d_{u,j} \omega_{u,j} + \psi \omega_{u,j}}_{\text{mill to mill transport (ethanol)}} \\
& + \underbrace{\sum_{u \in \mathcal{U}} \sum_{r \in \mathcal{R}} [\delta d_{u,r} (\nu_{u,r} + \rho_{u,r}) + \psi (\nu_{u,r} + \rho_{u,r})]}_{\text{mill to refinery transport (ethanol and SAF)}} \quad (\text{Stage 1 Logistic Cost})
\end{aligned} \tag{11}$$

$$\begin{aligned}
\Phi_2 = & \underbrace{\sum_{r \in \mathcal{R}} \sum_{a \in \mathcal{A}} [\delta d_{r,a} \chi_{r,a} + \psi \chi_{r,a}]}_{\text{refinery to airport (blended SAF)}} \quad (\text{Stage 2 Logistic Cost})
\end{aligned} \tag{12}$$

The total additional cost of the supply chain, Δ , (Equation 13) is calculated as the cost of purchasing ethanol, sugar, conventional jet fuel, and gasoline from the global market to meet demand. Specifically, we introduce a penalty cost equal to the 2023 average gasoline price⁵⁷ for the gasoline needed to replace the ethanol that would have been destined for the Brazilian fleet and is now converted into SAF. The parameters π_i refer to the market price of product i . Table 3 lists the nominal prices and the data sources. We consider the average Brazilian market price for the period from September 2023 to October 2024. The prices were available weekly and aggregated by their means, discounted by the Brazilian Inflation index IPCA.⁵⁸ Watson et al.⁵² provide details on the price discount procedure.

Table 3: Nominal product prices of sugar, ethanol, jet fuel, gasoline, and electricity

Symbol	Description	Nominal Value
π_s	Sugar price ⁵⁹	2,940 $\frac{\text{R\$}}{\text{t s}}$
π_e	Ethanol price ⁶⁰	2,280 $\frac{\text{R\$}}{\text{m}^3 \text{e}}$
π_f	Conventional jet fuel price ⁵⁷	4,130 $\frac{\text{R\$}}{\text{m}^3 \text{f}}$
π_g	Gasoline price ⁵⁷	2,600 $\frac{\text{R\$}}{\text{m}^3 \text{g}}$
π_p	Electricity price ⁶¹	324 $\frac{\text{R\$}}{\text{MWh}}$

$$\Delta = \underbrace{\pi_s p_s}_{\text{sugar}} + \underbrace{\pi_f \sum_{r \in \mathcal{R}} p_{r,f}}_{\text{jet}} + \underbrace{\pi_e p_e}_{\text{ethanol}} + \underbrace{\pi_g p_g}_{\text{gasoline}} \quad (\text{Additional Costs}) \quad (13)$$

Thus, this optimization formulation minimizes the total system cost (Equation 14):

$$\begin{aligned} \min \quad & \Lambda + \Phi + \Delta + \sum_{u \in \mathcal{U}} \Omega_u^U + \sum_{r \in \mathcal{R}} \Omega_r^R \\ \text{s.t.} \quad & \text{Eqs. (1) to (8)} \\ & \text{Eqs. (S4) to (S41)} \end{aligned} \quad (14)$$

As passed to the solver (before presolve), each instance of the MILP contains 147,507 continuous variables, 3,319 binary variables, 6,727 equality constraints, and 8,870 inequality constraints. Cases with ATJ investments at refineries instead fix the 335 mill investment variables and therefore contain 2,993 binary variables.

Investor: Maximize Total Mill Profits.

Alternatively, Cases 3 and 4 maximize total sugarcane mill profits (Equation 16). The total sugarcane mill profits are calculated as the difference between the total revenue of all mills (Equation 15) and the total mills' CAPEX, OPEX, and logistic costs (Stage 1). We assume the price of SAF equals the market price of conventional jet fuel, plus a premium paid by airlines or mandated by policy.

$$\begin{aligned} \Pi = \sum_{u \in \mathcal{U}} \left[\underbrace{\pi_s x_{u,s}}_{\text{sugar}} + \underbrace{\pi_e (x_{u,e1} + x_{u,e2} + x_{u,e3} - x_{u,e5})}_{\text{ethanol}} \right. \\ \left. + \underbrace{(\pi_f + \pi^{prem}) x_{u,k}}_{\text{SAF}} + \underbrace{\pi_p x_{u,p}}_{\text{electricity}} \right] \end{aligned} \quad (15)$$

(Mill Revenue)

$$\Theta = \Pi - (\Lambda^U + \Phi_1 + \sum_{u \in \mathcal{U}} \Omega_u^U) \quad (\text{Total Mill Profits}) \quad (16)$$

Equation 17 shows the optimization formulation. As passed to the solver (before presolve), each instance of the MILP contains 147,507 continuous

426 variables, 3,319 binary variables, 6,727 equality constraints, and 8,870 in-
 427 equality constraints.

$$\begin{aligned}
 &\max \quad \Theta \\
 &\text{s.t.} \quad \text{Eqs. (1) to (8)} \\
 &\quad \text{Eqs. (S4) to (S41)}
 \end{aligned} \tag{17}$$

428 *Recommended Incentives.*

429 In Case 5, which determines the necessary incentives for SAF supply
 430 chains, we consider a third optimization formulation. This formulation takes
 431 the perspective of an investor seeking to maximize sugarcane mill profits;
 432 however, we do not impose any SAF production constraints (neither upper
 433 nor lower system-wide bounds on SAF) and use SAF premium prices to
 434 determine the incentive to produce SAF favorably. Equation 18 shows the
 435 optimization formulation. As passed to the solver (before presolve), each
 436 instance of the MILP contains 147,842 continuous variables, 3,319 binary
 437 variables, 6,727 equality constraints, and 8,870 inequality constraints.

$$\begin{aligned}
 &\max \quad \Theta \\
 &\text{s.t.} \quad \text{Eqs. (1) to (4)} \\
 &\quad \text{Eqs. (6) to (8)} \\
 &\quad \text{Eqs. (S4) to (S41)}
 \end{aligned} \tag{18}$$

438 *Integer Cut Analysis*

439 Cases 1 through 4 and the integer cut analysis were computed using a
 440 MIP gap of 0.003%; the mill-specific incentive study used 0.03%, and Case
 441 5 and the sensitivity scenarios used 0.05%. The MIP gap (mixed-integer
 442 programming gap) measures how close the best integer (feasible) solution
 443 is to the best possible continuous (relaxed) solution. This gap is typically
 444 expressed as a percentage, with a smaller gap indicating that the best solution
 445 is closer to the lower bound. For both decision-making perspectives, the
 446 total objective values are on the order of hundreds of billions of R\$ per
 447 year. In contrast, the CAPEX for the smallest ATJ investment permitted in
 448 this analysis (28,008 m³ of SAF) is 7.3 M R\$ year⁻¹, approximately 0.003%
 449 of the largest objective value (corresponding to the chosen MIP gap). The
 450 difference in logistics costs between potential investment sites is even smaller,
 451 averaging $\sim 1 \times 10^5$ R\$ year⁻¹, and is not captured in the MIP gap to avoid

excessive computational time. The choice of MIP gap, therefore, matters most when selecting specific locations. Total costs, production volumes, and emissions are dominated by operating expenditures and are correspondingly insensitive to the gap.

For the supply chain design, there are numerous optimal solutions within the chosen MIP gap of the optimization solver. For investments at refineries, the chosen MIP gap is less limiting in determining the optimal SAF investment sites than for mills, as there are fewer potential locations (nine total) and the refineries are adequately spaced from one another. Even so, because blending is inexpensive and the logistic differences between refineries are small, refinery assignments should also be interpreted as one of many near-equivalent configurations. On the contrary, for SAF investments at sugarcane mills, there are 335 potential investment sites, with the shortest distance between mills in our dataset being less than 3 km. Thus, for Cases 1 and 3 (each decision-making perspective for upgrading at mills), ten optimal solutions within the chosen MIP gap were identified via an integer-cut analysis. In this analysis, after each solve, an additional constraint (a no-good cut) was added to the optimization model to exclude previously found integer solutions and force the solver to search for new ones. This process continued until ten optimal solutions were obtained (ten iterations). SI Section S3 provides more details on this methodology, and SI Equation S42 describes the no-good cut constraint.

Results and Discussion

We summarize the key findings from optimizing the supply chain network considering different objective functions, investment locations, SAF blend requirements, and incentives.

Sensitivity to the Decision-making Paradigm and SAF Blend Requirement

The decision-making perspective strongly influences the mills' optimal product portfolio. Figure 5 summarizes the main product flows, estimated emissions, total cost, and total profit of the optimal solutions of Cases 1 through 4 solved at SAF blend requirements from 0% (reference case) to 50% in increments of 10%, resulting in 24 total model instances.

The total system cost when minimizing costs is approximately 12 B R\$ less than that when maximizing profits. On the contrary, the maximizing

profit cases generate approximately 15 B R\$ more in total mill profits (Figure 5h and 5i). Furthermore, refinery-based SAF capacity leaves mill profits unaffected, whereas sugarcane mill-based capacity reduces profits as SAF blend requirements increase. Installing SAF capacity at refineries always increases the system cost relative to installing it at mills; however, the difference is less than 0.4% of the total system cost. It is important to note that this analysis overlooks the actual impacts of integrating SAF production with refineries, including effects on overall profit, because revenue streams and total mass and energy flows are not readily available for all refineries.

As expected, maximizing total mill profits favors sugar production over the less profitable products, ethanol and unincentivized SAF. On the contrary, minimizing total costs maximizes ethanol production, thereby reducing the amount of gasoline purchased to meet ground transportation fuel demand. The perspective of an investor results in an additional 10 Mt of sugar available for exports (Figure 5a). The increased sugar production when maximizing total mill profits results in 6 Mm³ less ethanol production and 4.3 Mm³ more gasoline purchased annually compared to the perspective of a central planner (Figure 5b and 5d). Given that gasoline is used to meet the remaining ground transportation demand, this difference in perspectives results in more than 6 Mt of CO₂ per year (Figure 5e). This scenario yields results closer to the current ethanol and sugar production mix and is more likely under current policies.

Additionally, the total sugar production does not vary with the SAF blend requirement (Figure 5a). Increasing total SAF production to 50% of current jet fuel demand does not affect Brazil’s annual sugar (food) supply. On the contrary, Brazil’s installed ethanol production capacity is sufficient to meet SAF demand; however, the remaining ethanol supply for ground transportation is limited. Because the analysis assumes mills operate at their installed processing capacity, these results represent the upper bound of SAF production achievable with the existing infrastructure and highlight the long-term potential of the Brazilian sugarcane industry.

Key Finding 1: The emissions reductions from a 50% SAF blend are offset by the emissions increase from increased gasoline consumption in ground transportation, resulting in an emissions increase of 2.7 Mt CO₂ year⁻¹ in Brazil compared to a 0% SAF baseline. While Brazil’s installed ethanol capacity can satisfy domestic SAF demand, fulfilling this demand requires reallocating ethanol away from ground transportation. A 50% SAF blend requires 5.2 Mm³ of ethanol, requiring an additional 3.4 Mm³ of gasoline

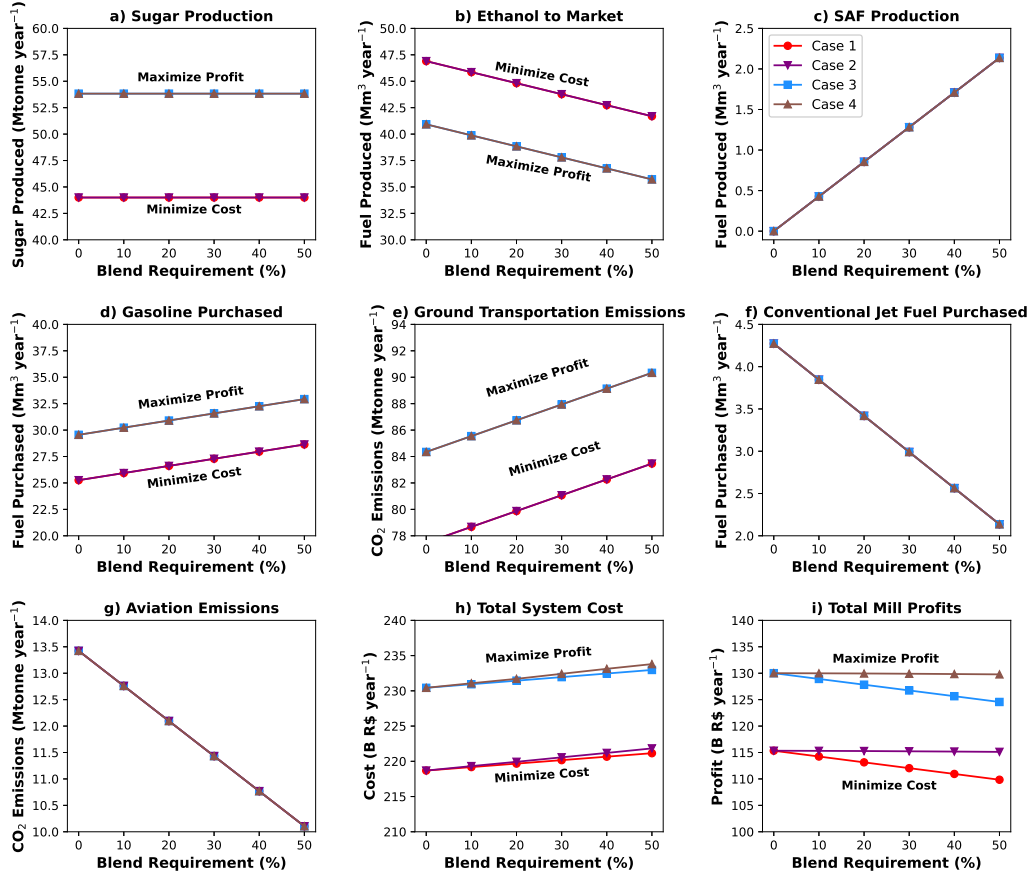


Figure 5: Nine figures summarizing the production or purchase amounts of (a) sugar, (b) ethanol for ground transportation, (c) SAF, (d) gasoline, and (f) conventional jet fuel; the estimated emissions from (e) ground transportation and (g) aviation; (h) the total system cost; and (i) the total mill profits within the supply chain solved for an increasing SAF blend requirement from 0% to 50% in increments of 10% with no incentives. Four case studies were considered, testing two decision-making perspectives and two investment locations. Case 1: (red) central planner w/o incentives, ATJ investments at sugarcane mills. Case 2: (purple) central planner w/o incentives, ATJ investments at refineries. Case 3: (blue) investor w/o incentives, ATJ investments at sugarcane mills. Case 4: (brown) investor w/o incentives, ATJ investments at refineries. The 0% SAF blend serves as the reference case for each of the first four case studies. Figure S21 in SI Section S7 presents a total system cost breakdown for each of the first four case studies.

524 purchased, annually compared to a 0% SAF baseline (Figure 5b and 5d).
 525 Replacing bioethanol with gasoline for ground transportation is a suitable
 526 option to balance energy demands; however, bioethanol has a much lower
 527 carbon intensity than gasoline ($21.3 \text{ gCO}_2 \text{ MJ}^{-1}$ ⁶² and $75.5 \text{ gCO}_2 \text{ MJ}^{-1}$,³²
 528 respectively). Thus, this fuel substitution leads to an additional 6.0 Mt CO_2
 529 year^{-1} from ground transportation (Figure 5e). We estimate that the com-
 530plementary reduction of aviation emissions of a 50% SAF blend, compared to
 531 a 0% SAF baseline, is $3.3 \text{ Mt CO}_2 \text{ year}^{-1}$, considering a SAF carbon intensity
 532 of $45 \text{ gCO}_2 \text{ MJ}^{-1}$ (Figure 5g). These estimates underscore the need to in-
 533clude life cycle analysis (LCA) in policy decisions. SI Section S4 documents
 534 all emission calculations.

535 If the ground transportation fleet in Brazil is slow to electrify, ATJ tech-
 536nological improvements are necessary for sugarcane ethanol-based SAF to
 537reduce net transportation (aviation and light-duty ground transportation sec-
 538tors) emissions relative to a 0% SAF baseline. Figure 6 quantifies the ATJ
 539technology targets for two key parameters required to reduce net transporta-
 540tion CO_2 emissions (relative to a 0% SAF baseline) in Brazil: the ethanol-
 541to-SAF conversion rate (which controls the volume of ethanol diverted from
 542ground transportation) and the SAF emissions (which control the mass of
 543 CO_2 avoided by using SAF). For this sensitivity analysis, coproduct produc-
 544tion in the ATJ process (diesel and gasoline) was assumed to be zero, and
 545the derivation of the theoretical maximum SAF conversion is provided in SI
 546Section S5.1. Figure 6 also shows sugarcane-based ATJ process parameters
 547from five recent LCA studies (circle markers).^{7,63–66} At the nominal ATJ
 548conversion ($0.41 \text{ m}^3 \text{ SAF m}^{-3} \text{ ethanol}$), a 79% reduction in SAF LCA emis-
 549sions is required for SAF adoption to be carbon neutral across the aviation
 550and light-duty ground transportation sectors relative to a 0% SAF baseline.
 551Similarly, with nominal SAF emissions ($45 \text{ gCO}_2 \text{ MJ}^{-1}$), the ATJ conversion
 552needs to increase by 80%, which lies above the theoretical maximum derived
 553in SI Section S5.1; carbon neutrality at nominal SAF emissions therefore
 554requires lowering the life-cycle emissions of the delivered fuel, not conver-
 555sion improvement alone. By carefully setting upper bounds on the life-cycle
 556emissions of delivered SAF, improving the ATJ technology, encouraging car-
 557bon capture, and coupling SAF production with the electrification of ground
 558transportation, SAF can help Brazil decarbonize.

559 The markers in Figure 6 are not all on a common coproduct accounting
 560basis: the nominal case charges the entire feedstock and process burden to
 561SAF, consistent with the zero-coproduct assumption above, whereas the five

562 literature studies credit their coproducts by allocation or displacement. The
 563 two vertical dashed lines mark ICAO's CORSIA default intensities for this
 564 pathway, at which a net emissions reduction would require ATJ conversions
 565 of 0.50 and 0.58 rather than 0.74. See SI Section S4.9 for details.

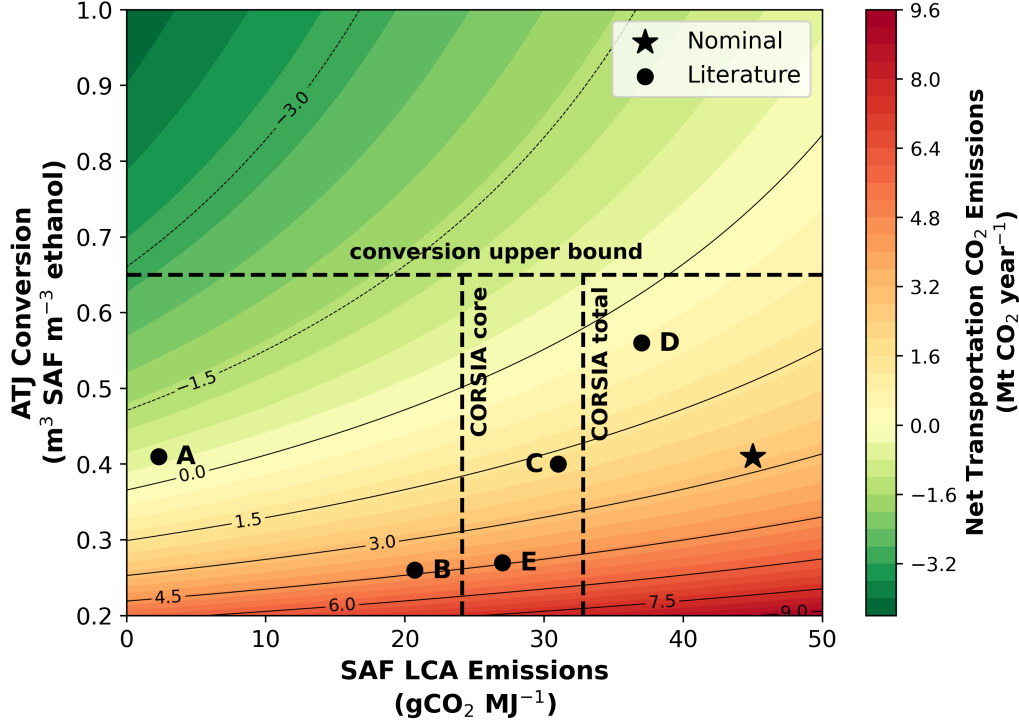


Figure 6: Sensitivity of the net CO₂ emissions under a hypothetical scenario of a 50% SAF blend compared to the present (0% SAF) as a function of ATJ conversion and SAF emissions. Green indicates net-negative emissions (emissions reduction) while red indicates net-positive emissions (emissions increase). The black star is the nominal case (ATJ conversion of 0.41 m³ SAF m⁻³ ethanol and SAF emissions of 45 gCO₂ MJ⁻¹). Circles A–E are five additional life cycle studies of the sugarcane-based ATJ process, listed in that order in SI Table S2.^{7,63–66} The horizontal dashed line marks the theoretical maximum ethanol-to-SAF conversion derived in SI Section S5.1; the two vertical dashed lines mark ICAO's CORSIA default life cycle emissions for this pathway, 24.1 and 32.8 gCO₂e MJ⁻¹.⁶⁷ SI Section S4.9 derives every plotted value from the primary data.

566 *Investment Locations in the Optimal Supply Chain Design*

567 Figure 7 explores the optimal locations of SAF-producing mills (green
 568 circles), ethanol-supplying mills (blue triangles), and SAF-producing and/or

569 blending refineries (black squares) for Cases 1 through 4, considering a 50%
570 SAF blend requirement. Table 4 summarizes the total number of each facility
571 type and the total distance traveled between each supply chain stage for each
572 case. All transportation metrics are reported as Mt·km, corresponding to the
573 movement of one Mt of material over a distance of one km. São Paulo has
574 a high number of SAF investments, as this state has the highest sugarcane
575 capacity and the highest jet fuel demand.

Table 4: The total number of SAF-producing mills (green circles), ethanol-supplying mills (blue triangles), and refineries (black squares), and the total mass-distance traveled in each stage for Cases 1 to 4 considering a 50% SAF blend requirement.

Case Study	SAF Mills	Ethanol Suppliers	SAF Refineries	Stage 1 (Mt·km)	Stage 2 (Mt·km)	Total (Mt·km)
1	7	27	6	489	316	805
2	0	40	7	608	446	1,054
3	6	38	1	325	878	1,203
4	0	55	6	653	1,282	1,935

576 For investments at sugarcane mills, the optimal supply chain design un-
577 der the central planner formulation (Case 1) recommends seven ATJ facil-
578 ities distributed across São Paulo (four) and the Northeast (three). This
579 particular configuration is one of several near-equivalent designs with the
580 same number and total capacity of facilities, but the selected mills differ,
581 resulting in a total transportation mass-distance of 805 Mt·km. In contrast,
582 the investor formulation (Case 3) recommends six ATJ facilities, all located
583 in São Paulo, yielding a higher total transportation mass-distance of 1,203
584 Mt·km. This concentration in São Paulo is driven by the region’s high den-
585 sity of large-capacity sugarcane mills, close proximity to existing refinery
586 infrastructure, and strong SAF demand associated with major population
587 centers and airports. When considering refinery-based investments, the cen-
588 tral planner (Case 2) selects seven ATJ facilities with a total transportation
589 mass-distance of 1,054 Mt·km, whereas the investor formulation (Case 4) se-
590 lects six facilities with a substantially higher transportation mass-distance of
591 1,935 Mt·km.

592 These differences arise because the investor formulations only account for
593 Stage 1 logistics, as profits are calculated at the mill level and therefore in-
594 clude moving ethanol from sugarcane mills to SAF production facilities and,
595 for mill-based SAF production, transporting SAF from the mill to the blend-

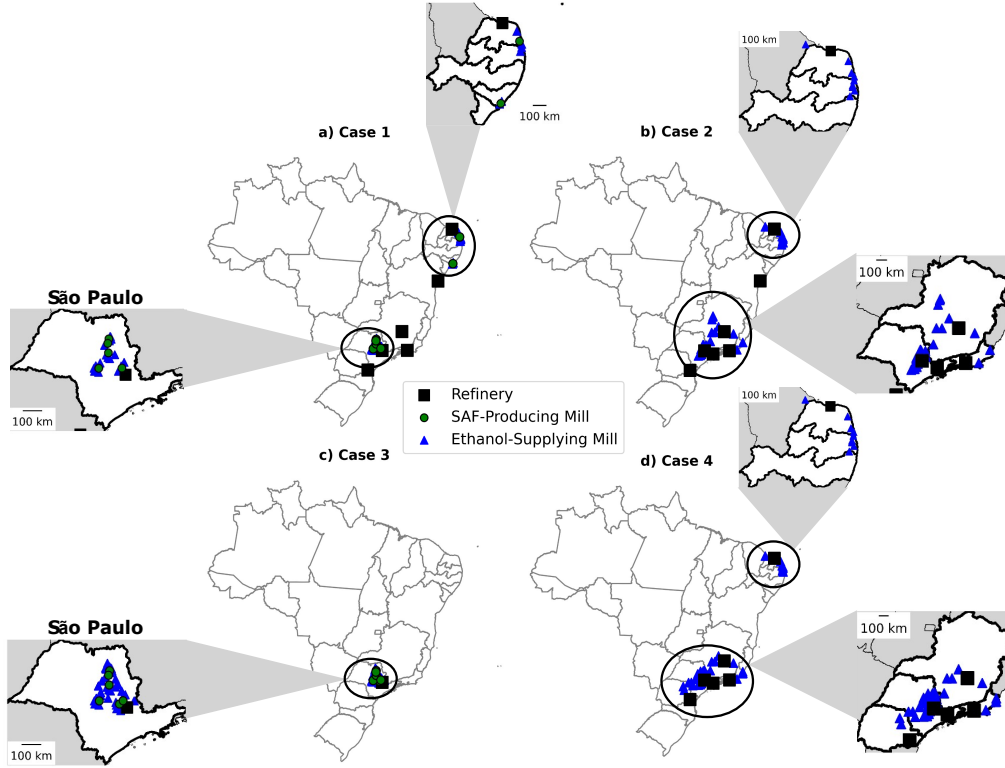


Figure 7: Four maps showing the optimal locations of SAF-producing mills (green circles), ethanol-supplying mills (blue triangles), and refineries (black squares) considering a 50% SAF blend requirement. (a) Case 1: central planner w/o incentives, ATJ investments at sugarcane mills. (b) Case 2: central planner w/o incentives, ATJ investments at refineries. (c) Case 3: investor w/o incentives, ATJ investments at sugarcane mills. (d) Case 4: investor w/o incentives, ATJ investments at refineries. Figures S1 to S20 in SI Section S6 show results for 10, 20, 30, and 40% blend requirements and full supply chain connections.

596 ing site. As a result, proximity to ethanol-supplying mills becomes the pri-
 597 mary siting criterion, while downstream transportation associated with SAF
 598 blending and distribution is not considered in the objective. Consequently,
 599 for mill-based investments, Case 3 achieves substantially lower Stage 1 trans-
 600 portation requirements (325 Mt·km) than Case 1 (489 Mt·km) by concentrat-
 601 ing facilities near ethanol production. Similarly, refinery-based investments
 602 in Case 4 result in only slightly higher Stage 1 transportation requirements
 603 (653 Mt·km) than Case 2 (608 Mt·km). However, the geographically concen-
 604 trated infrastructure selected under the investor formulations increases

605 downstream transportation distances, resulting in higher overall transporta-
606 tion requirements despite improved Stage 1 logistics.

607 Next, we consider the sensitivity of the optimal locations. Figure 8
608 presents ten alternative solutions within a 0.003% MIP gap (i.e., optimization
609 solver tolerance) for Cases 1 and 3 (each decision-making perspective for SAF
610 investments at mills), considering a 50% SAF blend requirement. A complete
611 tabulation of the results presented in Figure 8, including the selected SAF-
612 producing mills for each cut iteration and the associated supply chain costs
613 and profits, is available in the spreadsheet `integer_cut_organized_data`,
614 included in the SI. For investments at refineries (Cases 2 and 4), there is no
615 expected variation in the selected refinery within the 0.003% MIP gap. On
616 the contrary, for SAF investments at sugarcane mills, there are 335 potential
617 investment sites, with the shortest distance between mills less than 3 km.
618 Figure 8 highlights the locations of SAF investments and the percentage of
619 times each location was selected in a quality solution (color gradient). The
620 Methods section details the optimization model.

621 *Key Finding 2: Figure 8 reveals three mills located in São Paulo—Raízen*
622 *Barra, São João de Araras, and São Martinho—that are essential to all con-*
623 *sidered SAF supply chain designs.* The three sugarcane mills are selected in
624 10 out of 10 (100%) optimal solutions for both decision-making perspectives.
625 These three mills all send SAF to Refinaria de Paulínia for blending and
626 delivery to eight airports in central Brazil, including two in São Paulo, which
627 has the largest jet fuel demand. Raízen Barra and São Martinho are the two
628 largest mills within a 160 km radius of Refinaria de Paulínia, and among the
629 largest in our dataset, each processing 5,500,000 t of sugarcane per year, the
630 maximum capacity in the dataset and one shared by seven mills. São João
631 de Araras is the largest mill within a 40 km radius of Refinaria de Paulínia,
632 processing 4,000,000 t of sugarcane per year. These three mills are essential
633 for SAF capacity expansion in Brazil.

634 *Recommended Incentives*

635 Next, we analyze supply chain costs and results to inform recommended
636 minimum incentives. There is minimal variation in additional supply chain
637 costs as a function of the SAF blend requirement across all case studies, as
638 OPEX is the dominant cost factor and scales linearly with SAF production
639 volume. Figure 9a shows the additional cost imposed on the supply chain
640 by producing SAF as a function of SAF blend requirement for Cases 1 to 4.
641 The additional cost for upgrading at mills is 1.15 R\$ L⁻¹ and for refineries

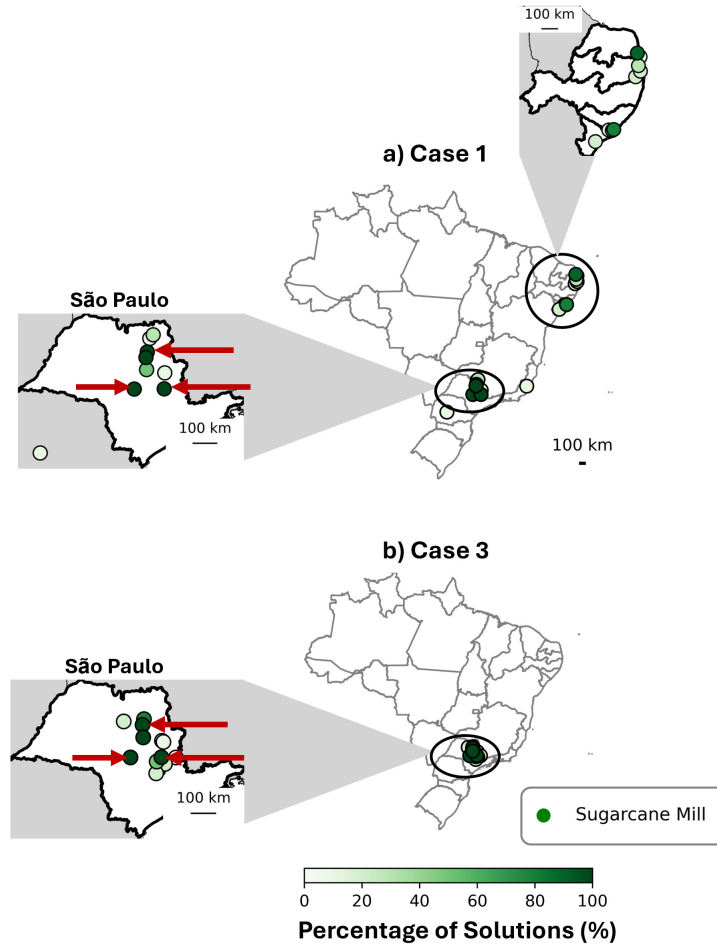


Figure 8: Two maps showing the percentage of times (color gradient) each ATJ investment location (green circles) for investments at mills is chosen among the ten optimal solutions for two case studies. (a) Case 1: central planner w/o incentives, ATJ investments at sugarcane mills. (b) Case 3: investor w/o incentives, ATJ investments at sugarcane mills. Zooms are provided for the state of São Paulo and the Northeast coast in Case 1 and for the state of São Paulo in Case 3. Red arrows point to three mills—Raízen Barra, São João de Araras, and São Martinho—located in São Paulo, which are chosen in 100% of optimal solutions regardless of the decision-making perspective.

642 is 1.5 R\$ L⁻¹. Furthermore, when comparing investment locations, the cost
 643 difference is small (0.35 R\$ L⁻¹), motivating shifting the economic burden
 644 from sugarcane mills to refineries with experience producing and distributing

645 jet fuel.

646 While the additional supply chain cost provides a useful estimate of the
 647 economic penalty associated with SAF production, it does not directly indicate the incentive required to make SAF investment attractive under a
 648 profit-maximizing objective. To estimate this incentive threshold, Figure 9b reports SAF production as a function of the SAF premium (incremented by
 649 0.1 R\$ L⁻¹) added to the conventional jet fuel price. This analysis corresponds to Case 5, in which SAF production is not mandated and no upper
 650 bound is imposed. The recommended SAF premium is defined as the minimum premium required for voluntary SAF production to reach at least 50%
 651 of Brazil's current jet fuel demand.
 652
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 654
 655 of Brazil's current jet fuel demand.

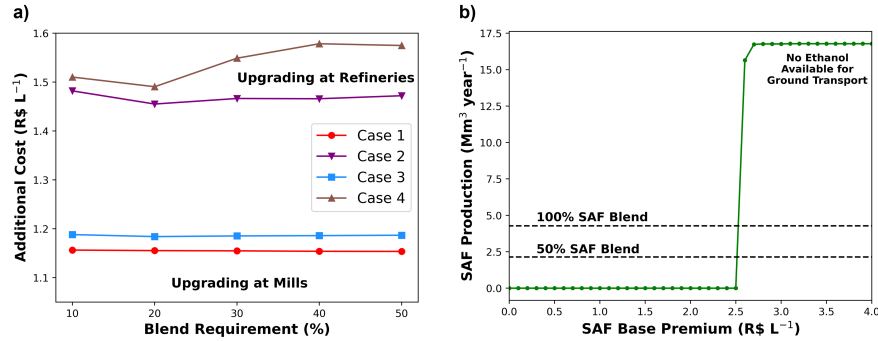


Figure 9: (a) The additional cost of SAF for Cases 1 to 4 compared to the reference case (0% required SAF blend) as a function of blend requirement for the four case studies. (b) The volume of SAF produced as a function of SAF premium price with no mandated SAF blend requirement (Case 5, no blend mandate, so SAF production is driven only by the premium). Case 1: (red) central planner w/o incentives, ATJ investments at sugarcane mills. Case 2: (purple) central planner w/o incentives, ATJ investments at refineries. Case 3: (blue) investor w/o incentives, ATJ investments at sugarcane mills. Case 4: (brown) investor w/o incentives, ATJ investments at refineries. Case 5: (green) investor w/ incentives.

656 *Key Finding 3: The recommended SAF premium price is 2.6 R\$ L⁻¹*
 657 *above conventional jet fuel to incentivize SAF production at sugarcane mills.*
 658 For a SAF premium between 0 R\$ L⁻¹ and 2.5 R\$ L⁻¹ no SAF production
 659 is observed; however, a sharp increase (15.6 Mm³) is observed at a premium
 660 of 2.6 R\$ L⁻¹, well above the 50% SAF blend requirement in Brazil (2.14
 661 Mm³). At a SAF premium of 3.1 R\$ L⁻¹, the maximum volume of SAF pro-
 662 duction available with the current installed sugarcane processing capacity,
 663 16.8 Mm³, is reached. This volume of SAF could be exported to contribute

approximately 36% of the global SAF capacity increase required to meet projected demand for 2030 under a net-zero emissions by 2050 scenario ($\sim 46 \text{ Mm}^3$). However, this volume of SAF production results in no ethanol available for ground transportation, leading to higher gasoline consumption and increased CO_2 emissions in the country. Thus, policymakers seeking decarbonization should consider limits on the volume of SAF incentivized until ground transportation can rely on other sustainable solutions, such as electrification.

The observed on/off behavior in SAF production is a consequence of the mathematical optimization structure and the underlying model assumptions. The CAPEX and logistics costs are small compared to the total supply chain operating cost (see SI Figure S21), meaning sugarcane mill profits are determined by the difference in price and production cost (value-add) multiplied by the volume of each product produced. Thus, within the linear optimization framework, there is a SAF price point (incentive) when the value-add of producing SAF is greater than selling ethanol to the market, thus shifting the mill's behavior to produce all SAF. If CAPEX or logistics costs contributed a larger fraction of the total cost, we would expect the curve to be less sharp, i.e., a more gradual slope.

The SAF price premium recommended by Case 5 to stimulate SAF production from sugarcane ethanol in Brazil is determined by the relative profitability of SAF compared with conventional sugarcane products. Consequently, the required incentive is inherently sensitive to changes in market prices of sugar, ethanol, and jet fuel, as well as ATJ technology parameters (production cost and conversion). To evaluate the robustness of the estimated incentive requirement, a sensitivity analysis was conducted in which key economic and process parameters were independently varied by $\pm 20\%$ from their baseline values. The recommended SAF premium for each perturbed scenario was determined as the minimum premium required for SAF production to satisfy at least 50% of the total jet fuel demand in Case 5. Figure 10 presents the sensitivity of the recommended SAF price premium as a tornado diagram.

Across the range of conditions examined, the required premium ranged from approximately 1.5 to 4.0 R\$ L^{-1} . The ethanol price and ATJ conversion have the greatest influence on the recommended SAF price premium. Higher ethanol prices make diverting ethanol to SAF production less economically attractive, while lower ATJ conversion efficiencies increase the amount of ethanol required to produce a given quantity of SAF. Jet fuel prices also

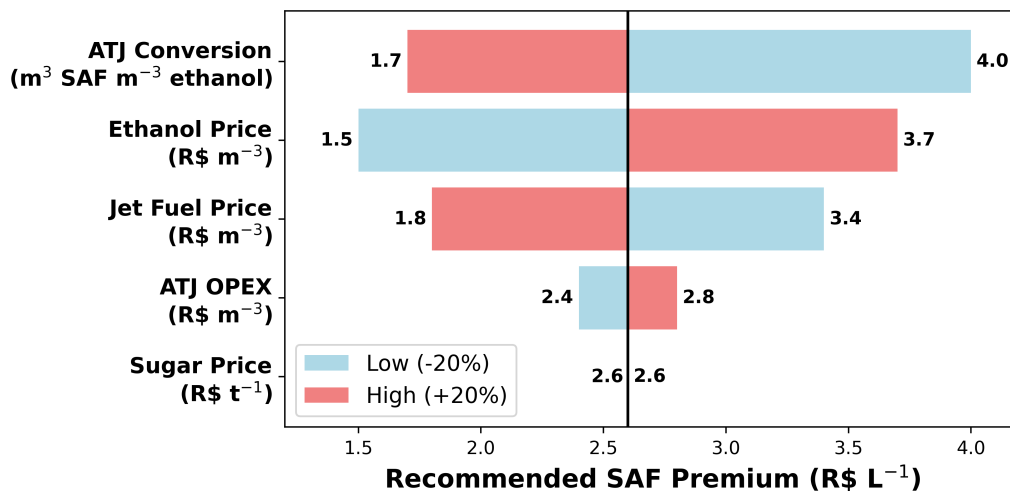


Figure 10: Tornado diagram illustrating the sensitivity of the recommended SAF price premium to key economic parameters (sugar price, ethanol price, and jet fuel price) and ATJ process parameters (conversion and OPEX). Each parameter was independently varied by $\pm 20\%$ relative to their baseline value. Bar labels indicate the resulting minimum SAF price premium ($\text{R\$ L}^{-1}$) under each scenario. The bar color represents an increase (red) or decrease (blue) in the parameter value relative to their baseline.

significantly influence the recommended SAF price premium. Higher jet fuel prices increase the value of SAF relative to ethanol, thereby reducing the additional incentive required to make SAF production economically attractive. In contrast, sugar price and ATJ operating costs have relatively little influence on the recommended SAF price premium, as sugar production is maintained regardless of SAF production, and variations in ATJ operating costs are small relative to product market prices. These findings suggest that policies aimed at promoting SAF production from sugarcane ethanol should account for volatility in ethanol and jet fuel markets, while continued improvements in ATJ conversion efficiency may reduce future incentive requirements by lowering feedstock demand.

Furthermore, we examined the difference between mill-specific incentives paid at year-end to cover any profit losses relative to the reference case or a flat premium price for selling SAF. The incentive mechanism (mill-specific vs. flat premium) has minimal effect on the total incentive paid with premium SAF prices at or below $2.5 \text{ R\$ L}^{-1}$ (SI Figure S22). The full details of this analysis can be found in SI Section S8.

719 Conclusions

720 Brazil possesses a unique opportunity to become a global leader in SAF
 721 production from bioethanol from the sugarcane industry. In this study, we ex-
 722 plore the optimal design of a SAF supply chain in Brazil, considering different
 723 perspectives (investor vs. central planner), investment locations, SAF blend
 724 mandates, and incentives. The production of SAF within the established
 725 Brazilian ethanol supply chain is attractive to investors with incentives. Our
 726 results shed light on the secondary effects of a potential SAF market within
 727 the Brazilian sugarcane industry, leading to the following conclusions:

728 *Conclusion 1: A 50% SAF blend mandate in Brazil results in 2.7 Mt*
 729 *of increased CO₂ emissions per year compared to the baseline (0% SAF).*
 730 Reduced ethanol supply resulting from increased SAF production leads to
 731 additional gasoline purchases annually and a net annual increase in CO₂ emis-
 732 sions. However, by carefully setting upper bounds on the life-cycle emissions
 733 of delivered SAF, improving ATJ technology, encouraging carbon capture
 734 at sugarcane mills, and coupling SAF production with the electrification of
 735 ground transportation, SAF can help Brazil decarbonize.

736 *Conclusion 2: The state of São Paulo is essential for SAF capacity ex-*
 737 *pansion.* Across all decision-making perspectives and high-quality solutions,
 738 SAF investments are concentrated in a small set of sugarcane mills in São
 739 Paulo, indicating that these sites should be prioritized for near-term capacity
 740 expansion.

741 *Conclusion 3: A SAF premium price of 2.6 R\$ L⁻¹ (0.5 US\$ L⁻¹) above*
 742 *the conventional jet fuel price is recommended to incentivize SAF production*
 743 *at sugarcane mills.* At this premium price, the supply chain produces 15.6
 744 Mm³ of SAF, well above the 50% SAF blend requirement (2.14 Mm³). How-
 745 ever, this volume of SAF production results in minimal ethanol available for
 746 ground transportation. Policy-makers must carefully limit the volumes of
 747 SAF incentivized until ground transportation can rely on other sustainable
 748 energy replacements.

749 The present analysis addresses key challenges surrounding the integration
 750 of SAF in the current Brazilian sugarcane supply chain, but it has several
 751 important limitations:

752 *Limitation 1: All mills and refineries are represented using a common set*
 753 *of techno-economic parameters.* Due to limited availability of site-specific
 754 cost, performance, and operational data, the model assumes identical invest-
 755 ment costs, operating costs, and process performance across facilities of the

756 same type. In reality, heterogeneity exists among Brazilian sugarcane mills
 757 and refineries, arising from differences in age, scale, technology, and opera-
 758 tional efficiency. Consequently, the results should be interpreted as repre-
 759 sentative system-level trends rather than precise predictions for individual
 760 facilities. Incorporating site-specific techno-economic data would likely pro-
 761 duce a more gradual adoption of SAF as incentives increase, rather than
 762 the stepwise investment behavior observed in Figure 9, while also reducing
 763 uncertainty in the estimated investment locations, costs, and incentive re-
 764 quirements. Obtaining such detailed facility-level data was beyond the scope
 765 of the present study.

766 *Limitation 2: A complete integration and cost analysis of ATJ invest-*
 767 *ments in refineries is not completed, as revenue streams and total mass and*
 768 *energy flows are not readily available for all refineries.* We hypothesize that
 769 this analysis will identify additional insights into integration opportunities
 770 for ATJ investments at refineries and potentially close the cost gap between
 771 investment locations (mills vs. refineries). This analysis is left for future
 772 work as obtaining the necessary data from refineries in Brazil was beyond
 773 the scope of this study.

774 *Limitation 3: This analysis assumes perfect information.* In reality, the
 775 central planner perspective can be more susceptible to inaccurate informa-
 776 tion. Market-based mechanisms, such as price signals, are often more robust
 777 in this regard.⁶⁸ Before implementing any policy, it is essential to further
 778 study the impact of uncertainty.

779 *Limitation 4: This analysis assumes independent mill behavior and*
 780 *does not explicitly model competition between sugarcane mills.* Capturing
 781 strategic interactions among mills would require alternative methodological
 782 frameworks, such as game-theoretic models, Nash equilibrium formulations,
 783 or equilibrium problems with equilibrium constraints.^{18,20–24,36} These ap-
 784 proaches are specifically designed to represent decentralized decision-making,
 785 heterogeneous stakeholders, and competitive market behavior. Incorporating
 786 mill-to-mill competition could provide additional insights into ethanol allo-
 787 cation, SAF investment decisions, and the effectiveness of policy incentives,
 788 ultimately improving the realism of SAF supply chain design and market
 789 analysis.

790 *Limitation 5: This analysis computes distances between supply chain*
 791 *nodes assuming a direct route.* More rigorous distance calculations are un-
 792 likely to affect the analysis results, as total transportation costs account
 793 for less than 0.25% of the total objective value. Additionally, although the

Brazilian transportation network for sugarcane-derived products is well established, incorporating infrastructure quality, terrain characteristics, and multimodal transportation options could further improve the fidelity of the logistics representation.

Limitation 6: This analysis focuses on costs and leaves LCA as future work. This was done, in part, due to the lack of mill and refinery-specific cost, performance, and environmental data. It is important to emphasize that, due to the lack of rigorous LCA, the emissions increase reported by SAF usage (2.7 Mt CO₂ year⁻¹) is only an approximation. Integrating LCA in process and supply chain design can help ensure environmentally responsible SAF production and mitigate the significant impacts of ethanol displacement.

Limitation 7: This analysis does not explicitly model ethanol storage or import/export dynamics. Ethanol availability is based on an annual sugarcane processing capacity; thus, the framework cannot evaluate whether surplus ethanol produced during peak harvest periods could be stored and used during the off-season to reduce imports. Incorporating seasonal production profiles, inventory constraints, storage infrastructure, and import/export market dynamics through a multi-period formulation could provide additional insights into ethanol self-sufficiency and the long-term interaction between domestic fuel markets and SAF deployment.

Limitation 8: The ATJ diesel coproduct is neither monetized nor credited. The ATJ process produces diesel, SAF, and gasoline (see $\theta_{e,d}$ and $\theta_{e,g}$ in SI Table S1). While gasoline contributes to meeting ground transportation demand, diesel is assumed to be consumed on-site by agricultural and mill equipment, outside the adopted light-duty ground transportation boundary. As such, the mills earn no revenue for the diesel, so the recommended SAF premium is an upper bound. Similarly, no credit is given for its displacement of fossil diesel, so the net emissions increase is an upper bound as well. Extending the analysis boundary to include heavy-duty fuels would capture both effects and is a natural direction for future work.

Despite the limitations and opportunities for future work, the present results provide several key insights to guide the growth of Brazil’s SAF supply chain. The general optimization framework is transferable across regions through its adaptable representation of feedstocks, conversion technologies, infrastructure, and policy constraints, enabling its application to SAF capacity expansion worldwide.

830 **Nomenclature**

831 **Abbreviations:**

832 ANP National Petroleum Agency

833 ATJ Alcohol-to-jet

834 CAPEX Capital Cost

835 CORSIA Carbon Offset and Reduction Scheme for International Aviation

836 ICAO International Civil Aviation Organization

837 LCA Life Cycle Analysis

838 MILP Mixed Integer Linear Program

839 MIP Mixed Integer Program

840 MJSP Minimum Jet Fuel Selling Price

841 OPEX Operating Cost

842 ProBioQAV Brazil's National Program for Sustainable Aviation Fuel

843 SAF Sustainable Aviation Fuel

844 SI Supporting Information

845 SPK Synthesized Paraffinic Kerosene

846 U.S. United States of America

847 **Units:**

848 \$ US Dollar

849 B Billion

850 gCO₂eq Gram of CO₂ Equivalent

851 GJ gigajoule

852 km kilometer

853	L	Liter
854	M	Million
855	m ³	Cubic Meter
856	MJ	megajoule
857	R\$	Brazilian Real
858	t	Metric Ton

859 **Author contributions**

860 M.J. Watson: Writing – original draft, Visualization, Methodology, Con-
 861 ceptualization. P.G. Machado: Writing – original draft, Methodology, Con-
 862 ceptualization. A.V. da Silva: Writing – original draft, Methodology, Con-
 863 ceptualization. C.O. Ribeiro: Methodology, Conceptualization, Supervision.
 864 C. Nascimento: Supervision. A.W. Dowling: Writing – review & editing,
 865 Supervision.

866 **Conflict of Interest**

867 The authors declare no competing financial interest.

868 **Data availability**

869 Supporting codes and data used for this manuscript are available at
 870 [https://github.com/dowlinglab/incentivizing-saf-insights-f](https://github.com/dowlinglab/incentivizing-saf-insights-from-Brazil)
 871 [rom-Brazil](https://github.com/dowlinglab/incentivizing-saf-insights-from-Brazil). Computations were performed with Gurobi⁶⁹ (v12.0.2) and
 872 Pyomo^{70,71} (v6.6.1) under Python, on Red Hat Enterprise Linux 9.7, using
 873 default settings unless otherwise noted. All computations were performed
 874 on the University of Notre Dame Center for Research Computing (CRC)
 875 using either dual 12-core Intel(R) Xeon(R) CPU E5-2680 v3 processors at
 876 2.50 GHz with 256 GB of RAM or dual 32-core AMD EPYC 7543 proces-
 877 sors at 2.80 GHz with 256 GB of RAM. Each model instance was solved in
 878 approximately 20 minutes.

879 **Supporting Information**

880 Full mathematical model, complete emission estimation details, and sup-
881 porting figures (PDF); detailed results of each integer cut iteration (XLSX).

882 **Acknowledgment**

883 The authors used Anthropic’s Claude (Claude Code, Opus 5) during revi-
884 sion of this manuscript. The tool was used to cross-check reported quantities
885 against the analysis code and the archived results, to correct the discrepan-
886 cies it identified, to draft explanatory text in the Supporting Information,
887 and to regenerate Figures 5 and 6 from the corrected model parameters. All
888 AI-assisted output was reviewed and verified by the authors, who take full
889 responsibility for the content of this work. SI Section S9 describes this use
890 in full.

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