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Mitigating carbon emissions through sustainable aviation fuels: costs and potential

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Abstract: In general, the certified pathways for the production of sustainable aviation fuels (SAFs) are still far from being competitive with fossil kerosene, although they have the potential to reduce greenhouse gas (GHG) emissions. However, the mitigation costs related to SAFs and how they compete with the carbon credits market remain unclear. The present study addressed these issues, evaluating SAF pathways based on hydrotreatment (HEFA process) of soybean oil, palm oil, used cooking oil (UCO) and beef tallow; dehydration and oligomerization of ethanol (ATJ technology) obtained from sugarcane, lignocellulosic residues, and steel off-gases; and the thermochemical conversion of lignocellulosic residues using the Fischer–Tropsch (FT) process and hydrothermal liquefaction (HTL). Residue-based pathways had lower mitigation costs. Used cooking oil / HEFA had the lowest value (185 USD tCO_{2e}⁻¹), followed by the thermochemical conversion of forestry residues (234–263 USD tCO_{2e}⁻¹). Of the 1G pathways, SAF production from 1G sugarcane ethanol (SC-1G/ATJ) performed better (495 USD tCO_{2e}⁻¹) than oil-based ones. In comparison with the carbon market, the mitigation costs of SAFs are much higher than the current prices or even future ones. However, several concerns about the credibility of the emission units and their effective mitigation effects indicate that SAFs could play an important role in aviation sector goals. Considering the potential of supplying SAF and mitigating emissions, SC-1G/ATJ was suggested as a preferred alternative in the short term. Of the residue-based pathways, Tallow / HEFA and FT of forestry residues are suggested as strategic alternatives. © 2020 The Authors. *Biofuels, Bioproducts, and Biorefining* published by Society of Chemical Industry and John Wiley & Sons, Ltd

Supporting information may be found in the online version of this article.

Keywords: sustainable aviation fuel; mitigation costs; economic feasibility; carbon market

Introduction

The aviation sector is responsible for around 2.5% of all greenhouse-gas (GHG) emissions and 3% of the oil products consumed in the world.¹ Still, the average energy intensity of aircraft operations (1.8 MJ passenger km⁻¹), which is exclusively supplied by fossil resources, is threefold higher than buses and rails, and similar to passenger cars, which have already consolidated initiatives for biofuels use. Ambitious goals for the aviation sector were set for future years,² such as improving CO₂ efficiency, achieving carbon-neutral growth from 2020, and reducing carbon emissions by 50% in 2050 compared with 2005 levels.

The Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) has addressed these goals in a detailed schedule composed of three phases.³ The pilot phase (2021–2023) and the first phase (2024–2026) are based on the voluntary participation of the states, while the second phase (2027–2035) would be applied to all states responsible by a determined share of international aviation activities. According to the current CORSIA guidelines, the carbon offsetting requirements, which are calculated from the annual carbon emissions of the airlines and their growth factor in the last years, could be achieved through offsetting market measures.^{4–7}

Six well-established standards in the carbon market were approved by the International Civil Aviation Organization (ICAO) as ‘emissions units programs’, which will initially supply CORSIA with emissions units eligible for offsetting requirements in the 2021–2023 cycle: American Carbon Registry (ACR), China GHG Voluntary Emission Reduction Program, Clean Development Mechanism (CDM), Climate Action Reserve (CAR), the Gold Standard (GS), and the Verified Carbon Standard (VCS).⁷ For all the standards, the eligible emissions units are limited to activities that started their first crediting period on 1 January 2016 and with respect to emissions reductions that occurred through 31 December 2020.

Furthermore, the offsetting requirements can be discounted by GHG emissions reductions from using alternative jet fuels, which have been highlighted as a strategic means of achieving the carbon targets, reducing the sector’s dependence on fossil fuels, and creating a new market for biofuels.^{4,8}

Until now, seven pathways have been approved to produce alternative jet fuels, which can be eligible as sustainable aviation fuels (SAFs) if they fill the CORSIA requirements:⁹ (i) hydrotreating of oil-based feedstocks (hydroprocessed esters and fatty acids, HEFA); (ii) dehydration and oligomerization of iso-butanol or ethanol (alcohol-to-jet, ATJ); (iii) direct conversion of sugar to hydrocarbons (DCSH); (iv) Fischer–Tropsch (FT) process of renewable or fossil feedstock; (v) FT process plus alkylation of light aromatics; (vi) catalytic

hydrothermolysis of oil-based feedstocks (CH); and (vii) hydrotreating of bio-derived hydrocarbons, which at present only includes the tri-terpenes produced by the *Botryococcus braunii* species of algae.¹⁰ All alternative jet fuels can be used within specific blending restrictions (v/v) with fossil kerosene.

Although several studies have confirmed the potential GHG reduction from using SAFs rather than fossil kerosene,^{11–19} the vast majority of the pathways are not yet economically competitive.^{17,20–26} However, the mitigation costs related to SAFs and how they compete with the carbon market are still unclear. Some of these issues have been explored in a very few studies with limited scope. Baral *et al.*²⁷ reported the mitigation costs of aviation fuels obtained from ionic liquid-based processes. Carvalho *et al.*²⁸ discussed the feasibility of HEFA of soybean oil and FT of lignocellulosic material assuming carbon taxes. Finally, Pavlenko *et al.*²⁹ identified the production pathways for alternative jet fuels that offer the most cost-effective carbon reductions in the European Union.

This study assessed the mitigation costs related to 12 SAF pathways and analyzed their feasibility in the face of established carbon markets. The pathways comprised ASTM-approved processes (HEFA, ATJ, and FT) and strategic feedstocks such as sugarcane (SC), soybean, palm, used cooking oil (UCO), beef tallow, agricultural and forestry residues (FR), and steel off-gases. All pathways were described for Brazil, given its recognized expertise and potential in bioenergy production.³⁰ The hydrothermal liquefaction (HTL technology) of lignocellulosic residues was also investigated as an attractive alternative because, although it is still a non-approved pathway, it has shown low costs.^{31,32}

Methodology

The mitigation costs related to SAF, which would be obtained through the pathways described below, were estimated using Eqn (1).^{33,34}

$$MC_i = \frac{P_i - P_{ref}}{ER_i} \quad (1)$$

where MC_i (USD/ton CO_{2e}) is the mitigation cost related to the SAF obtained through pathway i . P_i (USD GJ⁻¹) is the minimum selling price (MSP) of the SAF obtained through pathway i . P_{ref} (15.8 USD₂₀₁₉ GJ⁻¹) is the reference price of the fossil kerosene based on the average price paid to the producer in Brazil between 2017 and 2019.³⁵ ER_i (kgCO_{2e} GJ⁻¹) is the carbon emissions reduction by pathway i according to CORSIA guidelines.⁴

The original equation for calculating emissions reduction (ER) from the use of SAFs is based on the total mass consumed of SAF, the GHG reduction provided by SAF

compared with fossil kerosene on life cycle basis, and a fuel conversion factor related to fossil kerosene. As the carbon emission reduction is expressed in $\text{kgCO}_{2e} \text{GJ}^{-1}$ in Eqn (1), we adapted the original equation with a factor based on SAF density and its low heating value – see Eqn (2):

$$ER_i = 3.16 \times 23.0 \times \left(1 - \frac{EF_i}{89.0} \right) \quad (2)$$

where $3.16 \text{ (kgCO}_{2e} \text{ kg}^{-1}_{\text{fuel}})$ is the fuel conversion factor according to CORSIA. $23.0 \text{ (kg GJ}^{-1})$, taking $0.735 \text{ ton m}^{-3}_{\text{SAF}}$ and $32.0 \text{ GJ m}^{-3}_{\text{SAF}}$.³⁶ EF_i is the life-cycle carbon emissions related to SAF produced through the pathway i ($\text{gCO}_{2e} \text{ MJ}^{-1}$). $89.0 \text{ (gCO}_{2e} \text{ MJ}^{-1})$ is the baseline life-cycle emissions for fossil kerosene.⁴

The results are also explored considering the potential SAF production from each pathway and their sensitivity to the main parameters. Finally, the feasibility of the SAFs is compared with the emission units traded on the carbon market, considering current and future scenarios.

Description of the SAF pathways

The SAF would be obtained from first-generation (1G) and second-generation (2G) pathways. First-generation pathways are food based, i.e., obtained from soybean, palm, and sugarcane. Second-generation pathways are residues based, i.e., produced from used cooking oil (UCO), beef tallow, lignocellulosic residues, and steel off-gases. In general, the pathways comprise four stages: feedstock procurement – i.e., the agricultural stage for 1G pathways, or feedstock management, and collection for 2G pathways – intermediary processes, when deemed necessary, SAF conversion, and the transportation among the stages (see Fig. 1).

For the Soy/HEFA pathway, soybean oil production was described by a representative monoculture system³⁷ placed in the central region of Brazil – which is responsible for more than half of all Brazilian production of soybeans³⁸ – with further oil extraction by hexane.³⁹ The crop-to-mill and mill-to-refinery distances were at 200 and 600 km (one-way).

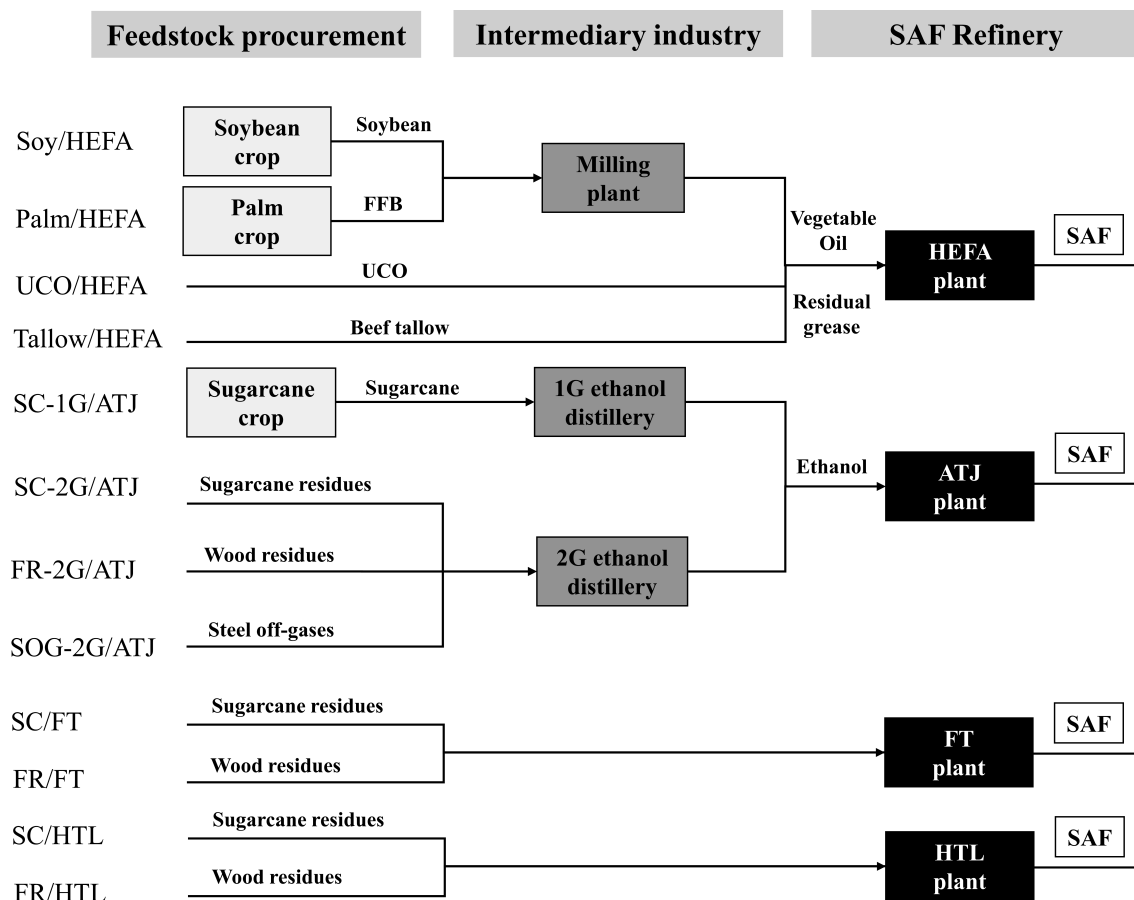


Figure 1. Sustainable aviation fuel pathways considered in this study. 1G: First-generation; 2G: Second-generation; SAF: Sustainable aviation fuel; ATJ: Alcohol-to-jet; FFB: Fresh fruit bunches; FR: Forestry residues; FT: Fischer-Tropsch; HEFA: Hydroprocessed esters and fatty acids; HTL: Hydrothermal liquefaction; SC: Sugarcane; SOG: Steel off-gases; UCO: Used cooking oil.

For the Palm/HEFA pathway, the system production of palm oil (*Elaeis guineensis*) was based on a Brazilian company⁴⁰ in the North region – the major palm production region in Brazil.⁴¹ Of the multiple products produced at the oil extraction plant, crude palm oil would be destined for SAF production, while empty fruit bunches (EFBs) would be returned to the field as fertilizer. Shells / husks guarantee a self-supply of energy at the extraction plant.⁴² Furthermore, addressing the company investment plans,⁴³ methane from anaerobic digestion of Palm Mill Oil Effluent (POME) is captured in closed ponds systems, cleaned, and subsequently used in a gas engine for power generation.^{44,45} The crop-to-mill distance was 32 km (one way) to avoid acidification of the fruits.^{40,42} The mill-to-refinery distance was similar to the soybean-based pathway.

Finally, the agricultural stage of the sugarcane-based pathway (SC-1G/ATJ) was mostly based on the database available in the Virtual Sugarcane Biorefinery (VSB) facility, which was developed by the Brazilian Biorenewable National Laboratory (LNBR).⁴⁶ Complete mechanized harvesting was considered, with 50% recovery of straw through bailing / loading systems. Industrial residues, such as vinasse and filter-cake, were returned to the field for fertilization purposes. The 1G ethanol was obtained from an optimized autonomous distillery for hydrated ethanol, according to the VSB models.⁴⁷ The crop-to-mill and mill-to-refinery distances were 36 and 600 km (one-way), respectively.

Of the 2G pathways, the UCO collection was based on Araujo *et al.*,⁴⁸ who evaluated the potential of this feedstock – collected from food-services in a large city – for biofuel production. As also assumed by those authors, no pretreatment processes for UCO were deemed necessary for SAF production as the feedstock suppliers work with standard processes that could guarantee the minimum quality for the further UCO use.⁴⁸

In turn, for the Tallow/HEFA pathway, beef tallow was directly obtained from rendering plants, which are typically integrated into slaughterhouses in Brazil.⁴⁹ The slaughterhouse-to-refinery distance was 600 km.

For ethanol based-pathways using lignocellulosic residues – i.e., SC-2G/ATJ and FR-2G/ATJ – the ethanol distilleries were 100 km from the feedstock collection points. The sugarcane residues comprise a mix of sugarcane bagasse and straw, which would be available at a 1G ethanol distillery after guaranteeing its self-supply of power and heat. Forestry residues comprise eucalyptus wood parts (branches, top, and barks), which are collected from the field.⁵⁰

Second-generation ethanol from sugarcane residues would be produced using steam explosion and enzymatic hydrolysis, according to the advanced configuration reported by Bonomi *et al.*⁴⁶ The enzyme would be purchased from suppliers, and the plant would be self-supplied by cellulignin

burning in a combined heat and power (CHP) system. The industrial yields for forestry residues were estimated using the VSB model with the proper adjustments made to the feed composition.⁵¹ The mill-to-refinery distance was also set at 600 km (one way).

The Steel off-gases (SOG)-2G/ATJ pathway considered ethanol production by fermentation of CO-rich off-gases, such as steel off-gases. The off-gases released by the basic oxygen furnace (BOF) in steel mills are fermented into ethanol in an annex plant,^{52,53} with minimal co-product creation and no co-product recovery, as described in Handler *et al.*⁵⁴ The steam demand would be supplied by a share of the reactor vent gas combined with the biogas obtained from the anaerobic digestion of the biological solids (spent microbial biomass) filtered out of the distillation. The transportation of ethanol mill-to-refinery was also set at 600 km (one-way).

Finally, the SAF conversion processes and the related yields for HEFA technology^{55,56} were assumed to be similar for all oil-feedstocks.^{11,14,31} The ATJ plant was fed by hydrated ethanol,²² and the yields for FT and HTL were based on de Jong *et al.*²⁰ and Tzanetis *et al.*,³² respectively. For both of these latter pathways, the collect point-to-refinery distance was 100 km (one-way). Table 1 shows the main yields. The hydrogen demand in HEFA and ATJ processes would be supplied by an external plant of steam methane reform (SMR). For FT and HTL processes, the hydrogen is internally produced.

Minimum selling price of SAF

The minimum selling price of SAF (USD₂₀₁₉ GJ⁻¹) was set when the cash flow results in a net present value equal to zero and when the internal return rate (IRR) of the investment attains the minimum attractive rate of return (MARR), which was 12% as also assumed in other studies.^{22,26,46}

The capital expenditures (CAPEX) for SAF technologies (HEFA, ATJ, FT, and HTL) were scaled up to an annual distillate production of 0.20 million m³, based on typical values found in the literature.^{22,25,31} The intermediary processes were scaled up considering typical commercial plants. In both cases, a scaling factor of 0.6 was used.^{26,31} Furthermore, a location factor of 1.14 was assumed for SAF technologies built in Brazil.⁶³

In turn, besides the material / utilities, the operational expenditures (OPEX) comprised labor, maintenance, and general taxes, which were set at 3.5%,²⁶ 3.0%,²¹ and 0.7%²¹ of the CAPEX, respectively. In general, transportation costs were based on the current tables for the minimum freight prices in Brazil.⁶⁴ All the assumptions are summarized in Table 2. See Table S1 in Appendix S1, in the supplementary material, for more details.

Table 1. Overall yields for SAF pathways.

Pathways	Feedstock procurement ^a	Intermediary industry	SAF refinery ^b
Soy oil/HEFA	3.1 t _{soybean} ha ⁻¹	0.195 t _{soybean oil} t _{soybean} ⁻¹ 0.805 t _{meal} t _{soybean} ⁻¹	SAF: 494.0 kg t _{oil} ⁻¹ Diesel: 233.0 kg t _{oil} ⁻¹ Naphtha: 70.0 kg t _{oil} ⁻¹ Light streams: 102.0 kg t _{oil} ⁻¹
Palm oil/HEFA	17.8 t _{FFB} ha ⁻¹	0.175 t _{palm oil} t _{FFB} ⁻¹ 0.013 t _{kernel oil} t _{FFB} ⁻¹ 0.023 t _{kernel meal} t _{FFB} ⁻¹ 0.037 kWh t _{FFB} ⁻¹	
Tallow/HEFA	n.a.	n.a.	
UCO/HEFA	n.a.	n.a.	
SC-1G/ATJ	80.0 tsc ha ⁻¹	93.2 L _{ethanol} tsc ^{-1c} 192 kWh tsc ⁻¹	SAF: 269.0 kg t _{ethanol} ⁻¹ Diesel: 22.0 kg t _{ethanol} ⁻¹ Naphtha: 126.4 kg t _{ethanol} ⁻¹
SC-2G/ATJ	n.a.	357.4 L _{ethanol} t _{LCM(db)} ^{-1d} 127.6 kWh t _{LCM(db)} ⁻¹	
FR-2G/ATJ	n.a.	308.4 L _{ethanol} t _{LCM(db)} ^{-1e} 158.5 kWh t _{LCM(db)} ⁻¹	
SOG-2G/ATJ	n.a.	0.271 L _{ethanol} Nm ⁻³ _{off-gases} ^f	
SC/FT	n.a.	n.a.	SAF: 24.8 kg t _{LCM (db)} ^{-1g} Diesel: 74.5 kg t _{LCM (db)} ⁻¹ Naphtha: 29.2 kg t _{LCM (db)} ⁻¹ Power: 219.0 kWh t _{LCM} ⁻¹
FR/FT	n.a.	n.a.	SAF: 29.8 kg t _{LCM (db)} ^{-1h} Diesel: 89.3 kg t _{LCM (db)} ⁻¹ Naphtha: 35.0 kg t _{LCM (db)} ⁻¹ Power: 262.5 kWh t _{LCM} ⁻¹
SC/HTL	n.a.	n.a.	SAF: 109.3 kg t _{LCM (db)} ⁻¹ⁱ Diesel: 38.3 kg t _{LCM (db)} ⁻¹ Naphtha: 65.6 kg t _{LCM (db)} ⁻¹ Heavy oil: 60.1 kg t _{LCM (db)} ⁻¹
FR/HTL	n.a.	n.a.	SAF: 131.1 kg t _{LCM (db)} ^{-1j} Diesel: 45.9 kg t _{LCM (db)} ⁻¹ Naphtha: 78.6 kg t _{LCM (db)} ⁻¹ Heavy oil: 72.1 kg t _{LCM (db)} ⁻¹

^aFFB: Fresh fruit bunches; tsc: ton sugarcane.

^bSAF: Sustainable aviation fuel (0.735 ton m⁻³, 32.00 GJ m^{-3 36}); diesel (0.757 ton m⁻³, 31.99 GJ m^{-3 36}); naphtha (0.678 ton m⁻³, 29.66 GJ m^{-3 36}). Light streams (0.552 ton m⁻³, 46.34 GJ ton^{-1 57}).

^cEthanol density: 0.810 ton m⁻³.

^dEthanol density: 0.810 ton m⁻³; LCM (db): sugarcane residues as lignocellulosic material, dry basis (14.4 MJ kg⁻¹, 45% moisture) composed by 85% of sugarcane bagasse and 15% of sugarcane straw^{46,58}.

^eEthanol density: 0.810 ton m⁻³; LCM (db): forestry residues as lignocellulosic material, dry basis (17.5 MJ kg⁻¹, 12% moisture)⁵⁹.

^fTotal off-gases input, assuming a theoretical maximum 80% HHV conversion to ethanol,⁶⁰ and the net off-gases input (0.936 L_{ethanol} Nm⁻³_{off-gases}),⁵⁴ i.e., the total off-gases input minus the venting gases from the process. Average off-gas generation from steel refining process through BOF technology: 100 Nm³_{off-gases} / ton crude steel.⁶¹ Average off-gases composition (60% CO, 20% CO and 20% N₂, in %vol.); LHV: 7.58 MJ Nm⁻³; density: 1.392 kg Nm⁻³. Ethanol density 0.789 ton m⁻³. Only in this pathway, SAF would be produced from anhydrous ethanol, as reported by the original reference. It was assumed that anhydrous ethanol input would not influence the overall conversion yields, since the ethylene production, which is the first stage of the ATJ-based process, does not present relevant discrepancies if an input of hydrated ethanol was assumed.⁶² Even though, lower costs for producing hydrated ethanol instead of anhydrous ethanol could slightly influence the economic analysis of the whole process.

^gThe yields were estimated according to the lower heating value (LHV) of the feedstocks.²⁰ LCM (db): sugarcane residues as lignocellulosic material, dry basis (14.6 MJ kg⁻¹, 45% moisture) composed by 85% of sugarcane bagasse and 15% of sugarcane straw^{46,58}.

^hThe yields were estimated according to the lower heating value (LHV) of the feedstocks.²⁰ LCM (db): forestry residues as lignocellulosic material, dry basis (17.5 MJ kg⁻¹, 12% moisture)⁵⁹.

ⁱThe yields were estimated according to the lower heating value (LHV) of the feedstocks.³² LCM (db): sugarcane residues as lignocellulosic material, dry basis (14.6 MJ kg⁻¹, 45% moisture) composed by 85% of sugarcane bagasse and 15% of sugarcane straw^{46,58}.

^jThe yields were estimated according to the lower heating value (LHV) of the feedstocks.³² LCM (db): forestry residues as lignocellulosic material, dry basis (17.5 MJ kg⁻¹, 12% moisture)⁵⁹.

Table 2. Economic description of the SAF pathways (Nth plant).

Pathways	Intermediary industry			SAF refinery		
	Scale (Mt _{feed}) ^a	CAPEX ^b (M USD)	OPEX+T ^c (USD t _{feed} ⁻¹)	Scale (Mt _{feed})	CAPEX (M USD)	OPEX+T (USD t _{feed} ⁻¹)
Soy oil/HEFA	0.83	158.7	30.1	0.16	403.5	316.7
Palm oil/HEFA	0.65	76.4	20.5	0.16	403.5	312.8
UCO/HEFA				0.16	403.5	493.0
Tallow/HEFA				0.16	403.5	316.7
SC-1G/ATJ	4.00	473.8	11.2	0.34	86.1	98.9
SC-2G/ATJ	0.22	149.8	121.3	0.34	86.1	98.9
FR-2G/ATJ	0.26	163.7	108.4	0.34	86.1	98.9
SOG-2G/ATJ	0.058	79.6	329.9	0.34	86.1	98.9
SC/FT				1.14	1084.1	96.0
FR/FT				0.95	972.4	103.6
SC/HTL				0.68	933.8	175.7
FR/HTL				0.56	933.8	196.2

^a'Scale' refers to the production scale of one industrial plant as assumed here. Specifically, for SOG-2G/ATJ, the production scale for the intermediary industry was expressed in 10⁶ m³_{ethanol} produced.
^bCAPEX: capital expenditures, including working capital (5% of the CAPEX).
^cOPEX: operational expenditures; T: transportation.

Table 3. Market values for the primary feedstocks.

Products	Market value		Ref.	Description
Soybean	374.0	(USD t ⁻¹)	38	Average price (2017–2019) in Rondonópolis market (Mato Grosso state).
Palm, FFB	84.5	(USD t ⁻¹)	41	Average production costs of fresh fruit bunches (FFB) in Brazil (2016–2018).
UCO	166.2	(USD t ⁻¹)	48	Based on the acquisition cost, according to a survey carried out in bars and restaurants in Rio de Janeiro (Brazil).
Beef tallow	665.3	(USD t ⁻¹)	65	Average price (2017–2019) in Brazil for center and south regions.
Sugarcane	18.1	(USD t ⁻¹)	66	Average price (2017–2019) of sugarcane stalks on the field.
Sugarcane residues	26.6	(USD t ⁻¹)	46	Based on the opportunity costs for lignocellulosic material, wet basis (45% moisture content), assuming mix (85%/15%) of sugarcane bagasse and sugarcane trash from the field.
Forestry residues	9.0	(USD t ⁻¹)	67	Based on firewood market, wet basis (12% moisture content).
Steel off-gases, at flares	0.0	(USD 1000Nm ⁻³)		Null cost was assumed for off-gases available on flares.

The total costs were allocated to the volume of SAF produced, considering the market values of the products (see Table 3). The cash flow considered a period of 25 years^{22,25,46} with full capacity, 100% equity,^{26,46} a linear annual depreciation of 10%,^{22,26} and 34% income taxes.^{22,46}

Greenfield plants and mature technologies (Nth plant) were considered in the reference scenario. Furthermore, the industrial stages were integrated, which means that the primary feedstocks – soybean, fresh fruit bunches (FFB), sugarcane stalks, agro/forestry residues, and waste greases – were assumed to be purchased from suppliers at average market prices (Table 3). All economic values were corrected to 2019 by the Brazilian inflation rate (IGP-DI⁶⁸), taking the average exchange rate of 3.86 BRL/USD.

The minimum selling price of SAF was also explored considering pioneer plants, using Eqn (3):

$$CAPEX_p = \frac{CAPEX_{N^{th}}}{GF} \quad (3)$$

where CAPEX_p are the capital expenditures for the pioneer plant (USD); CAPEX_{Nth} are the capital expenditures for the Nth plant (USD); and GF is the growth factor.

The growth factor reflects possible risks due to unexpected problems in the startup phase, and it comprises the complexity of the processes and technological immaturity. Hence, the growth factor was not applied to mature technologies, such as vegetable oil extraction and 1G ethanol production. The growth factors suggested by de Jong *et al.*³¹ were 0.83 for HEFA

technology, 0.42 for ATJ, 0.45 for FT, and 0.40 for HTL. A similar factor for 2G ethanol via enzymatic hydrolysis (0.53²⁵) was taken for ethanol production via syngas fermentation.

Carbon emissions of SAF

The carbon emissions along the SAF life cycle were estimated considering the CORSIA guidelines⁶⁹ and the description of the pathways presented above. An attributional life-cycle assessment was therefore performed from feedstock

procurement to SAF combustion in an aircraft engine. Only emissions of CH₄, N₂O, and non-biogenic CO₂ were accounted for, according to the 5th AR IPCC.⁷⁰

Co-production was handled by energy allocation. Residual feedstocks, such as UCO, agricultural / forestry residues, sugarcane bagasse, and beef tallow, were deemed wastes. Thus, only emissions related to collection and transportation were accounted for. The default values for land-use change (LUC) suggested by CORSIA⁷¹ for 1G pathways were taken here.

Databases Ecoinvent v3.3,⁷² USCLI,⁷³ and GREET⁷⁴ were used for background systems with some adaptations to the Brazilian context. See Table S2 in Appendix S1, in the supplementary material, for more details about the inventories. The total values assumed here are presented in Table 4.

Potential SAF supply and carbon mitigation

The pathways were also evaluated by their potential production of SAFs and carbon mitigation in Brazil,^{35,75} considering the availability of feedstocks and conversion yields assumed here (Table 1).

The potential areas for biomass expansion (soybean, palm, and sugarcane) were taken from Cervi *et al.*²⁵ That study evaluated the potential SAF production in Brazil through 13 pathways from food-based biomasses and wood-based ones. According to their economic feasibility and the agro-ecological suitability of the available areas for biomass growth, a spatially explicit economic optimization was carried out to supply the nearest airport. Biomass was assumed to expand

Table 4. Greenhouse gas emissions (kgCO_{2e} GJ⁻¹) related to SAF production and use.

Pathways	Core LCA value	LUC ^a	Total
Soy/HEFA	42.9	27.0	69.9
Palm/HEFA	34.4	39.1 ^b	73.5
UCO/HEFA	17.2	–	17.2
Tallow/HEFA	18.5	–	18.5
SC-1G/ATJ	36.0	8.7	44.7
SC-2G/ATJ	27.6	–	27.6
FR-2G/ATJ	27.4	–	27.4
SOG-2G/ATJ	24.8	–	24.8
SC/FT	3.9	–	3.9
FR/FT	2.4	–	2.4
SC/HTL	11.0	–	11.0
FR/HTL	10.3	–	10.3

^aDefault values according to CORSIA⁷¹ for Brazil.

^bFor palm production in Malaysia due to a lack of information for Brazil⁷¹.

Table 5. Residual feedstock availability for SAF production in Brazil.

Feedstock	Annual potential	Description
UCO	0.30 Mt	Used cooking oil collected from households and food services. For UCO from households, it was assumed that 35% ⁷⁶ of the annual acquisition of vegetable oils <i>per capita</i> in Brazil ⁷⁷ would be available for recycling. From this amount, only 10% would be collected, basing on the initiatives in Europe. ⁷⁶ The potential UCO from food services was assumed equivalent to 67% of the UCO available from households. ⁷⁶
Beef tallow	1.02 Mt	Total supply of beef tallow, considering the generation of 31.5 kg _{tallow} cattle head ⁻¹ ⁴⁹ and the slaughtering of 32.4 million cattle head (only bovine) in 2019. ⁷⁸
Sugarcane residues	100.1 Mt 55.3 Mt _(db)	Total residues available in ethanol distilleries after to guarantee the self-supply, and assuming that 7.5 t _{straw(db)} ha ⁻¹ ^{79,80} are kept on the field for ecological purposes. Sugarcane production in 2018. ⁸¹ Bagasse yield, 0.28 t _{bagasse} t _{sugarcane} ⁻¹ (50% moisture, 7.2 MJ kg ⁻¹). Total straw yield, 0.14 t _{straw(db)} t _{sugarcane} ⁻¹ (15% moisture, 13.3 MJ kg ⁻¹). Internal energy demand and losses in ethanol distillery, 1445 MJ t _{sugarcane} ⁻¹ . ^{82,83}
Forestry residues	16.6 Mt 14.6 Mt _(db)	Average annual generation of wood residues (barks, branches, and leaves) during the harvesting operations (167 kg _{residues} m ⁻³ _{wood} ·Cycle). ⁸⁴ The potential availability of wood residues from eucalyptus crops was estimated considering: Average yield of eucalyptus (35 m ³ ha ⁻¹ ·Year), crop cycle (7 years), area with eucalyptus in Brazil in 2018 (5.67 Mha), and 50% recovery of residues.
Steel off-gases	2.15 10 ⁹ Nm ³	Total availability of steel off-gases considering steel refining through BOF/LD technology and a generation of 100 Nm ³ t _{crude_steel} ⁻¹ . Only steel mills with a minimum generation of 280 10 ⁹ Nm ³ off-gases/year were considered, which would be suitable to supply an ethanol plant on a commercial scale.

only onto 'residual lands', i.e., areas not in use for other function in those years, such as croplands, pasture, rangeland, forest planted, natural forest, urban areas, and conservation areas. Hence, those authors considered SAF production only from abandoned agricultural land, shrublands, and grasslands. Under these conditions, in 2015, Soy/HEFA, Palm/HEFA, and SC-1G/ATJ could supply 4.9, 36.5, 13.1 million m³ of SAF, respectively, from the cultivation of 19.1 Mha of soybean, 23.5 Mha of palm, and 3.9 Mha of sugarcane.

The potential of 2G pathways was estimated based on Brazilian databases, literature, and specific criteria, as presented in Table 5. Finally, the total carbon mitigation for each pathway was estimated from the pathways' potential production and the respective potential emission reductions.

Sensitivity analysis for mitigation costs

Sensitivity analysis was performed. This comprised strategic parameters related to the evaluation of the mitigation costs, as follows:

1. Feedstock prices were set at $\pm 20\%$, according to their market variations in recent years.^{38,41,66,67,85} Specifically, for SOG-2G/ATJ, as several steel mills have recovered steel off-gases for internal use,⁶¹ an opportunity cost of the steel off-gases (117.5 USD/1000 Nm³) was taken according to the average price of natural gas (2016–2018) by energy parity (0.21 Nm³ off-gas Nm⁻³ natural gas).
2. Fossil kerosene prices were set at $\pm 30\%$, according to the national market variations in 2004–2019.³⁵
3. Process scales were set at $\pm 50\%$, which comprise typical scales for soybean mills³⁸ and 1G ethanol distilleries in Brazil⁴⁶; as well as for SAF plants according to literature.^{11,22,25} Similar ranges were taken for palm mills and 2G ethanol distilleries.
4. The MAAR was set at 8 to 12%, comprising possible investment scenarios.
5. Transportation distances were set at $\pm 50\%$, taking into account some possible varying distances in Brazil. The 'crop-to-mill' distance for palm and sugarcane was kept the same, due to the limitations reported by some authors.^{46,86}
6. Finally, considering the relevant role of the hydrogen input for SAF conversion, we took an external hydrogen supply from a water electrolysis (WE) plant (6.31 USD₂₀₁₉/ton⁸⁷ and 9.31 kgCO_{2e} kg⁻¹⁸⁸).

Alternative offsetting market-measures

The mitigation costs of SAFs were then compared with current and future prices of the emissions units traded on the carbon market, as the latter is one possible way for achieving the emission targets in the short-term, according to CORSIA.

The current prices of the emissions units were retrieved from several sources,^{89–91} corresponding to the values from 2016–2018. The values were also disaggregated by project category (forestry and land use, renewable energy, household devices, chemical processes, industrial manufacturing, waste disposal, energy efficiency/fuel switching, and transportation); by region (North America, Latin America & Caribbean, Asia, Africa, Europe, and Oceania); and by Program (American Carbon Registry – ACR, Clean Development Mechanism – CDM, Climate Action Reserve – CAR, Gold Standard – GS, and Verified Carbon Standard – VCS).

The future prices of the emission units were retrieved from Piris-Cabezas *et al.*⁹² That study addressed the carbon price variation on the market by applying a partial equilibrium model due to the coexistence of the Nationally Determined Contribution (NDC), according to the Paris Agreement, and CORSIA. It is worth mentioning that the Paris Agreement⁹³ is a bottom-up climate change-related international compromise in which each Party has presented its NDC. A NDC determines the national goals for emissions measures that are aligned with the global effort for holding the increase in global average temperatures below 2 °C.

For the purposes of this study, two scenarios were selected to determine the future carbon price ranges in 2030: i) minimum prices (5.90 USD tCO_{2e}⁻¹), assuming market actors will fully anticipate future policies in a globally integrated carbon market, but with a market demand based on current NDCs targets; ii) maximum prices (55.2 USD tCO_{2e}⁻¹), assuming market actors will fully anticipate future policies in a globally integrated carbon market, but with a market demand compatible with the 2 °C target.

Results and discussion

Techno-economic assessment of SAF

In general, none of the pathways was competitive with fossil kerosene (Jet A) (see Fig. 2), as pointed out in previous studies.^{20,21,23,26} The MSP of SAFs ranged from 26.7–44.6 USD GJ⁻¹, while fossil kerosene had an average price of 15.8 USD GJ⁻¹ in 2017–2019 in Brazil, reaching 20.9 USD GJ⁻¹ in the top 10 percentiles for 2004–2019.

The MSP related to 1G pathways remained in a narrow range of 33.7 USD GJ⁻¹ (SC-1G/ATJ) to 36.4 USD GJ⁻¹ (Soy/HEFA), where the feedstock was the major contributor responsible for 43% of the total costs in Soy/HEFA and around 32% in Palm/HEFA and SC-1G/ATJ. The capital expenditures contributed to roughly 30% of the total costs, mostly led by HEFA technology and ethanol distilleries in

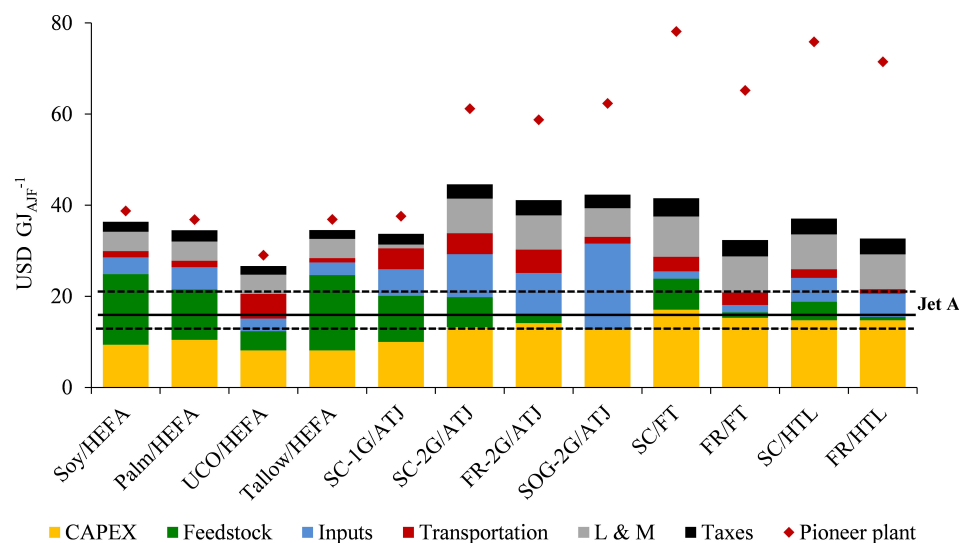


Figure 2. Breakdown of the minimum selling price (MSP) of SAFs. Integrated supply-chain for 1G-pathways. Fossil kerosene (Jet a) price in Brazil,⁸⁵ average values (2017–2019), top and bottom 10 percentile values (2004–2019). ATJ: Alcohol-to-jet; FT: Fischer–Tropsch; HEFA: Hydroprocessed esters and fatty acids; HTL: Hydrothermal liquefaction.

oil-based pathways and SC-1G/ATJ, respectively. The lower overall yield of SC-1G/ATJ ($27.6 L_{SAF}/t_{sugarcane}$) with respect to oil-based pathways ($131.1 L/t_{soybean}$ or $117.8 L_{SAF}/t_{FFB}$) resulted in the relevant contribution of transportation (13% of the total costs) for that pathway.

On the other hand, the MSP of SAF from residue-based pathways, i.e., 2G pathways, spreads over a broader range (26.7 – 44.6 USD GJ^{-1}). The conversion of used cooking oil into SAF (UCO/HEFA) had the lowest value, followed by thermochemical conversion of forestry residues using Fischer–Tropsch (FR/FT) or hydrothermal liquefaction (FR/HTL) technologies. The former was led by the low cost of the feedstock combined with a high overall yield ($670 L_{SAF}/t_{UCO}$) and the low capital expenditures related to HEFA technology in comparison with thermochemical technologies.

The low feedstock price explains the MSP related to the thermochemical conversion of forestry residues into SAF, although these pathways comprised the most capital-intensive technologies, such as gasification / syngas clean-up and hydrothermal liquefaction that corresponded to roughly half of the CAPEX in FT and HTL-based pathways. The thermochemical conversion of sugarcane residues had higher values than for forestry residues, especially because of the high feedstock price and the low conversion yields.

The MSP values are close for both FT and HTL technologies, given that the benefits of the higher HTL conversion yields ($178 L_{SAF}/t_{db}$ for FR/HTL and $149 L_{SAF}/t_{db}$ for SC/HTL) are counterbalanced by power demand and natural gas consumption for hydrogen production. On

the other hand, the self-supply of utilities in FT and the low expenditures with other inputs are compensated for by the low conversion yields ($40 L_{SAF}/t_{db}$ and $34 L_{SAF}/t_{db}$ for forestry and sugarcane residues, respectively).

The beef tallow price brought the MSP of Tallow/HEFA to similar values as 1G pathways. Beef tallow is a valuable co-product in Brazil, and it is mostly used for biodiesel production, corresponding to around 15% of the total volume of biodiesel produced.³⁵ Because of competition with soybean oil for the biodiesel market, beef tallow price directly follows the up-down trends of that vegetable oil. In recent years, the prices of beef tallow have been reported 5 to 22% lower than soybean oil,^{65,94} both taken from the Central region of Brazil, without taxes. A different trend or even decreasing prices for beef tallow should not be expected if this residual feedstock was also demanded by a new SAF market.

The ATJ-based pathways via 2G ethanol had the highest MSP. Even with a higher overall yield (90 – $100 L_{SAF}/t_{db}$) than FT-based pathways, the capital costs – which are mostly related to ethanol conversion (around 85% of the CAPEX) – and operational expenditures mostly related to enzyme purchase in SC-2G/ATJ and FR-2G/ATJ, or power demand for steel off-gas compression (SOG-2G/ATJ) pushed up the total costs. Regarding this later pathway, the surplus power generation from an optimized steel mill^{61,95} could eventually supply the integrated ethanol plant. If this were to happen, the MSP of SOG-2G/ATJ would decrease by around 33%, reaching 33.5 USD GJ^{-1} , but still two times higher than the average price of fossil kerosene.

The possible risks related to a new plant increased the total costs for capital-intensive technologies. The technological immaturity of hydrothermal liquefaction or the complexity of Fischer–Tropsch technology led to a MSP 100–105% and 89–100% higher than N^h plants for HTL and FT-based pathways, respectively. The values for the ATJ-based pathways could increase by 30–35%, mostly due to the technological immaturity of 2G-ethanol production. Even so, it is worth mentioning that values for pioneer plant were estimated from an aggressive approach because full-plant capacity availability in the first year was assumed.

Some trends reported here were also observed in other studies, such as the low MSP related to SAF obtained from used cooking oil, and the high values for SAF production from lignocellulosic residues *via* 2G ethanol (see Table 6).

The low values reported by Klein *et al.*,²² which were also estimated in Brazilian conditions, highlighted the

benefits of considering SAF production in an integrated biorefinery. Those authors proposed several integrated designs between an optimized autonomous ethanol distillery and SAF technologies, assuming the internal supply of utilities – which includes hydrogen production by WE – the ethanol and power surplus revenues, when it was the case, and the use of alternative diesel in agricultural operations. The MSP of SAF obtained via FT technology could even present negative values due to the great profits from ethanol revenues, although the authors pointed out the complexity of the integration of these technologies, considering the high requirement of mass and energy integration.

Santos *et al.*²⁶ also evaluated possible designs for SAF production in a sugarcane-based biorefinery in Brazil, including several pretreatment methods for lignocellulosic material, revenues of high-value co-products, fast pyrolysis of bagasse, or gasification followed by Fischer–Tropsch

Table 6. Economic feasibility and life cycle carbon emissions of SAF according to other studies.

Feedstock	SAF technology	MSP (USDGJ ⁻¹)		GHG emission (kgCO _{2e} GJ ⁻¹) ^a	
		This study	Other ref. ^b	This study	Other ref.
Soybean	HEFA	36.4	23.1 ²² 37.2 ²³	69.9 (42.9)	67.4 (40.4) ⁷¹ (22.0) ²² (40.1) ⁹⁶
Palm	HEFA	34.5	18.4 ²²	73.5 (34.4)	76.5 (37.4) ⁷¹ (17.0) ²² (14.2) ⁹⁶
UCO	HEFA	26.7	28.4 ²³ 33.3 ³¹	17.2	13.9 ⁷¹ 27.0 ¹¹
Beef tallow	HEFA	34.5	33.1 ²³	18.5	22.5 ⁷¹ 29.8 ¹⁴
Sugarcane	ATJ (<i>via</i> 1G ethanol)	33.7	51.8 ²¹ 27.2 ²² 44.9 ²⁶	44.7 (36.0)	32.8 (24.1) ⁷¹ (20.5) ²² (26.0) ¹¹
Lignocellulosic residues	ATJ (<i>via</i> 2G ethanol)	44.6 (SC) 41.1 (FR)	78.8 ²¹ 36.6 ²² 64.0–67.7 ²⁶ 55.5 ³¹	27.6 (SC) 27.4 (FR)	35.0 ¹¹ 28.4 ¹⁵ 24.8 ²²
Steel off-gases	ATJ (<i>via</i> 2G ethanol)	41.5	n.a.	24.8	n.a.
Lignocellulosic residues	FT	41.5 (SC) 32.4 (FR)	56.0 ²¹ –6.9 to 11.2 ²² 46.6 ³¹	3.9 (SC) 2.4 (FR)	7.7 to 8.3 ⁷¹ 6.0 ¹¹ 6.8 ¹⁵ 8.6 ²²
Lignocellulosic residues	HTL	37.1 (SC) 32.7 (FR)	24.4 ³¹	11.0 (SC) 10.3 (FR)	18 to 20 ¹¹

^aOnly for 1G pathways, the values in parenthesis represent the GHG emissions related to the life cycle without land use change (LUC). All the values retrieved of other references were estimated considering allocation approach for co-products, preferably energy allocation, as set out by CORSIA guidelines⁶⁹.

^bWhen necessary, the MSP was converted in USDGJ⁻¹ taking the exchange rate, density and heating value assumed in the original reference. When these data are not available in the original reference, it was assumed 32.0 GJm⁻³ and 0.735 t m⁻³, as LHV and density of SAF,³⁶ respectively.

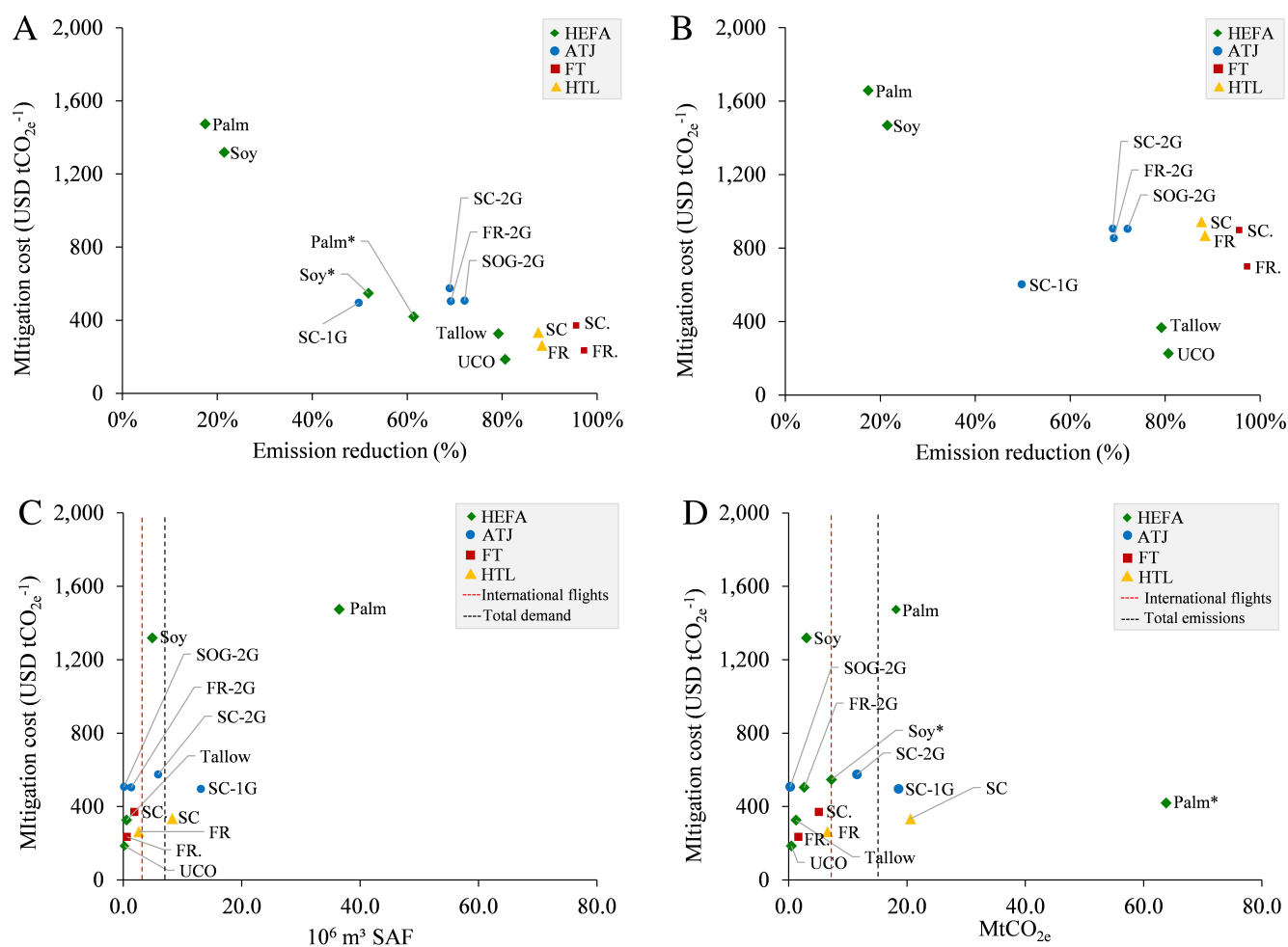


Figure 3. Mitigation costs of SAF considering the potential emission reduction by an N^{th} plant (a); the potential emission reduction by a Pioneer plant (b); the potential production of SAF assuming an N^{th} plant (c); and the potential carbon reduction assuming an N^{th} plant (d). Soy* and palm* means SAF produced from soybean and palm if areas with low-risks for LUC. 'International flights' mean the fuel demand or GHG emissions related to international flights originating in Brazil. 'Total values' mean the fuel demand or GHG emissions related to international and domestic flights in Brazil.⁷⁵

processing of lignin. The values reported by these authors for SAF production from 1G ethanol and fast pyrolysis of sugarcane bagasse were slightly lower than what was estimated here for SAF from 1G ethanol. However, the MSP increases if the integrated SAF production from 2G ethanol is also considered.

Finally, de Jong *et al.*³¹ evaluated only residue-based pathways and pointed out some trends as observed here, albeit with some discrepancies. The feedstock price of UCO taken by those authors was around six times more expensive than that was taken here, which led to a higher MSP. They also estimated lower values for HTL-based pathways, mainly led by CAPEX, which was roughly 40% cheaper than calculated here.

Mitigation costs of SAF

According to Fig. 3(a), there is a clear trend of low mitigation costs related to residues-based pathways. Used cooking oil / HEFA had the lowest value (185 USD tCO_{2e}⁻¹), followed by thermochemical conversion of forestry residues (234–263 USD tCO_{2e}⁻¹), hydrotreating beef tallow (326 USD tCO_{2e}⁻¹) and the thermochemical conversion of sugarcane residues (334–370 USD tCO_{2e}⁻¹). The SAF obtained from 2G ethanol were related to high mitigation costs (504–575 USD tCO_{2e}⁻¹) led by the high MSP, despite providing an emission reduction of approximately 70% compared to fossil kerosene.

Of the 1G pathways, the mitigation costs ranged from 495–1474 USD tCO_{2e}⁻¹, where the SAF production via 1G

sugarcane ethanol (SC-1G/ATJ) had better performance than oil-based pathways mostly due to the low emission reduction provided by soybean (21%) and palm (17%) (see Fig. 2(a)).

It is worth stressing that the GHG emissions related to Palm/HEFA consisted of a default value for emissions related to land-use change ($39.1 \text{ kgCO}_2\text{e GJ}^{-1}$) – which has been suggested for palm crops in Malaysia and Indonesia (see Table 4) – due to the lack of specific data for Brazil. As this value is not based on Brazilian data, and it corresponds to more than half of the emissions for the whole life cycle, it could lead to overestimations of the mitigation costs related to this pathway in Brazilian conditions.

Even so, SAFs produced via Palm/HEFA and Soy/HEFA could be strategic options under CORSIA guidelines if they were obtained from certified areas with low-risks for land use change. In that case, iLUC emissions could be assumed zero,⁶⁹ and the mitigation costs of these pathways could decrease substantially by 58 and 72%, respectively, achieving 550 USD $\text{tCO}_2\text{e}^{-1}$ (Soy/HEFA) and 420 USD $\text{tCO}_2\text{e}^{-1}$ (Palm/HEFA). Low-risks for land use change are possible when the feedstock is produced in unused lands or by management practices that provide an increase of the agricultural yield without land expansion.

Variations on the life-cycle emissions from different studies are expected due to inventory aspects and methodological issues, which can influence the mitigation costs. Although it is reasonable to suppose that techno-economic evaluations and GHG emissions estimations are based on the same pathway description, an airline operator can use the default values for life-cycle emissions suggested by CORSIA⁷¹ to report its inventory emissions. These default values are considerably different from those estimated here for SC-1G/ATJ and Fischer–Tropsch pathways (see Table 4). In comparison with the studies that supported the CORSIA values,⁹⁷ the major differences are the GHG emissions estimated for the conversion processes, such as ethanol and SAF production, and the feedstock procurement / transportation for Fischer–Tropsch processing of lignocellulosic residues. Furthermore, if these default values were assumed here, the mitigation costs could decrease by 25% for SC-1G/ATJ ($391 \text{ USD tCO}_2\text{e}^{-1}$) or increase by around 10% for FR/FT and SC/FT (252 and $388 \text{ USD tCO}_2\text{e}^{-1}$, respectively). Relevant discrepancies were not observed in other pathways.

Pioneer plants (Fig. 3(b)) of waste grease-based pathways (UCO/HEFA and Tallow/HEFA) had the best performance (225 and $366 \text{ USD tCO}_2\text{e}^{-1}$, respectively) followed by SC-1G/ATJ ($602 \text{ USD tCO}_2\text{e}^{-1}$), while Palm/HEFA ($1657 \text{ USD tCO}_2\text{e}^{-1}$) and Soy/HEFA ($1468 \text{ USD tCO}_2\text{e}^{-1}$) still reported the highest values. On the other hand, the mitigation costs related to immature or complex technologies, such as ATJ via

2G ethanol and thermochemical processes, ranged in 854 – $943 \text{ USD tCO}_2\text{e}^{-1}$, except the Fischer–Tropsch processing of forestry residues, which achieved roughly $700 \text{ USD tCO}_2\text{e}^{-1}$.

The effective feasibility of each pathway is better evaluated by considering the potential of each to produce SAF or provide carbon emission reductions in view of mitigation costs. According to Fig. 3(c), the potential SAF production of 1G pathways based on palm or sugarcane would exceed the total demand of SAF in Brazil (around 7.0 million m^3 ⁷⁵) at expenses of 33.7 – 34.8 USD GJ^{-1} , i.e., two times higher than the current average price of Jet A. Hydrothermal liquefaction of sugarcane residues also exceeded the total demand, but this pathway is under development and it has not been approved yet.

It is worth mentioning that the potential availability of feedstocks for 1G pathways was based on specific conditions. Based on the agro-ecological zoning for sugarcane in Brazil⁹⁸ and the recent expansion of the crop,^{81,99} around 9.5 Mha would be highly suitable for sugarcane expansion in the Center-South region, potentially providing 32.0 million m^3 of SAF. Here, sugarcane expansion into only 3.9 Mha was assumed.

In addition, here the palm expansion was assumed into 23.5 Mha of residual lands according to Cervi *et al.*,²⁵ while Ramalho Filho and Motta¹⁰⁰ reported that 7.4 Mha of deforested areas in the Amazon region would be highly suitable for palm expansion, with possible benefits in recovering degraded areas, providing income for family farmers, and improving the carbon balance. Palm/HEFA could provide 11.8 million m^3 of SAF, assuming the potential area reported by these latter authors.

In general, the individual potential of SAF production via residues-based pathways is lower than the fuel demand for international flights originating in Brazil. Although the thermochemical conversion of sugarcane residues presents higher potential than those based on forestry residues, they are related to higher costs. On the other hand, the strategic benefits of UCO/HEFA were decreased due to its small production potential.

Finally, according to Fig. 3(d), the potential carbon reduction of each pathway, especially the ones based on sugarcane via 1G ethanol or thermochemical conversion of sugarcane residues, could eventually provide a reduction equivalent to the total emissions estimated for the Brazilian aviation sector in 2018 ($16.7 \text{ MtCO}_2\text{e}$ ⁷⁵), at the cost of 334 to $575 \text{ USD tCO}_2\text{e}^{-1}$. Alternatively, the thermochemical conversion of forestry residues or Tallow/HEFA could provide an abatement of 25% (FR/FT), 17% (Tallow/HEFA), and 94% (FR/HTL) of related emissions to international flights originating in Brazil, respectively.

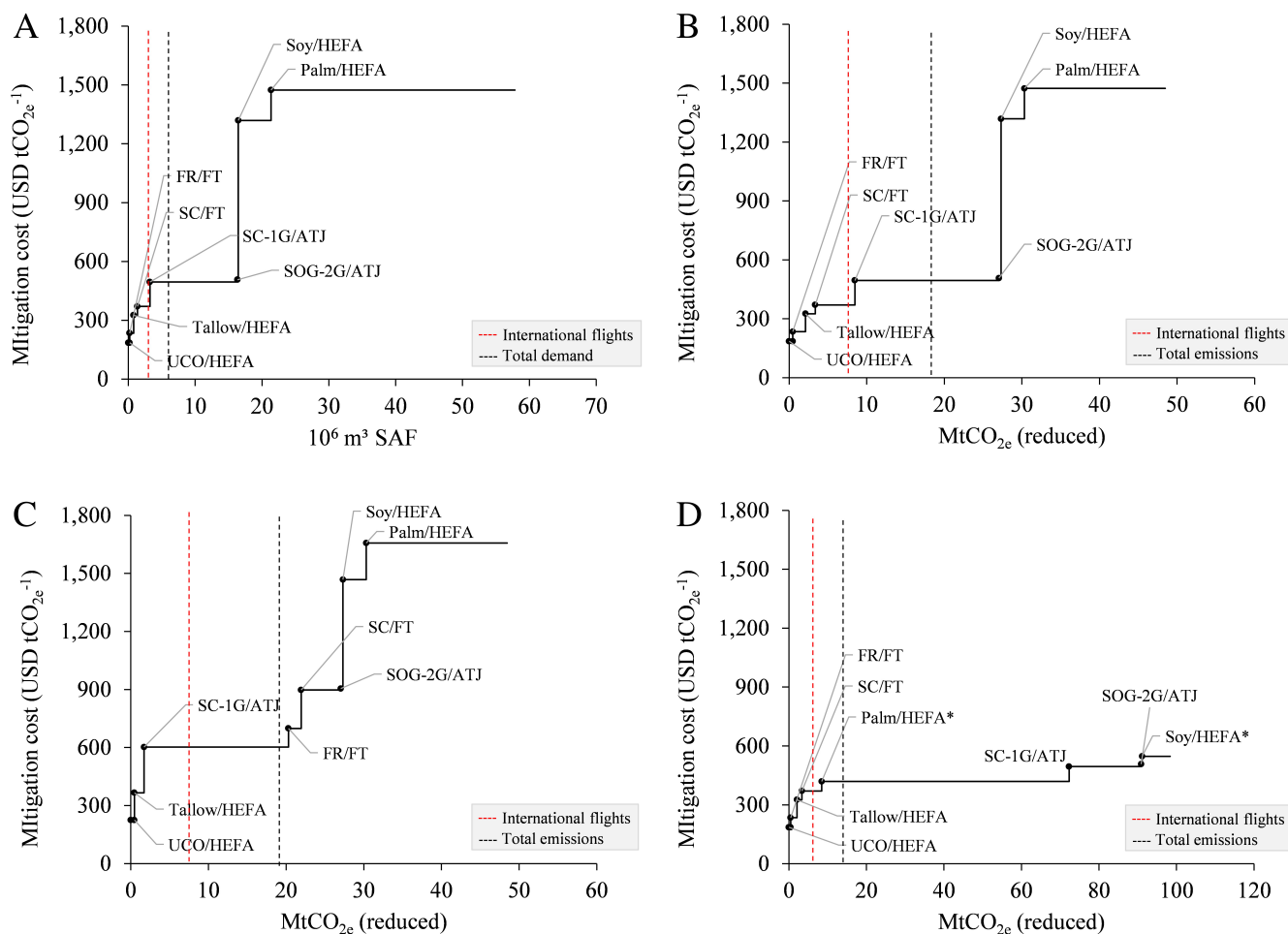


Figure 4. Supply curve of SAF assuming an N^{th} plant (a); carbon mitigation curve by SAF assuming an N^{th} plant (b); carbon mitigation curve assuming a pioneer plant (c). Carbon mitigation curve by SAF assuming an N^{th} plant, with SAF produced from soybean (soy*) and palm (palm*) obtained in areas with low-risks for LUC (d). ‘International flights’ mean the fuel demand or GHG emissions related to international flights originating in Brazil. ‘Total values’ mean the fuel demand or GHG emissions related to international and domestic flights in Brazil.⁷⁵

If the residual areas assumed here for palm expansion were certified as low-risk for land use change, Palm/HEFA* could provide great mitigation of around 63.8 MtCO_{2e}. However, this potential should be evaluated carefully. According to the CORSIA sustainability criteria,⁹ SAFs shall not be produced from areas whose previous use to 2008 was related to a high carbon stock, such as primary forests. Furthermore, to be certified as low-risk for LUC,⁶⁹ eligible unused land must fulfill specific criteria related to the previous use or the degradation level. Even so, the potential carbon mitigation by Palm/HEFA* could achieve 20.6 MtCO_{2e}, assuming palm expansion into degraded areas in the Amazon.¹⁰⁰

Ranking the pathways by their mitigation costs – which seems to be reasonable considering the ICAO goals – it is

possible to draw the supply and abatement curves presented in Fig. 4. The HTL technology is not approved yet, so it was not considered in the following graphs. Furthermore, pathways based on ATJ of 2G ethanol were disregarded, as they compete for feedstock with pathways based on Fischer–Tropsch technologies, which presented lower mitigation costs than those.

According to Fig. 4(a), residue-based pathways (FR/FT, SC/FT, Tallow/HEFA, and a tiny contribution of UCO/HEFA) could supply the Jet A demand by international flights originating in Brazil by costs ranging from 26.4 to 34.5 USDGJ⁻¹. The total volume estimated here from approved pathways (57.9 10⁶ m³) – which was led mainly by Palm/HEFA – could supply roughly 13% of the global demand

for fossil kerosene, or even 22% of demand for international flights.¹⁰¹

Regarding potential carbon reduction (Fig. 4(b)), waste grease-based pathways (UCO/HEFA and Tallow/HEFA) and thermochemical conversion of lignocelulosic residues could provide carbon mitigation equivalent to the emission from the international flights originating in Brazil (around 7.6 MtCO_{2e}) with moderate costs (185–371 USD tCO_{2e}⁻¹).

On the other hand, the costs increased assuming pioneer plants (Fig. 4(c)), and the pathway based on 1G ethanol (SC-1G/ATJ, 602 USD tCO_{2e}⁻¹) gained prominence providing carbon mitigation corresponding to all emissions from the Brazilian aviation sector. In contrast, the waste-grease pathways could provide carbon reduction close to 20% of the emissions from the international flights originating in Brazil with the lowest costs (225–266 USD tCO_{2e}⁻¹).

From a wider perspective, the pathways evaluated here could provide a total reduction of 48.5 MtCO_{2e}, which means 8% of the carbon emissions related to the international flights in the world, or 29% for international flights originating in Europe, or even 41% of the international flights originating on the American continent.¹⁰² Excluding oil-based 1G pathways due to their high costs, the pathways could reduce roughly 23% of the carbon emissions related to the international flights on the American continent, at expenses of 185–495 USD tCO_{2e}⁻¹.

However, if Soy/HEFA and Palm/HEFA were proven to be obtained from low-risk areas for land-use change (Fig. 4(d)), SAF produced in Brazil could mitigate 18% of the carbon emissions related to international aviation operations (98.4 MtCO_{2e}) at a cost of 185–547 USD tCO_{2e}⁻¹. It is worth remembering that the CORSIA criteria for eligible areas, as mentioned previously, must be taken into account, which could reduce this potential.

Sensitivity analysis

In general, the fossil fuel price is a relevant parameter for the feasibility of any biofuel program. Here, the mitigation costs of SAF pathways ranged similarly to the variations of the Jet A price ($\pm 30\%$), except for pathways based on 2G ethanol, whose values varies ($\pm 15\%$). The variation of the MARR ($\pm 30\%$) also implied close variations on 2G pathways ($\pm 30\%$), while led to ($\pm 20\%$) in 1G-based ones.

The sensitivity of the scale of industrial plants ($\pm 50\%$) was more relevant in capital-intensive pathways, such as those based on 2G ethanol (-30% to $+80\%$) and thermochemical processes (-20% to $+50\%$). In turn, variations on the feedstock price ($\pm 20\%$) were relevant for Soy/HEFA ($\pm 30\%$) and less than 20% for other pathways, including residue-

based ones, except for SOG-2G/ATJ. In this latter, if steel-off gases – which have been recovered for energy purposes in several steel mills⁶¹ – were priced by natural gas, the mitigation costs related to SOG-2G/ATJ would increase by 103% (1031 USD tCO_{2e}⁻¹).

HEFA-based pathways were more sensitive than ATJ-based ones for hydrogen production using WE, due to the higher hydrogen consumption. The high costs of this alternative hydrogen production is not compensated by the slight decrease in GHG emissions provided by WE in comparison with SMR, given the large power demand in the electrolysis process, even considering the relevant contribution of renewable sources in the Brazilian power grid. In general, hydrogen from WE could increase the mitigations costs related to oil-based pathways and UCO/HEFA by 25 to 45%, respectively.

The variation on transportation distances ($\pm 50\%$), in turn, could lead to variations of $\pm 25\%$ in UCO/HEFA, and less than 5% in the other pathways. Finally, the mitigation costs of each pathway could be reduced by around 80% and be increased twofold for 1G pathways assuming the cumulative variations. The range of the cumulative variations is a bit narrow (-70 to 120%) for 2G pathways, except for UCO/HEFA and SOG-2G/ATJ, which total values could increase threefold to fivefold, respectively.

Alternative offsetting market-measures

In comparison with the emission units traded in the carbon market, the mitigation costs of SAFs – considering the possible range from the sensitivity analysis (see Fig. 5) – are much higher than current prices (1.02–3.13 USD tCO_{2e}⁻¹) or even the future ones (5.90–55.2 USD tCO_{2e}⁻¹) (see Fig. 6). Some competitiveness is observed in UCO/HEFA and in the thermochemical conversion of forestry residues. Of the 1G pathways, only SAF production from sugarcane (SC-1G/ATJ) had a minimum value close to the maximum carbon price reported for future scenarios. It is important to highlight that the mitigation costs of Palm/HEFA are considerably influenced by the default factor related to land use change emissions. Thus, this pathway can eventually be competitive with the carbon market for a different LUC factor estimated in Brazil.

The current prices of the emission units can be presented in different ranges: (i) by program (1.02–3.13 USD tCO_{2e}⁻¹), as reported in Fig. 6, where the minimum and maximum values are related to CDM and Gold Standard; (ii) by the project category (1.67–5.01 USD tCO_{2e}⁻¹), where the minimum and maximum values are related to renewable energy/industrial manufacturing and household device projects, respectively;

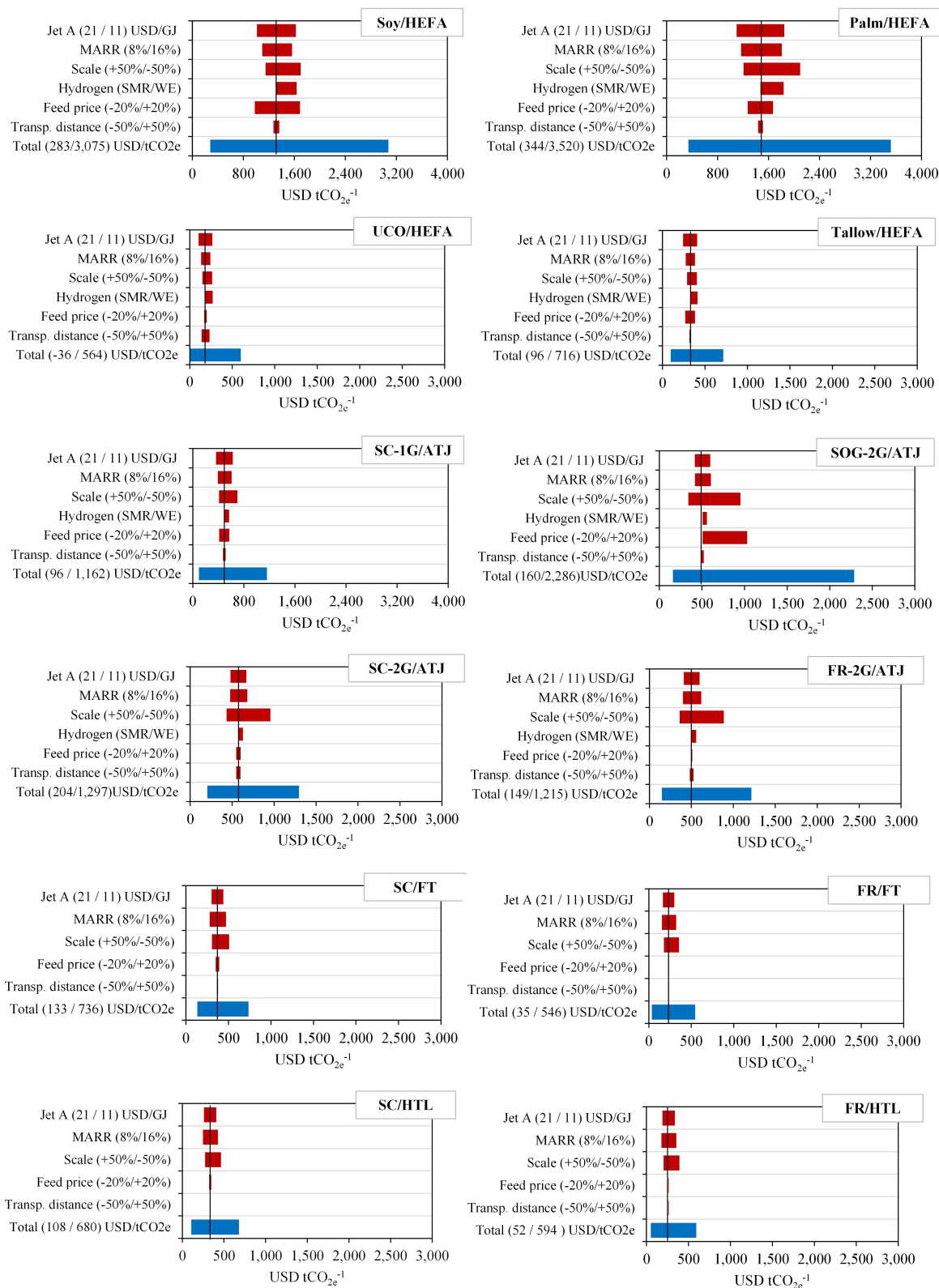


Figure 5. Sensitivity analysis of the mitigation costs of SAF.

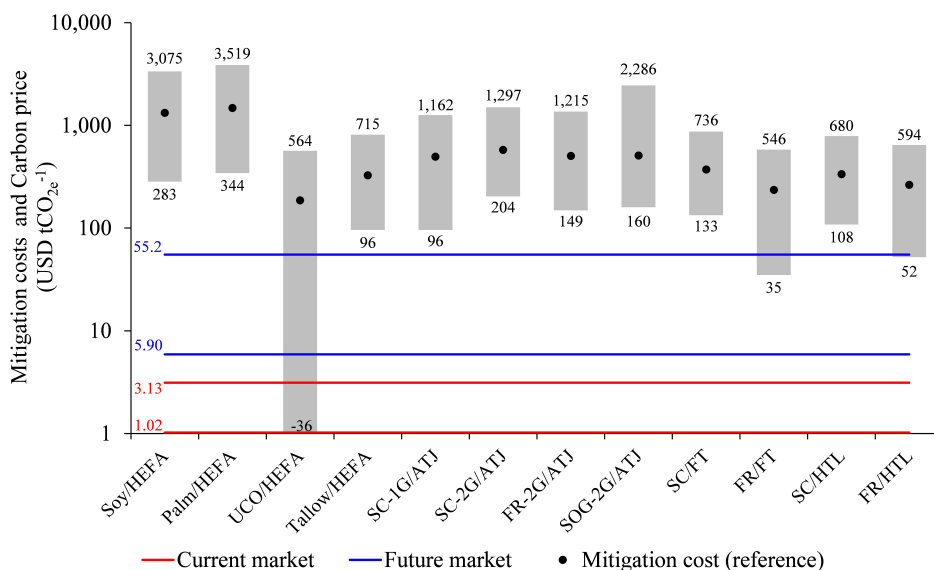


Figure 6. Comparison between the mitigation costs of SAF and the price of the emission units according to the carbon market.

and (iii) by region (0.70–4.20 USD tCO_{2e}⁻¹) where the minimum and maximum values are related to European projects and African projects, respectively.

Overall the mitigation costs of SAF remain significantly higher than offsetting costs in all situations, which confirms the preference for offsetting market-measures in the short-term and provokes a discussion about the effective role of SAFs in the ICAO goals.

The availability of the emission units in the carbon market is also a relevant parameter in this discussion. Ecosystem Marketplace¹⁰³ has compared the CORSIA demand by carbon offset for the first cycle (2021–2023) with the existing and potential emission units supply, based on the six approved programs, within the 2016–2020 timeframe. Results have shown that the existing supply is roughly 4.0 to 5.5-fold higher than CORSIA demand. Fearnough *et al.*¹⁰⁴ extended the analysis to the complete CORSIA duration (2021–2035), by considering data from the four largest Programs: CDM, VCS, GS, and CAR. They estimated a potential supply of 18 billion tCO_{2e} against a predicted demand of 2.7 billion tCO_{2e} for the aviation sector.

These results reaffirm that purchasing emission units is currently more feasible than direct investments in biofuels, as carbon offset prices are much lower (see Fig. 6), and there is strong availability in the market. An important question thus arises: do SAFs on GHG reduction still make sense?

First, it is worth stressing that the production and use of biofuels such as SAFs could directly or indirectly provide benefits beyond GHG mitigation, such as the development of national industry, possible socio-economic

improvements for farmers and local communities, and energy security.^{46,105–108}

Second, it is necessary to look more closely at the particularities of the carbon market to assess the effective benefits of carbon offsetting to understand whether the emissions units can really serve the purpose of mitigation.

Although a potential supply of emission units was reported approximately seven times higher than CORSIA's demand,¹⁰⁴ that study has defined different restriction scenarios, which could significantly reduce the availability of the emissions units.

In summary, the scenarios were defined under the following criteria: (i) emission reduction vintage, referring to the date on which the emissions actually occurred; (ii) registration vintage, considering the date of the project registration; (iii) investment decision vintage, related to the date of the financial decision to implement the project; and (iv) the start date of the project operations vintage, referring to the start of operations. For all the scenarios, only the vintage from 1 January 2017 was considered, as ICAO had already defined the 2016–2020 window for emission reductions for the first cycle.

Fearnough *et al.* (2019)¹⁰⁴ also added scenarios not related to vintage: (i) double-claiming scenarios, in which emission reductions could only come from projects that were not included in any mitigation targets from NDCs or should only consider emissions reductions from countries without listed NDC mitigation targets; (ii) vulnerability scenarios, where only projects with high or variable vulnerability would

be accepted for discontinuing GHG abatement without emission reductions revenues; and (iii) a scenario comprising only projects developed in less-developed countries (LDCs) and small-island developing states (SIDs).

These different scenarios represent possible eligibility choices or restrictions that could be applied both by CORSIA, in future phases, or even by the airlines, which could prioritize specific emission reductions, such as greater assurances of environmental integrity.

Then, a significant variation on the effective emission units' availability – i.e., from 6 million to 18 billion tCO_{2e} – can be observed. Of the 13 defined scenarios, seven stayed below CORSIA's estimated demand (2.7 billion tCO_{2e}). The restrictions had a significant impact on the potential supply, which would be related to the project age (investment decision, the start of operations) and topics related to double claiming, vulnerability, and project location.

Discussions on more restrictive rules for carbon offsetting are not new in the carbon market. The most widespread market mechanisms related to GHG mitigation were those defined by the Kyoto Protocol, especially the Clean Development Mechanism, which served as the most well known case. Among those experiences, some lessons have been learned and shared by different authors,^{109–115} mainly to support decisions for future protocols, such as the proposed market in Article 6 from the Paris Agreement.

Although CORSIA is not included at the Paris Agreement's goals, discussions and trends regarding perceptions of the market players should be considered. Some studies have expressed concerns about additionality, environmental integrity, and double counting of the emissions units.^{116–118} According to these authors, special attention should be given to additionality, which means that reductions must occur against a baseline scenario that would continue to happen without that project's intervention. Therefore, in order to demonstrate effective mitigation, the project must overcome at least one barrier: financial, institutional or technological.¹¹⁹

In this context, Cames *et al.*,¹²⁰ who evaluated CDM projects with potential emissions reductions from 2013 to 2020, indicated that at least 73% of the emissions were either unlikely to be additional or had been overestimated. This corroborates the scenario depicted by Fearnough *et al.*¹⁰⁴ for project vulnerability, when it was concluded that most of the existing carbon projects would continue to operate without carbon revenues and, therefore, that the effective mitigation could be questionable.

At the moment, emissions units could supply the CORSIA demand for the first cycle (2021–2023). On the other hand, taking into account the doubts related to the credibility of the emission units and uncertainties related to mitigation effects,

different scenarios should be expected after 2023, when more restrictive guidelines would lead to lower availability. In this almost certain gap, the SAFs could play an important role if the development of this new biofuel sector is supported by robust carbon policies. These policies could tackle the current disadvantages incorporated by CORSIA, which handle emission reduction in an equivalent way to emission offsetting.²⁹

Some existing policies already have supported biofuels, including SAFs. In 2017, the Brazilian government launched the National Policy on Biofuels (Renovabio),¹²¹ seeking to promote biofuel expansion. Of the determined instruments in Renovabio are the 'decarbonization credits' (CBIOs), which can be claimed by biofuel producers or importers, properly authorized by the national agency. Those credits have just been implemented, so price projections are still uncertain, even though they have already reached around 10.0 USD tCO_{2e}⁻¹ at the first negotiations held in June 2020.¹²² The program also covers compulsory additions of biofuels to fossil fuels, taxes, and financial and credit incentives. Only HEFA-based pathways are currently considered in the program scope,¹²³ but biofuel producers can request the incorporation of new pathways.

The Renewable Fuel Standard (RFS), which has been implemented in the USA since 2005,^{124,125} sets a minimum volume for renewable fuels for transportation.¹²⁶ Currently, only four pathways based on HEFA and FT technologies are approved by RFS.¹²⁷ The latest RIN prices ranged from 2.65–820 USD m⁻³ (0.01–3.50 USD/gallon).¹²⁸ Although the RFS assessment is based on the environmental performance of fuels, unlike Renovabio, it does not put a direct price on carbon emissions.

In California, the Low Carbon Fuel Standard (LCFS) has been implemented since 2011. It aims to reduce the carbon intensity (CI) of fuels used in transportation in 10% until 2020, compared with a 2010 base year.¹²⁹ Adjusted goals will improve overall CI fuel benchmarks until 2030. Although LCFS has addressed AJF as an "opt-in" provision, *i.e.* without specific obligations or targets, three AJF pathways based on Tallow/HEFA are currently approved. LCFS credit prices ranged from 160–217 USD tCO_{2e}⁻¹, according to July 2020 report.¹³⁰

Although all the previous policies are based on life cycle emissions, it is worth mentioning that specific methodology assumptions of each policy can lead to different performances in comparison with CORSIA, and hence, diverge trends than what was presented here.

Conclusion

In this study, the mitigation costs (USD tCO_{2e}⁻¹) related to SAF pathways were estimated, which ultimately reflected how much the carbon is reduced by each pathway.

Twelve food-based pathways (1G) and residues-based pathways (2G) comprising strategic feedstocks (soybean, palm, sugarcane, lignocellulosic residues, waste-greases, and steel-off gases), and approved technologies (HEFA, ATJ, FT, HTL) were evaluated.

In general, residue-based pathways had lower mitigation costs. Used cooking oil / HEFA had the lowest value (185 USD tCO_{2e}⁻¹), followed by the thermochemical conversion of forestry residues (234–263 USD tCO_{2e}⁻¹), hydrotreating of beef tallow (326 USD tCO_{2e}⁻¹), and the thermochemical conversion of sugarcane residues (334–370 USD tCO_{2e}⁻¹). The SAF from 2G ethanol had high values (500–570 USD tCO_{2e}⁻¹). Of the 1G pathways, SAF production using 1G sugarcane ethanol (SC-1G/ATJ) had a better performance than oil-based pathways. While the former resulted in 495 USD tCO_{2e}⁻¹, the latter ranged from 1320–1470 USD tCO_{2e}⁻¹. However, if Soy/HEFA and Palm/HEFA were obtained from certified areas with low-risks for land use change, the mitigation costs of these pathways could decrease to 550 USD tCO_{2e}⁻¹ and 420 USD tCO_{2e}⁻¹, respectively.

Considering the potential of each pathway to produce SAF or provide carbon emission reduction, residue-based pathways (FR/FT, SC/FT, Tallow/HEFA, and a tiny contribution of UCO/HEFA) could supply the international flights originating from Brazil. Regarding the potential carbon reduction, these same pathways could lead to a 25% reduction in carbon emissions related to international flights in Brazil with moderate costs (185–326 USD tCO_{2e}⁻¹).

In comparison with the carbon market, the mitigation costs of SAFs are much higher than the current prices (1.02–3.13 USD tCO_{2e}⁻¹) or even future ones (5.90–55.2 USD tCO_{2e}⁻¹). Some competitiveness was observed in UCO/HEFA and the thermochemical conversion of forestry residues, in specific conditions.

Nevertheless, SAFs could play an important role in aviation sector goals. Despite the other benefits provided by a new biofuel sector, there are several concerns about the credibility of the emissions units and their effective mitigation effects, which could lead to more restrict guidelines related to these offsetting measures. However, the development of this new sector must be supported by robust carbon policies based on mitigation costs in order to overcome the typical risks of first-of-kind technologies, as it is the case.

Finally, SC-1G/ATJ is the most suitable alternative in the short term, considering its potential to supply SAF and to mitigate emissions. Palm/HEFA could also be included after confirmation of the potential lower emissions related to land-use change in Brazilian conditions. Of the residues-

based pathways, Tallow/HEFA and FR/FT are strategic alternatives. However, the commercial risks for Tallow/HEFA due to possible competition with the biodiesel market and technological risks related to thermochemical conversion must be taken into account.

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