CORSIA: The First Internationally Adopted Approach to Calculate Life-cycle GHG Emissions for Aviation Fuels

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ABSTRACT

The aviation sector has grown at a significant pace in recent years, and despite improvements in aircraft efficiency, the sector's impact on climate change is a growing concern. To address this concern, the International Civil Aviation Organization (ICAO) established the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) to help reduce aviation greenhouse gas (GHG) emissions. This paper presents a methodology agreed by the 193 ICAO member states to evaluate the life-cycle GHG emissions of Sustainable Aviation Fuels (SAFs), in the CORSIA system. The core life-cycle assessment and induced land use change values of SAFs are presented to determine the GHG savings of certified pathways. The paper aims to present that a number of SAFs can yield significant life-cycle emission reductions compared to petroleum-derived jet fuel. This implies the potentially major role of SAFs in reducing aviation's carbon footprint.

HIGHLIGHTS

- The goal of the CORSIA is to reduce GHG emissions from international aviation.
- Internationally agreed LCA methodologies for GHG saving potentials are presented.
- Sustainable aviation fuels can reduce GHG emissions up to 90%
- SAFs GHG saving can exceed 100% when land use change is included.
- Further challenges for reducing the GHG emissions from aviation are discussed.

KEYWORDS

sustainable aviation fuels, aviation, bio kerosene, life-cycle assessment, GHG reductions, CORSIA

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LIST OF ABBREVIATIONS

ANL	Argonne National Laboratory,
ATJ	Alcohol-to-jet
CARB	California Air Resource Board
CEFs	Corsia Eligible Fuels
CI	Carbon intensities
CO_2e	Carbon dioxide equivalent
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
ETJ	Ethanol-to-jet
FOG	Fats, oils, and greases
FT	Fischer-Tropsch
GHG	Greenhouse gas
GREET	Greenhouse gases, Regulated Emissions, and Energy use in Technologies
GTAP	Global Trade Analysis Project
HEFA	Hydroprocessed esters and fatty acids
HVO	Hydrotreated vegetable oils
IATA	International Air Transport Association
iBuOH	Iso-butanol
ICAO	International Civil Aviation Organization
IIASA	International Institute for Applied Systems Analysis
JRC	European Commission Joint Reserach Centre
ILUC	Induced land use change
LCA	Life cycle assessment
LCAFs	Lower carbon aviation fuels
LUC	Land use change
MIT	Massachusetts Institute of Technology
MMT	Million metric tons
MSW	Municipal solid waste

NBC	Non-biogenic carbon
POME	Palm oil mill effluent
SAFs	Sustainable aviation fuels
SIP	Synthesized iso-paraffins
SOC	Soil organic carbon
SPK	Hydroprocessed hydrocarbons, esters and fatty acids
WTW	Well-to-wake

1. INTRODUCTION

In 2017, air transport accounted for 2% of the total global anthropogenic CO_2 emissions (approximately 859 million metric tons [MMT]) [1]. Furthermore, prior to the COVID-19 pandemic, the International Air Transport Association (IATA) anticipated a near-doubling of aviation activity between now and 2035, to 7.2 billion passenger journeys in 2035 [2]. Despite the impacts of the pandemic, aviation activity is expected to grow over the long term. Unless aviation activity can be decoupled from CO_2 emissions, this growth will lead to increasing impacts on climate change.

The United Nation's International Civil Aviation Organization (ICAO) uses scientific, data-driven decision making to develop measures to address the environmental impacts of aviation [3]. For example, a global CO_2 standard that regulates fuel efficiency for new aircraft went into effect in 2020 [4] and ICAO member states have an aspirational goal of a 2% annual fuel efficiency improvement. Based on such extensive scientific driven analysis of the aviation sector, in 2016, the ICAO Assembly agreed on the adoption of a global market-based scheme to limit international aviation CO_2 equivalent (CO_2e) greenhouse gas emissions (also referred as GHG, in the rest of the paper): the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) [3]. CORSIA requires airlines to offset CO_2e. emissions that exceed 2019 levels. On the basis of impact assessments and scientific available knowledge, CORSIA has been framed to allow offsetting either through credits or through the use of CORSIA Eligible Fuels (CEFs), such that international aviation achieves carbon neutral growth from 2020 [5].

Despite steady improvements in fuel efficiency, mainly achieved by new aircraft entering the fleet (from fuel consumption of 4.4 l/100 passenger-km in 2005 to 3.4 in 2017 (-24%) in Europe, and annual improvement of 2.3% between 1991 and 2009 in the United States and the continued down trend through 2018) [6–8], decarbonizing aviation remains a challenging task, due to rapid growth of the sector [9]. This is especially true for international aviation where pre-pandemic growth rates were above 4% per annum [10]. Alternative propulsion options (e.g., electric driven and hybrid systems) and alternatives to jet fuel (e.g., liquid natural gas and hydrogen) have been proposed, but have only been tested at the pilot-scale thus far. There are numerous unresolved technical issues associated with these alternatives [11]; therefore, stabilizing international aviation CO_2 emissions at 2019 levels will likely require the use of drop-in sustainable aviation fuels (SAFs). Drop-in SAFs do not require engine or system modifications in the aircraft, nor do they require dedicated refueling infrastructure [11,12].

CORSIA allows the use of SAFs (i.e., drop-in alternative jet fuels that fulfill a set of sustainability criteria and are derived from biomass or waste resources), in order to reduce airlines' carbon offsetting requirements. Under CORSIA, emissions reductions from the use of SAFs are calculated using a life-cycle assessment (LCA) approach, agreed upon at ICAO in 2018 [13]. With this agreement, the CORSIA LCA method has become the first internationally adopted approach for the calculation of life-cycle GHG emissions of aviation fuels. Four elements proved key to the agreed LCA method for CORSIA [13]: (1) use of life-cycle accounting for GHG emissions, (2) inclusion of induced land use change (ILUC), (3) safeguards to prevent deforestation, and (4) crediting of practices that mitigate the risk of land use change (LUC). These elements enabled a wide range of stakeholders to pursue different measures for SAFs to reduce CO_2e emissions on a life-cycle basis, while mitigating the risks of unintended consequences.

This paper aims to present the LCA-based methodology defined for the CORSIA initiative and to contribute to harmonizing and closing the gaps in existing calculation approaches [14–16]. First, the current technologies available for SAF production are presented. We then present the methodology for carbon intensity assessment under CORSIA. Since the main objective is to evaluate the life-cycle GHG emissions of SAFs for CORSIA, the GHG emissions (expressed in terms of CO_2e emissions), of each life-cycle step for a given SAF is presented (feedstock cultivation and collection, feedstock transportation, feedstock-to-fuel conversion, fuel transportation, and fuel combustion) to highlight the impact of key parameters on life-cycle GHG emission results. The approach adopted to quantify ILUC emissions for selected pathways is also described to show the potential contribution of this element to life-cycle GHG emissions. In the discussion section, we aim to stress that a number of SAFs can yield significant life-cycle emission reductions compared to petroleum-derived jet fuel, which potentially plays a major role in mitigating international aviation environmental impact. It is important to note that the presented methodology has become the first internationally adopted approach for calculating GHG emissions potential of aviation fuels.

2. SUSTAINABLE AVIATION FUELS (SAFS)

In order to be eligible for ICAO CORSIA, a CORSIA Eligible Fuel (CEF) must meet the sustainability criteria, which are currently defined as having life-cycle GHG emissions that are at least 10% below those of the petroleum jet fuel baseline and not being made from biomass obtained from land with high carbon stock [17]. LCA is the chosen tool to quantitatively assess the GHG emission saving offered by a specific alternative fuel. At the same time, work on other sustainability themes such as water; soil; air; conservation; waste and chemicals; human and labor rights; land use rights and land use; water use rights; local and social development; and food security is ongoing under the

ICAO Committee on Aviation Environmental Protection (CAEP). Additional sustainability criteria are under development within ICAO. Fuels produced from renewable or waste feedstocks that meet these CORSIA sustainability criteria are considered to be SAFs. Based on an extensive evaluation of the global petroleum jet fuel production, the average life-cycle GHG intensity baseline has been set at 89 gCO_2e/MJ [13] from well to wake (WTW), including crude oil recovery, transportation and refining, jet fuel transportation, and jet fuel combustion. Therefore, fuels that have life-cycle GHG emissions lower than 80.1 gCO_2e/MJ and are not threatening the conversion of high-carbon stock land are eligible for CORSIA.

There are two fuel categories under CEF: SAFs and Lower Carbon Aviation Fuels (LCAFs). While SAFs can be produced from renewables or wastes, LCAFs refer to fuels from fossil sources but with at least 10% lower life-cycle GHG emissions than those of the petroleum jet fuel baseline. The methodology to compute life-cycle GHG emissions for LCAFs is still under development in ICAO, whereas the LCA methodology for SAFs has been already approved and presented in this paper [18,19]. A fundamental characteristic of SAFs is compliance with ASTM standards [20,21]. ASTM D7566 [22] strictly regulates the specifications for blending of non-petroleum components with standard petroleum-based jet fuel, which is certified under ASTM D1655 [23]. These standards ensure these fuels are safe for use in aviation. As of writing, the following conversion processes and renewable feedstock types to produce SAFs have been approved by ASTM and included in annexes to ASTM D1655 and D7566 (Table 1). In addition, there are many additional SAF pathways in the pipeline for ASTM certification [20,24,25].

Table 1. Types of SAFs approved by ASTM

ASTM D7566 Annex A1	Fischer-Tropsch (FT) hydroprocessed synthesized paraffinic kerosene (SPK), mainly produced from woody residual biomass, municipal solid waste (MSW), etc. Maximum allowed blending rate: 50% v/v
ASTM D7566 Annex A2	Synthesized paraffinic kerosene from hydroprocessed esters and fatty acids (HEFA) from lipid feedstocks such as vegetable oils, used cooking oils, tallow, etc. Maximum allowed blending rate: 50% v/v
ASTM D7566 Annex A3	Synthesized iso-paraffins (SIP) from hydroprocessed fermented sugars. Maximum allowed blending rate: 10% v/v
ASTM D7566 Annex A4	FT synthesized paraffinic kerosene with aromatics (SPK/A) derived by alkylation of light aromatics from non-petroleum sources. Maximum allowed blending rate: 50% v/v
ASTM D7566 Annex A5	Alcohol-to-jet (ATJ) SPK using ethanol or isobutanol as an intermediate molecule. Maximum allowed blending rate: 50% v/v
ASTM D7566 Annex A6	Catalytic hydrothermolysis synthesized kerosene from fatty acid and fatty acid esters. Maximum allowed blending rate: 50% v/v
ASTM D7566 Annex A7	Hydroprocessed hydrocarbons, esters and fatty acids SPK by the *Botryococcus braunii* species of algae. Maximum allowed blending rate: 10% v/v
ASTM D1655 Annex A1	Co-processing of fats, oils, and greases (FOG) or Fischer Tropsch biocrude (unrefined hydrocarbon content coming from an FT reactor) in a traditional

	petroleum refinery, limited to 5% by volume in input into the refinery

3. Methodology for Carbon Intensity assessment under CORSIA

The GHG intensities of SAFs need to be calculated and monitored in a consistent and transparent manner for CORSIA. To facilitate this, LCAs have been performed by a working group under ICAO CAEP since 2014, of which all the authors were members [26]. Work is structured in technical groups, namely the “Core LCA” and the “ILUC” groups. The Core LCA working group developed the LCA methodologies for SAFs and established and endorsed a set of default core LCA emission values for selected SAF pathways. The ILUC working group defined assumptions, developed results in the relevant modeling tools and proposed a set of ILUC values for selected SAF pathways. Note that CORSIA default life-cycle emission values are calculated as the sum of the “core LCA” values (adding up direct emissions along the supply chains of individual SAFs) and the estimated “ILUC” emission values.

Applying LCA methodology [27] to alternative fuel production pathways has been proposed in many studies, mainly focusing on fuels used in the road transport sector [28,29]. For aviation, recent studies confirm the potential of alternative fuels to mitigate sectoral emissions [30–33]. For CORSIA, core LCA values have been defined using a process-based attributional LCA approach, accounting for mass and energy flows, along the whole fuel supply chain [13]. It is worth noting that this methodology represents the first internationally adopted approach for the calculation of life-cycle GHG emissions of aviation biofuels. The scope of the core LCA for SAFs (system boundary) includes all processes along the fuel production supply chain with significant GHG emissions. Figure 1 presents the system boundary of the CORSIA SAF core LCA, covering feedstock cultivation/collection, feedstock transportation, jet fuel production (conversion), jet fuel transportation, and jet fuel combustion.

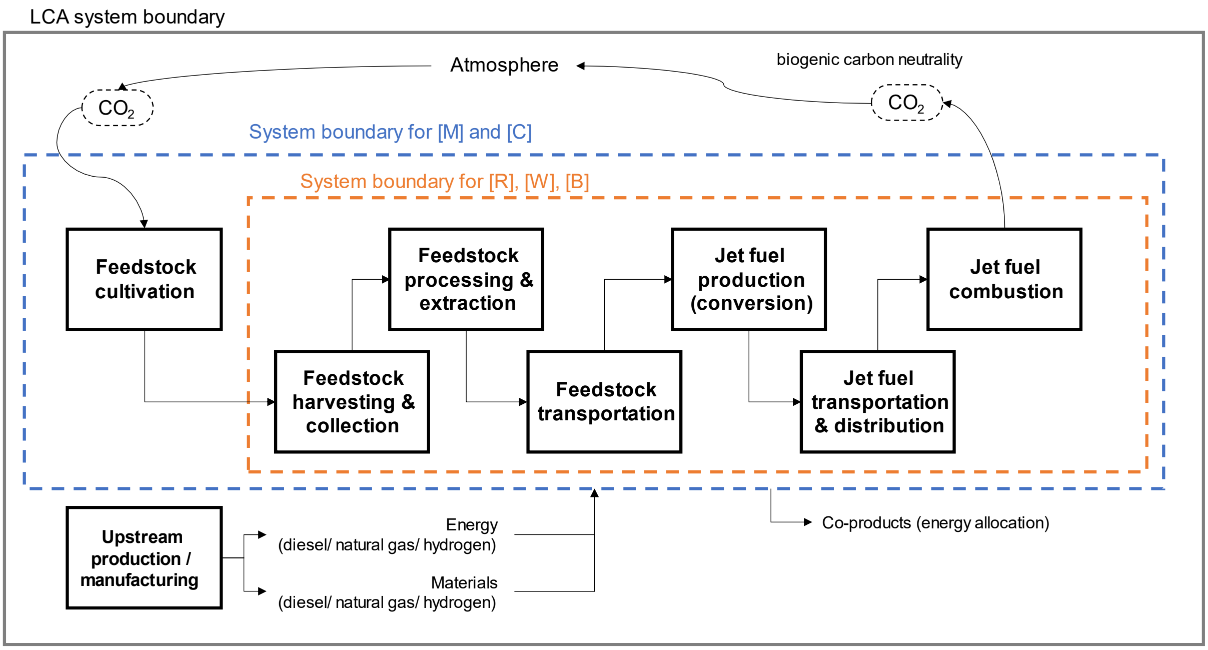

Figure 1. The system boundary for core LCA of CORSIA SAFs.

The variety of possible feedstocks and conversion technologies results in a total of 25 pathways, shown in Table 2, including 5 FT, 10 HEFA, 2 SIP, 8 ATJ (6 iso-butanol to jet and two ETJ) approved for use under CORSIA. These were the first pathways considered for inclusion under CORSIA, as they were identified to be those closest to commercial deployment. Using different feedstocks leads to significant differences in core LCA results, even for the same conversion technology. Feedstocks are categorized as main products [M], co-products [C], residues [R], wastes [W], and by-products [B]. This classification is important, as it defines the LCA system boundary to be considered: LCA of SAFs derived from main [M] and co-products [C] include emissions from feedstock production, whereas these emissions are not included for residues [R], waste [W] and by-products [B]. It is worth noting that MSW usually includes both biogenic and fossil carbon components, the share of each has a significant impact on LCA results. Therefore, the default LCA value for this pathway group is defined as a function of the non-biogenic carbon (NBC) content ($\%_{mass}$) of the MSW feedstock.

Table 2: List of the pathways and corresponding feedstocks

Conversion	Feedstock	Type
Fischer-Tropsch (FT)	Agricultural residues	[R]
	Forestry residues	[R]
	MSW	[W]
	Short-rotation woody crops	[M]
	Herbaceous energy crops	[M]
hydroprocessed esters and fatty acids (HEFA)	Tallow	[B]
	Used cooking oil	[W]
	Palm fatty acid distillate	[B]
	Corn oil	[B]
	Soybean oil	[M]
	Rapeseed oil	[M]
	Camelina	[M]
	Palm oil (closed pond)	[M]
	Palm oil (open pond)	[M]
	Brassica carinata	[M]
Synthesized iso-paraffins (SIP)	Sugarcane	[M]
	Sugarbeet	[M]
Iso-butanol alcohol-to-jet (Iso-BuOH ATJ)	Sugarcane	[M]
	Agricultural residues	[R]
	Forestry residues	[R]
	Corn grain	[M]
	Herbaceous energy crops	[M]
	Molasses	[C]
Ethanol-to-jet (ETJ)	Sugarcane	[M]
	Corn grain	[M]

For SAFs from main [M] and co-product [C] feedstocks, all GHG emissions resulting from the use of energy and chemicals for cultivation of feedstocks are included in the LCA. These emissions are dependent mainly on soil characteristics, farming practices affecting cultivation fuel consumption, and the use of fertilizer (nitrogen, phosphorus, and potassium), and the use of herbicide and insecticide. For feedstocks categorized as residues, waste, and by-products feedstocks [R, W, B], no upstream emissions burden before collection, recovery, and extraction are included in the LCA of SAFs. Note that the ILUC is only applicable to crops and not to [R, W, B] feedstock classes. The feedstock transportation stage includes GHG emissions of transportation of feedstock from farms (or feedstock collection stations) to fuel conversion facilities. The major parameters are distance, payload, and fuel economy of the transportation mode.

The fuel conversion stage considers GHG emissions generated by all energy and material inputs and outputs used for converting feedstocks into SAFs. For example, for HEFA pathways, energy and chemical requirements for oil extraction are included, as well as hydrogen, natural gas, and electricity requirements are for the HEFA process. For ETJ pathways, the enzymes and chemicals needed for ethanol production are included as well as energy inputs [13]. In quantifying GHG emissions for a specific fuel production pathway where conversion processes result in multiple products, the method to allocate emissions amongst multiple co-products and residues has a significant impact on the results [30]. In the CORSIA methodology, process emissions are allocated across the co-products based on their energy content [34]. For example, it is typical to produce diesel and naphtha along with jet fuel, and all upstream emissions are allocated amongst these products on the basis of their energy outputs from a given conversion process. The fuel transportation stage includes GHG emissions from transportation of SAFs from the fuel production facilities to end-use sites (i.e. aircraft refueling points); due to the international scope of CORSIA, transcontinental transport of the final product was excluded, and the closest point for fuel uplift from the point of fuel production was preferred as a more realistic option.For biomass-derived fuels, biogenic CO_2 emissions from fuel combustion are assumed to be offset by the biomass carbon uptake happened during the biomass growth, and therefore count as zero in the LCA of SAF. Jet fuel CO_2 combustion emissions only include CO_2 from fossil sources.

The core LCA methodology can be summarized in Equation 1, including terms for feedstock cultivation ($\mathbf{e_{fe\_c}}$); feedstock harvesting and collection ($\mathbf{e_{fe\_hc}}$); feedstock processing ($\mathbf{e_{fe\_p}}$); feedstock transportation to processing and fuel production facilities ($\mathbf{e_{fe\_t}}$); feedstock-to-fuel conversion processes ($\mathbf{e_{fefu\_p}}$); fuel transportation and distribution ($\mathbf{e_{fu\_t}}$); and fuel combustion in an aircraft engine ($\mathbf{e_{fu\_c}}$). For purposes of reporting or accounting emissions from biofuels combustion, the latter term ($\mathbf{e_{fu\_c}}$) is considered as being zero for the fuel fraction produced from biomass.

$$\text{Core LCA } [gCO_2e/MJ] = \mathbf{e_{fe\_c} + e_{fe\_hc} + e_{fe\_p} + e_{fe\_t} + e_{fefu\_p} + e_{fu\_t} + e_{fu\_c}} \qquad \text{Equation (1)}$$

The functional unit is MJ (lower heating value [LHV]) of fuel produced and combusted, and the results are expressed in grams of CO_2 equivalent per MJ of fuel (gCO_2e/MJ) combusted in the aircraft engine. GHG emissions from stages included in the fuel life-cycle include CO_2, N_2O, and CH_4 (with the exception of fuel combustion, which only includes CO_2), are expressed in terms of CO_2e using their 100-year global warming potentials, according to the Fifth Assessment Report (AR5) of Intergovernmental Panel on Climate Change (IPCC) [35]. One-time emissions associated with construction or manufacturing facilities (the so-called infrastructure-related emissions) are not included; their contribution to the LCA results of fuel products is usually small. Various institutions (Argonne National Laboratory, Joint Research Centre [JRC], Massachusetts Institute of Technology [MIT], University of Hasselt, University of Toronto, and Universidade Estadual de Campinas) performed LCA calculations for SAFs to support ICAO's CAEP. These institutions were tasked to assess core LCA values (carbon intensities [CIs]) of the same fuel pathways to reflect their LCA models and regionally-specific parameters, among other factors.

LCA results for a given pathway often differ due to unique data and assumptions (i.e. conversion efficiency, yield, etc.), which can reflect regional differences (e.g. agricultural practices, electricity generation mix, transportation distances, etc.). To account for these differences, while being able to set a single default core LCA value, a threshold of 8.9 gCO_2e/MJ (10% of the jet fuel baseline GHG intensity) was used. When the difference in independently calculated core LCA values from different institutions falls within this threshold, the mid-point value is taken as a representative default value. If the range of results is greater than 8.9 gCO_2e/MJ, either the parameters leading to the discrepancy are identified and harmonized appropriately or, where distinct differences exist, the region-specific data is used to develop region-specific pathway core LCA values as separate pathways. This approach was taken to establish default values applicable at a global scale, necessary for an international policy such as CORSIA.

Two databases/models have been used for evaluating the core LCA values: the E3 database (E3db) [36] and the Greenhouse gases, Regulated Emissions, and Energy use in Technologies (GREET®) model [37]. E3db is used by JRC and GREET is used by the other institutions. For the pathway-specific parameters, the LCA modeling group collected data mostly from the available literature. Mass and energy balance data, especially for the conversion processes, were also collected from industry to fill the gap between the literature and existing or planned industry practices. Among the production pathways, there are different technological and commercial readiness levels. Even among ASTM approved pathways, some could be still considered at pilot stages. All life-cycle inventory datasets are reported in the CORSIA Supporting Document [13]. The final goal of this exercise was to define the GHG emission savings of a specific SAF pathway by comparing the SAF default core LCA value with the life-cycle GHG emissions of conventional petroleum-derived jet fuels. It is worth noting that the fossil jet fuel a baseline was agreed for the purpose of defining a common benchmark value at the global scale; a variety of crude slates being processed in a variety of refinery configurations worldwide were analysed to determine the global average GHG intensity value for the baseline petroleum jet fuel.

Demand for crop-based biofuels may encourage cropland expansion and cause GHG emissions due to consequent LUC. As a result of interactions among commodity markets, connections between agricultural and non-agricultural markets, and international trade, LUC and related emissions may become a global phenomenon that goes beyond the regions producing biofuels [38–40]. These are called biofuels ILUC emissions. Several papers have reviewed the existing literature on ILUC values [41–46], mainly for road biofuels. That literature shows important disparities among models in the baseline assumptions, shock size, simulation approach, and the data used in calculating emissions. Resulting estimated ILUC emissions are subject to uncertainties and vary significantly among biofuels, feedstocks used, and production location. However, before this work in CORSIA, aviation biofuels ILUC emissions have not been quantified.

To estimate ILUC emissions for aviation biofuels, noticing the considerable uncertainty in ILUC simulation results, two different economic models, well-established on this topic, were used: GTAP-BIO [44,47,48] and GLOBIOM [49,50]. These models have been extensively employed in the past to estimate ethanol and biodiesel ILUC emissions and represent two different economic modeling approaches. GTAP-BIO is a computable general equilibrium model developed at the Center for Global Trade Analysis Project (GTAP) at Purdue University. GLOBIOM is a partial equilibrium mathematical programming (constrained optimization) model developed at the International Institute for Applied Systems Analysis (IIASA). The two models have different structures, and use data sets, parameters, and emission factors from different sources.

The estimation of ILUC emissions for the two models encompasses two phases. The first one is the determination of the ILUC due to an expansion in demand for a given biofuel using an economic model. The second one is the calculation of the GHG emissions using an emissions accounting framework. The emission accounting considers at least three major categories of terrestrial carbon fluxes: (1) emissions due to changes in vegetation living biomass (natural vegetation and average agricultural landscape) carbon stock, (2) emissions due to changes in soil carbon stock, and (3) emissions debt equivalent to forgone carbon sequestration. GTAP-BIO performs the evaluation in two successive steps, by coupling the LUC results with a separate emission calculation framework, AEZ-EF developed by Plevin et al. [51] and adopted by the California Air Resource Board (CARB). GLOBIOM has emission factors embedded within the model and performs these different calculations together.

4. Carbon Intensities of Sustainable Alternative Fuels for CORSIA

The core LCA values demonstrate that SAF pathways offer potentially significant GHG emission reductions in attributional life-cycle GHG emissions, relative to petroleum jet fuel. Figure 2 presents the impact of each process along the supply chain of a given SAF on the core LCA values. It is important to highlight that the emissions per LCA stage shown here, are defined by the mid-point values of independent LCAs results among different organizations of the Core LCA Working Group (as described above).

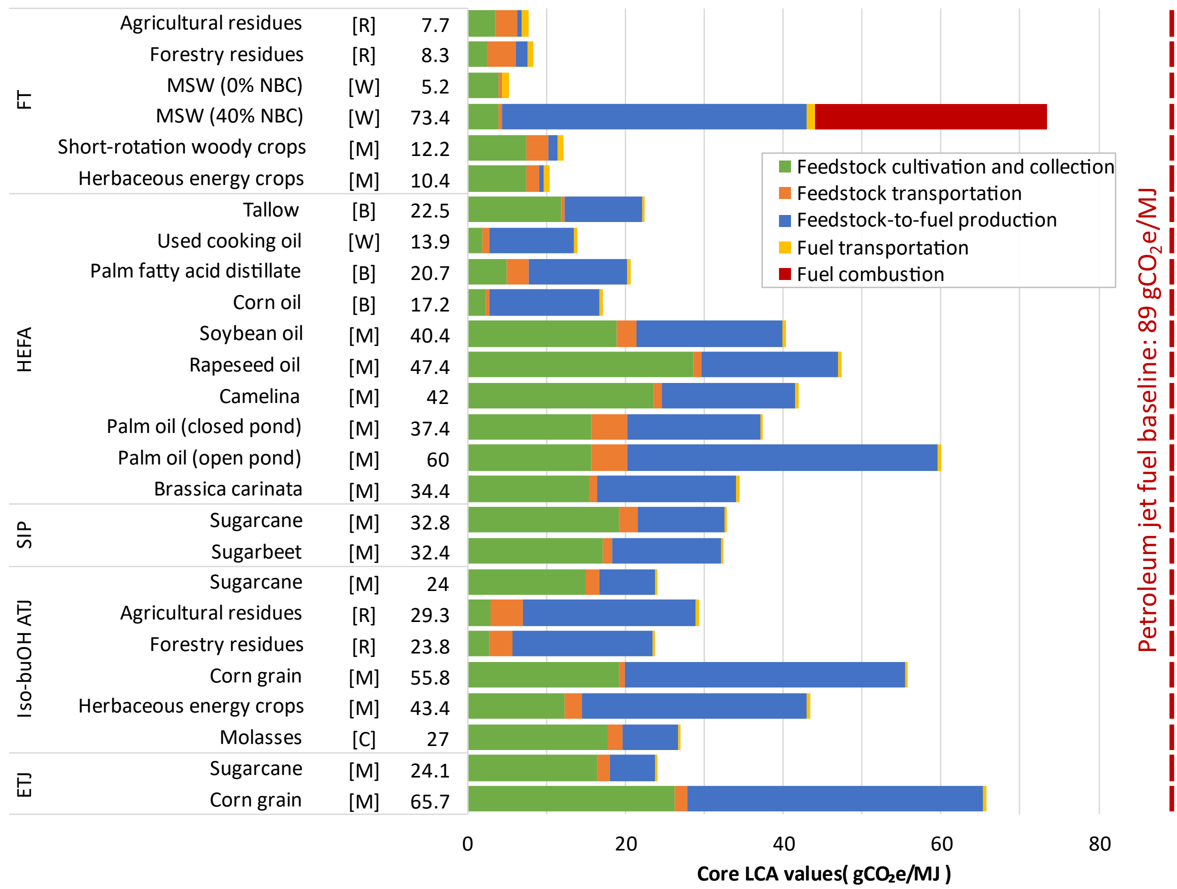

Figure 2. Default core LCA values of SAF production pathways approved by ICAO to date. (NBC: non-biogenic carbon content)

The GHG reduction benefits of SAFs compared to fossil-derived jet fuels are due to the CO_2 uptake of biomass feedstocks. In these cases, CO_2 from fuel combustion is offset by carbon uptake during photosynthesis, resulting in net-zero fuel combustion CO_2 emissions ($\mathbf{e}_{\mathbf{fu\_c}}$). Since the combustion emissions of petroleum jet fuels consist of 83% (74 gCO_2e/MJ) of its total life-cycle GHG emissions, avoiding this provides significant GHG emissions benefits.

In Figure 2, the FT MSW pathway shows non-zero fuel combustion emissions (red bar), due to 40% non-biogenic carbon composition of the feedstock. In case of using 100% biogenic MSW, combustion CO_2 emissions would be fully offset by the carbon uptake of feedstock growth. SAFs produced from main [M]- or co-products [C] biomass feedstocks generally have higher emissions associated with cultivation and collection ($\mathbf{e}_{\mathbf{fe\_c}}$ and $\mathbf{e}_{\mathbf{fe\_hc}}$), than other classes of feedstocks [R, W, B]. This is due to the decision that [R, W, B] feedstocks are not assigned with cultivation emissions. For crops ([M, C]), emissions from fertilizer and energy use have a significant impact on overall life-cycle GHG emissions. The differences in the length of the green bars show that use of waste and residual feedstocks, or low-input feedstocks (e.g. dedicated energy crops), is key lever to achieve low-GHG aviation fuels.

Different technologies result in significantly different GHG emissions during feedstock-to-fuel conversion ($\mathbf{e}_{\mathbf{fefu\_p}}$) (blue bars in the figure). FT, in general, has low conversion-related emissions, mainly because the process uses heat from syngas combustion (biogenic carbon emissions), except when the feedstock is MSW with NBC content. Other technologies require significant energy and chemical inputs, leading to noticeable process emissions. For HEFA, oil extraction and jet fuel production lead to emissions associated with the required energy and chemical inputs: mainly electricity, natural gas, and hydrogen. Unlike the FT process, which relies on energy from the biomass feedstock, the HEFA process relies mainly on fossil-based inputs, leading to higher conversion emissions. If renewable electricity, natural gas, and hydrogen are eventually used for these processes, their GHG emissions would be reduced significantly. There are two default core LCA values for palm HEFA pathways because CH_4 emissions from the palm oil mill effluent (POME) can vary significantly depending on biogas recovery (CH_4 capture). While the open pond case has considerable CH_4 emissions from POME, the closed pond case can capture 85% of CH_4.

SIP pathways use biological and chemical conversions, via fermentation of sugars into farnesene, hydrogenation to farnesane, and hydrocracking and isomerization to jet fuel product. The main process input is hydrogen for hydrotreating. The results for the iBuOH ATJ conversion processes show significant variation between independent LCA results, primarily due to different assumptions on feedstock transportation distance, co-location of feedstock-to-iBuOH and iBuOH upgrading facilities, net heat and enzyme demand for iBuOH fermentation, and final fuel transportation distances. For ETJ pathways' conversion process, sugarcane and corn grain pathways show significantly different values. The conversion consists of two major processes, ethanol production and ethanol-to-jet conversion. The major differences in the ETJ LCA results are mainly led by the feedstock yields, natural gas requirements for ethanol production, and ethanol yields. For all analyzed pathways while transportation-related emissions are not negligible, their contribution is less than 1 g CO_2e/MJ to the final core LCA values, resulted from the decision in the context of CORSIA to use the closest point for fuel uplift from the point of fuel production, as explained above.

The ILUC values were estimated for 14 of the technological pathways using biomass as main product or coproduct, in different locations where the feedstocks were largely produced. This led to 17 SAF production pathways when regions are considered, evaluated using the two models as presented in

Figure 3. The two modeling teams worked closely to compare the ILUC results and to explore the main drivers of the differences. Based on the comparison progress, some data were reconciled, and assumptions harmonized where relevant to reflect new findings from the literature, implement the most recent trustable and available data, and aligned model parameters where possible. Substantial progresses were made for all pathways in reducing the gap between the two model assessments through these harmonization efforts.

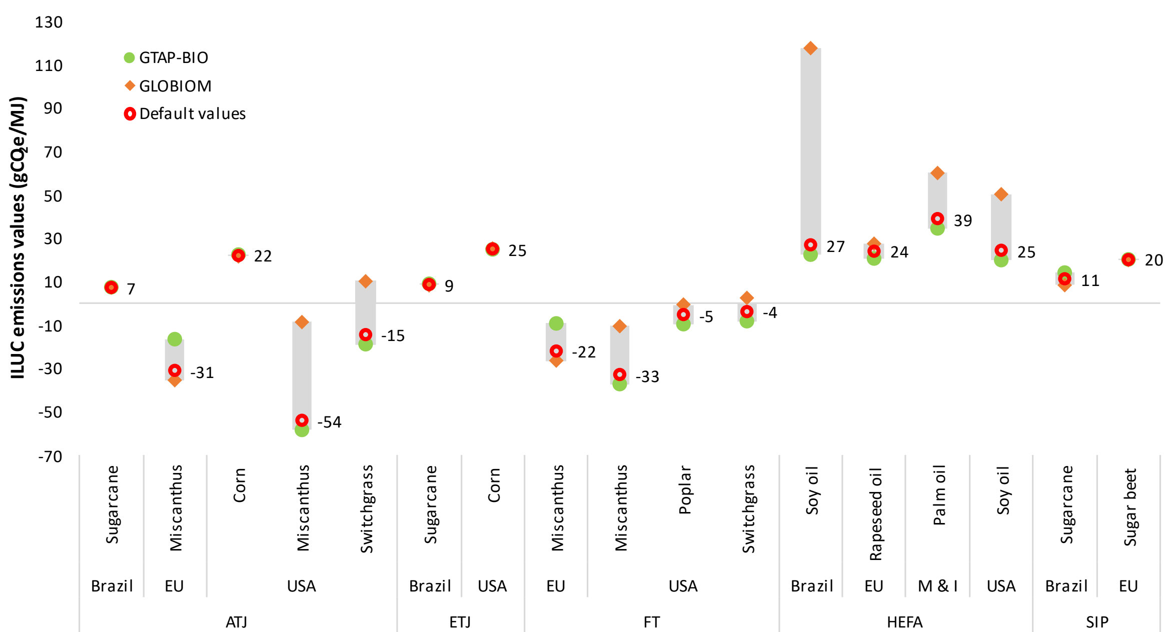

Figure 3. Default ILUC emissions values for the 17 relevant SAF pathways: GTAP-BIO and GLOBIOM results and defined default values after reconciliation (M & I: Malaysia/Indonesia).

As Figure 3 shows, the ILUC emissions for the starch and sugar pathways were found with close values across the two models. However, the ILUC emission differences for several vegetable oil pathways remained large, mainly due to the differences in modeling the uses of meals co-products and the markets for alternative vegetable oils [52]. Several cellulosic pathways were also found with relatively large differences, due to assumptions on the degree of soil organic carbon (SOC) sequestration. However, these latter pathways generally had negative or small emission intensities. These differences can be justified also in light of the broad scope of such modeling exercise, applied at world scale.

By consensus among the FTG experts, a similar approach to that used for the core LCA analysis has been proposed to reconcile values within a close range: when the estimates from the two models were within 10% of the baseline fossil fuel value of 89 gCO_2e/MJ (8.9 gCO_2e/MJ), the midpoint was used. This approach has been applied to reconcile seven pathways, including six sugar or starch pathways, and the EU rapeseed HEFA pathway. For the remaining pathways, it was decided to use the lower of the two model values, plus an adjustment factor of 4.45 gCO_2e/MJ. This adjustment factor represents half of the tolerance level of 8.9 gCO_2e/MJ, i.e. the minimum reduction requirement in CI for a SAF pathway to be CEF.

5. DISCUSSION

In spite of the challenges brought on by COVID-19, steady increase in aviation activity, and associated GHG emissions, is expected in the longer term. Unlike other sectors that have more alternatives to reduce GHG emissions, such as, for example, electrification for road transport, a dramatic leap in technology would be required to mitigate aviation's reliance on fossil liquid hydrocarbon fuels in the short to mid-term. Meanwhile, SAFs offer substantial opportunities to the aviation sector as a mean of reducing GHG emissions.

As proven by previous studies [7,11,12,24,53,54] and supported by the finding reported in this paper, biomass-based SAFs can be produced using existing technologies and facilities. Commercial plants exist globally that produce road transport fuels compliant with regulatory standards and represent today a significant technical production potential [53–56]. This potential would able to supply the aviation sector with ASTM-compliant biofuels, but demand is still in the ramp-up phase, mainly contained by higher costs. Among the approved alternatives, in terms of installed nominal capacity, HEFA and hydrotreated vegetable oils (HVO) facilities represent the largest share [57,58]. However, HVO refineries are typically optimized to produce a range of middle distillates, all of which can be used in diesel engines, but only a fraction of which can be used in jet engines. As such, an HVO fuel producer needs to invest in a distillation column to obtain a fuel that is suitable for jet aircraft [59]. In considering the uptake of SAFs, it is important to highlight that production today counts on comparatively lower plant capacity and a limited feedstock basket. In addition to the wastes and residues currently going to HEFA production, several options have been explored in recent studies for HEFA: e.g., carinata [60,61], pennycress [62], camelina [63–65], jatropha, cotton oil soapstock [66], tobacco oil [67], and new projects are set to demonstrate the potential for upscaling production [68]. Regarding other ASTM-certified conversion technologies, there are significant initiatives across the globe to prove the potential of the FT process from biomass [69,70]. Nonetheless, the technology remains unproven at commercial scale. The production of aviation biofuels from sugars is another promising pathway, and pilot plants are already supporting scale-up initiatives. For alcohol-to-jet, the supply of aviation biofuels for commercial flights already occurred [71,72], demonstrating significant maturity [73] of this technology.

ICAO CAEP's nominated experts have been working to define a suitable methodological framework for evaluating LCA values of additional SAF production pathways certified by ASTM, making use of the existing body of knowledge for the sector. In addition, ICAO recently broadened the definition of the CORSIA eligibility to include LCAFs alongside existing SAFs. Thus, if fossil-based aviation fuels can demonstrate reductions in life-cycle GHG emissions greater than 10% of that of baseline fuels, fossil-based low-carbon fuels may be also counted towards the target of stabilized CO_2 emissions in international aviation pursued by CORSIA. The core LCA values presented in this paper represent "default" values for specific pairs of feedstock-process combinations. They have been created by using feedstock- and pathway-specific representative data, with the goal of generating values that are suitable for use at a global scale. CORSIA also allows obligated parties to submit core LCA values along with the supporting data that represent their specific fuel production technology (called "actual" LCA values). It is worth noticing that an assessment of actual LCA values can be performed by using the described methodology, and undergoing a certification process [19].

As sustainability is a pillar of the whole CORSIA initiative and considering that SAF production may lead to cropland expansion, in CORSIA, ILUC GHG values are also considered along with the core LCA values. ILUC GHG emissions are estimated through a consequential approach with economic models, while Core LCA values are based on a process-based, attributional approach. The final values are generated by summing the core LCA and ILUC emission values, which are presented in the CORSIA document [18]. Many feedstocks and technologies can offer GHG saving when compared to the petroleum-derived baseline. Some pathways, due to the negative ILUC values, can result in negative emissions.

It is worth recalling that participation in the first phases of CORSIA is on a voluntary basis, and there are exemptions for some aviation activities. Despite this, CORSIA is expected to offset international aviation CO_2 emissions exceeding 2019 levels. A regular review of CORSIA is required under the terms of the ICAO 2016 agreement, which should allow for its continuous improvement. While SAFs could play a major role in contributing to reducing aviation sector's GHG emissions on the basis of their per-MJ GHG reduction potentials, we caution, however, that cost barriers have to be overcome in order to ensure the large-scale deployment of SAFs, and the corresponding GHG emissions benefits.

While the potential to mitigate the environmental impact of the international aviation sector has been captured by CORSIA, there are other ongoing initiatives at the country or regional level. The European Green Deal (EGD), the overarching policy framework from the European Commission released in 2019, aims to achieve a climate neural continent by 2050, defined high expectations of reducing transportation impact. The EC Renewable Energy Directive (REDII) pursues the decarbonization of the economy including the transport sector and defines specific support (1.2X multiplier) to stimulate the uptake of SAFs in aviation. Aviation is also part of the European Emission Trading Scheme (ETS). Finally, the ReFuelEU Aviation initiative tries to curb the sectoral impact by defining specific mandates for a minimum share of SAF, which would gradually increase over time. In the United States, the GHG emission reduction target by 2030 considers SAFs to play a role in the aviation sector [74], and the SAF Act has been introduced to incentivize SAFs [75]. All the initiatives are on an LCA-based GHG assessment to define the potential savings offered by SAFs.

6. CONCLUSIONS

Sustainable Aviation Fuels have been identified as a prominent means to reduce GHG emissions of the international aviation sector. The LCA methodology developed for CORSIA presented herein enables the calculation of GHG emissions reductions by SAFs for the international aviation sector. ILUC GHG emissions are considered together with core LCA values to achieve holistic GHG reductions by SAFs. It is worth remarking that the presented method has become the first internationally adopted approach for the calculation of life-cycle GHG emissions of aviation fuels, thus constituting a fundamental step towards the goal of a cleaner aviation sector. The potential GHG emission savings, in the framework of the performed attribution LCA, resulted up to 94% when compared to petroleum-derived baseline jet fuel (and more than 100% when considering negative GHG emissions of ILUC contribution for some SAF pathways). Consequently, we suggest that SAFs could play a major role in contributing to reducing aviation sector’s GHG emissions. Seeking for international agreements is a complex task, and further effort will have to be spent to enhance harmonization with other regional and/or national schemes. The CORSIA method can serve as a template for other transportation sectors that are globally connected such as marine transportation, and for other non-transport sectors.

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