

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

Matteo Prussi ^{a,*}, Uisung Lee ^{b,***}, Michael Wang ^b, Robert Malina ^c, Hugo Valin ^d, Farzad Taheripour ^e
César Velarde ^f, Mark D. Staples ^g, Laura Lonza ^h, James I. Hileman ⁱ

^a European Commission, Joint Research Centre (JRC), Ispra, Italy

b Systems Assessment Center, Energy Systems Division, Argonne National Laboratory, 9700 South Cass Avenue, Lemont, IL 60439, United States

© Hasselt University, Environmental Economics, Centre for Environmental Sciences, Hasselt University, Diepenbeek, Belgium

d Biodiversity and Natural Resources Program, International Institute for Applied Systems Analysis (IIASA), Schlossplatz 1, A-2361 Laxenburg, Austria

^e Department of Agricultural Economics, Purdue University, 403 West State Street, West Lafayette, IN, United States
^f SENASA/Aviation Safety & Security Agency (AESA) Environmental Unit, Madrid, Spain

g Laboratory for Aviation and the Environment, Department of Aeronautics and Astronautics, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, Massachusetts 02139, USA (ORCID: 0000-0002-3432-7533)

European Commission, DG Climate Action, Belgium

i Federal Aviation Administration, Office of Environment and Energy, Washington, D.C. 20591, United States

* First author: Matteo Prussi (matteo.prussi@ec.europa.eu) (ORCID: 0000-0003-3624-0367)

** Corresponding author: Uisung Lee (ulee@anl.gov) (ORCID: 0000-0002-0272-4876)

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.

40 **KEYWORDS**

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

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45 **LIST OF ABBREVIATIONS**

ANL	Argonne National Laboratory,
ATJ	Alcohol-to-jet
CARB	California Air Resource Board
CEFs	Corsia Eligible Fuels
CI	Carbon intensities
CO₂e	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 Research 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

47 **1. INTRODUCTION**

48 In 2017, air transport accounted for 2% of the total global anthropogenic CO₂ emissions
49 (approximately 859 million metric tons [MMT]) [1]. Furthermore, prior to the COVID-19 pandemic,
50 the International Air Transport Association (IATA) anticipated a near-doubling of aviation activity
51 between now and 2035, to 7.2 billion passenger journeys in 2035 [2]. Despite the impacts of the
52 pandemic, aviation activity is expected to grow over the long term. Unless aviation activity can be
53 decoupled from CO₂ emissions, this growth will lead to increasing impacts on climate change.

54 The United Nation's International Civil Aviation Organization (ICAO) uses scientific, data-driven
55 decision making to develop measures to address the environmental impacts of aviation [3]. For
56 example, a global CO₂ standard that regulates fuel efficiency for new aircraft went into effect in 2020
57 [4] and ICAO member states have an aspirational goal of a 2% annual fuel efficiency improvement.
58 Based on such extensive scientific driven analysis of the aviation sector, in 2016, the ICAO Assembly
59 agreed on the adoption of a global market-based scheme to limit international aviation CO₂ equivalent
60 (CO₂e) greenhouse gas emissions (also referred as GHG, in the rest of the paper): the Carbon
61 Offsetting and Reduction Scheme for International Aviation (CORSIA) [3]. CORSIA requires airlines
62 to offset CO₂e emissions that exceed 2019 levels. On the basis of impact assessments and scientific
63 available knowledge, CORSIA has been framed to allow offsetting either through credits or through
64 the use of CORSIA Eligible Fuels (CEFs), such that international aviation achieves carbon neutral
65 growth from 2020 [5].

66 Despite steady improvements in fuel efficiency, mainly achieved by new aircraft entering the fleet
67 (from fuel consumption of 4.4 l/100 passenger-km in 2005 to 3.4 in 2017 (-24%) in Europe, and
68 annual improvement of 2.3% between 1991 and 2009 in the United States and the continued down
69 trend through 2018) [6–8], decarbonizing aviation remains a challenging task, due to rapid growth of
70 the sector [9]. This is especially true for international aviation where pre-pandemic growth rates were
71 above 4% per annum [10]. Alternative propulsion options (e.g., electric driven and hybrid systems)
72 and alternatives to jet fuel (e.g., liquid natural gas and hydrogen) have been proposed, but have only
73 been tested at the pilot-scale thus far. There are numerous unresolved technical issues associated with
74 these alternatives [11]; therefore, stabilizing international aviation CO₂ emissions at 2019 levels will
75 likely require the use of drop-in sustainable aviation fuels (SAFs). Drop-in SAFs do not require
76 engine or system modifications in the aircraft, nor do they require dedicated refueling infrastructure
77 [11,12].

78 CORSIA allows the use of SAFs (i.e., drop-in alternative jet fuels that fulfill a set of sustainability
79 criteria and are derived from biomass or waste resources), in order to reduce airlines' carbon

80 offsetting requirements. Under CORSIA, emissions reductions from the use of SAFs are calculated
81 using a life-cycle assessment (LCA) approach, agreed upon at ICAO in 2018 [13]. With this
82 agreement, the CORSIA LCA method has become the first internationally adopted approach for the
83 calculation of life-cycle GHG emissions of aviation fuels. Four elements proved key to the agreed
84 LCA method for CORSIA [13]: (1) use of life-cycle accounting for GHG emissions, (2) inclusion of
85 induced land use change (ILUC), (3) safeguards to prevent deforestation, and (4) crediting of
86 practices that mitigate the risk of land use change (LUC). These elements enabled a wide range of
87 stakeholders to pursue different measures for SAFs to reduce CO₂e emissions on a life-cycle basis,
88 while mitigating the risks of unintended consequences.

89 This paper aims to present the LCA-based methodology defined for the CORSIA initiative and to
90 contribute to harmonizing and closing the gaps in existing calculation approaches [14–16]. First, the
91 current technologies available for SAF production are presented. We then present the methodology
92 for carbon intensity assessment under CORSIA. Since the main objective is to evaluate the life-cycle
93 GHG emissions of SAFs for CORSIA, the GHG emissions (expressed in terms of CO₂e emissions), of
94 each life-cycle step for a given SAF is presented (feedstock cultivation and collection, feedstock
95 transportation, feedstock-to-fuel conversion, fuel transportation, and fuel combustion) to highlight the
96 impact of key parameters on life-cycle GHG emission results. The approach adopted to quantify
97 ILUC emissions for selected pathways is also described to show the potential contribution of this
98 element to life-cycle GHG emissions. In the discussion section, we aim to stress that a number of
99 SAFs can yield significant life-cycle emission reductions compared to petroleum-derived jet fuel,
100 which potentially plays a major role in mitigating international aviation environmental impact. It is
101 important to note that the presented methodology has become the first internationally adopted
102 approach for calculating GHG emissions potential of aviation fuels.

103

104 **2. SUSTAINABLE AVIATION FUELS (SAFs)**

105 In order to be eligible for ICAO CORSIA, a CORSIA Eligible Fuel (CEF) must meet the
106 sustainability criteria, which are currently defined as having life-cycle GHG emissions that are at least
107 10% below those of the petroleum jet fuel baseline and not being made from biomass obtained from
108 land with high carbon stock [17]. LCA is the chosen tool to quantitatively assess the GHG emission
109 saving offered by a specific alternative fuel. At the same time, work on other sustainability themes
110 such as water; soil; air; conservation; waste and chemicals; human and labor rights; land use rights
111 and land use; water use rights; local and social development; and food security is ongoing under the

112 ICAO Committee on Aviation Environmental Protection (CAEP). Additional sustainability criteria
113 are under development within ICAO. Fuels produced from renewable or waste feedstocks that meet
114 these CORSIA sustainability criteria are considered to be SAFs. Based on an extensive evaluation of
115 the global petroleum jet fuel production, the average life-cycle GHG intensity baseline has been set at
116 89 gCO₂e/MJ [13] from well to wake (WTW), including crude oil recovery, transportation and
117 refining, jet fuel transportation, and jet fuel combustion. Therefore, fuels that have life-cycle GHG
118 emissions lower than 80.1 gCO₂e/MJ and are not threatening the conversion of high-carbon stock land
119 are eligible for CORSIA.

120 There are two fuel categories under CEF: SAFs and Lower Carbon Aviation Fuels (LCAFs). While
121 SAFs can be produced from renewables or wastes, LCAFs refer to fuels from fossil sources but with
122 at least 10% lower life-cycle GHG emissions than those of the petroleum jet fuel baseline. The
123 methodology to compute life-cycle GHG emissions for LCAFs is still under development in ICAO,
124 whereas the LCA methodology for SAFs has been already approved and presented in this paper
125 [18,19]. A fundamental characteristic of SAFs is compliance with ASTM standards [20,21]. ASTM
126 D7566 [22] strictly regulates the specifications for blending of non-petroleum components with
127 standard petroleum-based jet fuel, which is certified under ASTM D1655 [23]. These standards ensure
128 these fuels are safe for use in aviation. As of writing, the following conversion processes and
129 renewable feedstock types to produce SAFs have been approved by ASTM and included in annexes to
130 ASTM D1655 and D7566 (Table 1). In addition, there are many additional SAF pathways in the
131 pipeline for ASTM certification [20,24,25].

132 **Table 1.** Types of SAFs approved by ASTM

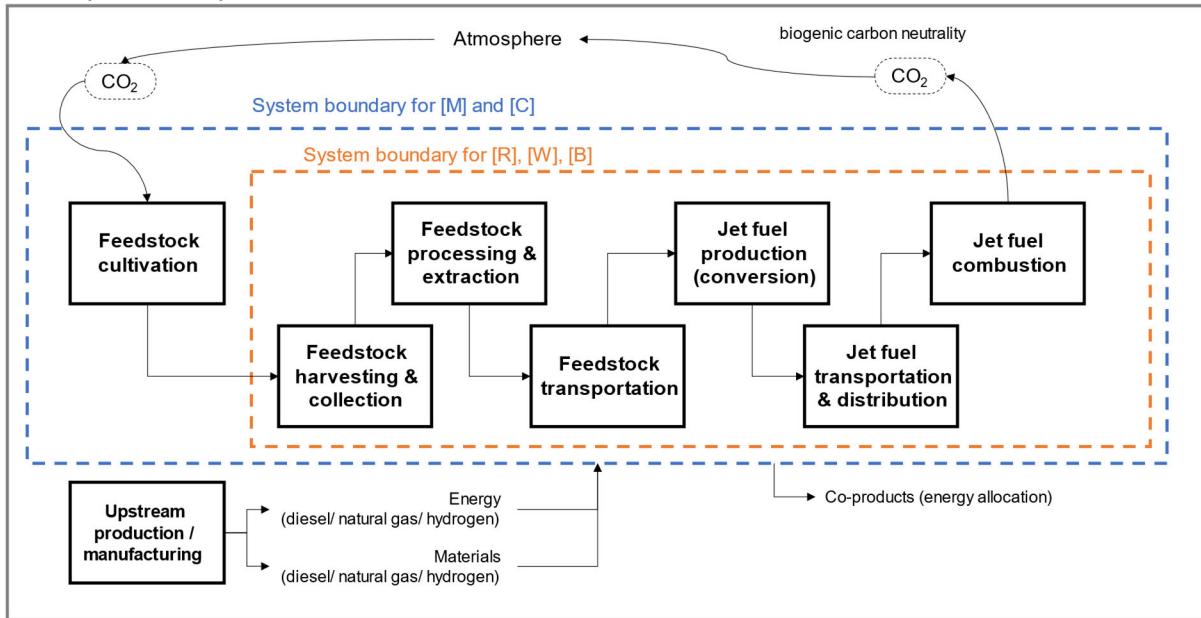
ASTM D7566 Annex A1	Fischer-Tropsch (FT) hydroprocessed synthesized paraffinic kerosene (SPK), mainly produced from woody residual biomass, municipal solid waste (MSW), etc. Maximum allowed blending rate: 50% v/v
ASTM D7566 Annex A2	Synthesized paraffinic kerosene from hydroprocessed esters and fatty 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 <i>Botryococcus braunii</i> 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

3. METHODOLOGY FOR CARBON INTENSITY ASSESSMENT UNDER CORSIA

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

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

LCA system boundary



156

157

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

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

171

Table 2: List of the pathways and corresponding feedstocks

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

174 For SAFs from main [M] and co-product [C] feedstocks, all GHG emissions resulting from the use of
 175 energy and chemicals for cultivation of feedstocks are included in the LCA. These emissions are
 176 dependent mainly on soil characteristics, farming practices affecting cultivation fuel consumption, and
 177 the use of fertilizer (nitrogen, phosphorus, and potassium), and the use of herbicide and insecticide.
 178 For feedstocks categorized as residues, waste, and by-products feedstocks [R, W, B], no upstream
 179 emissions burden before collection, recovery, and extraction are included in the LCA of SAFs. Note
 180 that the ILUC is only applicable to crops and not to [R, W, B] feedstock classes. The feedstock
 181 transportation stage includes GHG emissions of transportation of feedstock from farms (or feedstock
 182 collection stations) to fuel conversion facilities. The major parameters are distance, payload, and fuel
 183 economy of the transportation mode.
 184 The fuel conversion stage considers GHG emissions generated by all energy and material inputs and
 185 outputs used for converting feedstocks into SAFs. For example, for HEFA pathways, energy and
 186 chemical requirements for oil extraction are included, as well as hydrogen, natural gas, and electricity
 187 requirements for the HEFA process. For ETJ pathways, the enzymes and chemicals needed for

188 ethanol production are included as well as energy inputs [13]. In quantifying GHG emissions for a
189 specific fuel production pathway where conversion processes result in multiple products, the method
190 to allocate emissions amongst multiple co-products and residues has a significant impact on the
191 results [30]. In the CORSIA methodology, process emissions are allocated across the co-products
192 based on their energy content [34]. For example, it is typical to produce diesel and naphtha along with
193 jet fuel, and all upstream emissions are allocated amongst these products on the basis of their energy
194 outputs from a given conversion process. The fuel transportation stage includes GHG emissions from
195 transportation of SAFs from the fuel production facilities to end-use sites (i.e. aircraft refueling
196 points); due to the international scope of CORSIA, transcontinental transport of the final product was
197 excluded, and the closest point for fuel uplift from the point of fuel production was preferred as a
198 more realistic option. For biomass-derived fuels, biogenic CO₂ emissions from fuel combustion are
199 assumed to be offset by the biomass carbon uptake happened during the biomass growth, and
200 therefore count as zero in the LCA of SAF. Jet fuel CO₂ combustion emissions only include CO₂ from
201 fossil sources.

202 The core LCA methodology can be summarized in Equation 1, including terms for feedstock
203 cultivation (e_{fe_c}); feedstock harvesting and collection (e_{fe_hc}); feedstock processing (e_{fe_p}); feedstock
204 transportation to processing and fuel production facilities (e_{fe_t}); feedstock-to-fuel conversion
205 processes (e_{fefu_p}); fuel transportation and distribution (e_{fu_t}); and fuel combustion in an aircraft engine
206 (e_{fu_c}). For purposes of reporting or accounting emissions from biofuels combustion, the latter term
207 (e_{fu_c}) is considered as being zero for the fuel fraction produced from biomass.

$$\text{Core LCA [gCO}_2\text{e/MJ]} = e_{fe_c} + e_{fe_hc} + e_{fe_p} + e_{fe_t} + e_{fefu_p} + e_{fu_t} + e_{fu_c} \quad \text{Equation (1)}$$

208 The functional unit is MJ (lower heating value [LHV]) of fuel produced and combusted, and the
209 results are expressed in grams of CO₂ equivalent per MJ of fuel (gCO₂e/MJ) combusted in the aircraft
210 engine. GHG emissions from stages included in the fuel life-cycle include CO₂, N₂O, and CH₄ (with
211 the exception of fuel combustion, which only includes CO₂), are expressed in terms of CO₂e using
212 their 100-year global warming potentials, according to the Fifth Assessment Report (AR5) of
213 Intergovernmental Panel on Climate Change (IPCC) [35]. One-time emissions associated with
214 construction or manufacturing facilities (the so-called infrastructure-related emissions) are not
215 included; their contribution to the LCA results of fuel products is usually small. Various institutions
216 (Argonne National Laboratory, Joint Research Centre [JRC], Massachusetts Institute of Technology
217 [MIT], University of Hasselt, University of Toronto, and Universidade Estadual de Campinas)
218 performed LCA calculations for SAFs to support ICAO's CAEP. These institutions were tasked to
219 assess core LCA values (carbon intensities [CIs]) of the same fuel pathways to reflect their LCA

220 models and regionally-specific parameters, among other factors.

221 LCA results for a given pathway often differ due to unique data and assumptions (i.e. conversion
222 efficiency, yield, etc.), which can reflect regional differences (e.g. agricultural practices, electricity
223 generation mix, transportation distances, etc.). To account for these differences, while being able to
224 set a single default core LCA value, a threshold of 8.9 gCO₂e/MJ (10% of the jet fuel baseline GHG
225 intensity) was used. When the difference in independently calculated core LCA values from different
226 institutions falls within this threshold, the mid-point value is taken as a representative default value. If
227 the range of results is greater than 8.9 gCO₂e/MJ, either the parameters leading to the discrepancy are
228 identified and harmonized appropriately or, where distinct differences exist, the region-specific data is
229 used to develop region-specific pathway core LCA values as separate pathways. This approach was
230 taken to establish default values applicable at a global scale, necessary for an international policy such
231 as CORSIA.

232 Two databases/models have been used for evaluating the core LCA values: the E3 database (E3db)
233 [36] and the Greenhouse gases, Regulated Emissions, and Energy use in Technologies (GREET[®])
234 model [37]. E3db is used by JRC and GREET is used by the other institutions. For the pathway-
235 specific parameters, the LCA modeling group collected data mostly from the available literature.
236 Mass and energy balance data, especially for the conversion processes, were also collected from
237 industry to fill the gap between the literature and existing or planned industry practices. Among the
238 production pathways, there are different technological and commercial readiness levels. Even among
239 ASTM approved pathways, some could be still considered at pilot stages. All life-cycle inventory
240 datasets are reported in the CORSIA Supporting Document [13]. The final goal of this exercise was to
241 define the GHG emission savings of a specific SAF pathway by comparing the SAF default core LCA
242 value with the life-cycle GHG emissions of conventional petroleum-derived jet fuels. It is worth
243 noting that the fossil jet fuel a baseline was agreed for the purpose of defining a common benchmark
244 value at the global scale; a variety of crude slates being processed in a variety of refinery
245 configurations worldwide were analysed to determine the global average GHG intensity value for the
246 baseline petroleum jet fuel.

247 Demand for crop-based biofuels may encourage cropland expansion and cause GHG emissions due to
248 consequent LUC. As a result of interactions among commodity markets, connections between
249 agricultural and non-agricultural markets, and international trade, LUC and related emissions may
250 become a global phenomenon that goes beyond the regions producing biofuels [38–40]. These are
251 called biofuels ILUC emissions. Several papers have reviewed the existing literature on ILUC values
252 [41–46], mainly for road biofuels. That literature shows important disparities among models in the

253 baseline assumptions, shock size, simulation approach, and the data used in calculating emissions.
254 Resulting estimated ILUC emissions are subject to uncertainties and vary significantly among
255 biofuels, feedstocks used, and production location. However, before this work in CORSIA, aviation
256 biofuels ILUC emissions have not been quantified.

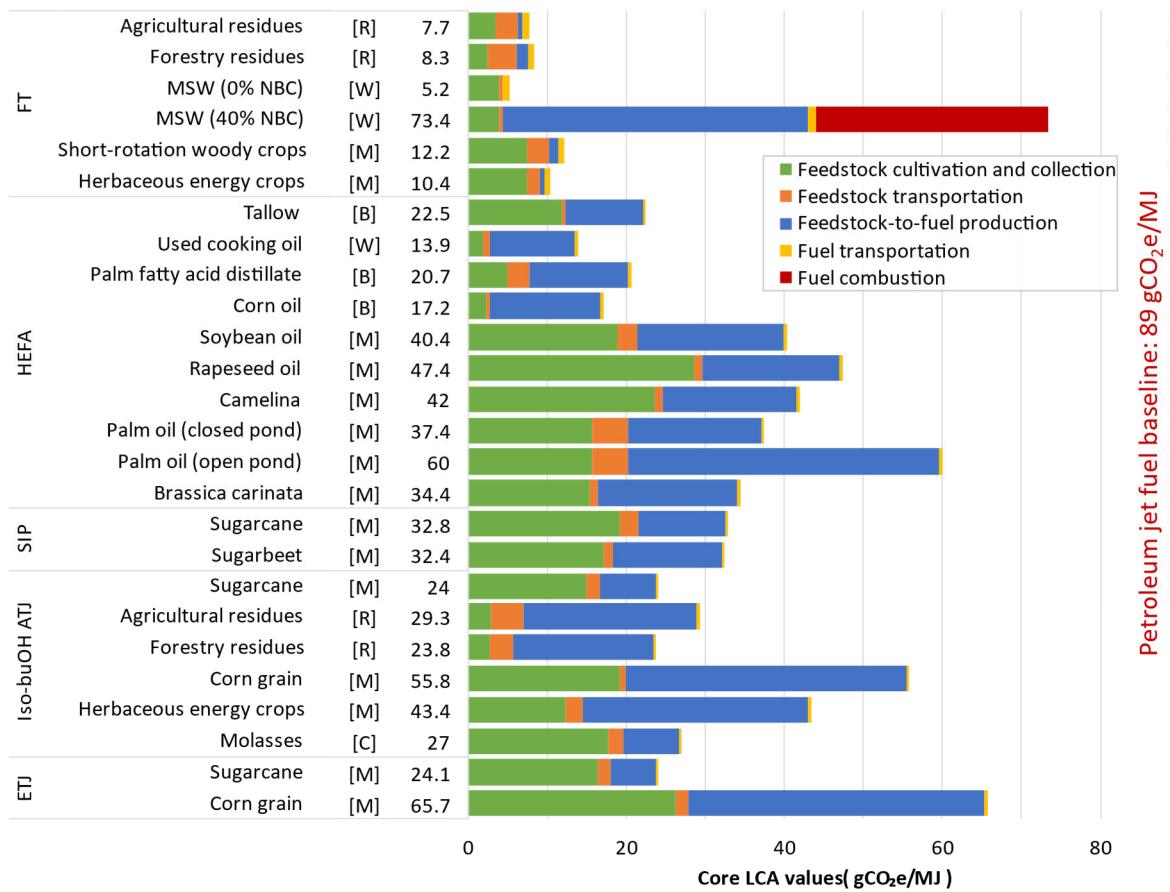
257 To estimate ILUC emissions for aviation biofuels, noticing the considerable uncertainty in ILUC
258 simulation results, two different economic models, well-established on this topic, were used: GTAP-
259 BIO [44,47,48] and GLOBIOM [49,50]. These models have been extensively employed in the past to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

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

277

278 **4. CARBON INTENSITIES OF SUSTAINABLE ALTERNATIVE FUELS FOR CORSIA**

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



Petroleum jet fuel baseline: 89 gCO₂e/MJ

285

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

288 The GHG reduction benefits of SAFs compared to fossil-derived jet fuels are due to the CO₂ uptake of
289 biomass feedstocks. In these cases, CO₂ from fuel combustion is offset by carbon uptake during
290 photosynthesis, resulting in net-zero fuel combustion CO₂ emissions (e_{fu_c}). Since the combustion
291 emissions of petroleum jet fuels consist of 83% (74 gCO₂e/MJ) of its total life-cycle GHG emissions,
292 avoiding this provides significant GHG emissions benefits.

293 In Figure 2, the FT MSW pathway shows non-zero fuel combustion emissions (red bar), due to 40%
294 non-biogenic carbon composition of the feedstock. In case of using 100% biogenic MSW, combustion
295 CO₂ emissions would be fully offset by the carbon uptake of feedstock growth. SAFs produced from
296 main [M]- or co-products [C] biomass feedstocks generally have higher emissions associated with
297 cultivation and collection (e_{fe_c} and e_{fe_hc}), than other classes of feedstocks [R, W, B]. This is due to
298 the decision that [R, W, B] feedstocks are not assigned with cultivation emissions. For crops ([M, C]),

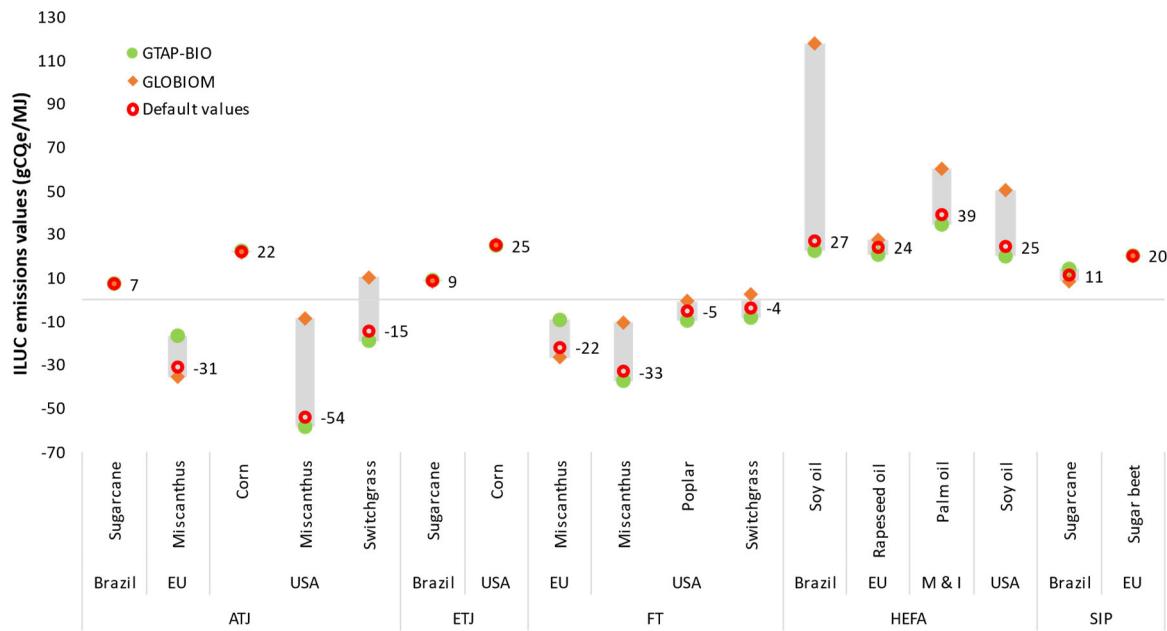
299 emissions from fertilizer and energy use have a significant impact on overall life-cycle GHG
300 emissions. The differences in the length of the green bars show that use of waste and residual
301 feedstocks, or low-input feedstocks (e.g. dedicated energy crops), is key lever to achieve low-GHG
302 aviation fuels.

303 Different technologies result in significantly different GHG emissions during feedstock-to-fuel
304 conversion (e_{refu_p}) (blue bars in the figure). FT, in general, has low conversion-related emissions,
305 mainly because the process uses heat from syngas combustion (biogenic carbon emissions), except
306 when the feedstock is MSW with NBC content. Other technologies require significant energy and
307 chemical inputs, leading to noticeable process emissions. For HEFA, oil extraction and jet fuel
308 production lead to emissions associated with the required energy and chemical inputs: mainly
309 electricity, natural gas, and hydrogen. Unlike the FT process, which relies on energy from the biomass
310 feedstock, the HEFA process relies mainly on fossil-based inputs, leading to higher conversion
311 emissions. If renewable electricity, natural gas, and hydrogen are eventually used for these processes,
312 their GHG emissions would be reduced significantly. There are two default core LCA values for palm
313 HEFA pathways because CH₄ emissions from the palm oil mill effluent (POME) can vary
314 significantly depending on biogas recovery (CH₄ capture). While the open pond case has considerable
315 CH₄ emissions from POME, the closed pond case can capture 85% of CH₄.

316 SIP pathways use biological and chemical conversions, via fermentation of sugars into farnesene,
317 hydrogenation to farnesane, and hydrocracking and isomerization to jet fuel product. The main
318 process input is hydrogen for hydrotreating. The results for the iBuOH ATJ conversion processes
319 show significant variation between independent LCA results, primarily due to different assumptions
320 on feedstock transportation distance, co-location of feedstock-to-iBuOH and iBuOH upgrading
321 facilities, net heat and enzyme demand for iBuOH fermentation, and final fuel transportation
322 distances. For ETJ pathways' conversion process, sugarcane and corn grain pathways show
323 significantly different values. The conversion consists of two major processes, ethanol production and
324 ethanol-to-jet conversion. The major differences in the ETJ LCA results are mainly led by the
325 feedstock yields, natural gas requirements for ethanol production, and ethanol yields. For all analyzed
326 pathways while transportation-related emissions are not negligible, their contribution is less than 1 g
327 CO₂e/MJ to the final core LCA values, resulted from the decision in the context of CORSIA to use the
328 closest point for fuel uplift from the point of fuel production, as explained above.

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

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



338

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

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

349 By consensus among the FTG experts, a similar approach to that used for the core LCA analysis has

350 been proposed to reconcile values within a close range: when the estimates from the two models were
351 within 10% of the baseline fossil fuel value of 89 gCO₂e/MJ (8.9 gCO₂e/MJ), the midpoint was used.
352 This approach has been applied to reconcile seven pathways, including six sugar or starch pathways,
353 and the EU rapeseed HEFA pathway. For the remaining pathways, it was decided to use the lower of
354 the two model values, plus an adjustment factor of 4.45 gCO₂e/MJ. This adjustment factor represents
355 half of the tolerance level of 8.9 gCO₂e/MJ, i.e. the minimum reduction requirement in CI for a SAF
356 pathway to be CEF.

357

358 5. DISCUSSION

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

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

382 remains unproven at commercial scale. The production of aviation biofuels from sugars is another
383 promising pathway, and pilot plants are already supporting scale-up initiatives. For alcohol-to-jet, the
384 supply of aviation biofuels for commercial flights already occurred [71,72], demonstrating significant
385 maturity [73] of this technology.

386 ICAO CAEP's nominated experts have been working to define a suitable methodological framework
387 for evaluating LCA values of additional SAF production pathways certified by ASTM, making use of
388 the existing body of knowledge for the sector. In addition, ICAO recently broadened the definition of
389 the CORSIA eligibility to include LCAFs alongside existing SAFs. Thus, if fossil-based aviation fuels
390 can demonstrate reductions in life-cycle GHG emissions greater than 10% of that of baseline fuels,
391 fossil-based low-carbon fuels may be also counted towards the target of stabilized CO₂ emissions in
392 international aviation pursued by CORSIA. The core LCA values presented in this paper represent
393 "default" values for specific pairs of feedstock-process combinations. They have been created by
394 using feedstock- and pathway-specific representative data, with the goal of generating values that are
395 suitable for use at a global scale. CORSIA also allows obligated parties to submit core LCA values
396 along with the supporting data that represent their specific fuel production technology (called "actual"
397 LCA values). It is worth noticing that an assessment of actual LCA values can be performed by using
398 the described methodology, and undergoing a certification process [19].

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

407 It is worth recalling that participation in the first phases of CORSIA is on a voluntary basis, and there
408 are exemptions for some aviation activities. Despite this, CORSIA is expected to offset international
409 aviation CO₂ emissions exceeding 2019 levels. A regular review of CORSIA is required under the
410 terms of the ICAO 2016 agreement, which should allow for its continuous improvement. While SAFs
411 could play a major role in contributing to reducing aviation sector's GHG emissions on the basis of
412 their per-MJ GHG reduction potentials, we caution, however, that cost barriers have to be overcome
413 in order to ensure the large-scale deployment of SAFs, and the corresponding GHG emissions
414 benefits.

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

427

428 **6. CONCLUSIONS**

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

444

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467

468 **DISCLAIMER**

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