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# The carbon footprint of alternative jet fuels produced in Brazil: exploring different approaches

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ABSTRACT

Although the potential of Alternative Jet Fuels (AJF) to reduce greenhouse gases (GHG) emissions has been widely reported upon in the literature, there are still discrepancies among the results. These may be due to the different GHG accounting methods, including those used by different Low-Carbon Policies (LCPs). To have a clearer understanding of the life cycle performance of AJF, the carbon footprint of ten pathways was estimated, comprising promising feedstocks – such as soybean, palm, sugarcane, sugarcane residues, forestry residues, used cooking oil, beef tallow, and steel off-gases – and ASTM-approved technologies: Hydroprocessed Fatty Acids, Alcohol-to-Jet, and Fischer-Tropsch. Six methodological approaches were used: the attributional and the consequential life cycle assessment, as well as guidelines for the four LCPs: *Renovabio* (Brazil), CORSIA (aviation sector), RFS (United States), and RED II (Europe). Soybean-based pathway (24 to 98.7 $gCO_{2e}$/MJ) had the low to no potential for reducing GHG when compared to their fossil counterparts, mainly due to land use change. Of all food-based pathways, AJF produced from sugarcane performed the best (-10.4 to 43.7 $gCO_{2e}$/MJ), especially when power surplus was credited. AJF from palm oil could present significant GHG reduction for palm expansion in degraded pasturelands. By contrast, Fischer-Tropsch of lignocellulosic residues showed the highest potential for reducing GHG (-95% to -130%). Different from food-based pathways, the potential GHG reduction of residues-based pathways converged within a narrower range (-130% to -50%), except when residual feedstocks have to be redirected from their current economic use. It could lead to GHG emissions higher than fossil fuel.

*Abbreviation*
1G: first-generation
2G: second-generation
AJF: Alternative Jet Fuel
ALCA: Attributional Life Cycle Assessment
ATJ: Alcohol-to-Jet
CHP: Combined Heat and Power
CLCA: Consequential Life Cycle Assessment
CORSIA: Carbon Offsetting and Reduction Scheme for International Aviation
dLUC: Direct Land Use Change
FR: Forestry residues
FT: Fischer-Tropsch
GHG: Greenhouse gases
HEFA: Hydroprocessed Fatty Acids
iLUC: Indirect Land Use Change
LCA: Life Cycle Assessment
LUC: Land Use Change
POME: Palm Mill Oil Effluent
PSA: Pressure Swing Adsorption
RED: Renewable Energy Directive
RFS: Renewable Fuel Standard
SC: Sugarcane
SOG: Steel off-gases
UCO: Used Cooking Oil

## 1. Introduction

The International Civil Aviation Organization (ICAO) has set ambitious goals for reducing greenhouse gas emissions (GHG) in the aviation sector (ICAO, 2016). These have been managed by the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) (ICAO, 2020), and the use of Alternative Jet Fuels (AJF) is one strategic way to

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achieve these goals (ICAO, 2017).

Similarly, other Low-Carbon Policies (LCP) have promoted biofuel production to tackle climate change issues. In Europe, the *Renewable Energy Directive* (RED) (European Union, 2018) states that at least 14% of the energy consumed in the transportation sector should be supplied by renewable sources by 2030 (EU Science Hub, 2020). Likewise, the United States set forth a target of 36 billion gallons for biofuels by 2022 by the *Renewable Fuel Standard* (RFS) (U.S. EPA, 2010), setting specific targets for different fuel categories. The current Brazilian program *Renovabio*(BRAZIL, 2017) seeks to reduce the carbon intensity of the national fuel matrix by up to 11% by 2029 by trading Decarbonization Credits (CBIO).

Under all the previous regulatory schemes, the potential GHG reduction for biofuels in comparison to their fossil counterparts has been a crucial indicator for the decision-making process. Generally, this has been estimated using the Life Cycle Assessment (LCA) tool, where GHG emissions along the whole biofuel life cycle are accounted for and compiled into the carbon footprint.

The carbon footprint for AJF has been largely explored in literature motivated by the ICAO goals (Agusdinata et al., 2011; Bailis and Baka, 2010; Cox et al., 2014; de Jong et al., 2017; Fan et al., 2013; Han et al., 2017; Klein et al., 2018; Moreira et al., 2014; Santos et al., 2017; Shonnard et al., 2010; Staples et al., 2014; Stratton et al., 2010; Tzanetis et al., 2017; Wong, 2008). Among these studies, variations in AJF performance are expected when considering different feedstocks, conversion technologies, and supply-chains. However, highly sensitive outcomes, with respect to the methodological aspects, have been observed in some publications, *e.g.* system boundaries, inventory assumptions, emission factors, and the way co-products are handled (Capaz and Seabra, 2016). This latter issue, which is one of the most critical aspects in LCA, addresses the effective environmental impact associated to the main product in multifunctional processes. In general, the total environmental impacts can be allocated between the different products according to the physical or economic relations between them; or credits related to co-products displacing of other products can be accounted for.

Some authors have suggested that LCA should be carried out strictly dependent on the specific questions that are addressed (Guinée et al., 2011; Sonnemann and Vigon, 2011; Tillman, 2000). As a result, two different LCA approaches have been cited in literature: i) the Attributional LCA (ALCA), which investigates the environmental performance of a product from an isolated perspective based exclusively on the physical input-output flows described by average data; and ii) the Consequential LCA (CLCA), which explores the effects and causal relations within the market by changing product demand using marginal data (Finnveden et al., 2009; JCR, 2010; U.S. EPA, 2010; Weidema, 2003; Weidema et al., 2018).

Nevertheless, the assumptions in the analyses are not always clearly associated with the approach adopted by the study (Thomassen et al., 2008; Tillman, 2000; Weidema, 2003), and specific features of calculating GHG can lead to different results for the same biofuel under different regulatory schemes (Khatiwada et al., 2012; Pereira et al., 2019). Meanwhile, the AJF performance has not consistently been explored under these different approaches, being limited to sensitivity analyses to the choice of one or another parameter.

In this context, the carbon footprint of several AJF pathways was estimated under different perspectives to have a clearer and more comprehensive understanding of how AJF may help reduce GHG emissions. Ten strategic AJF pathways were described in Brazilian conditions, since this country has a well-known history in bioenergy production, and great potential for exporting AJF worldwide (Cortez, 2014). The pathways comprised: i) hydroprocessed esters and fatty acids (HEFA) from soybean oil, palm oil, used cooking oil, and beef tallow; ii) Alcohol-to-Jet (ATJ) process from ethanol obtained from sugarcane, steel off-gases, and lignocellulosic residues, such as sugarcane residues and forestry residues; and iii) Fisher-Tropsch (FT) of lignocellulosic residues.

These pathways were evaluated using six methodological approaches: ALCA, CLCA, and four LCP regulatory systems (*Renovabio*, CORSIA, RFS, and RED). This study sought to point out trends and conflicts in AJF performance, ranking the best pathways, and indicating the critical issues for each approach.

## 2. Methods

### 2.1. Scope and boundaries

The goal of this study was to assess the environmental performance of AJF in terms of GHG emissions. The selected pathways, which are described in **Section 2.2**, comprise approved AJF technologies: HEFA, ATJ, and FT (ASTM, 2020), and promising feedstocks available in Brazil, according to the Roadmap for sustainable aviation fuels in Brazil developed by research agencies (Cortez, 2014). Thus, the potential of relevant energy crops, such as sugarcane and soybean was investigated. The potential of palm was included since it has high agricultural yields, and it is an oil-plant already cultivated in Brazil with considerable potential for expansion. Finally, the use of strategic residual feedtocks was also explored, such as used cooking oil (UCO), beef tallow, steel off-gases, and lignocellulosic residues, like sugarcane residues and forestry residues.

First, the performance of the selected pathways was explored considering average production conditions, *i.e.*, using the ALCA approach. Alternatively, the carbon footprint for marginal conditions was estimated using the CLCA approach. Finally, the performance of these pathways was evaluated according to the methodological recommendations given by relevant international biofuel policies.

The carbon footprint of AJF ($gCO_{2eq}/MJ_{AJF}$) comprised "*well-to-wake*" system boundaries for the ALCA and CLCA approaches, *i.e.* from the production of the feedstock all the way up to using the fuel. This value was then compared to fossil kerosene (Jet A, 89 $gCO_{2e}/MJ$) since the AJF intends to replace it (ICAO, 2020). The characterization factors were taken from the 5$^{th}$ IPCC report (IPCC, 2014). The environmental impact related to machinery, processing equipment, building construction, services, overhead (laboratories and office equipment), was not included. Since the environmental impacts related to them are diluted over their lifetime, it is expected a relatively minor contribution to the results. Also, the environmental burden related to catalyst use was disregarded due to the lack of information on the production conditions and uncertainties regarding catalyst loads or lifetime (Capaz et al., 2020). Assumptions for ALCA and CLCA are detailed in **Sections 2.3**.

The specific regulatory schemes and adjustments are detailed in **Section 2.4** for evaluating the AJF pathways considering the LCPs.

### 2.2. General description of the pathways

The pathways evaluated here (**Fig. 1**) were divided into first-generation (1G) pathways – *i.e.*, food-based pathways, like soybean oil, palm oil, and sugarcane – and second-generation (2G) pathways, *i.e.*, residue-based pathways, like UCO, beef tallow, sugarcane and forestry residues, and steel off-gases.

#### 2.2.1. Upstream and Intermediary stages

Soybean production was described as a monoculture system in Mato Grosso State (IBICT/SICV, 2019), which produces about 30% of all the soybeans grown in Brazil (around 120 million tonnes in 2018) (IBGE, 2019a). An extraction plant via hexane (Castanheira et al., 2015) would be located 400 km from the soybean plantations (one-way). The life cycle inventory (LCI) of Soy/HEFA is presented in Supplementary Material (**Tab. SM.3).**

Palm oil production (*Elaeis Guineensis*) was based on data from a Brazilian company (Agropalma, 2017a) located in the Pará State, which is responsible for about 90% of the national production (1.5 million

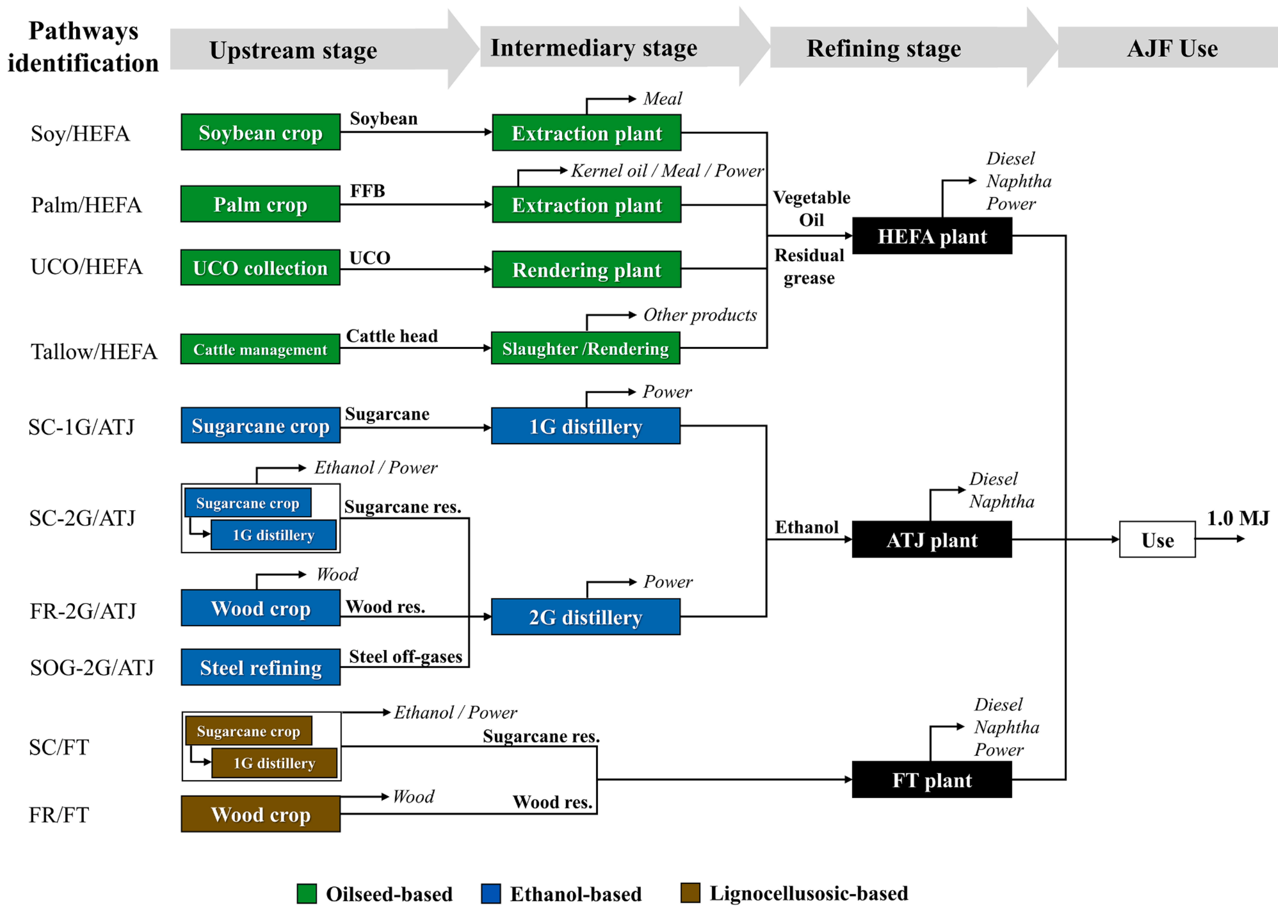



**Fig. 1.** Overview of the AJF pathways. Reference flows in **bold**; Co-products in *italic letters*. 1G: First-generation; 2G: Second-generation; ATJ: Alcohol-to-Jet; FFB: Fresh Fruit Bunches; FR: Forestry residues; FT: Fischer-Tropsch; HEFA: Hydroprocessed Esters and Fatty Acids; SC: Sugarcane; SOG: Steel off-gases; UCO: Used Cooking Oil.

tonnes of fresh fruit bunches, FFB, in 2018) (IBGE, 2019b). Of the various products that can be obtained at the oil extraction plant, crude palm oil would be used to produce AJF, and the empty fruit bunches (EFBs) would be returned to the field as fertilizer. Shells are used as a renewable self-supplying energy source at the extraction plant, as reported by de Souza et al., (2010). Palm kernel oil and meal were sent to the oil market and used as animal feed, respectively. Considering the company's investment plans (Agropalma, 2017b), it was considered that biogas from the anaerobic digestion of palm mill oil effluent (POME, 6.6 $kgCH_4/t_{FFB}$) was captured in closed pond system and used for power generation (36.8 $kWh/t_{FFB}$) (Chin et al., 2013). The distance between the palm plantation and the extraction plant was 30 km. The LCI of palm oil is presented in **Tab. SM.4.**

For grease-based pathways, the life cycle of beef tallow also must take cattle management, and slaughter/rendering processes into account, which have all been described for Brazil (Sousa et al., 2017). Industrial processes were described for an integrated slaughter and rendering plant, as is typically seen in Brazil (Garcilasso, 2014; Sousa et al., 2017).

The distance form collection and transportation of the feedstock to the rendering process (Seber et al., 2014) was 50 km for AJF derived from UCO, based on the average distance for collecting 1.0 tonne of UCO from food service establishments (Araujo et al., 2010). Both LCI for UCO and beef tallow are shown in **Tab. SM.5** and **SM.6**, respectively.

Data for the agricultural stage of sugarcane-based pathways was mostly retrieved from the *Virtual Sugarcane Biorefinery (VSB)* facility, developed by the Brazilian Biorenewable National Laboratory (LNBR) (Bonomi et al., 2016). The agricultural stage was described using average data values from São Paulo State, which is responsible for more than half of all Brazilian production of sugarcane and ethanol (UNICAData, 2020). Complete mechanized harvesting with 50% straw recovery using bailing/loading systems was considered. It was also assumed the application of vinasse and filter-cake on the field. Transporting straw and stalks to the ethanol distillery requires 36 km (LNBR, 2018).

The 1G ethanol was obtained from an optimized autonomous distillery for hydrated ethanol, according to the *VSB*(LNBR, 2018). Meanwhile, the pathways based on sugarcane residues, via 2G-ethanol or FT, were modeled considering a mix of bagasse and straw as feedstock. This material would be provided via an optimized 1G autonomous mill (Bonomi et al., 2016), which burns only the amount of residues required to supply its internal energy demand.

The 2G processes were modeled as stand-alone plants, *i.e.*, physically separated from the 1G processes, to allow for an independent evaluation. In this case, the process of ethanol production comprises steam explosion of the lignocellulosic residues, followed by enzymatic hydrolysis, assuming a mature technological level (Bonomi et al., 2016). Furthermore, it was considered using solid residues (*i.e.*, cellulignin) as an energy source in a Combined Heat and Power (CHP) system and returning industrial effluents, such as vinasse and pre-treatment flash, to the field. The detailed LCIs for ethanol production from sugarcane (1G and 2G) are presented in **Tab. SM.7** and **SM.8**, respectively.

The upstream inventory for forestry residues-based pathways was informed by a Brazilian pulp and paper company that uses eucalyptus (Coelho, 2018). Forestry residues – comprising branches, trunks, and barks – were chipped on the field and transported to the ethanol mill 40 km away. A similar 2G process designed for sugarcane residues for ethanol production was adjusted for forestry residues. The complete inventory is presented in **Tab. SM.9**.

Finally, the SOG-2G pathway considered ethanol production by fermenting the off-gases released in the steel refining processes. This novel technology has already reached commercial scale (Brooks et al., 2016; LanzaTech, 2018) and was described by Handler et al. (2016). The fermentation process was tailored to maximize ethanol production, with minimal co-product creation and no co-product recovery. Likewise, biogas from anaerobic digestion of the biological solids (spent microbial biomass) filtered from the distillation would be mixed with a portion of the reactor vent gas and used for internal energy supply. The remaining vented gas from the fermentation bioreactor would be scrubbed, oxidized, and released into the atmosphere. The LCI is presented in**Tab. SM.10**.

#### 2.2.2. *Refining stage*

The conversion technologies for obtaining AJF (HEFA, ATJ, and FT) were mostly based on Klein et al. (2018), who used the light streams (*e. g.*, propane) for self-supply. Furthermore, on-site hydrogen production was performed using Steam Methane Reform (SMR) (Spath and Mann, 2001).

The yields of oilseed-based feedstocks converted to liquid fuels using HEFA technology were assumed to be similar for all pathways, as also assumed by other authors (de Jong et al., 2017; Klein et al., 2018; Seber et al., 2014).

Hydrogen demand, however, was adjusted in some cases. The hydrotreating of palm oil and soybean oil would demand 37.2 kg $H_2$/$t_{feedstock}$ and 41.9 kg $H_2$/$t_{feedstock}$, respectively. The same hydrogen demand as soybean oil was considered for hydrotreating of UCO, as suggested by other authors (de Jong et al., 2017; Seber et al., 2014). An input value of 35.2 kg $H_2$/$t_{feedstock}$ was estimated for beef tallow, considering its composition (INRA, 2018). The power surplus generation was properly estimated in the latter case, since the hydrogen demand may influence internal electricity consumption on pressure swing adsorption (PSA) units.

The ATJ plant was considered be fed by hydrated ethanol and hydrogen at 11.0 kg $H_2$/$t_{ethanol}$. Finally, the conversion yields for eucalyptus to AJF via FT technology reported by (Klein et al., 2018) were taken to be similar to forestry residues.

The AJF plants are placed near to the three major Brazilian refineries for Jet A production, REVAP and REPLAN in São Paulo State, and REDUC in Rio de Janeiro State (ANP, 2020a). As a result, the distance from soybean extraction, from UCO rendering, from slaughterhouse, and from the ethanol distilleries to the AJF plants was set at 400 km (one-way) each. Palm oil can be transported 3,000 km using the new maritime route established between Belém Port (Pará State) and Santos Port (São Paulo State) (Agropalma, 2017b) to AJF plant.

Airports would be 200 km away from all AJF plants for all pathways, corresponding to the weighted distance between the Brazilian refineries and Guarulhos International Airport, where 30% of all fossil kerosene in Brazil is consumed (ANP, 2020a). A 600 km one-way distance between the FT plant and the airport was assumed. Carbon emissions related to all transportation stages mentioned previously were accounted for (see **Supplementary Material** for more details). Table 1 presents the main yields for each life cycle stage considered in this study.

#### 2.2.3. *AJF use*

The emissions profile of AJF, when used in aircraft operation, was taken by considering normal operational parameters during an international trip, as reported by (Ecoinvent, 2016). The carbon emissions related to AJF use were disregarded since they are considered biogenic. On the other hand, carbon emissions were appropriately accounted for in SOG-2G/ATJ, which is based on fossil carbon since coal is the primary carbon source used by steel mills in Brazil (Instituto Aço Brasil, 2018).

**Table 1**
Overall yields for AJF pathways. Co-products reported in *italic letters*.

| Pathways | Upstream yields[a] | Intermediary yields | Refining yields[b] |
|---|---|---|---|
| Soy oil/ HEFA | 3.12 $t_{soybean}$ / ha | 0.19 $t_{soybean\_oil}$ / $t_{soybean}$<br>*0.80 $t_{meal}$ / $t_{soybean}$* | AJF: 493.0 kg / $t_{oil}$<br>*AD: 233.0 kg/ $t_{oil}$*<br>*AN: 60.5 kg / $t_{oil}$*<br>*Power*[c] |
| Palm oil/ HEFA | 17.76 $t_{FFB}$ / ha | 0.175 $t_{palm\_oil}$ / t FFB<br>*0.013 $t_{kernel\_oil}$ / t FFB*<br>*0.023 $t_{kernel\_meal}$ / t FFB*<br>*0.037 kWh / t FFB* | |
| Tallow/ HEFA | 450.0 $kg_{live\ weight}$/ c.h. | 23.0 $kg_{tallow}$ / c.h.<br>*261.0 $kg_{carcass}$ / c.h.*<br>*55.3 $kg_{leather}$ / c.h.*<br>*79.7 $kg_{other}$ / c.h.* | |
| UCO/HEFA | *n.a.* | 0.78 $t_{refined\_UCO}$ / $t_{crude\_UCO}$ | |
| SC-1G/ATJ | 80 tsc / ha | 93.2 $L_{ethanol}$ / tsc<br>*192 kWh / tsc* | AJF: 217.9 kg / $m^3_{ethanol}$<br>*AD: 16.2 kg / $m^3_{ethanol}$*<br>*AN: 105.3 kg / $m^3_{ethanol}$* |
| SC-2G/ATJ | 115.6 $kg_{LCM(db)}$ / tsc<br>*85.4 $L_{ethanol}$ / tsc*<br>*31.6 kWh / tsc* | 357.4 $L_{ethanol}$ / $t_{LCM}$ (db)<br>*127.6 kWh / $t_{LCM(db)}$* | |
| FR-2G/ATJ | 25 $t_{LCM\ (db)}$ / ha<br>*340 $t_{wood\ (db)}$ / ha* | 308.4 $L_{ethanol}$ / $t_{LCM}$ (db)<br>*158.5 kWh / $t_{LCM(db)}$* | |
| SOG-2G/ATJ | 100 $Nm^3_{off\text{-}gases}$ / tcs[d] | 0.271 $L_{ethanol}$ /$Nm^3_{off\text{-}gases}$[e] | |
| SC/FT | 115.6 $kg_{LCM(db)}$ / tsc<br>*85.4 $L_{ethanol}$ / tsc*<br>*31.6 kWh / tsc* | n.a. | AJF: 56.3 kg / $t_{LCM}$ (db)<br>*AD: 46.2 kg /t $_{LCM}$ (db)*<br>*AN: 66.4 kg / t $_{LCM}$ (db)*<br>*Power: 454.9 kWh / t $_{LCM}$* |
| FR/FT | 25 $t_{LCM\ (db)}$ / (ha. cycle)<br>*340 $t_{wood\ (db)}$ / (ha. cycle)* | n.a. | AJF: 58.9 kg/$t_{LCM}$ (db)<br>*AD: 48.3 kg/$t_{LCM}$ (db)*<br>*AN: 70.1 kg/$t_{LCM}$ (db)*<br>*Power: 476.3 kWh/ $t_{LCM}$* |

[a] *FFB*: Fresh Fruit brunches; *c.h.*: cattle head; *tsc*: ton sugarcane; *tcs*: ton crude steel; *LCM (db)*: Lignocellulosic material (dry basis), for sugarcane residues (45% moisture), for forestry residues (12% moisture).

[b] AJF: Alternative Jet Fuel; AD: Alternative Diesel; AN: Alternative Naphtha.

[c] It was assumed a power surplus generation of 341.4 and 409.6 kWh/$t_{oil}$ from the hydrotreating of soybean oil (Soy/HEFA) and palm oil (Palm/HEFA) respectively (Klein et al., 2018). On the other hand, it was estimated a power surplus generation of 356.3 kWh/$t_{tallow}$ from the hydrotreating of beef tallow (Tallow/HEFA), considering: the power demand by Soy/HEFA (Klein et al., 2018), the hydrogen demand for tallow hydrotreating (35.2 kg $H_2$/$t_{tallow}$), and assuming that 40% of the power demand in HEFA process is related to PSA for hydrogen recycling (Klein, 2019). Finally, for UCO/HEFA, power surplus was assumed similar to Soy/HEFA.

[d] Average composition (64% CO, 20% $CO_2$ and 16% $N_2$, in %vol.); LHV: 7.58 MJ/$Nm^3$; density: 1.392 kg/$Nm^3$; carbon content: 0.324 kgC/$kg_{off\text{-}gas}$.

[e] It was estimated considering the net off-gases input,*i.e.*, the total off-gas input minus the venting gases, according to (Handler et al., 2016), and assuming theoretical maximum 80% HHV conversion to ethanol (LanzaTech, 2019).

### 2.3. *The Carbon footprint of AJF according to the ALCA and CLCA approaches*

#### 2.3.1. *Assumptions for the attributional analysis (ALCA)*

The carbon footprint using the ALCA method was based on the average data (see LCIs in **Tab SI.3** to **SI.13**), and the conversion yields in Table 1. Background systems such as chemicals, fertilizers, fuels, power etc. were obtained from the Ecoinvent v3.3 (Ecoinvent, 2016), USCLI (NREL, 2018), and the GREET databases (ANL, 2020). They have been adapted to some extent to the Brazilian context.

Several studies have recommended allocation as a more consistent method for cause-oriented analysis (Reinhard and Zah, 2009; Schmidt, 2008; Schmidt and Weidema, 2008; Sonnemann and Vigon, 2011; Tillman, 2000; Tzanetis et al., 2017; Weidema, 2003; Weidema et al., 2018) for handling co-products, and so economic allocation was applied by default according to the current prices of the materials (see **Tab. SM.1**).

Residual feedstocks were deemed “wastes” for 2G pathways in the reference case, complying with the ISO definition, “substances or objects which the holder intends or is required to dispose of” (ISO, 2006). This means that they were not burdened with any GHG emissions quantified in the upstream processes, except for in their collection and transportation. The allocation factors used in ALCA approach are presented in **Tab. SM.13**.

Assumptions related to Land Use Change (LUC) are detailed in **Section 2.3.3**.

### 2.3.2. *Assumptions for the consequential analysis (CLCA)*

CLCA was conducted according to the procedures suggested by Weidema (2003); Weidema et al. (2009). The demand for AJF was considered to be small over the long-term, which implies that the determining parameters of the overall market would not be affected, and that the suppliers would respond linearly to demand. Thus, economic equilibrium models used to assess market conditions and price elasticities were not deemed necessary. According to the Brazilian Plan for Energy Expansion (EPE, 2019), demand for fossil kerosene will increase up to 2029, when AJF would correspond to only 1% of the total fuel demanded for aviation operations in Brazil.

As was previously mentioned, the processes affected in the CLCA approach are generally described using marginal data, which are related to unconstrained, substitutable, and the most competitive processesand technologiesaccording to price relations in increasing market trends (Schmidt and Weidema, 2008; Weidema et al., 2009). The marginal

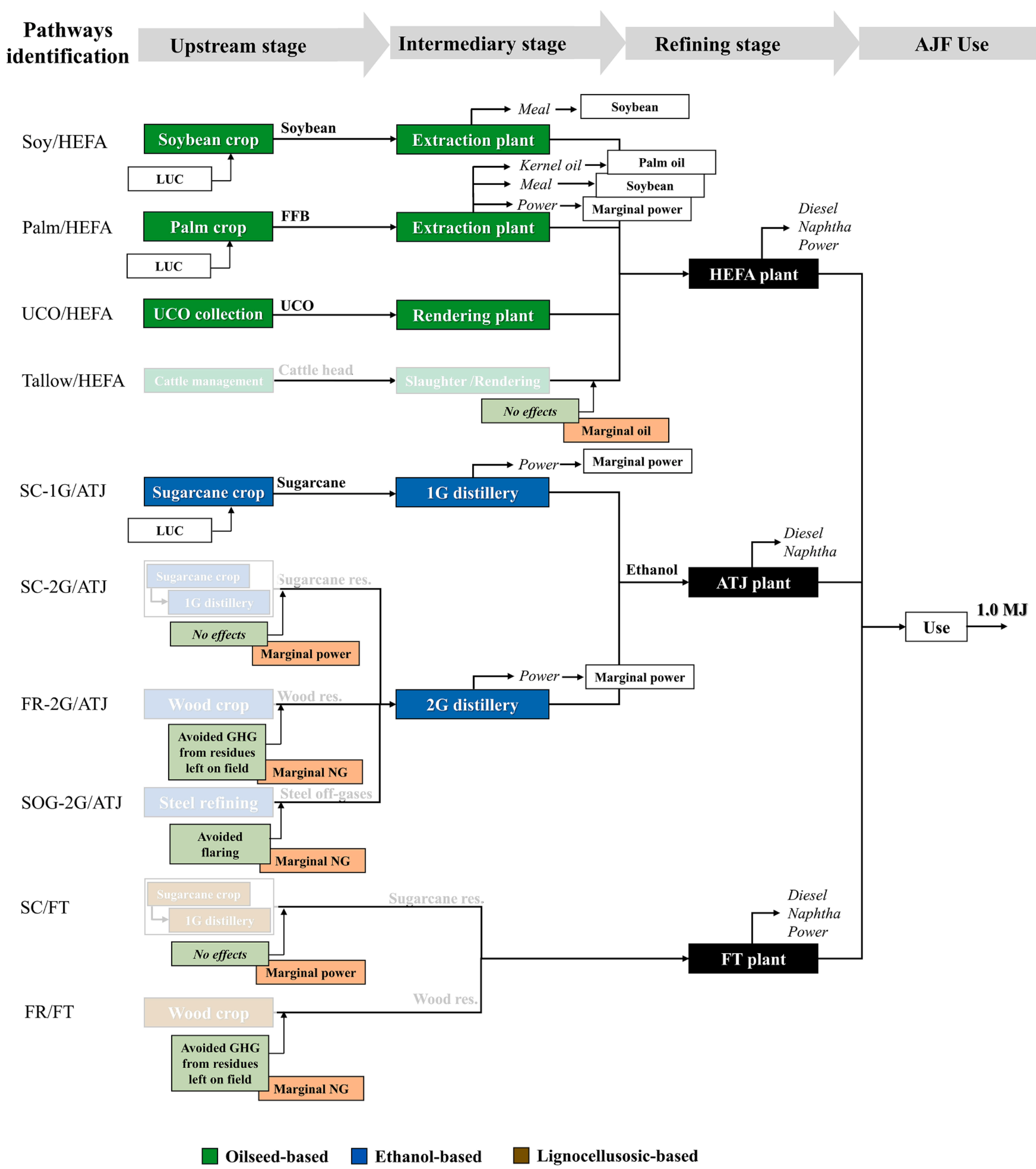



**Fig. 2.** The main effects considered in the CLCA for the reference case (boxes in light green) and in the sensitivity analysis (boxes in light red, see Section 2.3.4). FR: Forestry residues; SC: Sugarcane; SOG: Steel off-gases; NG: Natural gas; UCO: Used Cooking Oil; 1G: First-generation; 2G: Second-generation; ATJ: Alcohol-to-Jet; FR: Forestry residues; FFB: Fresh Fruit Bunches; FT: Fischer-Tropsch; HEFA: Hydroprocessed Esters and Fatty Acids.

processes considered in this study (see **Fig. 2**) are described as follows.

In Soy/HEFA, soybean oil is not a determining-product, given the low amount obtained with soybean meal and its market price (Reinhard and Zah, 2009; Schmidt et al., 2015). Therefore, theoretically, the additional demand for soybean oil for producing AJF would not lead to an additional demand for soybeans, but rather for marginal oil, which would substitute its current use. Palm oil from East Asia would be the marginal oil in this scenario, since it has been the cheapest vegetable oil with the fastest market growth over the last few years (Dalgaard et al., 2008; Escobar et al., 2014; Schmidt, 2015; Schmidt and Weidema, 2008). However, this is not a realistic scenario for Brazil for the following reasons:

i) Brazil is a net importer of palm oil (60.5 kt of palm oil in 2019) (BRAZIL/SECEX, 2020) and it is one of the major global producers of soybeans (8.6 Mt at the same year) (ABIOVE, 2020a). In this context, the price of these vegetable oils in Brazil does not necessarily adhere to the international market profile, *i.e.*, soybean oil in Brazil is competitive with imported palm oil (see **Section 3.1** in Supplementary Material, **Fig. SM.1** and **Fig. SM.2**);
ii) Palm (*Elaeis guineensis*) production in Brazil is still modest (1.57 Mt in 2018) (IBGE, 2019b), and is restricted to specific climate and soil conditions found only in Northern Brazil. By contrast, soybean production (117.9 Mt in 2018, see **Fig. SM.3**) is reinforced by a well-consolidated supply-chain with an idle capacity of around 13% (ABIOVE, 2020a) which could be easily activated for small demand increases, as assumed in this study.

As a result, the additional demand for AJF produced from soybean oil would imply an additional production of soybeans in Brazil.

The co-products identified along the Soy/HEFA pathway were dealt with by system expansion, as recommended for effect-oriented or change-oriented analysis, like the CLCA approach (Bernstad Saraiva et al., 2017; de Rosa et al., 2017; Ekvall and Weidema, 2004; Hamelin et al., 2011; Prapaspongsa et al., 2017; Rehl et al., 2012; Silalertruksa et al., 2009; Thomassen et al., 2008).

Therefore, soybean meal would displace the soybean system (1.2 $t_{soybean}/t_{soybean\_meal}$), which was identified as a marginal feed protein (Huo et al., 2009; Prapaspongsa and Gheewala, 2017; Schmidt, 2015). The soybean system was described using the same data here, however, without emissions related to Land Use Change (LUC).

Meanwhile, credits related to power surplus generation at HEFA plants were estimated by considering the displacement of marginal power generation in Brazil (0.465 $kgCO_{2e}/kWh$), using the current Clean Development Mechanism (CDM) methodology (UNFCCC, 2018). For more details, see **Section 3.2** in Supplementary Material.

Liquid biofuels co-produced at the refining stage were dealt with using energy allocation, as suggested by other authors (Han et al., 2013; Huo et al., 2008; Wang et al., 2011), since the displacement method may generate distorted results when co-products correspond to a relevant share of the output.

In Palm/HEFA, the additional demand for AJF would be supplied by an expansion in palm production in Brazil. Palm kernel oil and the meal obtained in the intermediary stage would displace the marginal processes for palm oil and soybean feed protein, respectively, as pointed out by some authors (Prapaspongsa et al., 2017; Prapaspongsa and Gheewala, 2017; Schmidt, 2015). The palm oil system, which has been described in detail for Thailand, would lead to 0.13 $kgCO_{2e}/kg_{palm\_oil}$ without LUC effects (Prapaspongsa et al., 2017). The soybean system was detailed by the same data here and, assuming a protein parity of 0.35 $kg_{soy\_meal}/kg_{palm\_meal}$ (Dalgaard et al., 2008), it would lead to 0.16 $kgCO_{2e}/kg_{palm\_meal}$, without LUC emissions. The other co-products (power surplus and liquid biofuels) were dealt with as described above.

A new demand for AJF produced via ATJ process from sugarcane ethanol (SC-1G/ATJ pathway) would imply additional land demands for sugarcane crops and subsequent milling and ethanol distilleries. Market competition within the established Brazilian ethanol industry would be unlikely in the coming years, since Brazil will probably remain a net gasoline importer (EPE, 2019). Other co-products (power surplus and liquid biofuels) were dealt with as described above.

For 2G pathways, residual feedstocks were assumed available for AJF production in the reference case. Therefore, no effect was accounted for relative to the feedstock supply, except for: i) forestry residues collected from the field, when avoided GHG emissions (13.3 $gCO_{2e}/kg_{(db)}$) were accounted for according to (Bragatto, 2010; IPCC, 2006a); ii) steel off-gases, when credits related to non-flaring were accounted for (1.65 $kgCO_{2e}/Nm^3_{off\text{-}gas}$), as was also considered in (Handler et al., 2016).

Assumptions related to LUC are detailed in **Section 2.3.3**. The consequential database available in Ecoinvent (Ecoinvent, 2016) was considered for background systems, albeit with some adaptations (see Supplementary Material, **Tabs SI.3** to **SI.13**).

### *2.3.3. Land Use Change (LUC)*

Variations in soil carbon stocks arising from land use changes (LUC) are important in bio-based life cycles. These variations can reduce or even nullify the possible benefits related to replacing fossil fuels with alternative fuels (Bailis and Baka, 2010; Moreira et al., 2014; Stratton et al., 2010; Wong, 2008).

This study does not propose a new approach for estimating the effects of LUC, in light of the extensive debate on the topic, but the effects of LUC on AJF performance were explored.

Direct LUC (dLUC) were included on 1G pathways in the ALCA approach, which addresses changes only within the assessed boundaries (ISO, 2018). The scenarios comprised carbon stocks for four different land use types (annual cropland, perennial cropland, pasture, and native vegetation) in each Brazilian State (Novaes et al., 2017) and the potential expansion areas for soybean (Nepstad et al., 2019), palm (Ramalho Filho and Motta, 2010), and sugarcane plantations (Manzatto et al., 2009). Direct dinitrogen monoxide ($N_2O$) emissions were also accounted for, assuming a default Carbon:Nitrogen (C:N) ratio of 15 (IPCC, 2006a). See **Tab SI.18** for more details.

On the other hand, a market-based analysis as the CLCA approach also account for indirect changes (iLUC) outside the assessed boundaries, which are typically estimated using economic models. The default factors suggested by ICAO (2019a) for soybean and sugarcane expansion in Brazil were used in this study, while the value suggested for Malaysia was used for palm crops due to the lack of specific data for Brazil.

The LUC effects from co-product displacement, such as soybean meal, palm kernel oil, and palm kernel meal, were assumed already accounted for in the LUC factor considered here.

Other LUC values reported in literature (Moreira et al., 2014; van der Hilst et al., 2018), which include indirect effects related to sugarcane expansion, were also investigated here. See **Tab SI.18** for more details.

### *2.3.4. Sensitivity analysis*

The sensitivity of the results from ALCA and CLCA approaches was investigated considering both 'process' and 'methodology' related aspects. Variations on agricultural yields were evaluated, as well as different designs for the refining stage, as proposed by other studies (ANL, 2020; de Jong et al., 2017). Transportation distances were arbitrarily varied by ±50%, except for transporting sugarcane stalks and palm oil. Furthermore, alternative hydrogen production from water electrolysis (James et al., 2013) was also assumed (see **Tab SI.2** at Supplementary Material).

Regarding methodological aspects, different allocation methods were considered in the ALCA approach, *i.e.*, according to the energy content (see **Tab SI.I**) and mass. For 2G pathways, since some residual feedstocks – such as beef tallow, sugarcane residues, and forestry residues – are traded as valuable products, so they were taken as co-products from the upstream stage. UCO and steel off-gases were not included in this latter assumption. **Tab. SM.14** presents the allocation factors used in ALCA.

It was investigated a full system expansion for co-products in the CLCA approach, *i.e.*, calculating credits for replacing diesel (3.68 $kgCO_{2e}/kg$) (IPCC, 2006b) and gasoline (3.52 $kgCO_{2e}/kg$) with alternative diesel and naphtha, respectively.

Additionally, the consequences of utilizing residual feedstocks in current use for AJF production were also investigated in CLCA, as suggested by Hanssen and Huijbregts (2019).

In this context, an additional demand for beef tallow, which is mostly used by the Brazilian biodiesel industry (EPE, 2020), would result in a marginal effect on the production of soybean oil, for the same reasons presented previously (see **Section 2.3.3**).

It was considered that an additional demand for sugarcane residues, which are commonly used to provide self-supplied energy at ethanol plants in Brazil (EPE, 2020), would result in marginal power generation, for the same reasons mentioned for power surplus (see **Section 2.3.3**).

In turn, it was assumed that forestry residues used to produce AJF would lead to an additional demand for natural gas, since more than 90% of the demand for wood from the pulp and paper sector is used for industrial heating (EPE, 2020) and the national market price trends for heating have suggested natural gas as a marginal supplier (see **Fig. SM.4** at Supplementary Material).

Finally, a marginal demand for natural gas was also considered in the SOG-2G pathway since steel off-gases are recovered for energy purposes at several steel mills (ABM, 2017). The replacement of steel off-gases by natural gas was considered using energy parity (0.206 $Nm^3_{natural\ gas}/Nm^3_{steel\ off\text{-}gases}$).

The marginal demand for natural gas in Brazil could be supplied by the *Pré-Sal* oil basin (off-shore) in both previous cases, given its increased production trend and its competitiveness with imported liquefied natural gas (see **Figs SI.5** and **SI.6** at Supplementary Material).

### 2.4. The carbon footprint of AJF according to the regulatory schemes

The carbon footprint was estimated here by adjusting the life cycle inventories to the guidelines of the regulatory schemes (see **Table 2**), including the methodological approach, assessment tools, and default values suggested by these schemes. Since there is still no reference for biofuel obtained from steel off-gases in any regulatory scheme, the pathway SOG-2G/ATJ was not evaluated here.

The carbon footprint was calculated using the RenovaCalc tool (v.6.1)(ANP, 2020b, 2018a) for the Renovabio. Even though only HEFA-based pathways were available in this tool, other life cycle stages, e.g., agricultural processes and ethanol production were considered here. The conversion processes for ATJ and FT technologies were modeled considering the Renovabio guidelines, including the emission factors provided by the tool (ANP, 2018b).

The CORSIA regulatory scheme does not have any specific assessment tool. Nonetheless, the values estimated using ALCA approach (see **Section 2.3.1**) with energy allocation were considered here. The default LUC values suggested by (ICAO, 2019a) were added when necessary.

The current summary of biofuel pathways, as evaluated by RFS (U. S. EPA, 2020) – which includes process emissions, LUC values, and effects on crops and livestock – does not report any AJF pathway. Therefore, the carbon footprint was estimated for this regulatory scheme by combining the specific life cycle stages already summarized and the GREET models (ANL, 2020) suggested for AJF conversion and transportation.

Finally, carbon emissions using RED II (EU Science Hub, 2020; European Union, 2018) were estimated considering the specific guidelines and emissions factors reported in (Edwards et al., 2019). The dLUC emissions for Brazil were estimated assuming soybean, palm, and sugarcane expansion on pasturelands (see **Section 2.3.3**).

In the RFS and RED systems, it was considered that AJF would be produced in Brazil and transported to the United States (10,500 km) and Europe (11,940 km) by ship, respectively.

## 3. Results

### 3.1. Carbon footprint using attributional and consequential approaches

All AJF pathways result in potential GHG reductions compared with fossil kerosene (89.0 $gCO_{2e}/MJ$), when the carbon footprint is estimated using the attributional approach (ALCA), and if no LUC values are accounted for (see **Fig. 3.A** and **Table 3**). Although the potential reduction of 1G pathways is less than the 2G potential – mainly due to

**Table 2**
General description of consolidated Low-Carbon Policies (LCPs) and specific assumptions for carbon footprint estimation.

| Parameters | Renovabio[a] | CORSIA | RFS[b] | RED[c] |
|---|---|---|---|---|
| *Geographic Scope* | Brazil | World | United States | Europe |
| *LCA approach* | Attributional | Attributional | Consequential | Attributional |
| *System boundaries* | Well-to-Wheel | Well-to-Wheel | Well-to-Wheel | Well-to-Wheel |
| *Functional unit* | $MJ_{biofuel}$ | $MJ_{biofuel}$ | $mmBTU_{biofuel}$ | $MJ_{biofuel}$ |
| *Fossil reference* | 87.5 $gCO_{2e}/MJ$ (Jet A) | 89.0 $gCO_{2e}/MJ$ (Jet A) | 91.9 $gCO_{2e}/MJ$[d] | 94 $gCO_{2e}/MJ$ |
| *GWP*[e] | AR5 ($CO_2$ / $CH_4$ / $N_2O$) | AR5 ($CO_2$ / $CH_4$ / $N_2O$) | AR2 ($CO_2$ / $CH_4$ / $N_2O$) | AR4 ($CO_2$ / $CH_4$ / $N_2O$) |
| *Co-products* | Energy allocation | Energy allocation | System expansion | Energy allocation, in general. Exergy allocation in CHP. |
| *Land use issues* | Considered as eligibility criteria, but it is not included in GHG calculations. | Default values for iLUC are included in carbon footprint estimation. | Direct and Indirect LUC are treated jointly, basing on economic modeling. | Estimation dLUC amortized by 20 years (baseline in Jan/08). iLUC as eligibility criteria. |
| *Calculation tools* | RenovaCalc | *n.a.* [f] | CENTURY; FASON (LUC inside USA); FAPRI-CARD (LUC abroad); GREET | *n.a.* [f] |

[a] RenovaCalc (ANP, 2020b) was used for Soy/HEFA, UCO/HEFA, Tallow/HEFA, and 1G/2G ethanol production. The carbon emissions for the other pathways were estimated considering the Renovabio methodology and the emission factors of RenovaCalc(ANP, 2018b, 2018a).

[b] Specific life cycle stages were described in (U. S. EPA, 2020): soybean oil production and LUC from "*biodiesel from soybean oil by transesterification*"; palm oil production and LUC from "*biodiesel from palm oil by transesterification*"; UCO rendering from "*biodiesel from yellow grease by transesterification*"; 1G ethanol production and LUC from "*ethanol from sugarcane by fermentation and dehydration in Brazil, trash collection, and marginal displacement of power surplus*"; 2G ethanol from lignocellulosic residues without LUC and other effects from "*ethanol from corn stover by biochemical enzymatic process*". FT-based pathways, refining stage and transportation were modeled in GREET (ANL, 2020).

[c] Emission factors from (Edwards et al., 2019). Here, the emissions from CHP systems were 100% allocated to the main product. LUC from (EMBRAPA, 2018).

[d] Petroleum diesel baseline 2005 (97.0 $gCO_{2e}/mmBTU$).

[e] Global Warming Potential with 100-year time horizon, according to IPCC (IPCC, 2020). AR5: Fifth Assessment Report ($CO_2$:1, $CH_4$: 28, and $N_2O$: 265); AR2: Second Assessment Report ($CO_2$:1, $CH_4$: 21, and $N_2O$: 310); AR4 ($CO_2$:1, $CH_4$: 25, and $N_2O$: 298).

[f] This LCP does not employ a specific assessment tool.

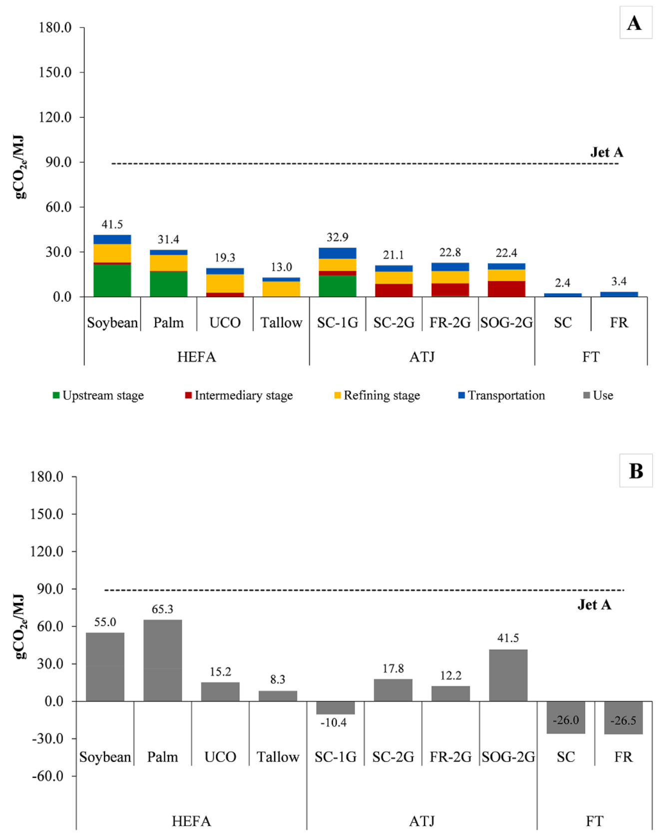



**Fig. 3.** Carbon footprint of AJF using ALCA without LUC (A) and CLCA (B).

burdens in the upstream stage – it ranges between 53% (Soy/HEFA) and 65% (Palm/HEFA and SC-1G/ATJ).

The field emissions in the upstream stage constitute more than 30% of the total carbon footprint of HEFA-based pathways, mostly because of the direct $N_2O$ emissions from the decomposition of the crop residues, *i. e.*, 9.4 $gCO_{2e}$/MJ and 11.8 $gCO_{2e}$/MJ in Soy/HEFA and Palm/HEFA, respectively. The field emissions correspond to 18% of the total carbon footprint for SC-1G/ATJ. Agricultural operations and chemical inputs represent 15% (Palm/HEFA) to 19% (SC-1G/ATJ) of the total results.

Hydrogen use in the refining stage is another critical process for the whole life cycle, resulting in at least 30% and 18% of the total GHG emissions for HEFA and ATJ-based pathways, respectively. The lower hydrogen demand when hydroprocessing palm oil and beef tallow results in a decrease of 2.0 $gCO_{2e}$/MJ compared with Soy/HEFA due to the higher amount of unsaturated fatty acids in soybean oil.

On the other hand, the contribution of the intermediary stage does not exceed 10% of the total values for 1G pathways. It is held by natural gas and used as an energy source in soybean oil production, and the self-supplying energy systems at ethanol distilleries and palm milling plants that process residues like sugarcane bagasse, palm fibers, and biogas from POME.

It is worth mentioning that POME treatment is an important issue for calculating GHG emissions for Palm/HEFA. Assuming that POME is treated in open ponds without gas capturing systems, as is currently done in Brazil (Agropalma, 2017b), the carbon footprint of Palm/HEFA could reach 58.5 $gCO_{2e}$/MJ, which translates to a 35% reduction in GHG in comparison with fossil kerosene.

The potential GHG reduction of 2G pathways ranges from 74% (SG-2G/ATJ, 21.1 $gCO_{2e}$/MJ) to more than 90% for FT-based pathways (2.4 - 3.4 $gCO_{2e}$/MJ). These latter are characterized by a very low dependence on external inputs as well as self-energy supplies.

Likewise, the production of 2G ethanol is a great burden on ATJ-based pathways. While the enzymes and chemical inputs correspond to around 30% of the carbon footprint of AJF produced from sugarcane residues (SC-2G/ATJ) and forestry residues (FR-2G/ATJ), the power demand is responsible for 36% of results of AJF obtained from steel off-gases (SOG-2G/ATJ). As to the latter pathway, the power surplus generation by an optimized steelmaking system, as observed in some Brazilian steel mills (ABM, 2017; ArcellorMittal Tubarão, 2016), could eventually supply an integrated ethanol plant. If this were to happen, the potential carbon footprint of SOG-2G/ATJ would decrease to 14.4 $gCO_{2e}$/MJ, with a potential 84% reduction in GHG in comparison with fossil kerosene.

Alternative Jet Fuels had lower carbon footprints when using the consequential approach (CLCA), as opposed to the ALCA approach. This was mainly because of credits given for displacing power generation based on natural gas and the null effects when residual feedstock is available for AJF production (Fig. 3.**B** and **Table 4**). These aspects can even lead to a negative carbon footprint, as observed in SC-1G/ATJ (-10.4 $gCO_{2e}$/MJ) and FT-based pathways (around -25 $gCO_{2e}$/MJ), which did not result in carbon capture but indicated potential GHG mitigation. Without these credits, the carbon footprint of these pathways would increase to 53.5 and around 2.0 $gCO_{2e}$/MJ, respectively, or to more than 28 gCO2e/MJ for AJF based on 2G-ethanol. In this latter case, the difference between FR-2Gh/ATJ (12.2 $gCO_{2e}$/MJ) and SC-2Gh/ATJ (17.8 $gCO_{2e}$/MJ) is mostly justified since power generation from ethanol production using forestry residue (158 kWh/$t_{db}$) was estimated to be higher than that from sugarcane residue (128 kWh/$t_{db}$). The avoided emissions reductions coming from recovering forestry residues also influenced these results.

By contrast, the high estimated value for SOG-2G/ATJ (41.5 $gCO_{2e}$/MJ), which results in 50% of GHG reduction in comparison with fossil kerosene, is caused by high power demand in the intermediary stage.

**Table 3**
Carbon footprint of AJF using the attributional approach (ALCA), without LUC.

| Life cycle stages | HEFA Soy | Palm | UCO | Tallow | ATJ SC1G | SC2G | FR2G | SOG2G | FT SC | FR |
|---|---|---|---|---|---|---|---|---|---|---|
| **Upstream** | **21.6** | **16.8** | **0.0** | **0.0** | **14.2** | **0.0** | **0.4** | **0.0** | **0.0** | **0.3** |
| Inputs | 6.4 | 4.0 | | | 3.0 | | 0.0 | | | 0.0 |
| Energy | 1.6 | 1.0 | | | 3.5 | | 0.4 | | | 0.3 |
| Field emissions | 13.6 | 11.8 | | | 7.6 | | 0.0 | | | 0.0 |
| **Intermediary** | **1.5** | **0.4** | **2.8** | **0.0** | **3.2** | **8.7** | **8.6** | **10.6** | **0.0** | **0.0** |
| Inputs | 0.2 | 0.0 | 0.0 | | 0.5 | 6.9 | 6.9 | 2.6 | | |
| Energy | 1.3 | 0.4 | 2.8 | | 2.7 | 1.8 | 1.7 | 8.0 | | |
| Other emissions | 0.0 | 0.0 | 0.0 | | 0.0 | 0.0 | 0.0 | 0.0 | | |
| **Refining** | **12.3** | **10.8** | **12.3** | **10.3** | **8.2** | **8.2** | **8.2** | **7.7** | **0.0** | **0.0** |
| Inputs | 12.1 | 10.7 | 12.1 | 10.2 | 6.0 | 6.0 | 6.0 | 6.0 | 0.0 | 0.0 |
| Energy | 0.2 | 0.2 | 0.2 | 0.2 | 2.1 | 2.1 | 2.1 | 1.7 | 0.0 | 0.0 |
| **Transportation** | **6.0** | **3.2** | **4.1** | **2.5** | **7.2** | **4.0** | **5.4** | **4.0** | **2.2** | **2.9** |
| **Use** | **0.2** | **0.2** | **0.2** | **0.2** | **0.2** | **0.2** | **0.2** | **0.0** | **0.2** | **0.2** |
| **TOTAL** | **41.5** | **31.4** | **19.3** | **13.0** | **32.9** | **21.1** | **22.8** | **22.4** | **2.4** | **3.4** |

**Table 4**
Carbon footprint of AJF using the consequential approach (CLCA).

| Life cycle stages | HEFA Soy | Palm | UCO | Tallow | ATJ SC1G | SC2G | FR2G | SOG2G | FT SC | FR |
|---|---|---|---|---|---|---|---|---|---|---|
| **Upstream** | **82.3** | **59.3** | **0.0** | **0.0** | **28.8** | **0.0** | **-2.4** | **-418.0** | **0.0** | **-1.5** |
| Affected supplier | 0.0 | 0.0 | | | 0.0 | | -2.9 | -418.0 | | -1.9 |
| LUC | 27.0 | 39.1 | | | 8.7 | | 0.0 | | | 0.0 |
| Inputs | 6.8 | 3.4 | | | 4.1 | | 0.0 | | | 0.0 |
| Energy | 10.3 | 2.0 | | | 5.1 | | 0.5 | | | 0.4 |
| Other emissions | 38.2 | 14.8 | | | 10.9 | | 0.0 | | | 0.0 |
| **Intermediary** | **-47.6** | **-3.3** | **3.1** | **0.0** | **-59.4** | **2.1** | **-2.8** | **331.4** | **0.0** | **0.0** |
| Co-prod. credits | -53.6 | -3.7 | 0.0 | | -64.0 | -11.1 | -15.9 | 0.0 | | |
| Inputs | 0.4 | 0.5 | 0.0 | | 0.7 | 11.2 | 11.2 | 14.5 | | |
| Energy | 5.6 | 0.0 | 3.1 | | 3.8 | 2.0 | 1.9 | 28.7 | | |
| Other emissions | 0.0 | 0.0 | 0.0 | | 0.0 | 0.0 | 0.0 | 288.1 | | |
| **Refining** | **7.6** | **5.3** | **7.6** | **5.5** | **11.3** | **11.3** | **11.3** | **34.8** | **-28.4** | **-28.3** |
| Co-prod. credits | -4.6 | -5.5 | -4.6 | -4.8 | 0.0 | 0.0 | 0.0 | 0.0 | -28.4 | -28.3 |
| Inputs | 12.0 | 10.7 | 12.0 | 10.1 | 5.9 | 5.9 | 5.9 | 5.9 | 0.0 | 0.0 |
| Energy | 0.2 | 0.2 | 0.2 | 0.2 | 5.4 | 5.4 | 5.4 | 28.9 | 0.0 | 0.0 |
| **Transportation** | **12.4** | **3.7** | **4.3** | **2.6** | **8.7** | **4.3** | **5.8** | **4.3** | **2.2** | **3.0** |
| **Use** | **0.2** | **0.2** | **0.2** | **0.2** | **0.2** | **0.2** | **0.2** | **89.0** | **0.2** | **0.2** |
| **TOTAL** | **55.0** | **65.3** | **15.2** | **8.3** | **-10.4** | **17.8** | **12.2** | **41.5** | **-26.0** | **-26.7** |

Carbon will eventually be released into the atmosphere for all life cycles, either by processing gases or in fuel combustion, so there is no net benefit associated with redirecting steel off-gases from being released into the atmosphere.

The carbon footprint of Soy/HEFA (53.2 $gCO_{2e}/MJ$) and Palm/HEFA (65.3 $gCO_{2e}/MJ$) led to the lowest potential GHG reduction – *i.e.*, 27% and 40%, respectively – with relevant effects on LUC values. The credits related to large soybean meal production (-53 $gCO_{2e}/MJ$) decisively influenced performance, specifically for Soy/HEFA.

### *3.2. LUC effects on 1G pathways*

When emissions related to dLUC are accounted for in Soy/HEFA using the attributional approach (ALCA), there were no GHG reductions (see **Fig. 4**). The highest carbon footprints are expected when areas with native vegetation are converted into croplands, as also observed in Palm/HEFA and SC-1G/ATJ. However, even when considering emissions from pasturelands converted into soybean plantations, the carbon footprint of the Soy/HEFA is still higher than fossil kerosene. Emissions increase slightly, or even decrease substantially, if pasturelands are converted into sugarcane or palm plantations, respectively.

Using the consequential approach (CLCA), the LUC effects suggested by ICAO (2019a) led to major positive emissions in Soy/HEFA and Palm/HEFA (see **Table 4**). It is worth pointing out that the LUC factor taken for Palm/HEFA was suggested for palm crops in Malaysia (ICAO, 2019a) due to a lack of specific data for Brazil.

The carbon footprint of SC-1G/ATJ using the CLCA approach (-10.4 $gCO_{2e}/MJ$) – which encompasses the default LUC values suggested by CORSIA for sugarcane expansion in Brazil, *i.e.* 8.7 $gCO_{2e}/MJ$, or 7.8 $kgCO_{2e}/t$ of sugarcane taking the conversion yields considered here – would increase considerably if the effects related to LUC were captured using different models. For instance, the values would reach to 1.4 $gCO_{2e}/MJ$ according to Moreira et al (2014), who estimated 28.5 $kgCO_{2e}/t$ of sugarcane expansion in Brazil, or to 24.3 $gCO_{2e}/MJ$ according to van der Hilst et al (2018), who estimated 56.3 $kgCO_{2e}/t$ of sugarcane. See **Tab. SM.18** for the modeling details.

### *3.3. Comparison with other studies in literature*

The attributional approach has been used in most studies on the

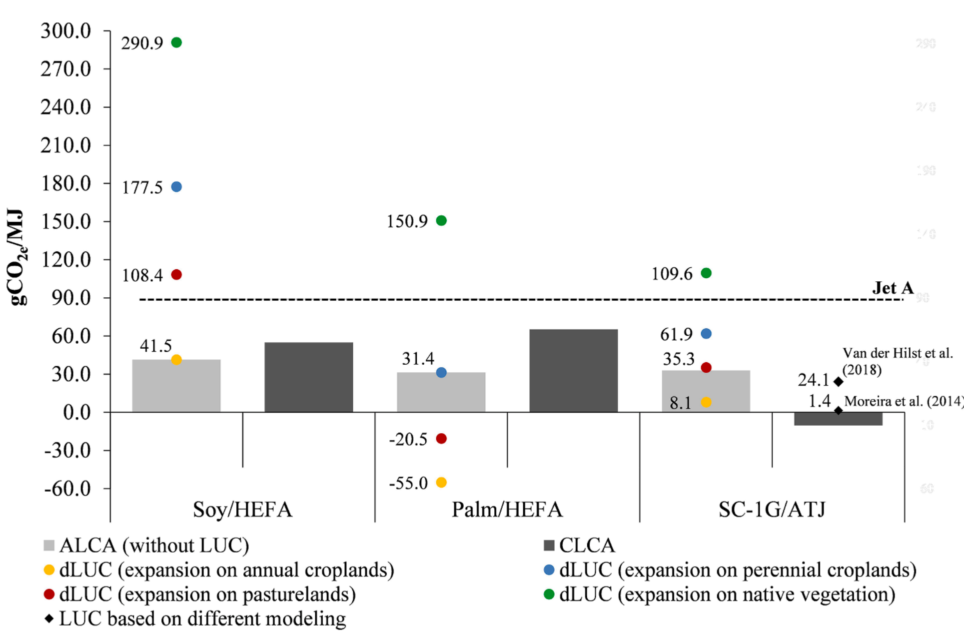



**Fig. 4.** Carbon footprint of AJF considering different LUC factors.

carbon footprint of AJF. For Soy/HEFA, the results estimated here (41.5 $gCO_{2e}/MJ$) are close to what was reported by Vásquez et al. (2019) (40.1 $gCO_{2e}/MJ$) for Brazil, or by Han et al. (2013) (39.0 $gCO_{2e}/MJ$) for soybeans produced in the United States.

On the other hand, the lower results reported by Klein et al. (2018) – 22.0 $gCO_{2e}/MJ$ for Soy/HEFA and 17.0 $gCO_{2e}/MJ$ for Palm/HEFA – are mostly explained by the design of the AJF conversion processes, which were integrated into ethanol distilleries with on-site hydrogen coming from water electrolysis. The power demand would be supplied by the power surplus generated at the ethanol distilleries.

Likewise, while Han et al. (2013) reported similar values for Palm/HEFA (34.0 $gCO_{2e}/MJ$) for Malaysia, Vásquez et al. (2019) estimated lower values for Palm/HEFA in Brazil (14.2 $gCO_{2e}/MJ$). The main differences arise at the agricultural stage, especially for $N_2O$ emission, and with the utility demands and yields calculated for the AJF conversion process,

The carbon footprint of UCO/HEFA is similar to what was reported by Seber et al. (2014). On the other hand, the same authors estimated higher values for Tallow/HEFA (29.8 $gCO_{2e}/MJ$) since they treated the rendering process separately from the slaughterhouse process, with higher energy consumption rates from natural gas.

Furthermore, Klein et al. (2018) reported lower values (20.5 $gCO_{2e}/MJ$) for SC-1G/ATJ, for the same reasons mentioned previously. Similarly, de Jong et al. (2017) estimated 26 $gCO_{2e}/MJ$ since the inventories adopted by these authors were mostly based on GREET (ANL, 2020).

Cavalett and Cherubini (2018) reported higher values for FR-2G/ATJ (28.4 $gCO_{2e}/MJ$) and FR/FT (6.8 $gCO_{2e}/MJ$) for residue-based pathways in Norway. Differences in the description of transportation distances and operations (*e.g.*, harvesting, chipping, and processing) might explain the differences between the studies. de Jong et al. (2017) reported 6.0 $gCO_{2e}/MJ$ for FR/FT, calculating for longer transportation distances and lower AJF yields than what were estimated here.

The consequential aspects addressed by some studies are generally limited to how co-products are handled. de Jong et al. (2017) reported a lower value for SC-1G/ATJ (22 $gCO_{2e}/MJ$) and FR/FT (-3.0 $gCO_{2e}/MJ$)

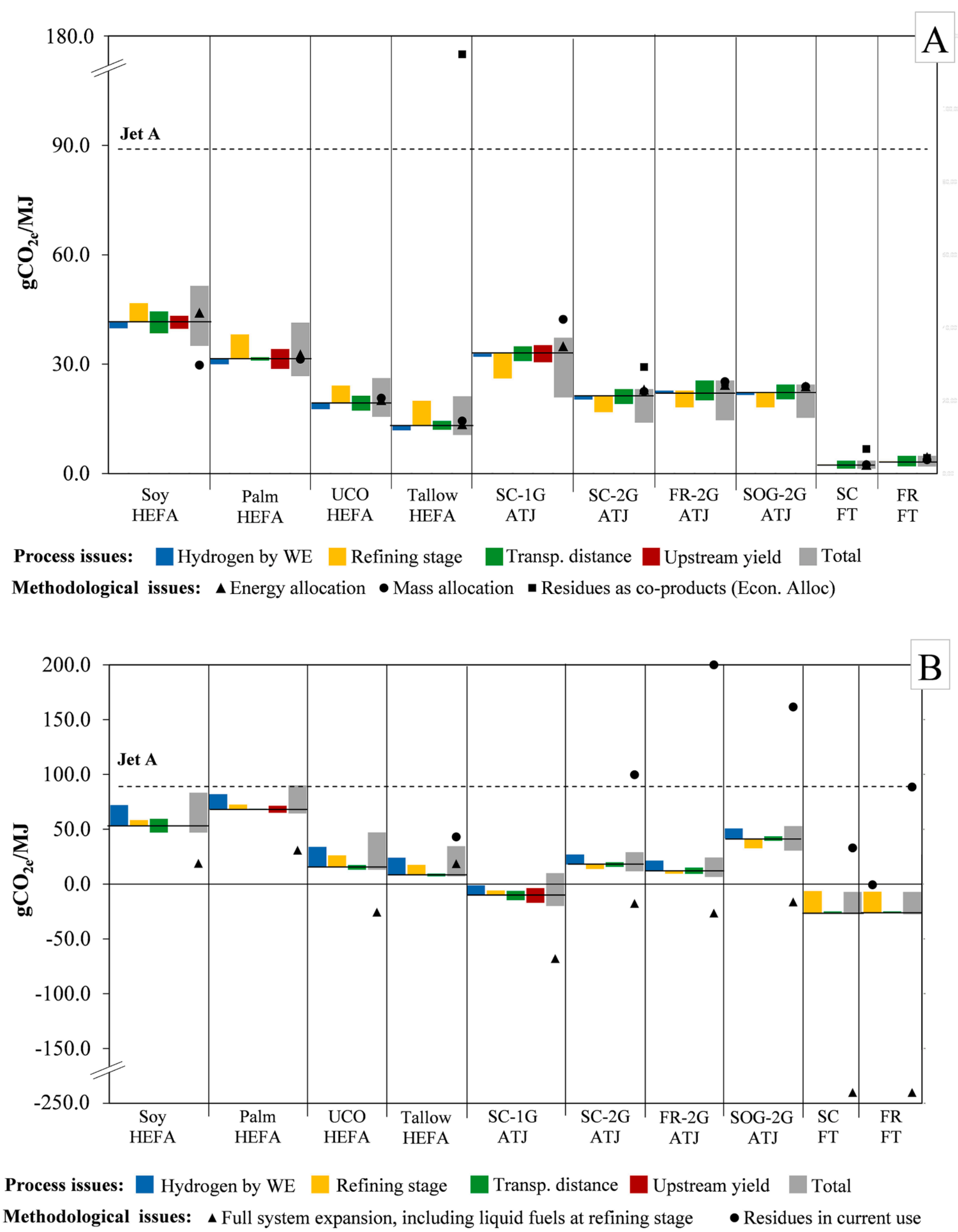



**Fig. 5.** Sensitivity analysis for the carbon footprint of AJF, according to the reference case (see the black line for each pathway). **A**: attributional approach (ALCA); **B**: consequential approach (CLCA). WE: Water electrolysis. Total: cumulative variations related to process issues.

when credits related to power surplus are accounted for. Cox et al. (2014) analyzed the carbon footprint of AJF from sugarcane molasses (8.0 $gCO_{2e}$/MJ), including the effects related to sorghum grain marginal demand and the displacement of fossil fuels by using alternative fuels co-produced with AJF.

### 3.4. Sensitivity analysis

The sensitivity of the carbon footprint to process and methodological issues are presented in **Fig. 5**. The black line for each pathway represents the reference case – *i.e.*, the carbon footprint estimated for each pathway – while bars and points represent the carbon footprint according to different processes issues and methodological choices, respectively.

Results of ALCA are more sensitive to methodological issues than process parameters (**Fig. 5.A**). The carbon footprint of Soy/HEFA decreases by 28% (29.7 $gCO_{2e}$/MJ) when considering mass allocation, due to the large production of soy meal. GHG emissions for this same pathway can range from -16% to +24% (35.0 - 51.5 $gCO_{2e}$/MJ), considering the cumulative variations in the upstream yield, transportation distances, hydrogen supply, and refining stage. Otherwise, the carbon footprint for SC-1G/ATJ increases by 29% (42.4 $gCO_{2e}$/MJ), assuming mass allocation. By comparison, the cumulative variations according to process-related issues can change the total values from -39% to +13%, which is the largest range among all pathways.

The potential GHG emissions from 2G pathways show considerable sensitivity to how residual feedstocks are handled, *e.g.*, used as co-products instead of waste. The carbon footprint of Tallow/HEFA can reach 169.5 $gCO_{2e}$/MJ, even when burdened with a small share of GHG emissions from livestock. Likewise, the results for sugarcane-based pathways can increase by 34% (SC-2G/ATJ, 29.2 $gCO_{2e}$/MJ) or 2-fold (SC/FT, 6.7 $gCO_{2e}$/MJ), while forestry-based pathways vary up to 25%. These ranges can be explained by higher GHG emissions coming from sugarcane production relative to forest crop production and the different system boundaries.

The design for the refining stage can lead to high variations in the results. The total values for HEFA-based pathways can increase by 13% (Soy/HEFA, 46.7 $gCO_{2e}$/MJ) to 51% (Tallow/HEFA, 20.0 $gCO_{2e}$/MJ), since the refining design proposed by ANL (2020) considers an external demand for natural gas and electricity from the grid instead of the internal use of light streams, as assumed here. Otherwise, the potential GHG reduction for all ATJ-based pathways decreases by 25%, due to the higher AJF yield given by ANL (2020). Variations in the results do not exceed 10% when hydrogen is produced using water electrolysis.

Similarly, the total values from CLCA approach (**Fig 3.4.B**) are substantially more sensitive to methodological issues.

The carbon footprint of Soy/HEFA and Palm/HEFA decreases by 65% and 55%, respectively, when considering full system expansion for all co-products, which includes credits related to liquid fuels at the refining stage. It can also lead to potential GHG mitigation for UCO/HEFA (-25.6 $gCO_{2e}$/MJ), SC-2G/ATJ (-17.6 $gCO_{2e}$/MJ), and FR-2G/ATJ (-26.4 $gCO_{2e}$/MJ). However, as observed in Huo et al. (2009) and Wang et al. (2011), the total values are sharply distorted in FT-based pathways (around -245 $gCO_{2e}$/MJ) since AJF corresponds to a small share of all final products.

In turn, if residual feedstock is redirected in any way from its current use, the carbon footprint of 2G pathways can overtake fossil kerosene, reaching 100 $gCO_{2e}$/MJ (SC-2G/ATJ) or roughly 160 $gCO_{2e}$/MJ (SOG-2G/ATJ) and 200 $gCO_{2e}$/MJ (FR-2G/ATJ). Likewise, SC/FT and FR/FT could potentially reduce GHG emissions by around 60% and 1%, respectively.

These effects may eventually provide a broader evaluation of the performance of residues-based pathways, as discussed in Hanssen and Huijbregts (2019), since some residual feedstocks are not always available. For instance, beef tallow – obtained from 30 million slaughtered cattle head (IBGE, 2019b) – has been mostly used by biodiesel industry, contributing to about 18% of Brazilian biodiesel production (ANP, 2020a). The remaining amount is destined for the cleaning industry (ABRA, 2019). Likewise, sugarcane bagasse is commonly used to supply the internal demand for ethanol and surplus power generation, corresponding to roughly 6% of all power generated in Brazil (EPE, 2020). In turn, around 60% of steel off-gases generated in Brazil have been recovered for supplying internal energy demands (ABM, 2017).

Regarding process-related parameters, the CLCA results are more sensitive to the hydrogen supply since the power demand for electrolysis would be supplied by a process based mostly on fossil fuels.

### 3.5. Carbon footprint of AJF according to regulatory schemes

In general, the carbon footprint of 2G pathways is lower than 1G pathways for all regulatory schemes (**Fig. 6**). While the 2G pathways range from -26 to +23 $gCO_{2e}$/MJ, mainly by disregarding the upstream stage, 1G pathways range from 13.8 to 98.7 $gCO_{2e}$/MJ, also due to the specificities at the agricultural stage and LUC effects. AJF produced from lignocellulosic residues could mitigate GHG emissions, as was reported by RFS, mainly in function of credits related to power surpluses. Furthermore, FT-based pathways, as also observed in ALCA and CLCA (**Section 3.1**), resulted in the greatest GHG reductions. The default life cycle emissions suggested by ICAO (2019a) are similar to what was estimated in this study for oil-based pathways, except for Tallow/HEFA, and SC-1G/ATJ. The results for each AJF pathway under each regulatory scheme are presented in **Tab. SM.19**. The main differences among the results are discussed as follows.

The *Renovabio* scheme had the lowest values of all the regulatory schemes based on the attributional approach (*Renovabio*, CORSIA, and RED), except for the 2G/ATJ and FT-based-pathways. Furthermore, it is worth mentioning that 2G pathways via ethanol in *RenovaBio* scheme (19-20 $gCO_{2e}$/MJ) has performed closer to 1G pathways (24-27 $gCO_{2e}$/MJ) than what was observed under other approaches. Regardless of the LUC effects – which are not accounted for in this regulatory scheme, but rather qualitatively considered as constraining eligible pathways (ANP, 2018c, 2018a) – the background data mostly justify these discrepancies, especially when compared to CORSIA.

Considering the relevant contribution of hydrogen input to the total values, as mentioned in Section 3.1, the emission factor related to the hydrogen production leads to differences between the results. For CORSIA scheme, it was assumed 10.8 $kgCO_{2e}/kgH_2$ (Spath and Mann, 2001), while the RenovaCalc tool assumes 2.38 $kgCO_{2e}/kgH_2$ for *Renovabio* and the Edwards et al. (2019) suggested 1.64 $kgCO_{2e}/kgH_2$ for the RED scheme. The different emissions factors for lignocellulosic material used as an energy source in ethanol production – *i.e.*, 6.2 to 26 $gCO_{2e}/kg_{(db)}$ for *Renovabio* and CORSIA, respectively – also justify some of the discrepancies observed for ATJ-based pathways between both schemes.

As presented in Section 3.1, direct field emissions can represent a relevant share of the total emissions. GHG calculation methods for direct field emissions are a bit different among regulatory schemes. Although *Renovabio* and CORSIA are both based on IPCC (2006a), they assume different nitrogen contents coming from crop residues for Soy/HEFA, which results in emissions from 0.94 and 2.07 $kgN_2O$/ha, respectively. On the other hand, all 1G pathways had lower values for direct field emissions in the RED scheme, since they were estimated using the Global Nitrogen Oxides Calculator (GNOC) (JRC, 2020). The main differences arise from direct emissions coming from mineral fertilizer. While IPCC (2006a) considers a fixed nitrogen input factor (1%) emitted as $N_2O$, this amount is estimated by GNOC by considering the environmental conditions of the producer region and the net emissions of a fertilized plot relative to an unfertilized one. The field emissions used in the RED scheme were 1.78, 3.57, and 1.75 $kgN_2O$/ha for Soy/HEFA, Palm/HEFA, and SC-1G/ATJ, respectively.

Foreground data and system boundaries also explain some differences between the results. The HEFA process considered in RFS was based on ANL (2020), which considered external energy supply. On the

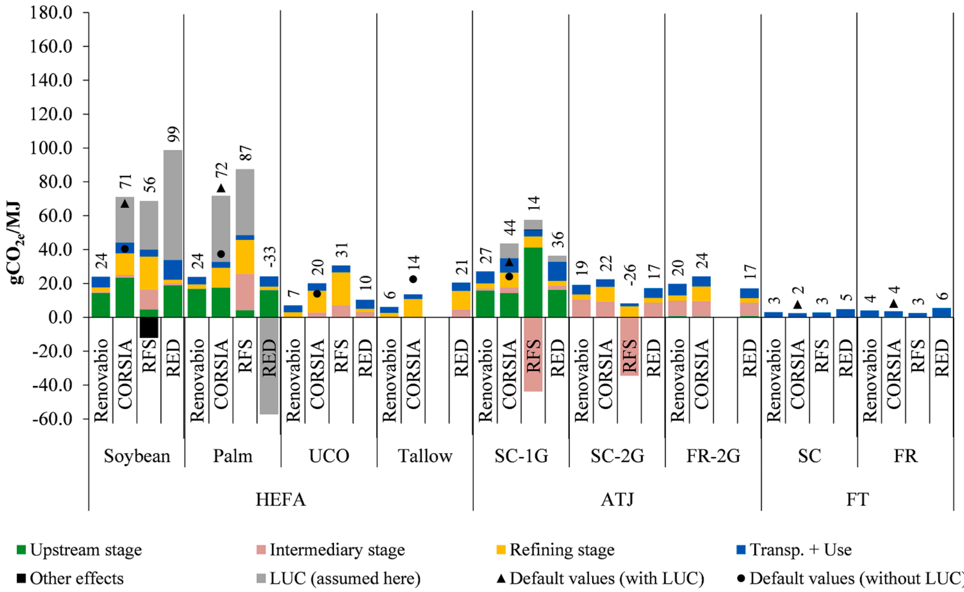



**Fig. 6.** Carbon footprint of AJF for different regulatory schemes.

other hand, *Renovabio* and CORSIA were based on Klein et al. (2018), who considered self-supply of energy using light streams obtained from the hydroprocessing. In turn, a relevant demand for natural gas in the beef tallow rendering process, which was not integrated to the slaughterhouse, leads to higher GHG emissions in the RED scheme. Finally, emission related to the transportation of AJF to the United States (1.8 $gCO_{2e}$/MJ) and Europe (3.7 $gCO_{2e}$/MJ) – which was considered in RFS and RED, respectively – corresponds to less than 15% of the total values in 1G pathways, or 20% to 70% in 2G pathways.

Credits related to co-products – especially from marginal power displacement – were accounted for only in the RFS scheme, which is based on a consequential LCA. These contributed to the low or even negative emissions values for ethanol-based pathways (see SC-1G/ATJ and SC-2G/ATJ, respectively).

Despite the differences related to background system, system boundaries, and co-products handling methods, LUC emissions are a relevant aspect between the regulatory schemes, especially for oil-based feedstocks.

The LUC emissions reported by RFS – which comprise direct and indirect effects inside and outside of the United States – correspond to around 40% of the carbon emissions in oil-based pathways – *i.e.*, 28.8 $gCO_{2e}$/MJ (Soy/HEFA) and 38.9 $gCO_{2e}$/MJ (Palm/HEFA) – and roughly 9% of the carbon emissions in SC-1G/ATJ (5.6 $gCO_{2e}$/MJ).

It is worth mentioning that only LUC emissions for SC-1G/ATJ in RFS are estimated considering sugarcane production in Brazil according to the available data in the current RFS summary (U. S. EPA, 2020). This value is close to the default LUC value reported by CORSIA (8.7 $gCO_{2e}$/MJ), which also encompasses direct and indirect effects, corresponding to 20% of the carbon footprint in SC-1G/ATJ in that case. For oilseed-based pathways, the default LUC value from the CORSIA scheme represents 40% and 54% of the carbon footprint of Soy/HEFA in Brazil and Palm/HEFA, respectively.

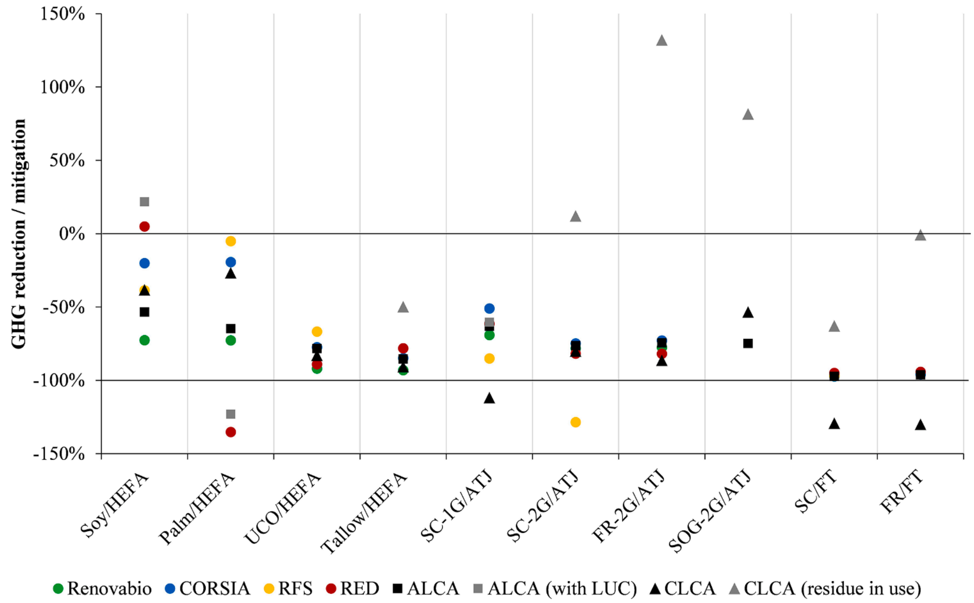
AJFs from Palm/HEFA and Soy/HEFA could be strategic options under CORSIA if they are obtained from low-risk areas for land use changes. In this case, iLUC emissions would be assumed to be zero (ICAO, 2019b), and their performance on GHG reductions could substantially increase to 50% and 63%, respectively. Low-risk areas for land use changes are possible when the feedstock is produced with management practices that provide increases in the agricultural yield, without land expansion, or from unused lands with little risk for displacement of other services, such as food, feed, and bioenergy (ICAO, 2019b).

For palm expansion, Ramalho Filho and Motta (2010) estimated that 29.6 Mha of deforested areas in the Amazon region would be suitable for palm expansion through tillage with modest technological levels. This value is close to the global palm harvest area in 2018 (FAO, 2018), which indicates a considerable potential for Brazilian palm expansion, as was also shown by some authors (Branford and Torres, 2018; Pirker et al., 2016). Soybean could eventually fit the low-risks iLUC requirements by CORSIA adopting management practices such as sequential cropping, which has already become a common practice in Brazil with maize, cotton, and millet (Waha et al., 2020). On the other hand, no gains in soybean yield have been observed through intercropping practices (Batista et al., 2019; Xu et al., 2020), and other authors have reported decreasing in agricultural productivity related to soybean-forestry systems (Balbinot Junior et al., 2018; Werner et al., 2017). The dLUC emissions, which are accounted for in the RED scheme, lead to extreme values for carbon footprint (-33 $gCO_{2e}$/MJ to +99 $gCO_{2e}$/MJ), when oilseed-based crops are assumed to expand on pasturelands. The dLUC values correspond to around 70% of the carbon footprint for Soy/HEFA, while they lead to negative emissions for Palm/HEFA.

According to the BRLUC model (EMBRAPA, 2018), around 40% of all soybean and palm plantations in Brazil have expanded onto native vegetation over the last 20-years, while roughly 83% of all sugarcane plantations have expanded onto pasture and arable lands, leading to lower GHG emissions.

Motivated by the relevant concerns about soybean expansion into the Amazon forest, the Brazilian Soy Moratorium – an agreement between soybean producers – has effectively helped reduce Amazon deforestation by soybean expansion, pushing up soybean expansion onto pasture lands (ABIOVE, 2020b). Even in that case, Soy/HEFA would present higher emission than fossil fuel according to RED scheme (see **Fig. 7**).

The current version of the European Directive has limited food/feed-based biofuels and proposed decreasing limits for high-iLUC risks biofuels. According to REDII (European Union, 2019), high-iLUC risk biofuels are obtained from feedstocks with significant expansion into high-carbon lands (European Union, 2018). This new approach has blocked palm oil imports from Malaysia or Indonesia, where expansion from the last years was mostly into forest lands and peatlands (European Commission, 2019). On the other hand, low iLUC risk biofuels – *i.e.*, obtained from residual feedstocks or obtained from abandoned or severely degraded lands or smallholders – will play an important role in




**Fi. 7.** GHG reduction/mitigation provided by AJF in comparison with its fossil counterparts, whose emission factor were considered as 87.5 $gCO_{2e}$/MJ for *Renovabio*; 89.0 $gCO_{2e}$/MJ for CORSIA, ALCA, and CLCA; 91.0 $gCO_{2e}$/MJ for RFS; and 94.0 $gCO_{2e}$/MJ for RED. “ALCA (with LUC)” and “RED” are based on crop expansion on pasturelands. “CLCA (residues in use)” also comprises the consequences of redirecting the residues from their current use for AJF production.

Europe. At first glance, the Brazilian palm obtained from degraded Amazon areas could fit the RED requirements for low-iLUC risk fuel. This possibility is not clear for sugarcane, and especially for soybean.

## 4. Conclusion

The carbon footprint of ten AJF pathways was estimated considering attributional (ALCA) and consequential (CLCA) approaches. Regulatory schemes based on current Low-Carbon Policies (LCP’s) were also assumed, such as *Renovabio* (Brazil), CORSIA (international aviation sector), RFS (Unites States), and RED (Europe). The pathways comprised strategic feedstocks, such as palm, waste grease, lignocellulosic residues, and steel off-gases, as well as crops with relevant production in Brazil, such as soybean and sugarcane.

In general, Soy/HEFA tends to provide the lowest GHG reduction when compared to their fossil-fuel counterparts, according to the methodological approaches evaluated in this study (see Fig. 7). Among the 1G pathways, the SC-1G/ATJ is the best alternative for most approaches, mainly when the surplus power is credited.

Direct LUC emissions impact 1G pathways where Soy/HEFA had the highest carbon footprint, corresponding to an increase by 5% (for RED scheme) to 20% (for ALCA) in GHG emissions when compared with fossil fuels. On the other hand, expanding palm plantations onto new areas with degraded pastureland would result in a -123% to -135% reduction in GHG emissions for Palm/HEFA.

LUC effects, including indirect ones, are also more relevant in oilseed-based pathways. They represent roughly 40% of the carbon footprint of Soy/HEFA (71.1 $gCO_{2e}$/MJ) under CORSIA scheme, while it corresponds to 20% of the total emissions of SC-1G/ATJ (43.8 $gCO_{2e}$/MJ).

Potential GHG reductions for 2G pathways tend to be higher than 1G pathways, and their results are more convergent since the burden of the upstream stage is commonly disregarded for residue-based pathways and residues are typically assumed free. Thus, the potential of FT-based pathways surpasses 95%, while the potential of pathways based on 2G ethanol from lignocellulosic residues, waste greases, and steel off-gases ranges from 75-130%, 78-93%, and 50-74%, respectively.

Conflicts arise when consequential aspects are accounted for, such as marginal power displacement and the possible effects related to residual feedstocks that are not freely available. Surplus power generation, especially in ethanol production and FT processes, can even lead to mitigating GHG (see SC-2G/ATJ and SC/FT in the RFS scheme, with potential mitigation of -100% to -130%). Likewise, in the CLCA approach, SC-1G/ATJ, SC/FT, and FR/FT had resulted in a -110% potential. On the other hand, the effects related to possible competition between current and alternative residual feedstock uses were addressed only by the CLCA approach, and it could provide higher emissions than fossil kerosene by up to 13%, 91%, and 115% for SC-2G/ATJ, SOG-2G/ATJ, and FR-2G/ATJ, respectively. These effects should eventually be addressed in regulatory systems to provide a broader evaluation of pathway performance since some residual feedstocks are not always available. Moreover, it is supposed that the investment in options where the residues are in current economic use would already be less attractive.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2020.105260.

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