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Alternative aviation fuels in Brazil
Environmental performance and economic feasibility

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Alternative aviation fuels in Brazil: environmental performance and economic feasibility

Dissertation

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by

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General content

Abbreviations

1G: first-generation;
2G: second-generation;
2Gh: second-generation ethanol from enzymatic hydrolysis;
2Gs: second-generation ethanol from syngas fermentation;
ACR: American Carbon Registry;
AJF: Alternative Jet Fuel;
ALCA: Attributional Life Cycle Assessment;
ATJ: Alcohol-to-Jet;
BC: Biochemical Conversion;
BOF: Basic Oxygen Furnace;
CAPEX: Capital Expenditures;
CAR: Climate Action Reserve;
CDM: Clean Development Mechanism;
CH: Catalytic Hydrothermolysis of oil-based feedstocks;
CHP: Combined Heat and Power;
CLCA: Consequential Life Cycle Assessment;
CORSIA: Carbon Offsetting and Reduction Scheme for International Aviation;
DCSH: direct conversion of sugar to hydrocarbons;
dLUC: Direct Land Use Change;
EFB: Empty Fruit Bunches;
FFB: Fresh Fruit Bunches;
FR: Forestry residues;
FT: Fischer-Tropsch;
GHG: Greenhouse gases;
GS: The Gold Standard;
HDCJ: Hydrotreated Depolymerized Cellulosic to Jet;
HEFA: Hydroprocessed Fatty Acids;
ICAO: International Civil Aviation Organization;
iLUC: Indirect Land Use Change;
INDC: intended nationally-determined climate;
IRR: Internal Return Rate;
LCA: Life Cycle Assessment;
LCM: Lignocellulosic material;
LNBR: Brazilian Biorenewable National Laboratory;
LUC: Land Use Change;
MARR: Minimum Attractive Rate of Return;
MSP: Minimum Selling Price;
MSW: Municipal solid wastes;
OPEX: Operational Expenditures;
POME: Palm Mill Oil Effluent;

RED: Renewable Energy Directive;
RFS: Renewable Fuel Standard;
RJF: Renewable Jet Fuels;
RPK: Revenue Passenger-Kilometer;
RTK: Revenue Tonne Kilometer;
SC: Sugarcane;
SMR: Steam Methane Reform;
SOG: Steel off-gases;
UCO: Used Cooking Oil;
VCS: Verified Carbon Standard;
VSB: Virtual Biorefinery Sugarcane;
WE: Water electrolysis;
WO: Wood residues.

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Summary

The aviation sector is responsible for only 3% of the anthropogenic carbon emissions in the world. However, this transport mode – which demands 3-fold more energy *per capita* than other collective modes, such as railway and bus transportation – is exclusively supplied by fossil fuels, and it has grown at an impressive rate of 7.5% per year in the last decade in the world. In line with the global aims to reduce Greenhouse Gases (GHG) emissions and the dependency on fossil fuels, the *decarbonization* of the aviation sector – which is typically based on cost-intensive projects with rigorous quality control – is a challenge.

Since the Paris Agreement did not address international flights – which are responsible for around 60% of the sector's operations – this gap should be fulfilled by international agency initiatives. Then, in 2010, the International Civil Aviation Organization (ICAO) set ambitious targets for reducing GHG emissions for international flights. Since 2016, the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) has managed these goals advocating for improvements in aircraft operation, carbon credits purchasing, and using alternative jet fuels (AJFs) by airlines. The current CORSIA scheme comprises of three subsequent phases from voluntary to mandatory commitments of the States.

Initiatives for expanding the use of biofuels "from the road to the sky" have popped-up in several places. Since 2011, more than 250 thousand commercial flights already operated with AJFs, six airports worldwide have already regularly supplied AJF, and a relevant scientific background has been built to support these related themes.

Even though, the sustainable energy transition of the highly competitive aviation sector should be tackled from a broader perspective, *i.e.*, combining environmental and socio-economic issues beyond GHG reductions and different assessment methods.

Although Brazil corresponds to a tiny share of 2% of global aviation operations, its huge biomass potential and recognized expertise in bioenergy production could place Brazil as a strategic global supplier of AJF in the future, as already pointed out by some studies.

This thesis contributed to fill knowledge gaps identified in this context, being motivated by the following questions: i) *Could AJF produced in Brazil reduce the GHG emissions in comparison with fossil fuel?* ii) *How much would cost the carbon mitigated by*

each AJF pathway?, and iii) *Could AJF bring other environmental benefits beyond the possible reduction of GHG emissions?*

From a recent Roadmap for aviation biofuels in Brazil – which was carried out by industry and academia experts – ten to fourteen promising and strategic pathways for AJF production were selected and evaluated in this thesis, comprising residues-based pathways and food crop-based pathways.

For food crop-based pathways (or first-generation, 1G pathways), hydrotreating of soybean and palm oil was considered, as well as the "alcohol-to-jet" process of ethanol from sugarcane. Of the residues-based pathways (or second-generation, 2G pathways), the hydrotreating of used cooking oil (UCO) and beef tallow was evaluated. Likewise, the "alcohol-to-jet" process of ethanol obtained from sugarcane residues, forestry residues, and steel off-gases was also considered, as well as the Fischer-Tropsch of sugarcane and forestry residues. The hydrothermal liquefaction of lignocellulosic residues was evaluated as a specific case since this technology is not approved for the aviation industry yet, and it does not reach the commercial scale. The overview of these pathways with the motivations and research gaps addressed in this thesis is presented in **Chapter 1**.

According to the ICAO goals, the potential GHG reduction of AJF in comparison to fossil kerosene is a crucial indicator for the decision-making process, and it is commonly estimated using Life Cycle Assessment (LCA). However, although this issue has been largely explored in literature, it is recognized its high sensitivity with respect to the methodological aspects. Then, to have a clearer and more comprehensive understanding of how AJF may help reduce GHG emissions, the carbon footprint of ten AJF pathways was estimated in **Chapter 2** through six methodological approaches: attributional LCA, consequential LCA, and four regulatory schemes: the *Renovabio* in Brazil, CORSIA for international aviation, the Renewable Fuel Standard (RFS) in the United States and the Renewable Energy Directive (RED) in Europe. Regarding the regulatory schemes, this thesis explored how AJF produced in Brazil would be evaluated according to these Low-Carbon Policy guidelines, given the potential of Brazil to supply these markets.

The main results showed that soybean-based pathway had low to no potential for reducing GHG when compared to their fossil counterparts, mainly due to the land use change effects. Among all the 1G pathways, AJF produced from sugarcane performed the best, especially when power surplus was credited. AJF from palm oil could present significant

GHG reductions for palm expansion in degraded pasturelands. In general, 2G pathways could provide higher GHG reduction, in a narrower range of values, than 1G pathways. Fischer-Tropsch from lignocellulosic residues showed the highest potential. Nonetheless, when the consequences in diverting residual feedstocks from their current use to produce AJF pathways are captured, it could lead to GHG emissions greater than those of fossil fuels.

On the other hand, even though AJFs have the potential for reducing GHG, the production costs are, in general, still far from being competitive with fossil kerosene. Furthermore, the pathway with the lowest production cost is not always the one that provides the most significant carbon reduction. Therefore a consistent comparison of different pathways for AJF production in terms of cost-effective reduction could support strategies for developing a future market of aviation biofuels.

So far, the mitigation costs (USD/tCO_{2e} reduced) of AJF have been explored in very few studies and with limited scope, while the ways how these costs compete with the carbon market – which is an alternative for airlines to achieve the GHG targets – are yet unclear. **Chapter 3** addressed these questions evaluating promising AJF pathways in Brazil. The results showed that residue-based pathways had lower mitigation costs. The hydrotreating used cooking oil presented the lowest values, followed by the thermochemical conversion of forest residues. Of the 1G pathways, AJF production from 1G sugarcane ethanol had a better performance than vegetable oil-based ones. Compared with the carbon market, the mitigation costs of AJFs are much higher (3 to 1400-fold) than the current prices or even future prices of the emission units traded. However, several concerns about the credibility of the carbon offsetting measures may result in AJFs playing an important role in aviation sector goals, which should be supported by robust carbon policies. From this perspective and considering both the potentials of supplying AJF and mitigating emissions, AJF production from 1G ethanol was suggested as a preferred alternative in the short-term. Hydrotreating palm oil could also be included if palm were obtained from areas with low-risks for land use changes. Among the residues-based pathways, hydrotreating beef tallow and the Fisher-Tropsch for forestry residues were presented as strategic alternatives.

Finally, it is reasonable to suppose that an effective and sustainable energy transition from fossil fuels to alternative ones should comprise other issues than GHG reduction. With the clear GHG reduction targets of the aviation sector, the potential of several pathways has been widely reported in the literature, while the environmental effects and the possible trade-offs between different environmental impacts remain rather unexplored. Therefore, in **Chapter 4**, an attributional LCA was carried out for the same AJF pathways evaluated in the previous chapter, considering the environmental trade-offs between climate change and seven other categories: fossil depletion, terrestrial acidification, eutrophication, human and environmental toxicity, and air quality-related categories, *e.g.*, particulate matter and photochemical oxidant formation. Even with the potential GHG reduction, AJF from 1G pathways presented trade-offs related to local environmental impacts. Pathways based on sugarcane ethanol generated values three times higher than those of fossil kerosene for terrestrial acidification and air quality impacts, and seven times higher for eutrophication. In turn, hydrotreating soybean oil caused levels of human toxicity that were five times higher than fossil fuel. For 2G pathways, when the residual feedstock is assumed as "waste" in the LCA modeling – resulting in a null burden for feedstock production – no relevant trade-offs were observed. On the other hand, if residual feedstocks are considered to be valuable by-products, hydrotreating beef tallow is the worst option, and pathways based on sugarcane residues could be related to higher impacts in comparison to soybean-based pathways for terrestrial acidification and air quality. Fisher-Tropsch pathways represent the lowest impacts for all categories, followed by hydrotreating used cooking oil.

Finally, in **Chapter 5**, the main findings of the previous chapters are combined and discussed, and in **Chapter 6,** the conclusions of the whole thesis are presented.

Resumo

O setor de aviação é responsável por apenas 3% das emissões antrópicas de carbono no mundo. No entanto, este meio de transporte, que consome três vezes mais energia *per capita* que outros modais de transporte coletivo, como trens e o ônibus, é exclusivamente abastecido por combustíveis fósseis e apresentou uma impressionante taxa de crescimento de 7.5% ao ano na última década. Em sintonia com as metas globais de reduzir as emissões de Gases de Efeito Estuda (GHG, em inglês) e a dependência de combustíveis fósseis, a *descarbonização* do setor de aviação é um desafio, visto que este setor geralmente depende de projetos com altos custos e está submetido a um rigoroso controle de qualidade.

Uma vez que o Acordo de Paris não aborda voos internacionais, que são responsáveis por 60% das operações do setor, iniciativas de agências setoriais poderiam preencher esta lacuna. Neste contexto, em 2010, a Organização Internacional de Aviação Civil (ICAO, em inglês), definiu metas ambiciosas para redução da emissão de GEE para voos internacionais. Desde 2016, o Esquema de Compensação e Redução de Carbono na Aviação Internacional (CORSIA, em inglês) tem gerenciado estas metas, defendendo a melhoria nas operações aéreas, compra de créditos de carbono, e a utilização de Combustíveis Alternativos de Aviação (AJF, em inglês) pelas companhias aéreas.

Iniciativas para expandir o uso de biocombustíveis "das estradas para os céus" tem aparecido em vários lugares. Desde 2011, mais de 250 mil voos comerciais já operaram com AJFs, seis aeroportos ao redor do mundo têm fornecido regularmente AJFs, e uma relevante base de dados de trabalhos científicos, em constante construção, tem dado suporte a estes temas.

Apesar disso, a transição energética sustentável do altamente competitivo setor de aviação deveria ser enfrentada numa perspectiva mais abrangente, *i.e.* combinando aspectos ambientais com socioeconômicos além da redução de GEE, bem como diferentes formas avaliação.

Embora o Brasil corresponda à pequena parcela de 2% das operações aéreas mundiais, seu relevante potencial de biomassa e reconhecida expertise na produção de bioenergia poderiam, futuramente, colocá-lo numa posição estratégica de fornecedor global de AJF, conforme já indicado por alguns estudos.

Assim, esta tese contribuiu para responder à algumas lacunas identificadas neste contexto e motivadas pelas seguintes perguntas: i) *O AJF produzido no Brasil poderia reduzir as emissões de GEE em comparação com o combustível fóssil?*, ii*) Quanto custaria o carbono mitigado por cada rota de produção de AJF?*, iii) *O AJF poderia trazer outros benefícios ambientais além da possível redução das emissões de GEE?*

A partir de um recente *Roadmap* para biocombustíveis de aviação no Brasil, que foi conduzido por experts da indústria e da universidade, dez a quatorze promissoras e estratégicas rotas produtivas de AJF foram selecionadas e avaliadas nesta tese, abrangendo rotas baseadas em resíduos e culturas agrícolas.

Para as rotas produtivas baseadas em culturas agrícolas (ou de primeira geração, rotas 1G), foram considerados o hidrotratamento do óleo de soja e de palma, bem como o processo "alcohol-to-jet" do etanol a partir de cana-de-açúcar. Das rotas produtivas baseadas em resíduos (ou de segunda geração, rotas 2G), foram analisados o hidrotratamento do óleo residual de cozinha (UCO, em inglês) de do sebo bovino. Da mesma forma, o processo "alcohol-to-jet" do etanol obtido de resíduos de cana-de-açúcar, resíduos florestais, ou gases de aciaria foi também considerado, bem como o Fischer-Tropsch de resíduos de cana e de florestas. A liquefação hidrotérmica (HTL, em inglês) de resíduos de cana e de florestas foi avaliada como um caso específico, uma vez que esta tecnologia ainda não está aprovada para a indústria de aviação, e não atingiu a escala comercial. Um resumo destas rotas produtivas com as motivações e questões abordadas nesta tese está apresentada no **Capítulo 1**.

De acordo com os objetivos da ICAO, a potencial redução de GHG através de AJF em comparação com o querosene fóssil é um indicador crucial para o processo de tomada de decisão e é comumente estimado usando a Avaliação do Ciclo de Vida (LCA, em inglês). No entanto, embora essa questão tenha sido amplamente explorada na literatura, reconhece-se a alta sensibilidade dos resultados aos aspectos metodológicos. Então, para ter uma compreensão mais clara e abrangente de como AJF pode ajudar a reduzir as emissões de GEE, a pegada de carbono para dez rotas produtivas de AJF foi estimada no **Capítulo 2** por meio de seis abordagens metodológicas: atribucional, consequencial e quatro esquemas regulatórios: o *Renovabio* no Brasil, o *CORSIA* para a aviação internacional, o *Renewable Fuel Standard* (RFS) nos Estados Unidos e a *Renewable Energy Directive* (RED) na Europa. Com relação aos esquemas regulatórios, esta tese explorou como os AJF produzidos no Brasil seriam avaliados de acordo com as diretrizes de Políticas de Baixo Carbono (LCPs, em inglês), dado o potencial do Brasil para abastecer esses mercados.

Os principais resultados mostraram que a rota produtiva baseada em soja apesentou baixo ou nenhum potencial de redução de GHG quando comparada ao combustível fóssil, principalmente devido aos efeitos da mudança no uso da terra. Entre as rotas 1G, o AJF produzido a partir da cana-de-açúcar teve o melhor desempenho, especialmente quando o excedente de eletricidade foi creditado. O AJF do óleo de palma pode apresentar reduções significativas de GHG em caso de expansão da palma em pastagens degradadas. De maneira geral, as rotas 2G proporcionaram uma redução maior de GHG, em uma faixa mais estreita de valores, do que as rotas 1G. Fischer-Tropsch (FT) de resíduos lignocelulósicos apresentou o maior potencial para redução. No entanto, quando as consequências em desviar matérias-primas residuais de seu uso atual para produzir AJF são capturadas, isso poderia levar a emissões de GHG maiores do que as de combustíveis fósseis.

Por outro lado, embora os AJFs possam proporcionar a redução de GHG, os custos de produção estão, em geral, ainda longe de serem competitivos com o querosene fóssil. Além disso, a rota produtiva de menor custo nem sempre é o que proporciona a redução de carbono mais significativa. Portanto, uma comparação consistente de diferentes rotas em termos de custo-benefício poderia apoiar estratégias para o desenvolvimento de um futuro mercado de biocombustíveis para aviação.

Até o momento, os custos de mitigação de AJF (USD/tCO_{2e} reduzido) foram explorados em poucos estudos e com escopo limitado, enquanto as formas como esses custos competem com o mercado de carbono – que é uma alternativa para as companhias aéreas atingirem as metas de redução de GHG – ainda não estão claras. O **Capítulo 3** abordou essas questões, avaliando rotas produtivas de AJF promissoras no Brasil. Os resultados mostraram que as rotas baseadas em resíduos tiveram menores custos de mitigação. O hidrotratamento do óleo de cozinha usado apresentou os menores valores, seguido pela conversão termoquímica dos resíduos florestais. Das rotas 1G, a produção de AJF a partir do etanol de cana-de-açúcar teve um desempenho melhor do que as rotas baseadas em óleos vegetais. Em comparação com o mercado de carbono, os custos de mitigação de AJFs são muito mais elevados (3 a 1400 vezes) do que os preços atuais, ou mesmo preços futuros, das unidades de emissão comercializadas. No entanto, várias preocupações sobre a credibilidade das medidas de compensação de carbono sugerem que os AJFs desempenharão um papel importante nas metas do setor de aviação, e que devem apoiados por políticas de carbono robustas. Nessa perspectiva e considerando tanto os potenciais de suprimento de AJF quanto de mitigação de emissões, a produção de AJF a partir do etanol 1G foi sugerida como alternativa preferencial no curto prazo. O hidrotratamento de óleo de palma também poderia ser considerado se a palma fosse obtida de áreas com baixo risco de mudanças no uso da terra. Dentre as vias baseadas em resíduos, o hidrotratamento de sebo bovino e o Fisher-Tropsch de resíduos florestais se apresentaram como alternativas estratégicas.

Finalmente, é razoável supor que uma transição energética eficaz e sustentável dos combustíveis fósseis para os alternativos deva envolver outras questões além da redução da emissão de GHG. Com as claras metas de do setor de aviação, o potencial de descarbonização proporcionado por várias rotas produtivas de AJF tem sido amplamente discutido na literatura, enquanto outros efeitos ambientais e os possíveis *trade-offs* entre diferentes impactos ambientais permanecem pouco explorados. Portanto, no **Capítulo 4**, uma ACV atribucional foi realizada para as mesmas rotas produtivas de AJF avaliadas no capítulo anterior, considerando os *trade-offs* entre a contribuição para as mudanças climáticas – ou seja, a redução de GHG – e outras sete categorias de impactos ambientais: esgotamento de fontes fósseis, acidificação terrestre, eutrofização, toxicidade humana e ambiental, e categorias relacionadas à qualidade do ar, como formação de material particulado e formação de oxidante fotoquímico. Mesmo com a potencial redução de GHG, as rotas 1G apresentaram *trade-offs* relacionados aos impactos ambientais locais. As rotas baseadas no etanol da cana-de-açúcar resultaram em valores três vezes maiores do que os do querosene fóssil para os impactos da acidificação terrestre e da qualidade do ar, e sete vezes maiores para a eutrofização. Por sua vez, o hidrotratamento do óleo de soja resultou em níveis de toxicidade humana cinco vezes maiores do que o combustível fóssil. Para as rotas 2G, quando a matéria-prima residual é assumida como "*waste*" na modelagem LCA – resultando em uma carga nula para a produção de matéria-prima – nenhum *trade-off* relevante foi observado. Por outro lado, se as matérias-primas residuais forem consideradas "co-produtos", o hidrotratamento de sebo bovino seria a pior opção, e as rotas baseadas em resíduos de cana-de-açúcar estariam relacionadas a impactos mais elevados em comparação com as rotas à base de soja para acidificação terrestre e qualidade do ar. As rotas baseadas em Fisher-Tropsch representam os impactos mais baixos para todas as categorias, seguidas do hidrotratamento de óleo de cozinha usado.

Finalmente, no **Capítulo 5**, os principais resultados dos capítulos anteriores são combinados e discutidos, e no **Capítulo 6**, as conclusões de toda a tese são apresentadas.

Overzicht

De luchtvaartsector is verantwoordelijk voor slechts 3% van de antropogene koolstofemissies in de wereld. Deze vervoerswijze - die grofweg driemaal zo energie-intensief is dan andere collectieve vervoerswijzen, zoals trein- en busvervoer - wordt uitsluitend geleverd door fossiele brandstoffen, en is in het laatste decenium met een indrukwekkend tempo van 7,5% per jaar op wereldbasis gegroeid. In lijn met de mondiale doelstellingen om de uitstoot van broeikasgassen (GHG) en de afhankelijkheid van fossiele brandstoffen te verminderen, is het koolstofarm maken van de luchtvaartsector - die doorgaans gebaseerd is op kost-intensieve projecten met een strenge kwaliteitscontrole - een uitdaging.

Doordat de Overeenkomst van Parijs geen betrekking had op internationale vluchten - die verantwoordelijk zijn voor ongeveer 60% van de activiteiten van de sector - zou deze lacune moeten worden opgevuld door initiatieven van internationale agentschappen. Vervolgens stelde de Internationale Burgerluchtvaartorganisatie (ICAO) in 2010 ambitieuze doelen voor het verminderen van de uitstoot van GHG voor internationale vluchten. Sinds 2016 heeft het CO2-compensatie- en reductieschema voor de internationale luchtvaart (CORSIA) deze doelen behaald door te pleiten voor verbeteringen in de exploitatie van vliegtuigen, het kopen van CO2-credits en het gebruik van alternatieve vliegtuigbrandstoffen (AJF's) door luchtvaartmaatschappijen. De huidige CORSIA-regeling omvat drie opeenvolgende fasen, van vrijwillige naar verplichte verplichtingen van de staten.

Initiatieven om het gebruik van biobrandstoffen "van de weg naar de lucht" uit te breiden, zijn op verschillende plaatsen opgedoken. Sinds 2011 zijn er al meer dan 250 duizend commerciële vluchten uitgevoerd met AJF's, hebben zes luchthavens wereldwijd al regelmatig AJF geleverd en is er een relevante wetenschappelijke basiskennis opgebouwd om deze gerelateerde thema's te ondersteunen.

Toch moet de duurzame energietransitie van de zeer concurrerende luchtvaartsector moet in een breder perspectief worden aangepakt, d.w.z. door ecologische en sociaaleconomische kwesties te combineren die verder gaan dan de reductie van broeikasgassen, en daarmee ook het gebruiken van verschillende beoordelingsmethoden.

Hoewel Brazilië goed is voor een klein aandeel van 2% van de wereldwijde luchtvaartactiviteiten, zou Brazilië door zijn enorme biomassapotentieel en erkende expertise op het gebied van bio-energieproductie in de toekomst een strategische wereldwijde leverancier van AJF kunnen worden, zoals al in sommige studies is aangegeven.

Dit proefschrift beoogt bij te dragen aan het opvullen van kennishiaten die in deze context zijn geïdentificeerd, gemotiveerd door de volgende onderzoeksvragen: i) *Kan AJF geproduceerd in Brazilië de uitstoot van broeikasgassen verminderen in vergelijking met fossiele brandstof?*, ii) *Hoeveel zou de koolstof die door elk AJF-traject wordt gemitigeerd, kosten*? en iii) *Kan AJF andere milieuvoordelen opleveren dan de mogelijke vermindering van de uitstoot van broeikasgassen*?

Uit een recente Roadmap voor biobrandstoffen in de luchtvaart in Brazilië - die werd uitgevoerd door experts uit de industrie en de academische wereld - werden in dit proefschrift tien tot veertien veelbelovende en strategische routes voor AJF-productie geselecteerd en geëvalueerd, bestaande uit op residuen gebaseerde routes en op voedselgewassen gebaseerde routes.

Voor voedselgewas gebaseerde routes (of eerste generatie, 1G-routes), werd hydrotreatment van soja- en palmolie beschouwd, evenals het "alcohol-naar-jet" -proces van ethanol uit suikerriet. Van de op residuen gebaseerde routes (of tweede generatie, 2G-routes), werd de hydrotreatment van gebruikte frituurolie (UCO) en runder tallow geanalyseerd. Evenzo werd het "alcohol-naar-jet" -proces van ethanol verkregen uit suikerrietresiduen, bosbouwresiduen en staalafgassen in aanmerking genomen, evenals de Fischer-Tropsch bewerking van suikerriet- en bosbouwresiduen. De hydrothermische liquefactie van suikerriet en houtresiduen werd als een specifiek geval beoordeeld, aangezien deze technologie nog niet is goedgekeurd voor de luchtvaartindustrie en de commerciële schaal niet bereikt is. Het overzicht van deze trajecten met de motivaties en hiaten in het onderzoek die in dit proefschrift worden aangepakt, wordt gepresenteerd in **Hoofdstuk 1**.

Volgens de ICAO-doelstellingen is de potentiële reductie van broeikasgassen van AJF in vergelijking met fossiele kerosine een cruciale indicator voor het besluitvormingsproces, en wordt deze gewoonlijk geschat met behulp van levenscyclusanalyse (LCA). Hoewel dit probleem grotendeels in de literatuur is onderzocht, wordt erkend dat de resultaten zeer gevoelig zijn voor methodologische aspecten. Om een duidelijker en uitgebreider begrip te krijgen van hoe AJF kan helpen de uitstoot van broeikasgassen te verminderen, werd de koolstofvoetafdruk voor tien AJF-trajecten in **hoofdstuk 2** geschat aan de hand van zes methodologische benaderingen: attributionele

LCA, daaruit voortvloeiende LCA en vier reguleringsschema's: de Renovabio in Brazilië, CORSIA voor internationale luchtvaart, de Renewable Fuel Standard (RFS) in de Verenigde Staten en de Renewable Energy Directive (RED) in Europa. Met betrekking tot de reguleringsschema's, onderzocht dit proefschrift hoe AJF geproduceerd in Brazilië, zou worden geëvalueerd volgens Low-Carbon Policy richtlijnen, gezien het potentieel van Brazilië om deze markten te bevoorraden.

De belangrijkste resultaten toonden aan dat de op sojabonen gebaseerde route weinig tot geen mogelijkheden had om broeikasgassen te verminderen in vergelijking met hun fossiele tegenhangers, voornamelijk als gevolg van de effecten van veranderingen in landgebruik. Van alle 1G-routes presteerde AJF geproduceerd uit suikerriet het beste, vooral wanneer het stroomoverschot werd gecrediteerd. AJF uit palmolie zou aanzienlijke broeikasgasreducties kunnen opleveren bij palmuitbreiding in gedegradeerde weidegebieden. In het algemeen kunnen 2G-routes een hogere reductie van broeikasgassen opleveren, in een kleiner waardenbereik, dan 1G-routes. Fischer-Tropsch uit lignocellulose-residuen het hoogste potentieel voor het verminderen van broeikasgassen. Als de gevolgen van het inzetten van restgrondstoffen voor AJF productie in plaats van hun huidige gebruik worden meegenomen, kan dit echter leiden tot grotere broeikasgasemissies dan die van fossiele brandstoffen.

Terwijl AJF's het potentieel hebben om broeikasgassen te verminderen, zijn de productiekosten over het algemeen nog lang niet concurrerend met fossiele kerosine. Bovendien is het pad met de laagste productiekosten niet altijd het pad dat de belangrijkste koolstofreductie oplevert. Een consistente vergelijking van verschillende routes voor AJF-productie in termen van kosteneffectieve reductie zou strategieën kunnen ondersteunen voor het ontwikkelen van een toekomstige markt van luchtvaartbiobrandstoffen.

In deze context blijkt dat de mitigatiekosten (USD/tCO_{2e} verlaagd) van AJF slechts in zeer weinig studies, en met een beperkte reikwijdte per studie, zijn onderzocht, zodat het niet duidelijk is hoe deze kosten concurreren met de koolstofmarkt - wat een alternatief is voor luchtvaartmaatschappijen om de broeikasgasdoelstellingen te halen. **Hoofdstuk 3** behandelde deze vragen bij het evalueren van veelbelovende AJF-trajecten in Brazilië. De resultaten toonden aan dat op residuen gebaseerde routes lagere mitigatiekosten hadden. De hydrotreatment van gebruikte bakolie vertoonde de laagste waarden, gevolgd door de thermochemische omzetting van bosresten. Van de 1G-routes presteerde AJF-productie uit

1G-suikerrietethanol beter dan productie op basis van plantaardige olie. In vergelijking met de koolstofmarkt zijn de mitigatiekosten van AJF's veel hoger (3 tot 1400 maal) dan met handel, zowel met de huidige prijzen als zelfs toekomstige prijzen van de emissie-eenheden die op de koolstofmarkt worden verhandeld. Verschillende zorgen over de geloofwaardigheid van de CO2-compenserende maatregelen wijzen er echter op dat AJF's een belangrijke rol kunnen spelen bij de doelstellingen van de luchtvaartsector, die moeten dan wel worden ondersteund door robuust koolstofbeleid. Vanuit dit perspectief en gezien zowel de mogelijkheden om AJF te leveren als de uitstoot te verminderen, werd AJF-productie uit 1G-ethanol voorgesteld als een geprefereerd alternatief op korte termijn. Hydrotreated Palmolie zou ook kunnen worden geprefereerd indien palm wordt verkregen uit gebieden met lage risico's voor veranderingen in landgebruik. Onder de op residuen gebaseerde trajecten werden de hydrobehandeling van rundvet en de Fisher-Tropsch voor bosbouwresiduen gepresenteerd als strategische alternatieven.

Ten slotte is het redelijk om te veronderstellen dat een effectieve en duurzame energietransitie van fossiele brandstoffen naar alternatieve brandstoffen andere overwegingen moet omvatten dan de vermindering van broeikasgassen. Met de duidelijke reductiedoelstellingen voor broeikasgassen van de luchtvaartsector is het potentieel van verschillende trajecten breed uitgemeten in de literatuur, terwijl de milieueffecten en de mogelijke afwegingen tussen verschillende milieueffecten nog vrij onontgonnen zijn. Hiertoe werd in **hoofdstuk 4** een attributionele LCA uitgevoerd voor dezelfde AJF-routes die in het vorige hoofdstuk zijn geëvalueerd, waarbij rekening werd gehouden met de ecologische afwegingen tussen klimaatverandering en zeven andere categorieën: uitputting van fossiele brandstoffen, terrestrische verzuring, eutrofiëring, toxiciteit voor mens en milieu, en luchtkwaliteitgerelateerde categorieën, bijv. fijnstof en de vorming van fotochemische oxidatiemiddelen. Zelfs met de potentiële reductie van broeikasgassen, presenteerde AJF van 1G-routes trade-offs met betrekking tot lokale milieueffecten. Paden op basis van suikerrietethanol genereerden waarden die drie keer hoger waren dan die van fossiele kerosine voor terrestrische verzuring en luchtkwaliteitseffecten, en zeven keer hoger voor eutrofiëring. Op zijn beurt veroorzaakte hydrobehandeling van sojaolie niveaus van menselijke toxiciteit die vijf keer hoger waren dan die van fossiele brandstof. Voor 2G-trajecten, wanneer de restgrondstof in de LCA-modellering als "afval" wordt meegenomen - resulterend in een nullast voor de grondstofproductie - werden geen relevante trade-offs waargenomen. Aan de andere kant, als residuale grondstoffen worden beschouwd als waardevolle bijproducten, is de hydrobehandeling van rundvet de slechtste optie, en kunnen routes op basis van suikerrietresiduen in verband worden gebracht met hogere effecten, in vergelijking met op sojabonen gebaseerde routes, voor terrestrische verzuring en luchtkwaliteit. Fisher-Tropsch-routes vertegenwoordigen de laagste effecten voor alle categorieën, gevolgd door hydrobehandeling van gebruikte bakolie.

Ten slotte worden in **Hoofdstuk 5** de belangrijkste bevindingen van de voorgaande hoofdstukken gecombineerd en bediscussieerd, en in **Hoofdstuk 6** worden de conclusies van het hele proefschrift gepresenteerd.

1 Introduction

1.1. A new challenge

The aviation sector is responsible for around 3% of the global energy demand, 11% of the energy consumed by the transportation sector[1], while emitting approximately 2.5% of global anthropogenic carbon dioxide[2]. Despite these modest contributions, the aviation industry features specific aspects:

- It depends almost exclusively on fossil fuels, mostly fossil kerosene, which lead to a relevant share of the operational costs. The global demand of 390 billion liters in 2017 represented more than 30% of the total cost for airline operations[3].
- Even though the energy intensity of commercial aircraft operations have decreased 2.8% per year since 2005[4], the average values (1.8 MJ/passenger.km) are 3 times higher than mass transportation modes – such as buses and railways – and similar to passenger cars, which already have consolidated initiatives for using biofuels[2].
- The relevant growth rate of the global aviation sector (3.8% per year, 1973-2017) in terms of energy use is close to that of the road transportation (4.2%)[1]. Furthermore, following the increase of the commercial flights activity, even with the improvements from operational and technical measures and new aircraft projects, aviation emissions have risen on average 2% yearly since 2000[4]. The contribution for the total carbon dioxide emissions could reach 3% of the total emissions in 2030[3], or even 6% by 2050[5].

International flights corresponded to around 60% of the fuel demanded in the aviation sector[6], 63% of the global operations in terms of RPK ("Revenue Passenger-Kilometer"), and 70% of global operations in terms of RTK ("Revenue Tonne Kilometer", including passengers)[7]. However, unlike domestic aviation, international operations were not addressed by the intended nationally-determined climate (INDC's) actions from the Paris Agreement, which has driven the International Civil Aviation Organization (ICAO) to take the lead regarding this issue[8].

ICAO has set forth some ambitious goals for decarbonizing international flights in the competitive market of the aviation industry, which is highly dependent on fossil fuels subject to price volatility, while also reporting average growth rates over the last few years[9].

In general, the ICAO's goals are as follows: i) improve CO_2 efficiency by an average of 1.5% per year from 2009 until 2020; ii) achieve carbon-neutral growth by 2020; iii) reduce carbon emissions by 50% in 2050 compared to 2005 levels.

To achieve these targets, several actions could be implemented (as illustrated by **Figure 1.1**), such as technology development, operation/infrastructure improvements, and economic-based measures.

In general, technological actions are related to aircraft designs, composite lightweight materials, advances in engine technology, and by partially replacing fossil fuels for alternative fuels. Since research and development in the aircraft manufacturing sector is a capital and time-intensive endeavor, incremental designs or adjustments have been preferred to new revolutionary products[4].

In turn, operation actions comprise more efficient flight procedures, baggage loading strategies, and weight reduction measures. Infrastructure improvements mean implementing more efficient air traffic management measures and improving airport infrastructure. Finally, market-based measures are related to carbon offsetting by emission units purchased in the carbon market.

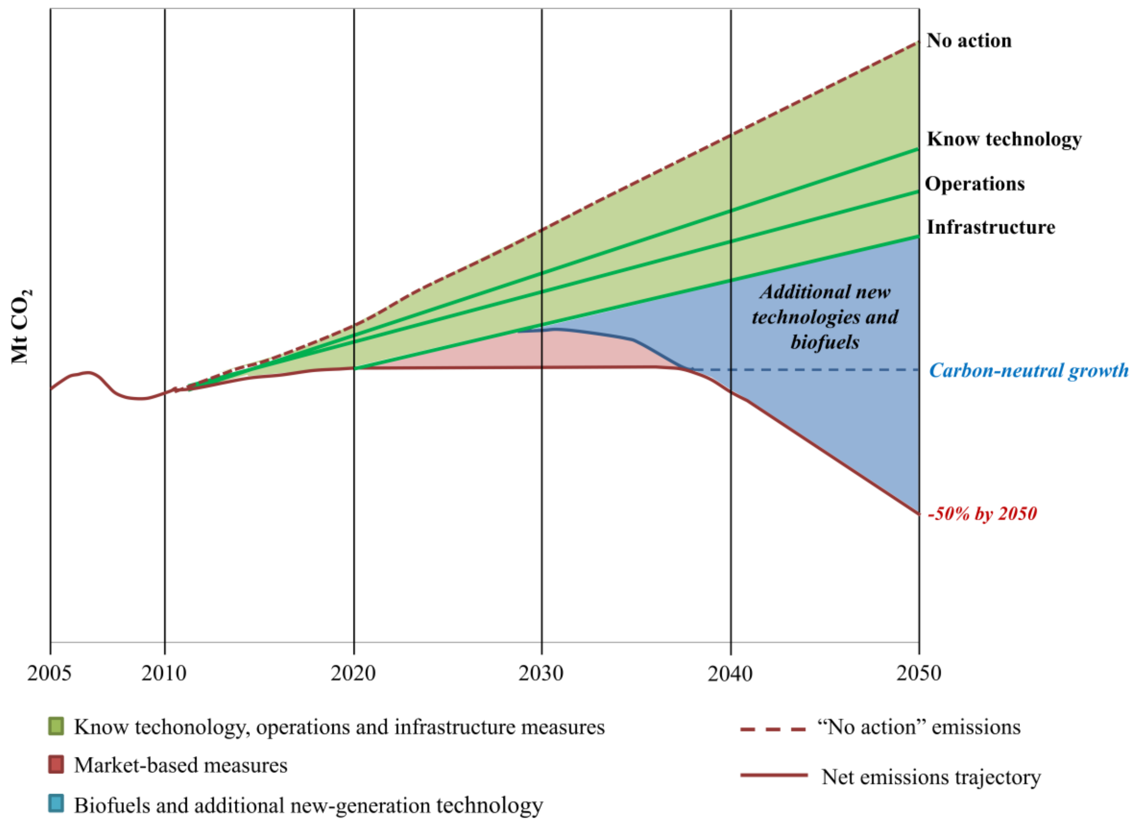


Figure 1.1: GHG reduction in aviation sector according to the possible actions, adapted from ATAG (2010)[10]

ICAO initiatives have culminated with the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA)[11] approved by the 39th ICAO Assembly in 2016[12]. CORSIA has managed these reduction goals on Greenhouse Gases (GHG) emissions in a detailed schedule comprised of three phases. The Pilot phase (2021-2023) and the First phase (2024-2026) are applied to international flights between volunteer States, while the Second phase (2027-2035) would be mandatory for all States, except for lesser developed countries, small island developing states, and landlocked developing countries. Recently, airline companies have suggested re-discussing the deadlines and other aspects of the CORSIA implementation, especially because of the great economic impacts on aircraft operations during the Covid-19 crises[13].

According to the CORSIA guidelines[14–17], the carbon offsetting requirements, which are calculated from the annual carbon emissions of the airplane operators and their growth factor over the last years, could be achieved by purchasing emission units (carbon credits) in the carbon market. Furthermore, the offsetting requirements can be discounted by GHG emission reductions coming from using sustainable aviation fuels (SAF) which have shown to be a strategic means of achieving the carbon targets[18] and reducing the sector's dependency of fossil fuels. This has sparked a new market for biofuels.

This thesis focuses exclusively on the opportunities and challenges for producing alternative jet fuels (AJF), which are also known as renewable jet fuels (RJF). Both terms can be related to "SAF" if the alternative fuel fit the current CORSIA eligibility criteria[14], which state that SAF: i) must provide at least a 10% reduction in GHG emissions compared to fossil kerosene, considering the whole life cycle; ii) must not be produced from biomass cropped after January 2008 in areas with high carbon stocks. However, regardless of the nomination, they must, above all else, be certified as a drop-in fuel.

1.2. *Drop-in* jet fuels

The strict quality control of the well-consolidated aviation industry may naturally be extended to alternative fuels. Only "drop-in fuels" would be accepted for replacing Jet A, *i.e.,* conventional fossil kerosene used in civil aircraft[18].

In general, a drop-in fuel is defined as "*liquid hydrocarbons that are functionally equivalent to petroleum fuels and are fully compatible with existing petroleum infrastructure*"[19]. Specifically, a "drop-in jet fuel blend" means "*substitute for conventional* *jet fuel, that is completely interchangeable and compatible with conventional jet fuel when blended with conventional jet fuel. A drop-in fuel blend does not require adaptation of the aircraft/engine fuel system or the fuel distribution network and can be used "as is" on currently flying turbine-powered aircraft*"[20].

A fuel production "pathway", as mentioned along with this thesis, comprises all the production stages, starting with feedstock acquisition, followed by its pre-treatment to achieve the requirements of the conversion processes, and finally the conversion processes to produce aviation fuel. The several pathways (see **Figure 1.2**) to produce AJF from biomass –which eventually may lead to GHG reductions– are classified into three groups: lipid conversion, biochemical conversion, and thermochemical conversion, and are detailed as follows.

1.2.1. Lipid conversion

Hydrotreating/hydrocracking vegetable oils, animal fats or grease residues - a process called Hydroprocessed Esters and Fatty Acids (HEFA), or Hydroprocessed Renewable Jet (HRJ) or Hydrogenated Vegetable Oil (HVO) - is currently the best-known AJF process and has been tested in large-scale production of aviation biofuels[21–28].

In HEFA process, the oleaginous feedstock undergoes hydrotreatment with hydrogen in the presence of a catalyst. Unsaturated carbon-bonds are saturated and oxygen is removed. Subsequently, the hydrocarbon chains are hydrocracked in different ranges, isomerized and, finally, fractioned producing drop-in kerosene, and other products, such as diesel, naphtha, and propane. The amount of drop-in diesel and kerosene can be adjusted by operational conditions.

Currently, after ethanol and biodiesel, drop-in diesel from HEFA process represents the third largest biofuel in volume produced in the world. Although with still modest volumes (6.5 billion liters), HEFA biofuels production grew 8.3% in 2018-2019, with potential to achieve an annual capacity production of 22 billion liters, considering the plants under construction[29]. This growing potential directly affects the production capacity of AJF.

Alternatively, the Catalytic Hydrothermolysis (CH)[30,31] process takes fatty acids obtained from oleaginous feedstock hydrolysis and hydrotreating them, which are then fractioned into different hydrocarbon ranges, including the drop-in jet fuel.

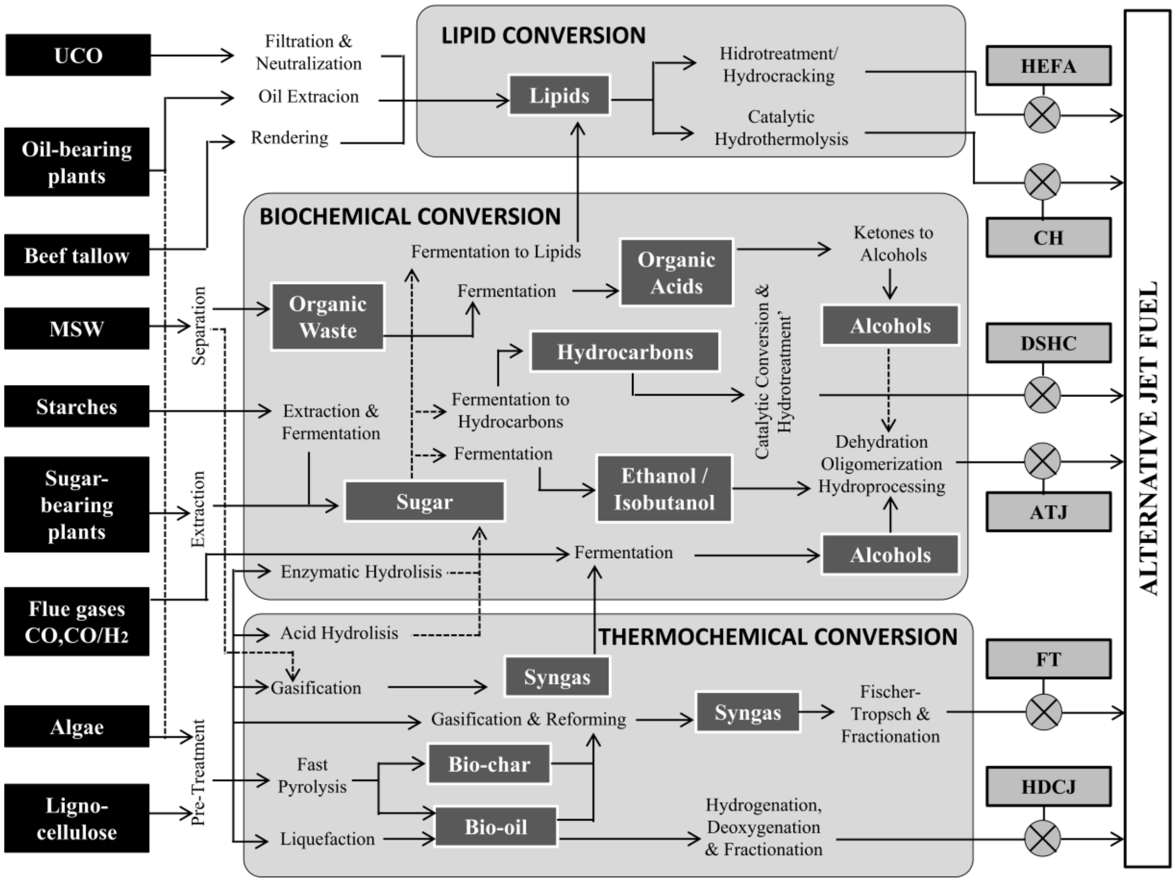


Figure 1.2: Main pathways to produce AJF, adapted from Boeing (2013)[32]. Alcohol-to-Jet (ATJ). Catalytic Hydrothermolysis (CH). Direct Sugar to Hydrocarbons (DSHC). Fischer-Tropsch (FT). Hydroprocessed Esters and Fatty Acids (HEFA). Hydrotreated Depolymerized Cellulosic to Jet (HDCJ). Municipal solid wastes (MSW). Used Cooking Oil (UCO).

1.2.2. Biochemical Conversion

Sugars that are either freely available in biomass or obtained from starch or lignocellulose can be converted into drop-in kerosene using the Alcohol-to-Jet (ATJ) process with alcohols (ethanol or isobutanol) as an intermediary product. Alcohol molecules are dehydrated, oligomerizeted, and finally hydrogenated to suitable hydrocarbon chains to be used as a drop-in fuel[33–35]. The production of alcohol is an important bottleneck in this pathway and has a relevant influence on the environmental performance and production costs of the final products[36]. First (1G) and second generation (2G) ethanol[33,34,37,38], as well as ethanol from gas fermentation[39–41] have been tested as feedstock.

On the other hand, sugars can also be directly converted into hydrocarbons through the Direct Sugar to Hydrocarbons (DSHC) process[42]. Genetically modified microorganisms are used to produce isoprenoids, such as farnesene, which are then hydrogenated into farnesane. Other pathways to convert the organic fractions of municipal solid wastes into alcohols or sugar to lipids, for further conversion into AJF, are under preliminary analysis at an experimental scale[24,39].

1.2.3. Thermochemical conversion

Of all the thermochemical pathways, one option is biomass gasification, followed by a syngas clean-up, and the known Fischer-Tropsch (FT) process[43–45]. The syngas is catalytically converted into liquid long-chain hydrocarbons, which are then cracked, isomerized and fractioned into drop-in jet fuel and other products.

Alternatively, biomass can be thermally decomposed to bio-oil using fast pyrolysis[46] or hydrothermal liquefaction[45,47], with water in subcritical conditions. The bio-oil is then upgraded – via catalytic reactions with hydrogen input –to a kerosene-like carbon-chain. Both pathways comprise the Hydrotreated Depolymerized Cellulosic to Jet (HDCJ) technology.

1.2.4. Certified pathways for AJF

The most common specification for aviation fuel is D1655-ASTM[48] (Standard Specification for Aviation Turbine Fuels), which also allows alternative fuels if they comply with the specific requirements of the D7566-ASTM (Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons)[49]. Indeed, an eligible drop-in jet fuel must be certified according to D7566-ASTM before it can be blended with fossil kerosene. Up until 2020, seven AJF pathways have already been certified, with specific Jet A blending limits (see **Table 1.1**). Some pathways are undergoing the certification process[50], such as: HEFA from algae oil, and ATJ ethanol with aromatics.

It is worth mentioning that recently D1655-ASTM[48] approved the fuel obtained from the co-processing of renewable content – *i.e.*, vegetable oils, greases, and Fisher-Tropsch biocrude – with crude-oil in oil refineries (maximum blend 5% v/v). Since the scope of this thesis lies on AJF – *i.e.*, potential drop-in fuels – produced in dedicated plants, co-processed fuels were not addressed by this study.

1.3. Brazil’s role in this new challenge

Historically, Brazil is one of the global leaders in renewable energy use. About half of the total energy supplied in Brazil comes from renewable energy sources – such as biomass, hydropower, and wind – mostly lead by sugarcane products, which were responsible for 16.2% of the national energy supply (52.8 Mtoe) in 2019[53].

Table 1.1: Currently approved pathways to produce drop-in aviation fuel according to ASTM (2020)[49,51,52]

Pathways	Year	Feedstock	Blend	Technology developers and fuel producers
FT-SPK *Synthesized Paraffinic Kerosene from Fischer-Tropsch*	2009	Syngas from gasification of biomass like municipal solid waste (MSW), agricultural and forest wastes, and wood and energy crops and non-renewable feedstocks such as coal and natural gas.	50%	• Sasol • Sheel • Syntroleum • Synfuels • Rentech • Solena • Red Rock Biofuels
HEFA-SPK *Synthesized Paraffinic Kerosene from Hydroprocessed Esters and Fatty Acids*	2011	Oil-based materials, such as vegetable oil and waste greases.	50%	• Neste Oil • Total • Honeywell UOP • Alt Air Fuels • Agrisoma Biosciences • PetroChina • Sappire Energy • PEMEX • ASA • SG Biofuels • Syntroleum
HFS-SIP *Synthesized Iso-Paraffins from Hydroprocessed Fermented Sugars*	2014	Sugar-based material.	10%	• Amyris
FT-SPK/A *Synthesized Paraffinic Kerosene with aromatics from Fischer-Tropsch*	2015	Syngas from gasification of biomass like municipal solid waste (MSW), agricultural and forest wastes, and wood and energy crops and non-renewable feedstocks such as coal and natural gas.	50%	• Sasol • Sheel • Syntroleum
ATJ-SPK *Synthesized Paraffinic Kerosene from Alcohol-to-Jet*	2016	Sugars, starches, and lignocellulosic material.	50%	• Terrabon/MixAlco • Coskata • Solazyme • Cobalt • Gevo • LanzaTech • Byogy Renewables
CH-SK *Catalytic Hydrothermolysis Synthesized Kerosene*	2020	Oil-based materials, such as vegetable oil and waste greases.	50%	• ARA • Euglena • Aemetis/Chevron Lummus Global
HHC-SPK *Hydroprocessed Hydrocarbons, Esters and Fatty Acids Synthetic Paraffinic Kerosene*	2020	Tri-terpenes produced by the *Botryococcus braunii* species of algae.	10%	• IHI World

The contribution of bioenergy is relevant in the transportation sector, where biofuels have constituted roughly 25% (or 21.3 Mtoe in 2019) of the energy consumed in this sector. The contribution of liquid biofuels has been especially relevant in the road transportation sector over the last decades, based on accumulated learning and recognized expertise[54,55]. While 33.8 million m³ of ethanol were consumed in Brazil last year, directly or blended with gasoline, around 4.7 million m³ of biodiesel were used in mandatory blends with fossil diesel (10% v/v)[53]. Both biofuel supply-chains are supported by a well-consolidated agroindustry of 380 sugarcane mills and 110 biodiesel plants[56].

On the other hand, the aviation sector in Brazil remains exclusively dependent on fossil kerosene and aviation gasoline. The Energy Research Office of the Brazilian Government has predicted a modest (or realistic) contribution of only 1% of AJFs to the total fuel demand of this sector in 2030[57].

1.3.1. The aviation sector in Brazil

The aviation sector in Brazil comprises roughly 540 civil public airports spread around the country, but 50-60% of the total operations are concentrated in São Paulo and Rio de Janeiro[58]. In 2019 total operations in Brazil reached 165 billion RPK and 17.4 billion RTK, with an annual growth rate of 11.6% (2005-2019)[58]. The international operations originating in Brazil have constituted 40-45% of the total RPK and RTK. In comparison with global operations, the Brazilian aviation sector represents 2.0% and 1.5% of the total operations (including domestic ones) and international flights, respectively[7,58].

The energy demand from the aviation sector in Brazil – which never exceeded 15% of the total energy demand from the national transportation sector[53] – is mostly led by fossil kerosene and corresponds to approximately 1.7% of global kerosene consumption (5.8 Mtoe in 2019)[2]. Due to the significant growth rate over the last years (4.4% per year between 2005 and 2019), Jet A demand reached 7.2 million m³ in 2019, mostly for use in domestic flights (**Figure 1.3**). It is worth mentioning that up to 10-15% of this amount is related to private aviation operations, such as helicopters[59]. According to official government reports[52,57], the increasing demand for fossil kerosene in the coming years would be supplied at the expense of keeping Brazil's dependence on imports for this resource.

The current pandemic crisis related to the novel coronavirus (COVID-19) has led to unprecedented impacts on aviation operations. According to an ICAO report[60] – which summarizes and updates several other related studies – a 54.7% decline of RPK and USD 345-386 billion potential loss of operating revenues, including international and domestic flights, are expected in 2020 compared to 2019. On the other hand, a maximum decrease of daily CO_2 emissions by around 60% (or -1.7 Mt CO_2/day) was also estimated in April 2020 compared with mean 2019 levels[61]. This is not expected to be different in Brazil, where aviation operations of the first semester (January to May) of 2020 regressed to the same levels of 2007, and the fossil kerosene demand was 38% lower than what was consumed in the same period in 2019[58]. It is expected that GHG emissions in 2020 will be reduced proportionally to the reduced aviation operations.

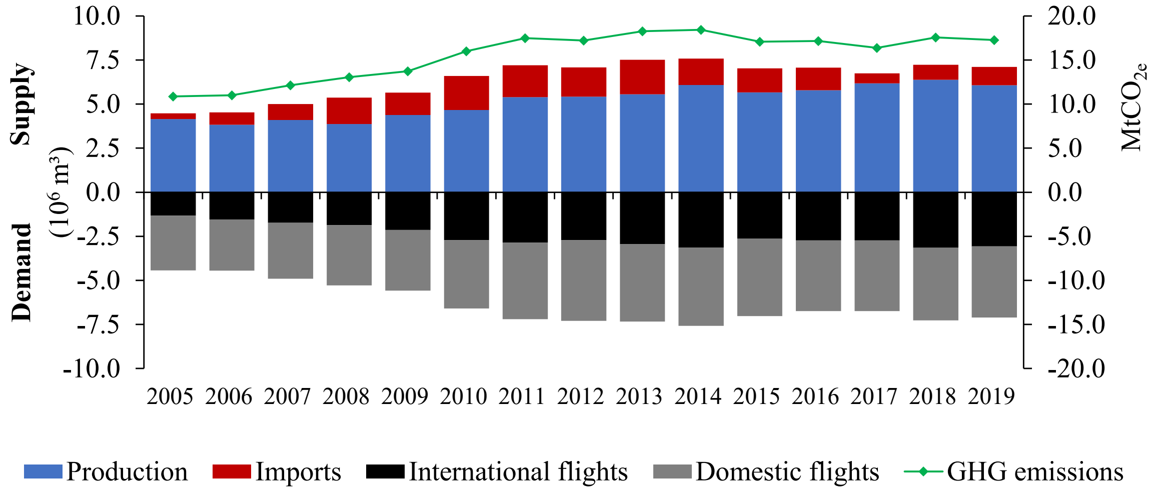


Figure 1.3: Fossil kerosene (Jet A) supply and demand in Brazil, adapted from EPE[53]. GHG emissions estimated according to ANAC[59].

Even with uncertainties related to the future in light of the current crisis, it is forecasted that AJF could supply 1% of the Brazilian demand by fossil kerosene in 2029[57]. In addition, the AJF contribution would reach 14% in 2050, representing an equivalence of around 30% of the fossil kerosene imports[52]. However, the development of a new sector for biofuels to supply customers that have been historically oil-dependent does not happen overnight. So, trends and strategies should be (re)discussed, pointing out the best practices and obstacles to overcome new challenges[18,24,62–64].

In this context, despite the Brazilian aviation sector representing a modest share of global operations, Brazil could be a strategic supplier of AJF, since it has a large bioenergy potential and production and has expertise in modern bioenergy production, which has been reconciled with food security and rural development[3,54].

1.3.2. Pathways for AJF production in Brazil

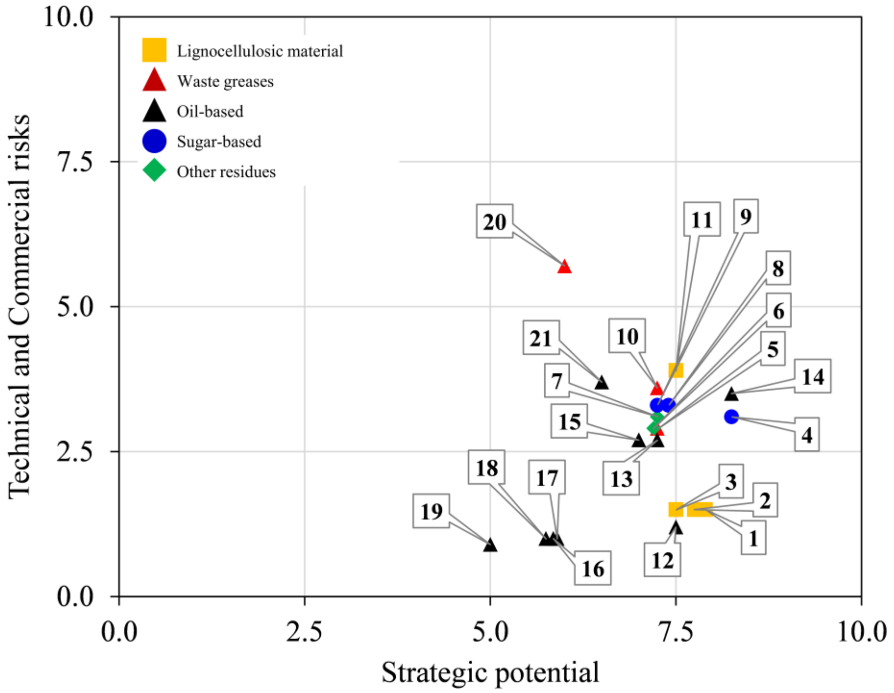
In a recent study, Cortez *et al.*[3] presented a detailed roadmap for aviation biofuels in Brazil, comprising potential feedstocks and pathways. Some results, shown in **Figure 1.4** and **Figure 1.5**, came from a multi-criteria analysis carried in eight workshops with over 30 stakeholders, comprising private and public sector, academia, and non-governmental organizations.

In this study, possible AJF pathways were evaluated in the Brazilian context from technical/commercial risks and strategic potentials. In general, technical risks are related to process complexities, dependency on new or external technologies, and the need for qualified labor. In turn, commercial risks are related to access to feedstocks, possible competition with existing markets, and economic feasibility. Finally, the strategic potential reflects the overall potential of the feedstock or pathway being explored to supply the new demand for AJF. Technical and commercial risks were scored in a range of 0-5 points each, while the strategic potential was scored in 0-4 points. The scores of both former aspects were combined in the same axis in a range of 0-10, as in the original reference, while the score of the latter aspect was scaled up to 0-10 in another axis to provide better visualization.

According to **Figure 1.4**, wood residues and sugarcane bagasse were pointed out as strategic feedstocks due to their apparent availability and no direct competition with food supplies.

In 2018, a considerable amount of 45.8 Mt of wood residues on 7.7 Mha of planted forests was generated during field operations (70% of the total) and industrial processes. In the former case, the residues have been kept on the field for agronomic purposes, and in the latter, the residues were internally used for energy supply[65]. On the other hand, sugarcane bagasse has been commonly used in sugarcane mills in combined heat-power systems, which provide roughly 6% of the power generated in Brazil[53] after guaranteeing the self-supply of the industrial plant. Possible competition with current energy use can lead to relevant commercial risks when allocating this material for AJF production.

Furthermore, agricultural residues are related to high technical risks due to technological barriers for collecting and transporting them from the field. Nonetheless, the feasibility of sugarcane straw recovery has been frequently studied in Brazil[66–75] since the current legislation in São Paulo State[76,77] – the major Brazilian sugarcane producer[78] – and other States has promoted the mechanical harvesting of sugarcane without previous-burning.



Feedstocks	
1	Forestry wood residues
2	Sugarcane bagasse
3	Industrial forestry residues
4	Sugarcane
5	Tallow
6	Off-gases
7	MSW
8	Sorghum
9	Cassava
10	UCO
11	Agricultural residues
12	Palm
13	Jatropha
14	Algae
15	Camelina
16	Sunflower
17	Rapessed
18	Peanut
19	Soybean
20	Sewage
21	Other palm trees

Figure 1.4: Multi-criteria analysis for potential AJF feedstocks, adapted from Cortez *et al.*[3]

Of the oil-based feedstocks, well-known oilseeds in Brazil present low risks for supplying the new demand for AJF, but with varying strategic potential. Soybean is presumably the most feasible option in the short-term[79], due to the consolidated supply-chain, an impressive growth rate (8.8% per year, 2007-2018), and huge production in Brazil, which provided 123.1 Mt from 34 Mha in 2018, of which around 65% was exported[80,81], while the remaining is processed in Brazil for producing soybean oil and meal. Currently, soybean oil (1.7 Mt) corresponds to more than 70% of the Brazilian biodiesel production[81].

However, considering the oil content and agricultural yields, oil palm has a higher potential than soybean oil. Although Brazil is currently responsible for only 0.5% of global palm production (1.6 Mt in 0.11 Mha in 2017)[82], using areas mostly located in the northern region because of climate requirements, the agroecological zoning of palm in Brazil has indicated that 29.7 Mha of land is available[83] for crop expansion on deforested Amazonian lands.

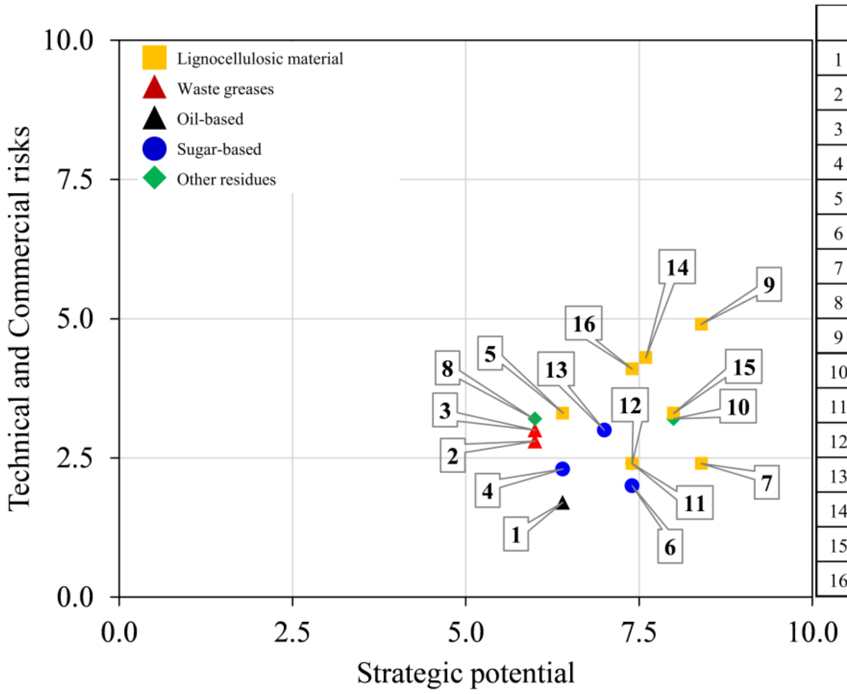
Other oil-based feedstocks – which are not still well-established in Brazil or need to overcome agronomic obstacles, such as camelina and jatropha – present high risks to be used for AJF production in the short-to-medium term[24]. Other palm trees, such as macaw, which has been studied in Brazil[34,84–87], could be included in this range of risk.

In turn, the high agricultural yields of sugarcane, combined with Brazil's remarkable production (620 Mt of sugarcane cropped in 10 Mha[78]) and expertise place sugarcane as a strategic feedstock for the short-term[79]. However, large investments have been required to promote increasing yields and crop expansion in non-traditional areas. Furthermore, the high opportunity cost of the sugarcane products, due to the well-consolidated market of sugar and ethanol, can lead to commercial risks. Other sugar/starch-based pathways such as sorghum and cassava have lower potentials since they are non-traditional crops in Brazil for energy applications and gaps regarded to agronomic and industrial issues must yet be overcome.

Other waste materials – such as used cooking oil (UCO), beef tallow, and flue gases – show high risks due to the low or scattered availability and the need for pre-treatments before industrial processing due to impurities. Furthermore, competition with current use practices can increase commercial risks. For instance, beef tallow is mostly consumed by the biodiesel industry in Brazil[53], providing roughly 15% of the national biodiesel production in the last years[88]. Furthermore, several Brazilian steel mills have recovered off-gases to be internally used as energy source[89].

A similar evaluation was carried out for potential technologies for producing AJF, comprising intermediary processes – such as fermentation, gasification, and hydrolysis – and refining technologies (certified by ASTM[49] or not). Technical complexity, technological availability, market acceptance of the products, and the probability of success were some of the aspects considered.

Figure 1.5 combines both evaluations related to feedstocks and technologies. The pathways were divided into 1G (*i.e.*, food-based) and 2G pathways (*i.e.*, residues-based). According to this figure, ATJ pathways from lignocellulosic materials (wood residues and sugarcane bagasse) had the best combination of low risk and high strategic potential. ATJ from 1G sugarcane ethanol and FT pathways also had a good performance, but the opportunity costs related to intermediary products in the former case and the technical obstacles to reach industrial scale in the later are relevant barriers. The low maturity of other thermochemical technologies (FP and HTL) and intermediary processes, such as "sugar-to-lipids" and gas fermentation, justify the poor performance of these pathways. Finally, HEFA pathways, which are already based on well-established technologies, presented low strategic potential (on average) for oilseeds due to possible food competition, oil content, and agricultural yields for not well-known crops in Brazil. The high commercial risks for waste grease-based pathways would be related to the effective availability and possible competition with the current use.



	Pathways
1	HEFA - Vegetable oil (average value)
2	HEFA - Beef tallow
3	HEFA - UCO
4	HEFA - Lipids from sugar-base material
5	HEFA - Lipids from lignocellulosic material
6	ATJ - 1G alcohol from sugar-base material
7	ATJ - 2G ethanol from lignocellulosic material
8	ATJ - 2G ethanol from off-gases
9	ATJ - 2G ethanol from syngas
10	ATJ - 2G ethanol from MSW
11	FT - Lignocellulosic material
12	FT - Bio-oil/Char from lignocellulosic material
13	DSCH - sugar-based material
14	DSCH - lignocellulosic material
15	FP - Lignocellulosic material
16	HTL - Lignocellulosic material

Figure 1.5: Multi-criteria analysis for the potential AJF pathways evaluated by Cortez *et al.*[3]

1.3. Knowledge gaps and research questions

Although ICAO goals are clearly associated with GHG reductions on international flights, the production and use of AJF may lead to a strategic energy transition in a sector historically dependent on fossil fuels.

To provide a sustainable energy transition, the potential of each AJF pathway should be evaluated in a broader perspective, *i.e.*, from different methodological approaches, combining environmental and economic issues, and considering other environmental aspects beyond GHG reductions. In this context, an overarching research question arises, ***can Brazil help a sustainable energy transition for the aviation sector?*** The present thesis is fully developed on this question, aiming to extend (and to deepen) this discussion addressing the research gaps and research questions identified as follows.

1.3.1. Potential reduction of GHG emissions through AJF

The potential GHG reduction of biofuels in comparison to their fossil counterparts is a crucial indicator for the decision-making process. Generally, this indicator is estimated using the Life Cycle Assessment (LCA) tool, where GHG emissions along the whole biofuel life cycle are inventoried and compiled.

In general, different results are expected for AJF from different feedstocks, conversion technologies, and supply-chains. However, the high sensitivity of the outcomes with respect to methodological choices – such as system boundaries, inventories assumptions including (or not) consequential aspects, characterization factors, co-products handling, Land Use Change (LUC) effects – are well known and they can lead to a wide range of results for the same pathway, as presented by Capaz and Seabra[90] (see **Figure 1.6**).

Some authors[91–93] suggest that the way the systems are modeled should be strictly dependent on the questions that are addressed. In this sense, if the interest lays on attributing impacts to a specific product based exclusively on its supply-chain flows, or on estimating the consequences by changing demand, the LCA can be carried out through two different approaches: attributional LCA (ALCA) or consequential LCA (CLCA), respectively[94–99].

Generally, ALCA describes the production system using average data assuming a *status-quo* configuration, and the allocation of the environmental burden to the co-products is considered a consistent method in a *cause-oriented* approach as attributional analysis. In turn, the CLCA approach focuses on the direct (and indirect) effects of a demand of a product or service. The inventory should be comprised of marginal data, including the possible effects related to co-production, which is suitably handled by system expansion[93–96,100–103].

Nevertheless, the methodological assumptions in several studies are not linked to a research question; or a mix of assumptions are taken without a clear and careful association to the attributional or consequential proposal of the study[93,96,101]. In addition, some studies have reduced the consequential analysis to a sensitivity parameter of co-product handling, while other have assumed similar background datasets for both analyses, which can lead to discrepancies[104].

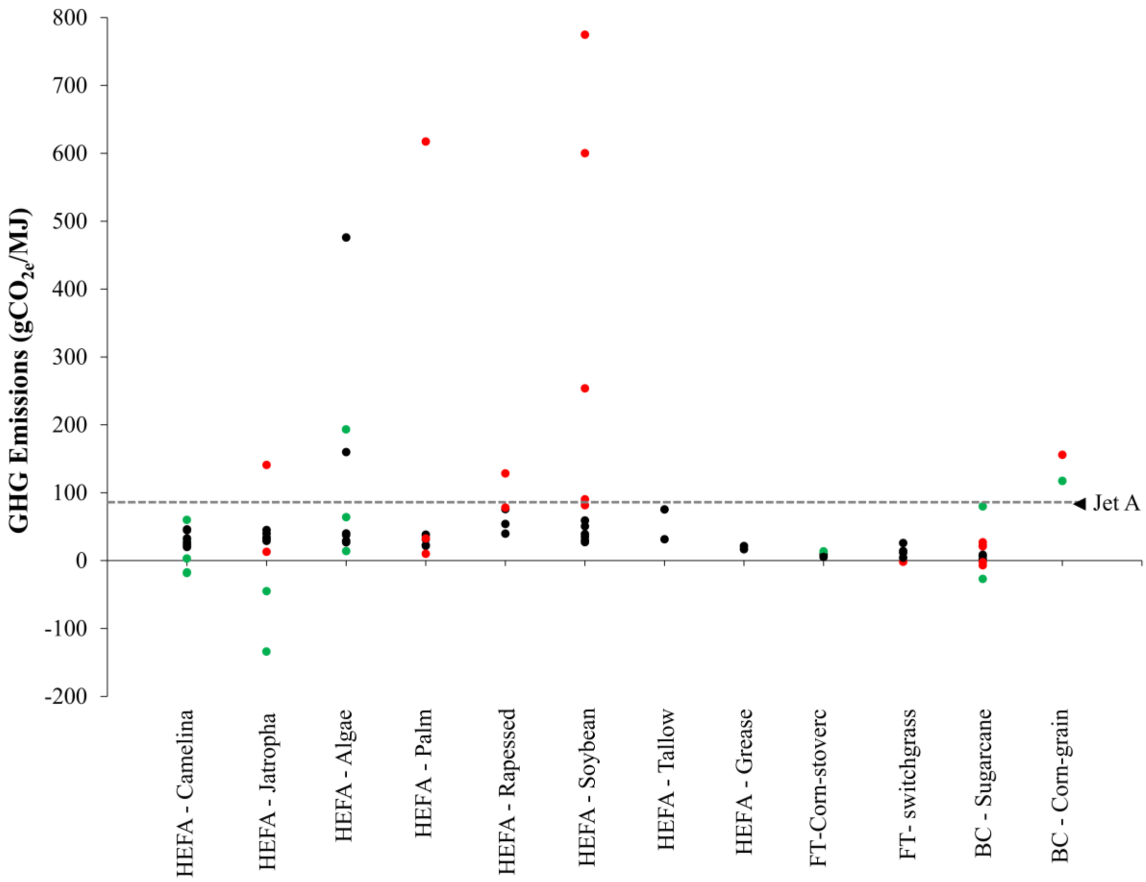


Figure 1.6: Range of LCA results related to AJF in comparison to fossil kerosene (Jet A). Red dots include emissions from land use change (LUC). Green dots include consequential aspects. HEFA: Hydroprocessed Esters and Fatty Acids; FT: Fischer-Tropsch; BC: Biochemical Conversion. Adapted from Capaz and Seabra[90].

For instance, if Camelina meal is used as a fuel or to displace soybean meal, the GHG emissions of AJF from Camelina oil could be 60 gCO_{2e}/MJ [26] or -18 gCO_{2e}/MJ [105,106], respectively (see **Figure 1.6**).

Likewise, if seedcake and husks are used as fertilizer, the life cycle performance of AJF from Jatropha would be 40 gCO_{2e}/MJ; but if these co-products substitute fuel oil in a boiler or are used for power generation displacing the US grid electricity, the GHG emissions would be negative (-134 gCO_{2e}/MJ [27] and -45 gCO_{2e}/MJ [107]), respectively. In turn, GHG emissions from sugarcane molasses RJF were reported near fossil kerosene (80 gCO_{2e}/MJ) if sorghum were to replace the current molasses use[108].

Besides the consequential aspects, the emissions related to LUC can lead to high variance in the results (see **Figure 1.6**). For instance, the estimated carbon footprint of AJF from Jatropha ranges between 13 gCO_{2e}/MJ, if Jatropha is planted on agricultural or pasture lands, and 141 gCO_{2e}/MJ, if it is cultivated on original shrublands[27]. Similarly, GHG emissions from AJF produced from soybean oil could vary from 80 to 775 gCO_{2e}/MJ, assuming that *Cerrado* fields (Brazilian savanna) and tropical rainforest areas are converted to grow soybean crop, respectively[107]. Emissions were estimated between 10 and 617 gCO_{2e}/MJ, for AJF from palm oil, assuming that, respectively, logged-over forests and peatland rainforests[109] are converted. For FT-switchgrass, AJF could lead to a mitigation of -2.0 gCO_{2e}/MJ[107] considering the effect of carbon sequestration. Finally, the DSHC of sugarcane sugars would feature life cycle emissions of 21 gCO_{2e}/MJ[42], considering the direct and indirect effects of land use change in Brazil.

Alternatively, Low-Carbon Policies (LCP) for promoting biofuel production – such as the *Renewable Energy Directive* (RED II)[110] in Europe, the *Renewable Fuel Standard* (RFS)[97] in the United States, *Renovabio*[111] in Brazil, and (CORSIA)[11] for the international aviation sector – are fundamentally based on GHG emission accounting. Then, a given biofuel may have different potentials for emissions reduction according to the different LCPs, due to specific assumptions, databases, and tools[112,113]. Regarding the potential of Brazil as an international supplier of AJF, it would be strategic to estimate the AJF performance under each regulatory scheme.

In this context, to have a clearer and more comprehensive understanding of the potential of AJF for reducing GHG emissions, the following research question is addressed in this thesis: *Could AJF produced in Brazil reduce the GHG emissions in comparison with fossil fuel?**(RQ1)***. To address this research question, the performance of promising AJF pathways was evaluated under six methodological approaches, including: ALCA and CLCA, and four LCP regulatory systems (*Renovabio*, CORSIA, RFS, and RED) – seeking for trends and conflicts, rankings the AJF pathways, and indicating the critical issues for each approach.

1.3.2. Mitigation costs of AJF

According to the current CORSIA guidelines[14–17], airline operators can achieve their carbon reduction requirements by purchasing carbon credits and/or by using *"eligible fuels"*[14], *i.e.*, AJFs, which fit the sustainability criteria mentioned in **section 1.1**.

Although several studies have confirmed the potential GHG reduction from AJFs in comparison to fossil kerosene, the vast majority of the pathways are not yet economically competitive (see **Table 1.2**). Furthermore, the lowest-cost pathway is not necessarily the one that provides the most significant carbon reductions.

Table 1.2: Minimum Selling Price (MSP) of AJF and GHG emissions of AJF along its life cycle

Feedstock	AJF technology	MSP (USD/GJ)[a]	GHG emission ($kgCO_{2e}/GJ$)[b]
Fossil kerosene	**-**	**13.4 - 17.7**	**89.0**
Soybean	HEFA	23.1 [34] 37.2 [117]	67.4 *(40.4)* [118] *(22.0)* [34] *(40.1)* [21]
Palm	HEFA	18.4 [34]	76.5 *(37.4)* [118] *(17.0)* [34] *(14.2)* [21]
UCO	HEFA	28.4 [117] 33.3 [119]	13.9 [118] 27.0 [120]
Beef tallow	HEFA	33.1 [117]	22.5 [118] 29.8 [25]
Sugarcane	ATJ (via 1G ethanol)	51.8 [121] 27.2 [34] 44.9 [37]	32.8 *(24.1)* [118] *(20.5)* [34] *(26.0)* [120]
Lignocellulosic residues	ATJ (via 2G ethanol)	78.8 [121] 36.6 [34] 64.0 - 67.7 [37] 55.5 [119]	35.0 [120] 28.4 [122] 24.8 [34]
Lignocellulosic residues	FT	56.0 [121] -6.9 to 11.2 [34] 46.6 [119]	7.7 to 8.3 [118] 6.0 [120] 6.8 [122] 8.6 [34]
Lignocellulosic residues	HTL	24.4 [119]	18 to 20 [120]

[a] When necessary, the MSP were converted in USD/GJ taking the exchange rate (1.1096 USD/EUR), density and heating values assumed in the original reference. It was assumed: 32.0 GJ/m^3 and 0.735 t/m^3 for the LHV and density of AJF[141], respectively, when these data were not available in the original reference. For comparison, the average price of fossil kerosene in Brazil, which follows the international oil market, ranged from 13.4 to 17.4 USD/GJ between 2017-2019[88].
[b] The values in parenthesis, only 1G pathways, represent GHG emissions related to the life cycle without land use change (LUC). All these values were retrieved from other references and were estimated considering allocation approaches for co-products, preferably energy allocation as set out by CORSIA guidelines[142]. The default emission factor for fossil kerosene assumed in CORSIA is 89.0 $kgCO_{2e}/MJ$[143].

Regarding techno-economic feasibility, some trends have been observed when comparing the lower production costs related to AJF obtained from used cooking oil in contrast to the higher ones related to AJF from 2G ethanol. Some discrepancies were estimated by Klein *et al.*[34], who assumed AJF production integrated to an ethanol distillery. In that case, the minimum selling price (MSP) of AJF could even result in negative values for FT of lignocellulosic residues due to the great profits from co-product revenues. On the other hand, in general, residues-based pathways have lower carbon emissions than those of 1G-based pathways, mainly because of LUC emissions arising from the latter and the null environmental burden related to the upstream activities in the former.

Furthermore, the mitigation costs (USD/tCO_{2e} reduced) related to AJF pathways and their competitiveness with the emission units traded in the carbon market have been explored in very few studies with limited scope. Baral *et al.*[114] reported on the mitigation costs of aviation fuels obtained from ionic liquid-based processes. Carvalho *et al.*[115] discussed the feasibility of HEFA from soybean oil and FT of lignocellulosic material assuming carbon taxes. Finally, Pavlenko *et al.*[116] identified the production pathways for alternative jet fuels that offer the most cost-effective carbon reductions in the European Union.]

These issues were addressed through the following question*: How much would cost the carbon mitigated by each AJF pathway?* ***(RQ2).*** Similar pathways addressed for ***RQ1*** in the previous subsection were evaluated here by their mitigations costs (USD/tCO_{2e}) and the potential for supplying AJF in Brazil. Finally, they were compared with the offsetting market-measures considering that both options have been regarded by the CORSIA guidelines as equally applicable mechanisms.

1.3.3. Beyond the carbon footprint

As mentioned previously (see **Figure 1.6** and **Table 1.2**) the potential GHG emissions reduction by using AJF has been largely explored in the literature, considering the ambitious ICAO goals. However, only a tiny share of these studies[21,34,108,122,123] has done an extended life cycle assessment to study other impact categories than climate change.

For instance, Staples *et al.*[123] evaluated the water footprint of middle distillate fuels in the United States. Cox *et al.*[108] reported the environmental performance of AJF from microalgae, Pongamia oil, and sugarcane molasses in Australia, in terms of eutrophication potential and water, land, and fossil energy usage. Klein *et al.*[34] analyzed different designs for producing AJF integrated with sugarcane mills in Brazil, addressing environmental aspects related to human toxicity, terrestrial acidification, agricultural land occupation and fossil depletion. Cavalett and Cherubini[122] investigated AJF production from forest residues in Norway and studied the environmental issues within the context of the Sustainable Development Goals (SDGs)[124]. Finally, Vásquez *et al.*[21] compared AJF production from soybean oil and palm oil for seven mid-point environmental impact categories, and four damage indicators.

The above-mentioned studies are scope-limited by either considering a few categories or a small number of technological options in specific contexts. Thus, possible trade-offs between climate change and other environmental impact categories remain unexplored.

In this sense, it is relevant to ask: *could AJF production lead to other environmental benefits beyond GHG emissions mitigation*? **(RQ3).** Aiming to fill this knowledge gap, we carried out a harmonized attributional life cycle assessment comprising promising and strategic pathways in Brazil. Trade-offs between GHG emissions and other impact categories were analyzed, such as fossil depletion, terrestrial acidification, eutrophication, human and environmental toxicity, particulate matter and photochemical oxidant formation.

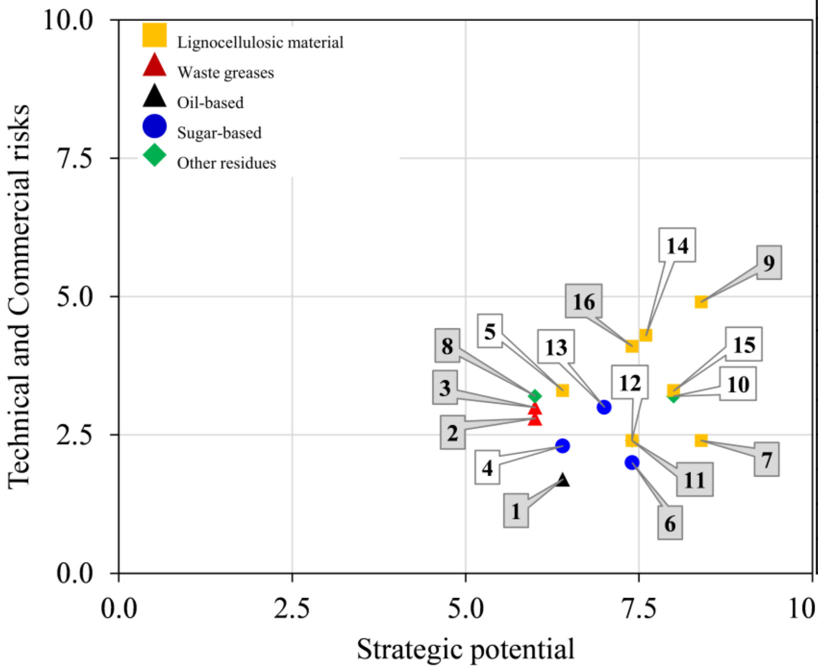
Notwithstanding the environmentally sound appeal of using wastes as feedstocks, it is frequently argued if such materials could still be regarded as wastes as their use gains relevance, while in some instances, alternative uses may already be consolidated. The effects on the environmental performance of AJF pathways (on life cycle basis) from residual feedstocks were explored in this chapter, considering the rather arbitrary definitions around wastes and by-products.

1.4. Selected AJF pathways addressed in this thesis

This thesis focuses on eight pathways labeled in grey boxes in **Figure 1.7**, mostly based on approved technologies for AJF production (see **Table 1.1**). These pathways can be differentiated into up to fourteen pathways when considering palm oil, forestry residues, and sugarcane residues separately.

From the 1G pathways, three pathways reported with low risks by Cortez *et al.*[3] were evaluated: the hydrotreatment of soybean oil (Soy/HEFA) and palm oil (Palm/HEFA), and the dehydration/oligomerization of 1G sugarcane ethanol (SC-1G/ATJ). Soy/HEFA and SC-1G/ATJ have been considered the most feasible pathways in the short-term for Brazil[79], while Palm/HEFA could be developed through a strategic palm expansion in the coming years.

Regarding Soy/HEFA, it is reasonable to expect that AJF from soybean would come from soybean crop expansion to avoid competition with the current market, even considering the remarkable soybean production in Brazil, which corresponds to 35% of the global production[81]. There is a recognized potential for soybean expansion in Brazil, and soybean production has broken production records year after year[81]. Furthermore, the Brazilian Soy Moratorium – an agreement between soybean producers – has managed the concerns about soybean expansion into the Amazon forest. From this agreement, the deforestation rate in Amazon areas with soybean production fell from 0.85 Mha/year (2002-2008) to 0.18 Mha/year (2008-2018). In 2018/2019, only 1.8% of the deforested area in the Amazon region was linked to soybean production[125]. On the other hand, despite the considerable soybean expansion onto pasturelands over the last decade, a rapid expansion onto native vegetation areas of Brazilian savannas (Cerrado biome) has been observed[126], which also motivated some discussions since the relevant ecological role of cerrado for regional climate stabilization and biodiversity preservation.



	Pathways
1	HEFA - Vegetable oil (average value)
2	HEFA - Beef tallow
3	HEFA - UCO
4	HEFA - Lipids from sugar-base material
5	HEFA - Lipids from lignocellulosic material
6	ATJ - 1G alcohol from sugar-base material
7	ATJ - 2G ethanol from lignocellulosic material
8	ATJ - 2G ethanol from off-gases
9	ATJ - 2G ethanol from syngas
10	ATJ - 2G ethanol from MSW
11	FT - Lignocellulosic material
12	FT - Bio-oil/Char from lignocellulosic material
13	DSCH - sugar-based material
14	DSCH - lignocellulosic material
15	FP - Lignocellulosic material
16	HTL - Lignocellulosic material

Figure 1.7: Multi-criteria analysis for the potential AJF pathways evaluated by Cortez et al.[3]. The AJF pathways evaluated in this thesis are indicated in the grey boxes.

Similar to Soy/HEFA, the potential production of AJF from sugarcane via 1G ethanol could be supplied by sugarcane expansion. According to the agro-zoning plan for sugarcane expansion[127], around 11.3 Mha of pasturelands would be highly suitable for sugarcane expansion. In turn, the potential of Palm/HEFA is directly linked with the possible expansion onto degraded areas[83]. On the other hand, there is permanent concern about the palm production areas being developed close to the Amazon rainforest[128,129]. It is worth mentioning that using palm oil for biodiesel production, especially by smallholders, was a constant promise in the early years of the Brazilian Biodiesel program. Due to technical and mainly political problems, palm production did not take off[130] and Brazil continues to be a net importer of palm oil, which is mostly used for food[131]. The possible AJF production from palm oil also must tackle these challenges.

Promising 2G pathways based on forestry residues and sugarcane residues were also evaluated, such as ATJ from 2G ethanol and Fischer-Tropsch. The technologies considered for 2G ethanol production comprise the enzymatic hydrolysis of the lignocellulosic feedstocks, after pretreatment [38], and gasification of lignocellulosic material with subsequent syngas fermentation[41,132]. Although AJF production through Hydrothermal liquefaction (HTL) of lignocellulosic residues is still a non-approved pathway, it was also investigated as an attractive alternative since its lower costs in comparison with other alternatives[47,119]. However, it is important to stress that, regardless of the bottlenecks related to the industrial processes, the effective availability of the feedstock is a crucial issue. The availability of the sugarcane residues considered here (bagasse and straw), which is currently used in sugarcane mills, depends on the technological improvements at the industrial plants to provide surplus materials after guaranteeing the self-supply[133]. On the other hand, forestry residues emerge as a strategic feedstock for AJF production since they are highly available on fields[65].

Aiming to evaluate the performance of waste grease-based pathways, the hydrotreating of UCO and beef tallow was also included in the present thesis. While the beef tallow has already been demanded by a consolidated market, including biodiesel production, the potential production of AJF from UCO is a bit uncertain. Despite increasing initiatives for collecting and using UCO, there is no well-developed supply-chain for that in Brazil like in Europe[134]. Even so, this pathway has already been used in some commercial flights[135] and is commonly investigated as a promising feedstock due to the potentially low costs[25,120,136–138].

Finally, the pathway based on 2G ethanol obtained from steel off-gases was also explored for Brazil, combining a novel technology for producing ethanol by fermenting CO-rich gases – which has already reached the commercial scale[40,139,140] – with the potential of the Brazilian steel industry. **Table 1.3** summarizes all pathways evaluated in this thesis. Some of them were not considered in all chapters due to the chapter's scope and the available data when the chapter was developed.

Table 1.3: AJF pathways evaluated in this thesis

Pathway		Feedstock	Technology for AJF conversion	Chapters		
				2	3	4
1	Soy/HEFA	Soybean oil	HEFA	X	X	X
2	Palm/HEFA	Palm oil	HEFA	X	X	
3	UCO/HEFA	UCO	HEFA	X	X	X
4	Tallow/HEFA	Beef tallow	HEFA	X	X	X
5	SC-1G/ATJ	1G ethanol from sugarcane	ATJ	X	X	X
6	SC-2Gh/ATJ	2G ethanol from sugarcane residues	Enzymatic hydrolysis / ATJ	X	X	X
7	SC-2Gs/ATJ	2G ethanol from sugarcane residues	Syngas fermentation / ATJ			X
8	FR-2Gh/ATJ	2G ethanol from forestry residues	Enzymatic hydrolysis / ATJ	X	X	X
9	FR-2Gs/ATJ	2G ethanol from forestry residues	Syngas fermentation / ATJ			X
10	SOG-2G/ATJ	2G ethanol from steel off-gases	Gas fermentation/ATJ	X	X	
11	SC/FT	Sugarcane residues	Fischer-Tropsch	X	X	X
12	FR/FT	Forestry residues	Fischer-Tropsch	X	X	X
13	SC/HTL	Sugarcane residues	Hydrothermal liquefaction		X	
14	FR/HTL	Forestry residues	Hydrothermal liquefaction		X	

1.5.Thesis outline

Considering the knowledge gaps and research questions mentioned previously, this thesis is outlined as presented in **Table 1.4.**

Table 1.4: Thesis outline and related research questions

Chapters	Research questions		
	RQ1	RQ2	RQ3
Chapter 1: *Introduction*	-	-	-
Chapter 2: *The carbon footprint of alternative jet fuels produced in Brazil: exploring different approaches*	X		
Chapter 3: *Mitigating carbon emissions through sustainable aviation fuels: costs and potential*		X	
Chapter 4: *Environmental trade-offs of renewable jet fuels in Brazil: beyond the carbon footprint*			X
Chapter 5: *Discussions*	X	X	X
Chapter 6: *Conclusions*	-	-	-

It is worth mentioning that the *alternative jet fuel* (AJF) was also referred to here as *sustainable aviation fuel* (SAF, in **Chapter 3**) or *renewable jet fuel* (RJF, **in Chapter 4**), according to the suggestion of the journal's editor or reviewers where these chapters were published. Regardless of that, these acronyms intend to mean "drop-in aviation fuels", already approved or not.

References

1. IEA. Key World Energy Statistics [Internet]. Paris; 2019. Available from: www.iea.org/statistics/
2. IEA. Data and Statistics [Internet]. 2020 [cited 2020 Apr 28]. Available from: https://www.iea.org/data-and-statistics
3. Cortez LAB, Nigro FEB, Nassar AM, Cantarella H, Nogueira LAH, Moraes MAFD de, et al. Roadmap for sustainable aviation biofuels for Brazil — A Flightpath to Aviation Biofuels in Brazil [Internet]. São Paulo: Edgard Blücher; 2014. 272 p. Available from: http://openaccess.blucher.com.br/article-list/roadmap-aviation-272/list
4. Teter J, Feuvre P Le, Bains P, Re L Lo. Aviation - Tracking report [Internet]. 2020 [cited 2020 Jul 25]. Available from: https://www.iea.org/reports/aviation
5. Maniatis K, Weitz M, Zschocke A. 2 million tons per year: a performing biofuels supply chain for EU aviationNo Title [Internet]. 2011. Available from: https://ec.europa.eu/energy/sites/ener/files/20130911_a_performing_biofuels_supply_chain.pdf
6. IEA. IEA Sankey Diagram [Internet]. 2020 [cited 2020 Jul 25]. Available from: https://www.iea.org/sankey/
7. ICAO. Annual Report of the Council - 2018 [Internet]. *Annual Reports of the Council.* Montreal; 2019 [cited 2020 Aug 7]. Available from: https://www.icao.int/publications/pages/annual-reports.aspx
8. Gonçalves VK. Climate Change and International Civil Aviation Negotiations. *Context Int [Internet]*. 2017 May 8;39(2):443–58. Available from: http://www.scielo.br/scielo.php?script=sci_arttext&pid=S0102-85292017000200443&lng=en&tlng=en
9. ICAO. Resolutions 37th Assembly [Internet]. 2010. Available from: http://www.icao.int/Meetings/AMC/Assembly37/Documents/ProvisionalEdition/a37_res_prov_en.pdf
10. ATAG. Beginners's Guide to Aviation Eficiency [Internet]. 2010. p. 24. Available from: http://www.atag.org/our-publications/latest.html
11. ICAO. Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) [Internet]. *International Civil Aviation Organization.* 2020 [cited 2020 Apr 28]. Available from: https://www.icao.int/environmental-protection/Pages/market-based-measures.aspx
12. ICAO. Assembly Resolutions in Force; A39-2: Consolidated statement of continuing ICAO policies and practices related to environmental protection — Climate change [Internet]. Montreal; 2016. Report No.: Doc 10075. Available from: https://www.icao.int/Meetings/a39/Documents/Resolutions/10075_en.pdf
13. The Guardian. Airlines lobby to rewrite carbon deal in light of coronavirus. 2020; Available from: https://www.theguardian.com/business/2020/apr/08/airlines-lobby-to-rewrite-carbon-deal-due-to-coronavirus
14. ICAO. Annex 16 - Environmental Protection, Volume IV - Carbon Offsetting and Reduction Scheme for Internationl Aviation (CORSIA) [Internet]. Montreal; 2018. Available from: https://www.icao.int/environmental-protection/CORSIA/Pages/SARPs-Annex-16-Volume-IV.aspx

15. ICAO. Doc 9501, Envinronmental Technical Manual Volume IV, Procedures for demonstrating compliance with the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) [Internet]. Montreal, Canada; 2019. Available from: https://www.icao.int/environmental-protection/CORSIA/Pages/ETM-V-IV.aspx
16. ICAO. Doc 9 -CORSIA Emissions Unit Eligibility Criteria [Internet]. Montreal; 2019. Available from: https://www.icao.int/environmental-protection/CORSIA/Pages/implementation-elements.aspx
17. ICAO. Doc 8 - CORSIA Eligible Emission Units [Internet]. Montreal; 2020. Available from: https://www.icao.int/environmental-protection/CORSIA/Pages/implementation-elements.aspx
18. ICAO. Sustainable Aviation Fuel Guide [Internet]. 2017. Available from: https://www.icao.int/environmental-protection/GFAAF/Pages/default.aspx
19. Karatzos S, Mcmillan J, Saddler J. The potential and challenges of "drop in" biofuels [Internet]. *IEA Bioenergy - Task 39*. 2014. Available from: http://task39.org/files/2014/01/Task-39-drop-in-biofuels-report-summary-FINAL-14-July-2014-ecopy.pdf
20. CAAFI. Commercial Aviation Alternative Fuels Initiative - Glossary [Internet]. 2019 [cited 2019 Oct 31]. Available from: http://www.caafi.org/resources/glossary.html#D
21. Vásquez MC, Martínez A, Castillo EF, Silva EE. Holistic approach for sustainability enhancing of hydrotreated aviation biofuels, through life cycle assessment: A Brazilian case study. *J Clean Prod [Internet]*. 2019 Nov;237(2019):117796. Available from: https://linkinghub.elsevier.com/retrieve/pii/S0959652619326563
22. Pearlson MN. A Techno-economic and Environmental Assessment of Hydroprocessed Renewable Distillate Fuels [Internet]. *Department of Aeronautics and Astronautics*. Massachusetts Institute of Technology; 2011. Available from: http://dspace.mit.edu/bitstream/handle/1721.1/65508/746766700.pdf?sequence=1
23. Chuck CJ. Biofuels for Aviation: Feedstocks, Technology and Implementation. *Vol. 1, Statewide Agricultural Land Use Baseline 2015*. Elsevier; 2016. 374 p.
24. Cortez LAB. Roadmap for sustainable aviation biofuels for Brazil. *Blucher, editor.* São Paulo; 2014. 272 p.
25. Seber G, Malina R, Pearlson MN, Olcay H, Hileman JI, Barrett SRH. Environmental and economic assessment of producing hydroprocessed jet and diesel fuel from waste oils and tallow. *Biomass and Bioenergy [Internet]*. 2014;67:108–18. Available from: http://linkinghub.elsevier.com/retrieve/pii/S0961953414002189
26. Agusdinata DB, Zhao F, Ileleji K, DeLaurentis D. Life cycle assessment of potential biojet fuel production in the United States. *Environ Sci Technol [Internet]*. 2011;45(21):9133–43. Available from: http://www.ncbi.nlm.nih.gov/pubmed/21958200
27. Bailis RE, Baka JE. Greenhouse gas emissions and land use change from Jatropha curcas-based jet fuel in Brazil. *Environ Sci Technol.* 2010;44(22):8684–91.
28. Li X, Mupondwa E. Life cycle assessment of camelina oil derived biodiesel and jet fuel in the Canadian Prairies. *Sci Total Environ [Internet]*. 2014;481(1):17–26. Available from: http://dx.doi.org/10.1016/j.scitotenv.2014.02.003
29. REN21. Renewables 2020 - Global Status Report [Internet]. Paris; 2020. Available from: https://www.ren21.net/reports/global-status-report/
30. Li L, Coppola E, Rine J, Miller JL, Walker D. Catalytic Hydrothermal Conversion of

Triglycerides to Non-ester Biofuels. *Energy & Fuels [Internet]*. 2010 Feb 18;24(2):1305–15. Available from: https://pubs.acs.org/doi/10.1021/ef901163a

31. McGarvey E, Tyner WE. A stochastic techno-economic analysis of the catalytic hydrothermolysis aviation biofuel technology. *Biofuels, Bioprod Biorefining [Internet]*. 2018 May;12(3):474–84. Available from: http://doi.wiley.com/10.1002/bbb.1863
32. Boeing, Embraer, Fapesp, Unicamp. Flightpath to aviation BioFuels in Brazil: Action Plan. 2013;54. Available from: http://www.fapesp.br/publicacoes/flightpath-to-aviation-biofuels-in-brazil-action-plan.pdf
33. Staples MD, Malina R, Olcay H, Pearlson MN, Hileman JI, Boies A, et al. Lifecycle greenhouse gas footprint and minimum selling price of renewable diesel and jet fuel from fermentation and advanced fermentation production technologies. *Energy Environ Sci [Internet]*. 2014;7(5):1545. Available from: http://xlink.rsc.org/?DOI=c3ee43655a
34. Klein BC, Chagas MF, Junqueira TL, Rezende MCAF, Cardoso T de F, Cavalett O, et al. Techno-economic and environmental assessment of renewable jet fuel production in integrated Brazilian sugarcane biorefineries. *Appl Energy [Internet]*. 2018 Jan;209(August 2017):290–305. Available from: https://doi.org/10.1016/j.apenergy.2017.10.079
35. Atsonios K, Kougioumtzis M, D. Panopoulos K, Kakaras E. Alternative thermochemical routes for aviation biofuels via alcohols synthesis: Process modeling, techno-economic assessment and comparison. *Appl Energy [Internet]*. 2015 Jan;138:346–66. Available from: http://dx.doi.org/10.1016/j.apenergy.2014.10.056
36. Geleynse S, Brandt K, Garcia-Perez M, Wolcott M, Zhang X. The Alcohol-to-Jet Conversion Pathway for Drop-In Biofuels: Techno-Economic Evaluation. *ChemSusChem [Internet]*. 2018 Nov 9;11(21):3728–41. Available from: http://doi.wiley.com/10.1002/cssc.201801690
37. Santos CI, Silva CC, Mussatto SI, Osseweijer P, van der Wielen LAM, Posada JA. Integrated 1st and 2nd generation sugarcane bio-refinery for jet fuel production in Brazil: Techno-economic and greenhouse gas emissions assessment. *Renew Energy [Internet]*. 2018 Dec;129:733–47. Available from: http://dx.doi.org/10.1016/j.renene.2017.05.011
38. Bonomi A, Cavalett O, Pereira da Cunha M, Lima MAP, editors. Virtual Biorefinery [Internet]. 1st ed. Cham: Springer International Publishing; 2016. 285 p. (Green Energy and Technology). Available from: http://link.springer.com/10.1007/978-3-319-26045-7
39. Brooks KP, Snowden-Swan LJ, Jones SB, Butcher MG, Lee G-SJ, Anderson DM, et al. Low-Carbon Aviation Fuel Through the Alcohol to Jet Pathway. *In: Biofuels for aviation: feedstocks, technology and implementation.* London: Elsevier Inc.; 2016. p. 109–50.
40. Handler RM, Shonnard DR, Griffing EM, Lai A, Palou-Rivera I. Life Cycle Assessments of Ethanol Production via Gas Fermentation: Anticipated Greenhouse Gas Emissions for Cellulosic and Waste Gas Feedstocks. *Ind Eng Chem Res [Internet]*. 2016 Mar 30;55(12):3253–61. Available from: http://pubs.acs.org/doi/10.1021/acs.iecr.5b03215
41. de Medeiros EM, Noorman H, Maciel Filho R, Posada JA. Production of ethanol fuel

via syngas fermentation: Optimization of economic performance and energy efficiency. *Chem Eng Sci X [Internet]*. 2020 Jan;5:100056. Available from: https://linkinghub.elsevier.com/retrieve/pii/S2590140020300022

42. Moreira M, Gurgel AC, Seabra JEA. Life Cycle Greenhouse Gas Emissions of Sugar Cane Renewable Jet Fuel. *Environ Sci Technol.* 2014;48:14756−14763.
43. Klerk A De. Fischer–Tropsch fuels refinery design. *Energy Environ Sci [Internet].* 2011;4(4):1177. Available from: http://xlink.rsc.org/?DOI=c0ee00692k
44. Zhu Y, Tjokro Rahardjo, S. Valkenburg C, Snowden-Swan L, Jones S, Machinal M. Techno-economic Analysis for the Thermochemical Conversion of Biomass to Liquid Fuels. Richland (USA); 2011.
45. Tews IJ, Zhu Y, Drennan CV, Elliott D., Snowden-Swan LJ, Onarheim K, et al. Biomass direct liquefaction options: technoeconomic and life cycle assessment. *Pacific Northwest National Laboratory.* Washington; 2014.
46. Jones S, Valkenburg C, Walton C. Production of gasoline and diesel from biomass via fast pyrolysis, hydrotreating and hydrocracking: a design case [Internet]. *Pacific Northwest National Laboratory.* Washington; 2009. Available from: http://citeseerx.ist.psu.edu/viewdoc/summary?doi=10.1.1.161.1652%5Cnhttp://www.pnl.gov/main/publications/external/technical_reports/PNNL-18284rev1.pdf
47. Tzanetis KF, Posada JA, Ramirez A. Analysis of biomass hydrothermal liquefaction and biocrude-oil upgrading for renewable jet fuel production: The impact of reaction conditions on production costs and GHG emissions performance. *Renew Energy [Internet].* 2017;113:1388–98. Available from: http://dx.doi.org/10.1016/j.renene.2017.06.104
48. ASTM. ASTM D1655-20b Standard Specification for Aviation Turbine Fuels. West Conshohocken, Pennsylvania, USA; 2020.
49. ASTM. ASTM D7566-20 Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons. West Conshohocken, Pennsylvania, USA; 2020.
50. CAAFI. Current Fuels in the D4054 Qualification Process [Internet]. *Fuel Qualification.* 2020 [cited 2020 Jul 26]. Available from: http://www.caafi.org/focus_areas/fuel_qualification.html
51. Wang W-C, Tao L, Markham J, Zhang Y, Tan E, Batan L, et al. Review of Bio-jet fuel conversion technologies [Internet]. *Technical Report NREL/TP-5100-66291.* 2016. Available from: www.nrel.gov/publications.
52. EPE. Analysis Of Biofuels' Current Outlook 2019 [Internet]. Rio de Janeiro; 2020. Available from: https://www.epe.gov.br/pt/publicacoes-dados-abertos/publicacoes/analise-de-conjuntura-dos-biocombustiveis-2019
53. EPE. National Energy Balance [Internet]. Brasilia; 2020 [cited 2019 Oct 26]. Available from: https://ben.epe.gov.br/BENSeriesCompletas.aspx
54. Augusto Horta Nogueira L, Silva Capaz R. Biofuels in Brazil: Evolution, achievements and perspectives on food security [Internet]. *Vol. 2, Global Food Security.* Elsevier; 2013. p. 117–25. Available from: http://dx.doi.org/10.1016/j.gfs.2013.04.001
55. Nogueira LAH, Capaz RS, Souza SP, Seabra JEA. Biodiesel program in Brazil: learning curve over ten years (2005-2015). *Biofuels, Bioprod Biorefining [Internet].* 2016 Nov;10(6):728–37. Available from: http://doi.wiley.com/10.1002/bbb.1718

56. MapBiomas. Infrastructure data [Internet]. 2020 [cited 2020 Jul 27]. Available from: https://mapbiomas.org/dados-de-infraestrutura?cama_set_language=pt-BR
57. EPE. PDE 2030 – The Ten-Year Energy Expansion Plan 2030 [Internet]. Brasilia; 2020. Available from: http://www.epe.gov.br/pt/publicacoes-dados-abertos/publicacoes/plano-decenal-de-expansao-de-energia-pde
58. ANAC. Air Transport Statistical Database [Internet]. *National Civil Aviation Agency.* 2020 [cited 2020 Jul 30]. Available from: https://www.anac.gov.br/assuntos/dados-e-estatisticas/dados-estatisticos/dados-estatisticos
59. ANAC. National Inventory of the atmospheric emissions of civil aviation - Base 2018. Brasilia; 2019.
60. ICAO. Effects of Novel Coronavirus (COVID-19) on Civil Aviation: Economic Impact Analysis [Internet]. Montreal; 2020. Available from: https://www.icao.int/sustainability/Documents/COVID-19/ICAO_Coronavirus_Econ_Impact.pdf
61. Le Quéré C, Jackson RB, Jones MW, Smith AJP, Abernethy S, Andrew RM, et al. Temporary reduction in daily global CO2 emissions during the COVID-19 forced confinement. *Nat Clim Chang [Internet]*. 2020 Jul 19;10(7):647–53. Available from: http://www.nature.com/articles/s41558-020-0797-x
62. Dodd H. Strategic Considerations [Internet]. *Sustainable Aviation Fuel Symposium - IATA*. Singapore; 2018 [cited 2019 Dec 6]. Available from: https://www.iata.org/events/Pages/alternative-fuels-symposium.aspx
63. Feuvre P Le. The Big Picture [Internet]. *Sustainable Aviation Fuel Symposium - IATA*. Singapore; 2018 [cited 2019 Nov 6]. Available from: https://www.iata.org/events/Pages/alternative-fuels-symposium.aspx
64. IATA. IATA 2015 Report on Alternative Fuels. Effective December 2015. Montreal: International Air Transport Association; 2015. Report No.: 10th Edition.
65. IBA. Annual Report - Brazilian Tree Industry [Internet]. 2019 [cited 2020 Jul 14]. p. 80. Available from: http://iba.org/images/shared/Biblioteca/IBA_RelatorioAnual2017.pdf
66. Cervi WR, Lamparelli RAC, Seabra JEA, Junginger M, van der Hilst F. Bioelectricity potential from ecologically available sugarcane straw in Brazil: A spatially explicit assessment. *Biomass and Bioenergy [Internet]*. 2019 Mar;122(January):391–9. Available from: https://doi.org/10.1016/j.biombioe.2019.02.001
67. Cervi WR, Lamparelli RAC, Seabra JEA, Junginger M, van der Hilst F. Spatial assessment of the techno-economic potential of bioelectricity production from sugarcane straw. *Renew Energy [Internet]*. 2020 Aug;156:1313–24. Available from: https://linkinghub.elsevier.com/retrieve/pii/S0960148119318531
68. de Campos LHF, de Carvalho SJP, Christoffoleti PJ, Fortes C, da Silva JS. Sistemas de manejo da palhada influenciam acúmulo de biomassa e produtividade da cana-de-açúcar (var. RB855453). *Acta Sci - Agron.* 2010;32(2):345–50.
69. Vasconcelos ALS, Cherubin MR, Feigl BJ, Cerri CEP, Gmach MR, Siqueira-Neto M. Greenhouse gas emission responses to sugarcane straw removal. *Biomass and Bioenergy [Internet]*. 2018;113(September 2017):15–21. Available from: https://doi.org/10.1016/j.biombioe.2018.03.002
70. Caldeira-Pires A, Benoist A, Luz SM da, Silverio VC, Silveira CM, Machado FS. Implications of removing straw from soil for bioenergy: An LCA of ethanol

production using total sugarcane biomass. *J Clean Prod [Internet]*. 2018;181:249–59. Available from: https://doi.org/10.1016/j.jclepro.2018.01.119

71. Chum HL, Warner E, Seabra JEA, Macedo IC. A comparison of commercial ethanol production systems from Brazilian sugarcane and US corn. *Biofuels, Bioprod Biorefining [Internet]*. 2014 Mar;8(2):205–23. Available from: http://doi.wiley.com/10.1002/bbb.1448
72. Seabra JEA, Tao L, Chum HL, Macedo IC. A techno-economic evaluation of the effects of centralized cellulosic ethanol and co-products refinery options with sugarcane mill clustering. *Biomass and Bioenergy [Internet]*. 2010;34(8):1065–78. Available from: http://dx.doi.org/10.1016/j.biombioe.2010.01.042
73. Cardoso TF, Watanabe MDB, Souza A, Chagas MF, Cavalett O, Morais ER, et al. Economic, environmental, and social impacts of different sugarcane production systems. *Biofuels, Bioprod Biorefining [Internet]*. 2018 Jan;12(1):68–82. Available from: http://doi.wiley.com/10.1002/bbb.1829
74. Hassuani SJ, Leal MRLV, Macedo I de C. Biomass Power Generation: Sugar Cane Bagasse and Trash. São Paulo; 2005 Mar.
75. Cardoso T de F, Cavalett O, Chagas MF, Morais ER de, Carvalho JLN, Franco HCJ, et al. Technical and economic assessment of trash recovery in the sugarcane bioenergy production system. *Sci Agric [Internet]*. 2013 Oct;70(5):353–60. Available from: http://www.scielo.br/scielo.php?script=sci_arttext&pid=S0103-90162013000500010&lng=en&tlng=en
76. Government of São Paulo State. Law 11241, 19/09/2002 [Internet]. *Dispõe sobre a eliminação gradativa da queima da palha da cana-de-açúcar e dá providências correlatas.* 2002. Available from: https://www.al.sp.gov.br/repositorio/legislacao/lei/2002/lei-11241-19.09.2002.html
77. Government São Paulo State. Agroenviromental protocol [Internet]. 2017 [cited 2017 Nov 19]. Available from: http://www.ambiente.sp.gov.br/etanolverde/
78. UNICAData. Statistics of Sugarcane Industry Union [Internet]. 2020 [cited 2020 Jul 14]. Available from: http://www.unicadata.com.br/
79. Cantarella H, Nassar AM, Cortez LAB, Baldassin R. Potential feedstock for renewable aviation fuel in Brazil. *Environ Dev [Internet]*. 2015;15:52–63. Available from: http://dx.doi.org/10.1016/j.envdev.2015.05.004
80. IpeaData. IGP-DI - General price index domestic supply [Internet]. *Institute for Applied Economic Research.* 2020 [cited 2020 May 5]. Available from: http://www.ipeadata.gov.br/
81. ABIOVE. Database of Oil Brazilian Industry [Internet]. *Brazilian Association of Vegetable Oil Industries.* 2020 [cited 2020 Aug 2]. Available from: http://abiove.org.br/en/statistics/
82. FAO. FAOSTAT [Internet]. *Food and Agriculture Organization.* 2018 [cited 2018 Jan 10]. Available from: http://faostat.fao.org/site/339/default.aspx
83. Ramalho Filho A, Motta PEF. Zoneamento Agroecológico, Produção e Manejo para a Cultura da Palma de Óleo na Amazônia. Rio de Janeiro; 2010.
84. Wang Z, Pashaei Kamali F, Osseweijer P, Posada JA. Socioeconomic effects of aviation biofuel production in Brazil: A scenarios-based Input-Output analysis. *J Clean Prod [Internet]*. 2019 May 16 [cited 2019 May 22];230:1036–50. Available from:

https://www.sciencedirect.com/science/article/pii/S0959652619316713?via%3Dihub#appsec1

85. Carvalho D De, José A, Neto S, Aguiar A, Tamires D, Pereira V. Economic feasibility of biodiesel production from Macauba in Brazil. *Energy Econ [Internet].* 2013;40:819–24. Available from: http://dx.doi.org/10.1016/j.eneco.2013.10.003
86. Fernández-Coppel IA, Barbosa-Evaristo A, Corrêa-Guimarães A, Martín-Gil J, Navas-Gracia LM, Martín-Ramos P. Life cycle analysis of macauba palm cultivation: A promising crop for biofuel production. *Ind Crops Prod [Internet].* 2018 Dec;125(August):556–66. Available from: https://doi.org/10.1016/j.indcrop.2018.09.036
87. Cervi WR, Lamparelli RAC, Seabra JEA, Junginger M, de Jong S, van der Hilst F. Spatial modeling of techno-economic potential of biojet fuel production in Brazil. *GCB Bioenergy [Internet].* 2020 Feb 14;12(2):136–57. Available from: https://onlinelibrary.wiley.com/doi/abs/10.1111/gcbb.12659
88. ANP. Oil, Natural Gas and Biofuels Statistical Yearbook 2019 [Internet]. Rio de Janeiro; 2020. Available from: http://www.anp.gov.br/publicacoes/anuario-estatistico/anuario-estatistico-2020
89. ABM. Seminário de Balanço Energético Global e Utilidades [Internet]. *Seminar on Global Energy Balances and Utiliities.* Belo Horizonte, Brazil: Brazilian Mettalurgy, Materials and Mining Association; 2017 [cited 2019 Oct 20]. Available from: https://www.abmbrasil.com.br/
90. Capaz RS, Seabra JEA. Life cycle assessment of biojet fuels. *In: Chuck CJ, editor. Biofuels for aviation: feedstocks, technology and implementation.* Amsterdam: Academic Press is an imprint of Elsevier; 2016. p. 279–94.
91. Sonnemann G, Vigon B. Global Guidance Principles for Life Cycle Assessment Databases. A Basis for Greener Processes and Products. 'Shonan Guidance Principles. UNEP/SETAP; 2011. 160 p.
92. Guinée JB, Heijungs R, Huppes G, Zamagni A, Masoni P, Buonamici R, et al. Life Cycle Assessment: Past, Present, and Future. *Environ Sci Technol.* 2011 Jan;45(1):90–6.
93. Tillman A-M. Significance of decision-making for LCA methodology. *Environ Impact Assess Rev [Internet].* 2000 Feb;20(1):113–23. Available from: http://linkinghub.elsevier.com/retrieve/pii/S0195925599000359
94. Finnveden G, Hauschild MZ, Ekvall T, Guinée J, Heijungs R, Hellweg S, et al. Recent developments in Life Cycle Assessment. *J Environ Manage [Internet].* 2009 Oct;91(1):1–21. Available from: http://linkinghub.elsevier.com/retrieve/pii/S0301479709002345
95. JCR. International Reference Life Cycle Data System (ILCD) Handbook: General guide for Life Cycle Assessment - Detailed guidance. 1st ed. *Joint Research Centre - Institute for Environment and Sustainability, editor.* Luxembourg; 2010. 417 p.
96. Weidema BP. Market information in life cycle assessment [Internet]. *Vol. 863, Danish Ministry of the Environment.* Denmark: Danish Environmental Protection Agency, Danish Ministry of the Environment; 2003. Report No.: Environmental Project No. 863. Available from: http://www.norlca.org/resources/780.pdf
97. U.S. EPA. Renewable Fuel Standard Program (RFS2) Regulatory Impact Analysis. *EPA-420-R-10-006.* 2010.

98. Miller SA, Keoleian GA. Framework for Analyzing Transformative Technologies in Life Cycle Assessment. *Environ Sci Technol [Internet]*. 2015 Mar 3;49(5):3067–75. Available from: http://pubs.acs.org/doi/10.1021/es505217a
99. Weidema BP, Pizzol M, Schmidt J, Thoma G. Attributional or consequential Life Cycle Assessment: A matter of social responsibility. *J Clean Prod [Internet]*. 2018 Feb;174:305–14. Available from: http://linkinghub.elsevier.com/retrieve/pii/S0959652617325829
100. Brander M. Comparative analysis of attributional corporate greenhouse gas accounting, consequential life cycle assessment, and project/policy level accounting: A bioenergy case study. *J Clean Prod [Internet]*. 2017 Nov;167:1401–14. Available from: https://linkinghub.elsevier.com/retrieve/pii/S0959652617303116
101. Thomassen MA, Dalgaard R, Heijungs R, de Boer I. Attributional and consequential LCA of milk production. *Int J Life Cycle Assess [Internet]*. 2008 Jun 1;13(4):339–49. Available from: http://link.springer.com/10.1007/s11367-008-0007-y
102. Schmidt JH, Weidema BP. Shift in the marginal supply of vegetable oil. *Int J Life Cycle Assess [Internet]*. 2008 May 11;13(3):235–9. Available from: http://dx.doi.org/10.1065/lca2007.07.351
103. Ekvall T, Weidema BP. System boundaries and input data in consequential life cycle inventory analysis. *Int J Life Cycle Assess [Internet]*. 2004;9(3):161–71. Available from: http://link.springer.com/10.1007/BF02994190
104. Weidema BP. Estimation of the size of error introduced into consequential models by using attributional background datasets. *Int J Life Cycle Assess [Internet]*. 2017 Aug 3;22(8):1241–6. Available from: http://link.springer.com/10.1007/s11367-016-1239-x
105. Fan J, Shonnard DR, Kalnes TN, Johnsen PB, Rao S. A life cycle assessment of pennycress (Thlaspi arvense L.) -derived jet fuel and diesel. *Biomass and Bioenergy [Internet]*. 2013;55:87–100. Available from: http://linkinghub.elsevier.com/retrieve/pii/S0961953413000056
106. Shonnard DR, Williams L, Kalnes TN. Camelina-Derived Jet Fuel and Diesel: Sustainable Advanced Biofuels. *Environ Prog [Internet]*. 2010;29(3):382–92. Available from: http://www3.interscience.wiley.com/journal/122545120/abstract
107. Stratton RW, Wong HM, Hileman JI. Life Cycle Greenhouse Gas Emissions From Alternative Jet Fuels, Partnership for Air Transportation Noise and Emission Reduction [Internet]. Cambridge; 2010. Available from: http://web.mit.edu/aeroastro/partner/reports/proj28/partner-proj28-2010-001.pdf.
108. Cox K, Renouf M, Dargan A, Turner C, Klein-Marcuschamer D. Environmental life cycle assessment (LCA) of aviation biofuel from microalgae, Pongamia pinnata , and sugarcane molasses. *Biofuels, Bioprod Biorefining [Internet]*. 2014 Jul;8(4):579–93. Available from: http://doi.wiley.com/10.1002/bbb.1488
109. Wong HM. Life-cycle assessment of greenhouse gas emissions from alternative jet fuels. Massachusetts Institute of Technology; 2008.
110. European Union. Renewable Energy Directive (EU) 2018/2001 - Promotion of the use of energy from renewable sources [Internet]. 2018. Available from: https://eur-lex.europa.eu/eli/dir/2018/2001/oj
111. BRAZIL. Law 13.576 - 26 December 2017 [Internet]. *National Policy of Biofuels (Renovabio).* Brazil; 2017 [cited 2019 May 24]. Available from:

http://www.planalto.gov.br/ccivil_03/_ato2015-2018/2017/lei/L13576.htm
112. Khatiwada D, Seabra J, Silveira S, Walter A. Accounting greenhouse gas emissions in the lifecycle of Brazilian sugarcane bioethanol: Methodological references in European and American regulations. *Energy Policy [Internet]*. 2012;47:384–97. Available from: http://dx.doi.org/10.1016/j.enpol.2012.05.005
113. Pereira LG, Cavalett O, Bonomi A, Zhang Y, Warner E, Chum HL. Comparison of biofuel life-cycle GHG emissions assessment tools: The case studies of ethanol produced from sugarcane, corn, and wheat. *Renew Sustain Energy Rev [Internet]*. 2019 Aug;110(October 2017):1–12. Available from: https://doi.org/10.1016/j.rser.2019.04.043
114. Baral NR, Kavvada O, Mendez-Perez D, Mukhopadhyay A, Lee TS, Simmons BA, et al. Techno-economic analysis and life-cycle greenhouse gas mitigation cost of five routes to bio-jet fuel blendstocks. *Energy Environ Sci [Internet]*. 2019;12(3):807–24. Available from: http://xlink.rsc.org/?DOI=C8EE03266A
115. Carvalho F, Silva FTF, Szklo A, Portugal-Pereira J. Potential for biojet production from different biomass feedstocks and consolidated technological routes: a georeferencing and spatial analysis in Brazil. *Biofuels, Bioprod Biorefining [Internet]*. 2019 Nov 27;13(6):1454–75. Available from: https://onlinelibrary.wiley.com/doi/abs/10.1002/bbb.2041
116. Pavlenko AN, Searle S, Christensen A. The cost of supporting a lternative jet fuels in the European Union. 2019. (2019-5).
117. Bann SJ, Malina R, Staples MD, Suresh P, Pearlson M, Tyner WE, et al. The costs of production of alternative jet fuel: A harmonized stochastic assessment. *Bioresour Technol [Internet]*. 2017 Mar;227:179–87. Available from: https://linkinghub.elsevier.com/retrieve/pii/S0960852416316911
118. ICAO. CORSIA Default Life Cycle Emissions Values for CORSIA Eligible Fuels [Internet]. Montreal; 2019. Available from: https://www.icao.int/environmental-protection/CORSIA/Pages/CORSIA-Eligible-Fuels.aspx
119. de Jong S, Hoefnagels R, Faaij A, Slade R, Mawhood R, Junginger M. The feasibility of short-term production strategies for renewable jet fuels - a comprehensive techno-economic comparison. *Biofuels, Bioprod Biorefining [Internet]*. 2015 Nov;9(6):778–800. Available from: http://doi.wiley.com/10.1002/bbb.1613
120. de Jong S, Antonissen K, Hoefnagels R, Lonza L, Wang M, Faaij A, et al. Life-cycle analysis of greenhouse gas emissions from renewable jet fuel production. *Biotechnol Biofuels [Internet]*. 2017 Dec 14;10(1):64. Available from: http://biotechnologyforbiofuels.biomedcentral.com/articles/10.1186/s13068-017-0739-7
121. Diederichs GW, Ali Mandegari M, Farzad S, Görgens JF. Techno-economic comparison of biojet fuel production from lignocellulose, vegetable oil and sugar cane juice. *Bioresour Technol [Internet]*. 2016 Sep;216:331–9. Available from: http://dx.doi.org/10.1016/j.biortech.2016.05.090
122. Cavalett O, Cherubini F. Contribution of jet fuel from forest residues to multiple Sustainable Development Goals. *Nat Sustain [Internet]*. 2018 Dec 19;1(12):799–807. Available from: http://www.nature.com/articles/s41893-018-0181-2
123. Staples MD, Olcay H, Malina R, Trivedi P, Pearlson MN, Strzepek K, et al. Water consumption footprint and land requirements of large-scale alternative diesel and jet

fuel production. *Environ Sci Technol.* 2013;47(21):12557–65.

124. UN. Work of the Statistical Commission Pertaining to the 2030 Agenda for Sustainable Development: Resolution Adopted by the General Assembly on 6 July 2017 [Internet]. 2017. Available from: http://ggim.un.org/documents/A_RES_71_313.pdf
125. ABIOVE. Soy Moratorium -Twelth Year. São Paulo; 2020.
126. Nepstad LS, Gerber JS, Hill JD, Dias LCP, Costa MH, West PC. Pathways for recent Cerrado soybean expansion: extending the soy moratorium and implementing integrated crop livestock systems with soybeans. *Environ Res Lett [Internet]*. 2019 Apr 15;14(4):044029. Available from: https://iopscience.iop.org/article/10.1088/1748-9326/aafb85
127. Manzatto CV, Assad ED, Bacca JFM, Zaroni MJ, Pereira SEM. Zoneamento Agroecológico da Cana-de Açúcar. *Documentos 110.* Rio de Janeiro; 2009.
128. Branford S, Torres M. Brazilian Amazon oil palm deforestation under control, for now [Internet]. *Mongabay Series: Amazon Agribusiness.* 2018 [cited 2020 Sep 7]. Available from: https://news.mongabay.com/2018/05/brazilian-amazon-oil-palm-deforestation-under-control-for-now/
129. Benami E, Curran LM, Cochrane M, Venturieri A, Franco R, Kneipp J, et al. Oil palm land conversion in Pará, Brazil, from 2006-2014: Evaluating the 2010 Brazilian Sustainable Palm Oil Production Program. *Environ Res Lett.* 2018;13(3).
130. Abreu A de. Prejuízo em cacho - Petrobras enterra centenas de milhões de reais em projeto de biocombustível a partir do dendê, que não produziu nem um litro de óleo. *Revista Piauí [Internet]*. 2020; Available from: https://piaui.folha.uol.com.br/prejuizo-em-cacho/
131. MDIC. COMEX-STAT Brazilian foreign trade statistics [Internet]. *Ministry of Industry, Foreign Trade and Services.* 2019 [cited 2019 Dec 8]. Available from: http://comexstat.mdic.gov.br/en/home
132. de Medeiros EM, Posada JA, Noorman H, Osseweijer P, Filho RM. Hydrous bioethanol production from sugarcane bagasse via energy self-sufficient gasification-fermentation hybrid route: Simulation and financial analysis. *J Clean Prod [Internet]*. 2017 Dec;168:1625–35. Available from: https://doi.org/10.1016/j.jclepro.2017.01.165
133. Seabra JEA, Macedo IC. Comparative analysis for power generation and ethanol production from sugarcane residual biomass in Brazil. *Energy Policy.* 2011 Jan;39(1):421–8.
134. Hillairet F, Allemandou V, Golab K. Analysis of the current development of household UCO collection systems in the EU [Internet]. Coivert; 2016. Available from: https://theicct.org/sites/default/files/publications/Greenea Report Household UCO Collection in the EU_ICCT_20160629.pdf
135. Chiaramonti D, Prussi M, Buffi M, Tacconi D. Sustainable bio kerosene: Process routes and industrial demonstration activities in aviation biofuels. *Appl Energy [Internet]*. 2014;136:767–74. Available from: http://dx.doi.org/10.1016/j.apenergy.2014.08.065
136. de Jong S, Hoefnagels R, Faaij A, Slade R, Mawhood R, Junginger M. The feasibility of short-term production strategies for renewable jet fuels - a comprehensive techno-economic comparison. *Biofuels, Bioprod Biorefining [Internet]*. 2015 Nov;9(6):778–

800. Available from: http://doi.wiley.com/10.1002/bbb.1613

137. Caldeira C, Queirós J, Noshadravan A, Freire F. Incorporating uncertainty in the life cycle assessment of biodiesel from waste cooking oil addressing different collection systems. *Resour Conserv Recycl [Internet]*. 2016 Sep;112:83–92. Available from: http://dx.doi.org/10.1016/j.resconrec.2016.05.005
138. Ho S-H, Wong Y-D, Chang VW-C. Evaluating the potential of biodiesel (via recycled cooking oil) use in Singapore, an urban city. *Resour Conserv Recycl [Internet]*. 2014 Sep;91(2014):117–24. Available from: http://dx.doi.org/10.1016/j.resconrec.2014.08.003
139. LanzaTech. World's First Commercial Waste Gas to Ethanol Plant Starts Up [Internet]. 2018 [cited 2019 Jul 31]. Available from: https://www.lanzatech.com/2018/06/08/worlds-first-commercial-waste-gas-ethanol-plant-starts/
140. LanzaTech. Virgin Atlantic and LanzaTech Celebrate as Revolutionary Sustainable Fuel Project Takes Flight [Internet]. 2018 [cited 2019 Jul 31]. Available from: https://www.lanzatech.com/2018/10/04/virgin-atlantic-lanzatech-celebrate-revolutionary-sustainable-fuel-project-takes-flight/
141. ANP. Renovacalc - v.6.1 [Internet]. *National Agency of Petroleum Natural Gas and Biofuels - Renovabio.* 2020 [cited 2020 Feb 16]. Available from: http://www.anp.gov.br/producao-de-biocombustiveis/renovabio/renovacalc
142. ICAO. CORSIA - Methodology for Calculating Actual Life Cycle Emissions Values. Montreal; 2019.
143. ICAO. CORSIA Supporting Document: Eligible Fuels – Life Cycle Assessment Methodology [Internet]. Montreal; 2019. Available from: https://www.icao.int/environmental-protection/CORSIA/Documents/CORSIA Supporting Document_CORSIA Eligible Fuels_LCA Methodology.pdf

2 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 (24-98.7 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 first-generation (1G) 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 1G pathways, the potential GHG reduction of second-generation (2G) 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.

Keywords: alternative jet fuel; life cycle assessment; carbon footprint; low-carbon policies; attributional modeling; consequential modeling.

2.1. Introduction

The International Civil Aviation Organization (ICAO) has set ambitious goals for reducing greenhouse gas emissions (GHG) in the aviation sector[1]. These have been managed by the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA)[2], and the use of Alternative Jet Fuels (AJF) is one strategic way to achieve these goals[3].

Similarly, other Low-Carbon Policies (LCP) have promoted biofuel production to tackle climate change issues. In Europe, the *Renewable Energy Directive* (RED)[4] states that at least 14% of the energy consumed in the transportation sector should be supplied by renewable sources by 2030[5]. Likewise, the United States set forth a target of 36 billion gallons for biofuels by 2022 by the *Renewable Fuel Standard* (RFS)[6], setting specific targets for different fuel categories. The current Brazilian program *Renovabio*[7] 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[8,9,18–21,10–17]. 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[22]. 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[23–25]. 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[6,26–29].

Nevertheless, the assumptions in the analyses are not always clearly associated with the approach adopted by the study[25,28,30]. Likewise, specific features of calculating GHG can lead to different results for the same biofuel under different regulatory schemes[31,32]. Furthermore, 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[33]. 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.

2.2. Methods

2.2.1. 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 2.2.2**, comprise approved AJF technologies: HEFA, ATJ, and FT[34], and promising feedstocks available in Brazil, according to the Roadmap for sustainable aviation fuels in Brazil developed by research agencies[33]. 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 material 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 also 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.* accounting 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[2]. The characterization factors were taken from the 5th IPCC report[35]. 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[36]. Assumptions for ALCA and CLCA are detailed in **sections 2.2.3**.

The specific regulatory schemes and adjustments are detailed in **section 2.2.6** for evaluating the AJF pathways considering the LCPs.

2.2.2. General description of the pathways

The pathways evaluated here (**Figure 2.1**) 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 Used Cooking Oil (UCO), beef tallow, sugarcane, forestry residues, and steel off-gases.

Soybean production was described as a monoculture system in Mato Grosso State[37], which produces about 30% of all the soybeans grown in Brazil (around 120 million tons in 2018)[38]. An extraction plant via hexane[39] would be located 400 km from the soybean plantations (one-way). The life cycle inventory (LCI) of Soy/HEFA is presented in Supplementary Material (**Table SM.3).**

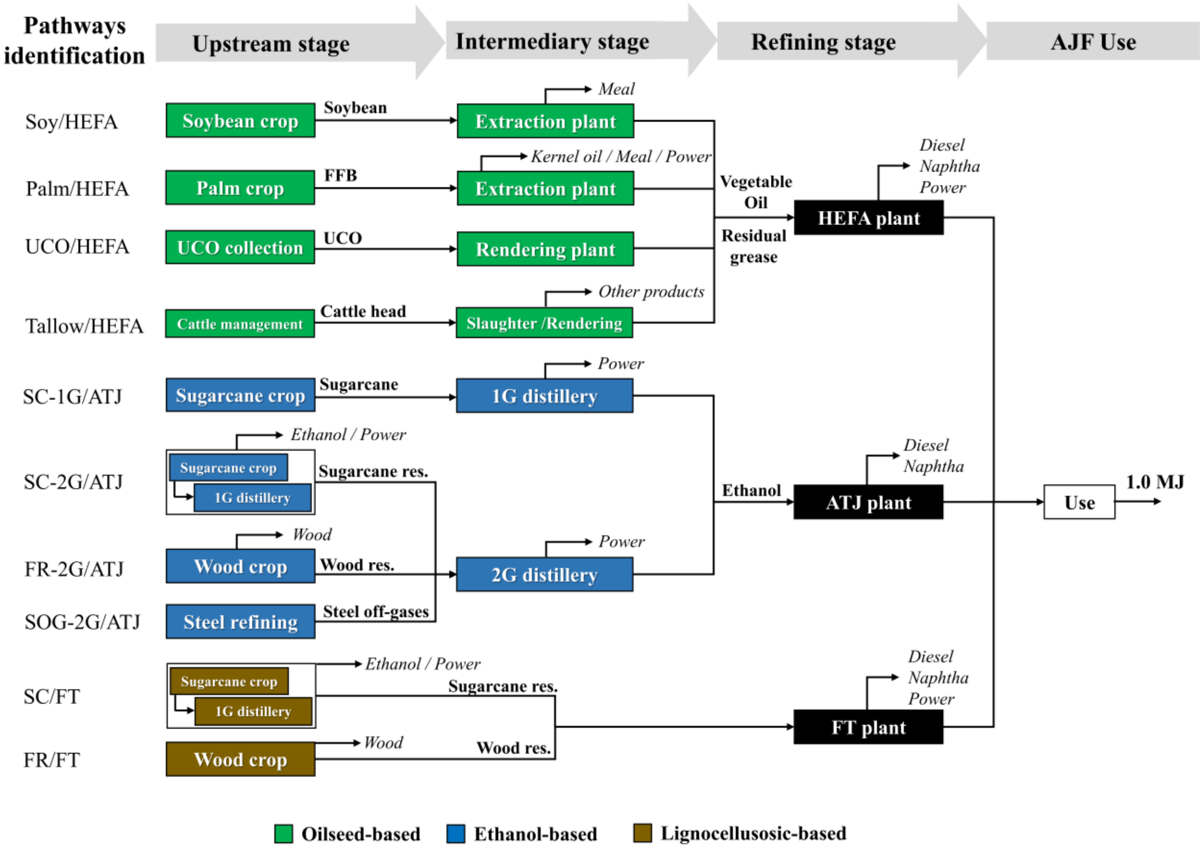

Figure 2.1: Overview of the AJF pathways. 1G: First-generation; 2G: Second-generation; ATJ: Alcohol-to-Jet; FFB: Fresh Fruit Bunches; FR: Forestry residues; FT: Fischer-Tropsch; HEFA: Hydroprocessed Esters and Fatty Acids; SC: Sugarcane; SOG: Steel off-gases; UCO: Used Cooking Oil.

Palm oil production (*Elaeis Guineensis*) was based on data from a Brazilian company[40] located in the Pará State, which is responsible for about 90% of the national production (1.5 million tons of fresh fruit bunches, FFB, in 2018)[41]. 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.*[42]. Palm kernel oil and meal were sent to the oil market and used as animal feed, respectively. Considering the company's investment plans[43], it was considered that biogas from the anaerobic digestion of palm mill oil effluent (POME, 6.6 $kgCH_4/t_{FFB}$) was captured in a closed pond system and used for power generation (36.8 kWh/t_{FFB})[44]. The distance between the palm plantation and the extraction plant was 30 km. The LCI of palm oil is presented in **Table 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[45]. Industrial processes were described for an integrated slaughter and rendering plant, as is typically seen in Brazil[45,46].

The distance from collection and transportation of the feedstock to the rendering process[47] was 50 km for AJF derived from UCO, based on the average distance for collecting 1.0 ton of UCO from food service establishments[48]. Both LCI for UCO and beef tallow are shown in **Table 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)[49]. 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[50]. 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[51].

The 1G ethanol was obtained from an optimized autonomous distillery for hydrated ethanol, according to the *VSB*[51]. 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[49], 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[49]. 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 **Table 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[52]. 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 **Table 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[53,54] and was described by Handler *et al.*[55]. 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 **Table SM.10**.

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)[56].

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[9,11,47].

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[11,47]. An input value of 35.2 kg $H_2/t_{feedstock}$ was estimated for beef tallow, considering its composition[57]. 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.*[9] 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 in São Paulo State, REPLAN also in São Paulo State, and REDUC in Rio de Janeiro State[58]. 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) to the new palm oil refinery located in Limeira (São Paulo State)[43].

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[58]. 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 2.1** presents the main yields for each life cycle stage considered in this study. 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[59]. The carbon emissions related to AJF use were disregarded, since they are considered biogenic. On the other hand, carbon emissions along the life cycle were appropriately accounted for in SOG-2G/ATJ (which is based on fossil carbon) since coal is the primary carbon source used at steel mills in Brazil[60].

2.2.3. The Carbon footprint of AJF according to the ALCA and CLCA approaches

Assumptions for the attributional analysis (ALCA)

The carbon footprint using the ALCA method was based on the average data (see LCIs in **Table SM.3** to **SM.13**), and the conversion yields in **Table 2.1**. Background systems such as chemicals, fertilizers, fuels, power, etc. were obtained from the Ecoinvent v3.3[59], USCLI[61], and the GREET databases[62]. 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[13,23,25,28,29,63–65] for handling co-products, and so economic allocation was applied by default according to the current prices of the materials (see **Table SM.1**).

Table 2.1: Overall yields for AJF pathways. Co-products reported in *italic letters*

Pathways	Upstream yields [a]	Intermediary yields	Refining yields [b]
Soy /HEFA	3.12 $t_{soybean}$ / ha	0.19 $t_{soybean\_oil}$ / $t_{soybean}$ *0.80* t_{meal} / $t_{soybean}$	AJF: 493.0 kg / t_{oil} *AD: 233.0 kg/* t_{oil} *AN: 60.5 kg /* t_{oil} *Power* [c]
Palm /HEFA	17.76 t_{FFB} / ha	0.175 t_{palm_oil} / t $_{FFB}$ *0.013* t_{kernel_oil} / t $_{FFB}$ *0.023* t_{kernel_meal} / t $_{FFB}$ *0.037 kWh / t* $_{FFB}$	
Tallow/HEFA	450.0 $kg_{live\ weight}$/c.h.	23.0 kg_{tallow} / c.h. *261.0* $kg_{carcass}$ */ c.h.* *55.3* $kg_{leather}$ */ c.h.* *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 *192 kWh / tsc*	AJF: 217.9 kg / $m^3_{ethanol}$ *AD: 16.2 kg /* $m^3_{ethanol}$ *AN: 105.3 kg /* $m^3_{ethanol}$
SC-2G/ATJ	115.6 $kg_{LCM(db)}$ / tsc *85.4* $L_{ethanol}$ */ tsc* *31.6 kWh / tsc*	357.4 $L_{ethanol}$ / $t_{LCM(db)}$ *127.6 kWh /* $t_{LCM(db)}$	
FR-2G/ATJ	25 $t_{LCM\ (db)}$ / ha *340* $t_{wood\ (db)}$ */ ha*	308.4 $L_{ethanol}$ / $t_{LCM(db)}$ *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 *85.4* $L_{ethanol}$ */ tsc* *31.6 kWh / tsc*	n.a.	AJF: 56.3 kg / $t_{LCM(db)}$ *AD: 46.2 kg* /$t_{LCM(db)}$ *AN: 66.4 kg* / $t_{LCM(db)}$ *Power: 454.9 kWh* / t_{LCM}
FR/FT	25 $t_{LCM\ (db)}$ / (ha.cycle) *340* $t_{wood\ (db)}$ */ (ha.cycle)*	n.a.	AJF: 58.9 kg / $t_{LCM(db)}$ *AD: 48.3 kg* / $t_{LCM(db)}$ *AN: 70.1 kg* / $t_{LCM(db)}$ *Power: 476.3 kWh* / t_{LCM}

[a] *FFB*: Fresh Fruit brunches; *c.h.*: cattle head; *tsc*: tonne of sugarcane; *tcs*: tonne of 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 [9]. 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 [9], 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 [142]. 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 [55], and assuming theoretical maximum 80% HHV conversion to ethanol [143].

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' [66]. 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 the Supplementary Material section in **Table SM.14**. Assumptions related to Land Use Change (LUC) are detailed in **section 2.2.4**.

Assumptions for the consequential analysis (CLCA)

CLCA was conducted according to the procedures suggested by Weidema[28] and Weidema *et al.*[67]. 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[68], 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 processes and technologies according to price relations in increasing market trends[63,67]. The marginal processes considered in this study (see **Figure 2.2**) 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[65,69]. 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[63,70–72]. 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)[73] and it is one of the major global producers of soybeans (8.6 Mt in the same year)[74]. 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 Supplementary Material, **Figure SM.1** and **Figure. SM.2**);

ii) Palm (*Elaeis guineensis*) production in Brazil is still modest (1.57 Mt in 2018) [41], and is restricted to specific climate and soil conditions found only in Northern Brazil. By contrast, soybean production (117.9 Mt in 2018, see **Figure SM.3**) is reinforced by a well-consolidated supply-chain with an idle capacity of around 13%[74] which could be easily activated for small demand increases, as were assumed in this study.

As a result, the additional demand for AJF produced from soybean oil would imply an additional production of soybeans 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[30,75–81].

Therefore, soybean meal would displace the soybean system (1.2 $t_{soybean}/t_{soybean\_meal}$), which was identified as a marginal feed protein[71,82,83]. 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[84]. For more details, see **section 4.2** in Supplementary Material.

Liquid biofuels co-produced at the refining stage were dealt with using energy allocation, as suggested by other authors[85–87], 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[71,76,82]. 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[76]. The soybean system was detailed by the same data here and, assuming a protein parity of 0.35 $kg_{soy\_meal}/kg_{palm\_meal}$[70], 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.

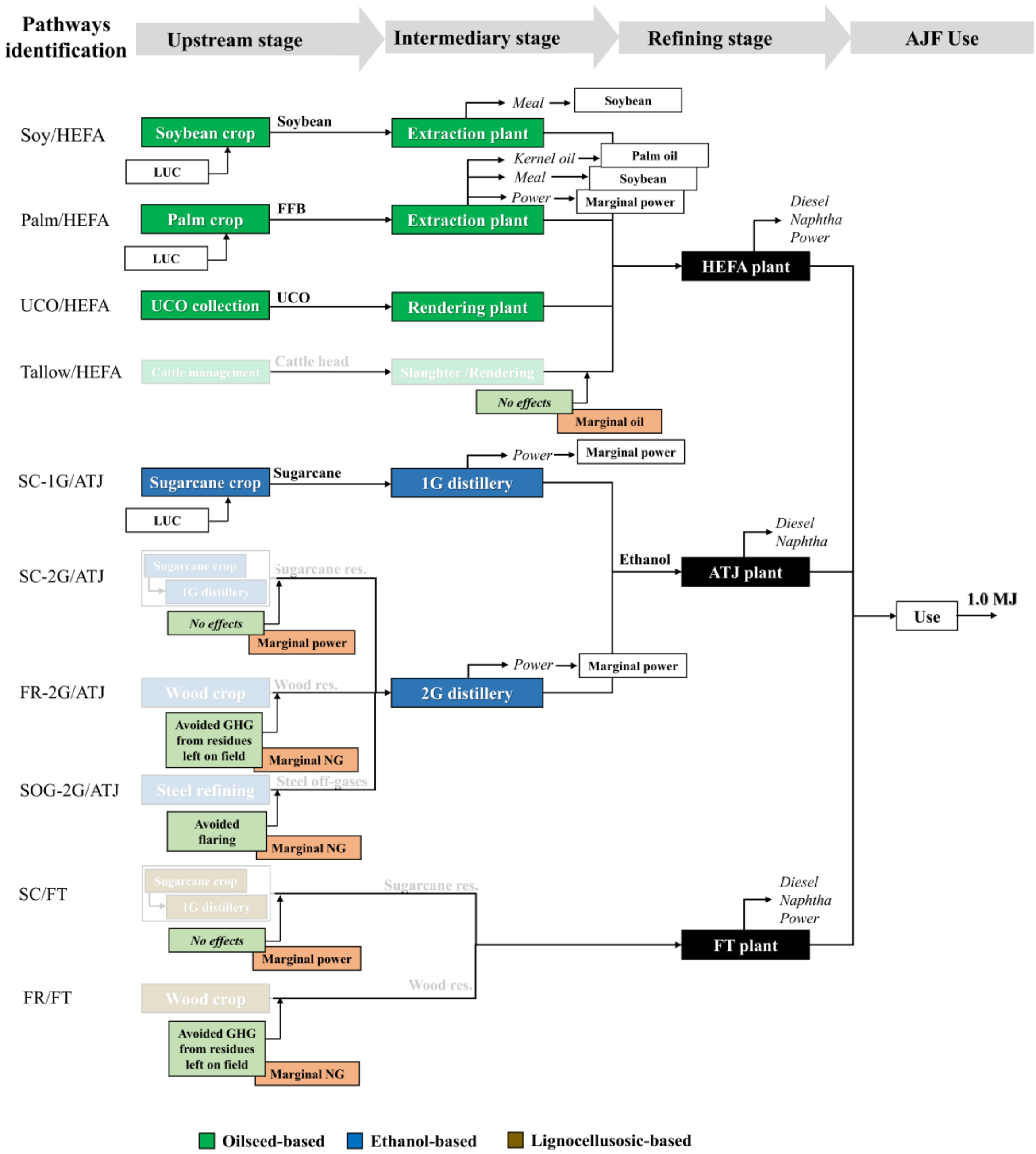

Figure 2.2: The main effects considered in the CLCA for the reference case (boxes in light green) and in the sensitivity analysis (boxes in light red, see section 2.3.4). FR: Forestry residues; SC: Sugarcane; SOG: Steel off-gases; NG: Natural gas; UCO: Used Cooking Oil; 1G: First-generation; 2G: Second-generation; ATJ: Alcohol-to-Jet; FR: Forestry residues; FFB: Fresh Fruit Bunches; FT: Fischer-Tropsch; HEFA: Hydroprocessed Esters and Fatty Acids.

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[68]. 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[88,89]; ii) steel off-gases, when credits related to non-flaring were accounted for (1.65 $kgCO_{2e}/Nm^3_{off\text{-}gas}$)[55].

Assumptions related to LUC are detailed in **section 2.2.4**. The consequential database available in Ecoinvent[59] was considered for background systems, albeit with some adaptations (see Supplementary Material, **Tables SM.3** to **SM.13**).

2.2.4. 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[15,16,19,21].

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[90]. The scenarios comprised carbon stocks for four different land use types (annual cropland, perennial cropland, pasture, and native vegetation) in each Brazilian State[91] and the potential expansion areas for soybean[92], palm[93], and sugarcane plantations[94]. Direct dinitrogen monoxide (N_2O) emissions were also accounted for, assuming a default Carbon:Nitrogen (C:N) ratio of 15 [89]. See **Table SM.18** for more details.

On the other hand, a market-based analysis as the CLCA approach also accounts for indirect changes (iLUC) outside the assessed boundaries, which are typically estimated using economic models. The default factors suggested by CORSIA[95] 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 already accounted for in the LUC factor considered here.

Other LUC values reported in literature[21,96], which include indirect effects related to sugarcane expansion, were also investigated here. See **Table SM.18** for more details.

2.2.5. 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[11,62]. Transportation distances were arbitrarily varied by ±50%, except for transporting sugarcane stalks and palm oil. Furthermore, alternative hydrogen production from water electrolysis[97] was also assumed (see **Table SM.2** at Supplementary Material).

Regarding methodological aspects, different allocation methods were considered in the ALCA approach, *i.e.*, according to the energy content (see **Table SM.1**) 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. **Table 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 $kgCO_{2e}/kg$)[98] 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[99]. In this context, an additional demand for beef tallow, which is mostly used by the Brazilian biodiesel industry[100], would result in a marginal effect on the production of soybean oil, for the same reasons presented previously (see **section 2.2.3**).

It was considered that an additional demand for sugarcane residues, which are commonly used to provide self-supplied energy at ethanol plants in Brazil[100], would result in marginal power generation, for the same reasons mentioned for power surplus (see **section 2.2.3**).

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[100] and the national market price trends for heating have suggested natural gas as a marginal supplier (see **Figure 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[101]. 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 **Figures SM.5** and **SM.6** at Supplementary Material).

2.2.6. 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 2.2**), 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)[102,103] 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[104]. 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 CORSIA[95] were added when necessary.

The current summary of biofuel pathways, as evaluated by RFS[105] – 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[62] suggested for AJF conversion and transportation.

Table 2.2: 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[102] 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[103,104].

[b] Specific life cycle stages were described in [105]: 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[62].

[c] Emission factors from [106]. Here, the emissions from CHP systems were 100% allocated to the main product. LUC from [122].

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

[e] Global Warming Potential with 100-year time horizon, according to IPCC[144]. 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.

Finally, carbon emissions using RED II[4,5] were estimated considering the specific guidelines and emissions factors reported in Edwards *et al.*[106]. The dLUC emissions for Brazil were estimated assuming soybean, palm, and sugarcane expansion on pasturelands (see **section 2.2.4**).

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.

2.3. Results

2.3.1. 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 **Figure 2.3.A** and **Table 2.3**). Although the potential reduction of 1G pathways is less than the 2G potential – mainly due to 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 degree of unsaturated fatty acids.

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[43], 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, intermediary 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 the results of AJF obtained from steel off-gases (SOG-2G/ATJ), respectively. As to the latter pathway, the power surplus generation by an optimized steelmaking system, as observed in some Brazilian steel mills[101,107], could eventually supply the 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.

In general, AJF had lower carbon footprints when using the consequential approach (CLCA), as opposed to the ALCA approach, mainly because of credits given for displacing power generation based on natural gas and the null effects when a residual feedstock is available for AJF production (**Figure 2.3.B** and **Table 2.4**). 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 forest 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.

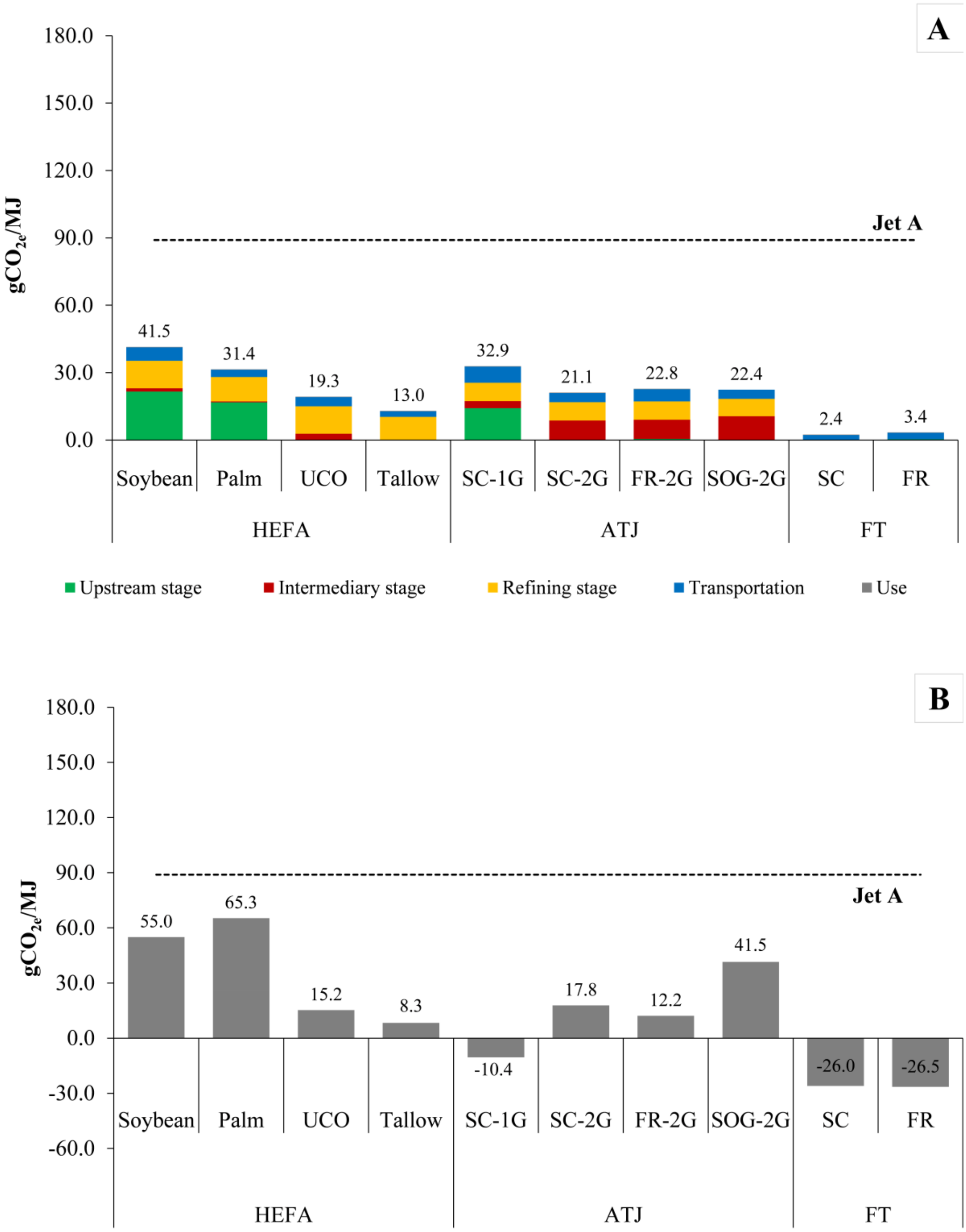

Figure 2.3: Carbon footprint of AJF using ALCA without LUC (A) and CLCA (B)

Table 2.3: Carbon footprint of AJF using the attributional approach (ALCA), without LUC

Life cycle stages	HEFA				ATJ				FT	
	Soy	Palm	UCO	Tallow	SC 1G	SC 2G	FR 2G	SOG 2G	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 2.4: Carbon footprint of AJF using the consequential approach (CLCA)

Life cycle stages	HEFA				ATJ				FT	
	Soy	Palm	UCO	Tallow	SC 1G	SC 2G	FR 2G	SOG 2G	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**

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. 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 (55.0 gCO_{2e}/MJ) and Palm/HEFA (65.3 gCO_{2e}/MJ) led to the lowest potential GHG reduction – *i.e.*, 40% and 27%, 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.

2.3.2. 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 **Figure 2.4**). 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 CORSIA[95] led to major positive emissions in Soy/HEFA and Palm/HEFA (see **Table 2.4**). It is worth pointing out that the LUC factor taken for Palm/HEFA was suggested for palm crops in Malaysia[95] 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 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.*[96], who estimated 56.3 $kgCO_{2e}$/t of sugarcane. See **Table SM.18** for the modeling details.

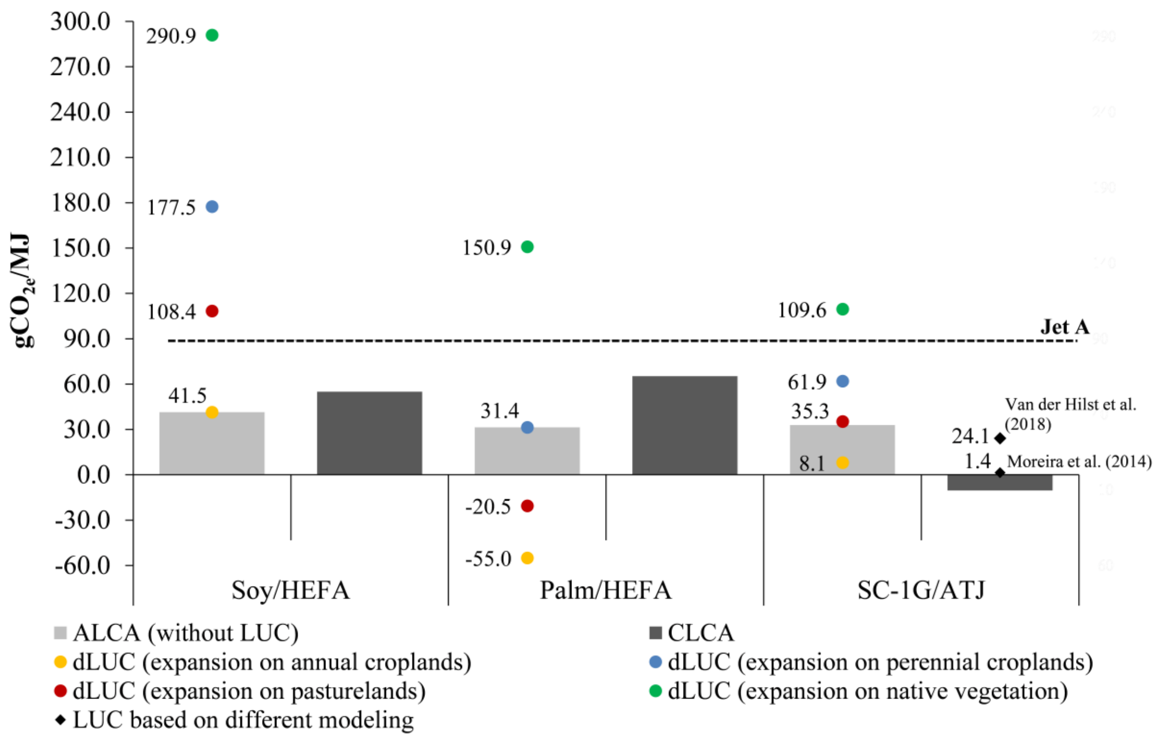

Figure 2.4: Carbon footprint of AJF considering different LUC factors

2.3.3. Comparison with other studies in literature

The attributional approach has been used in most studies on the 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.*[108] (40.1 gCO_{2e}/MJ) for Brazil, or by Han *et al.*[87] (39.0 gCO_{2e}/MJ) for soybeans produced in the United States.

On the other hand, the lower results reported by Klein *et al.*[9] – 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.*[87] reported similar values for Palm/HEFA (34.0 gCO_{2e}/MJ) for Malaysia, Vásquez *et al.*[108] 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.*[47]. 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.*[9] reported lower values (20.5 gCO_{2e}/MJ) for SC-1G/ATJ, for the same reasons mentioned previously. Similarly, de Jong *et al.*[11] estimated 26 gCO_{2e}/MJ since the inventories adopted by these authors were mostly based on GREET[62].

Cavalett and Cherubini[109] 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.*[11] reported a lower value for SC-1G/ATJ (22 gCO_{2e}/MJ) and FR/FT (-3.0 gCO_{2e}/MJ) when credits related to power surplus are accounted for. Cox *et al.*[20] 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.

2.3.4. Sensitivity analysis

The sensitivity of the carbon footprint to process and methodological issues are presented in **Figure 2.5**. 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 process issues and methodological choices, respectively.

Results of ALCA are more sensitive to methodological issues than process parameters (**Figure 2.5.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 decreases by 25% (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.

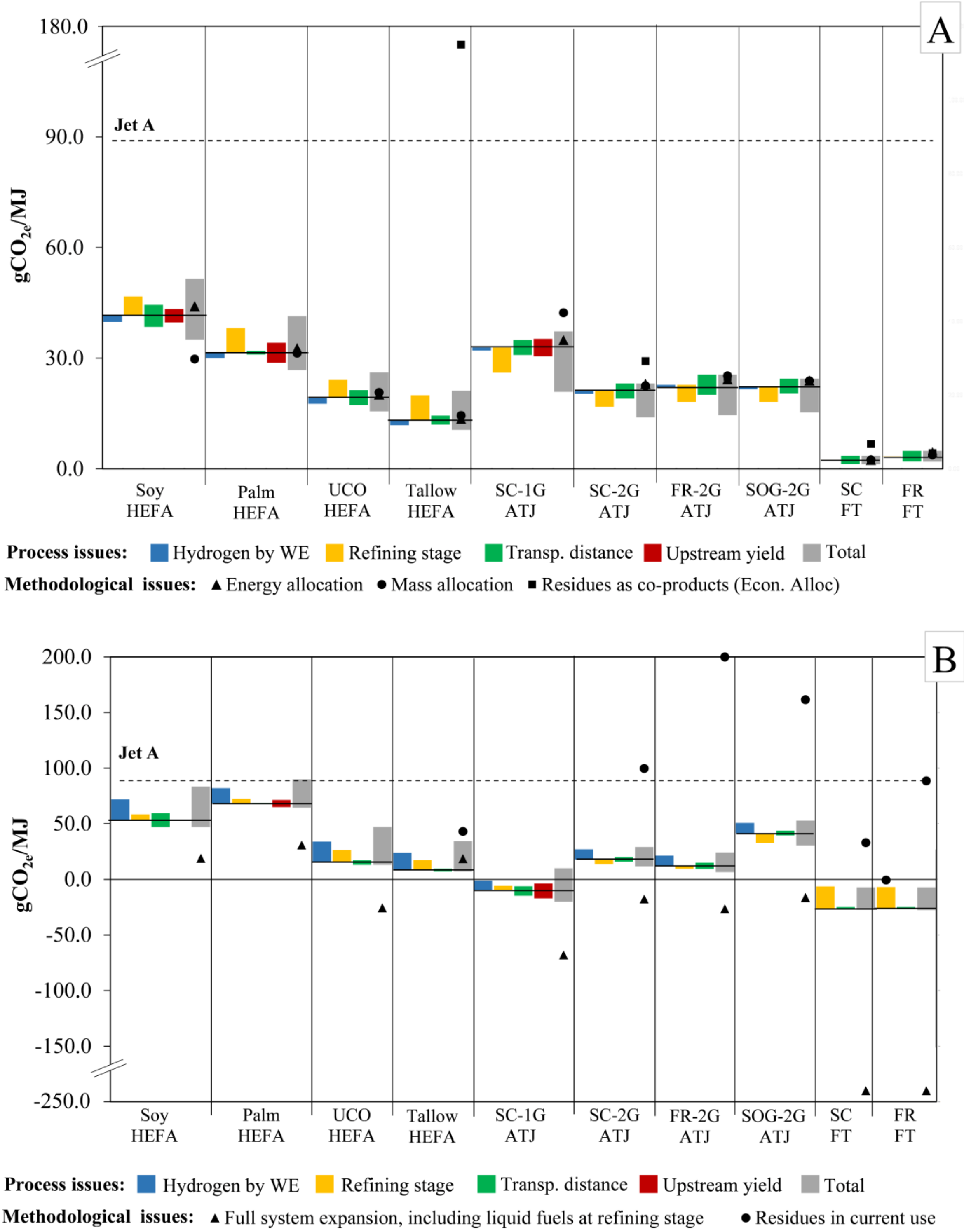

Figure 2.5: Sensitivity analysis for the carbon footprint of AJF, according to the reference case (see the black line for each pathway). A: attributional approach (ALCA); B: consequential approach (CLCA). WE: Water electrolysis. Total: cumulative variations related to process issues.

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 raising cattle. 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 forest-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 (**Figure 2.5.B**) are substantially more sensitive to methodological issues.

The carbon footprint of Soy/HEFA and Palm/HEFA decrease 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[99], since some residual feedstocks are not always available. For instance, beef tallow – obtained from 30 million slaughtered cattle head[41] – has been mostly used by biodiesel industry, contributing to about

18% of Brazilian biodiesel production[58]. The remaining amount is destined for the cleaning industry[110]. 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[100]. In turn, around 60% of steel off-gases generated in Brazil have been recovered for supplying internal energy demands[101]. 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.

2.3.5. 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 (**Figure 2.6**). 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 2.3.1**) resulted in the greatest GHG reductions. The default life cycle emissions suggested by ICAO (2019) 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 **Table 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, specifically in the *Renovabio* scheme, that 2G pathways via ethanol (19-20 gCO_{2e}/MJ) have 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[103,111] – 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 $kgCO_{2e}/kgH_2$ [56], while the RenovaCalc tool assumes 2.38 $kgCO_{2e}/kgH_2$ for *Renovabio* and the Edwards *et* *al.*[106] 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.

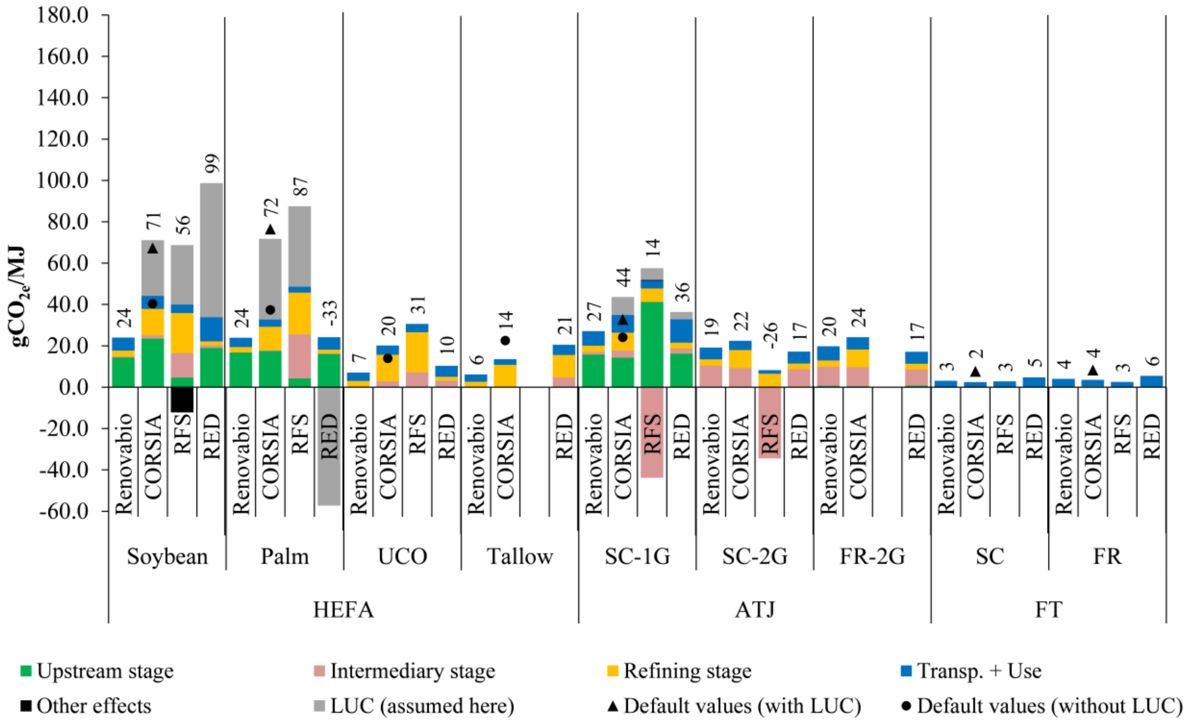

Figure 2.6: Carbon footprint of AJF for different regulatory schemes

As presented in **section 2.3.1**, 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[89], 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)[112]. The main differences arise from direct emissions coming from mineral fertilizer. While IPCC[89] 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[62], which considered external energy supply. On the other hand, *Renovabio* and CORSIA were based on Klein *et al.*[9], 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 systems, 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[105]. 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[113], 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[113].

For palm expansion, Ramalho Filho and Motta[93] 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[114], which indicates a considerable potential for Brazilian palm expansion, as was also shown by some authors[115,116]. In turn, 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[117]. On the other hand, no gains in soybean yield have been observed through intercropping practices[118,119]. Likewise, other authors have reported decreasing in agricultural productivity related to soybean-forestry systems[120,121]. 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[122], 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[123]. Even in that case, Soy/HEFA would present higher emission than fossil fuel according to RED scheme (see **Figure 2.7**).

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[124], high-iLUC risk biofuels are obtained from feedstocks with significant expansion into high-carbon lands[4]. 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[125]. 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 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.

2.4. Conclusions

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.

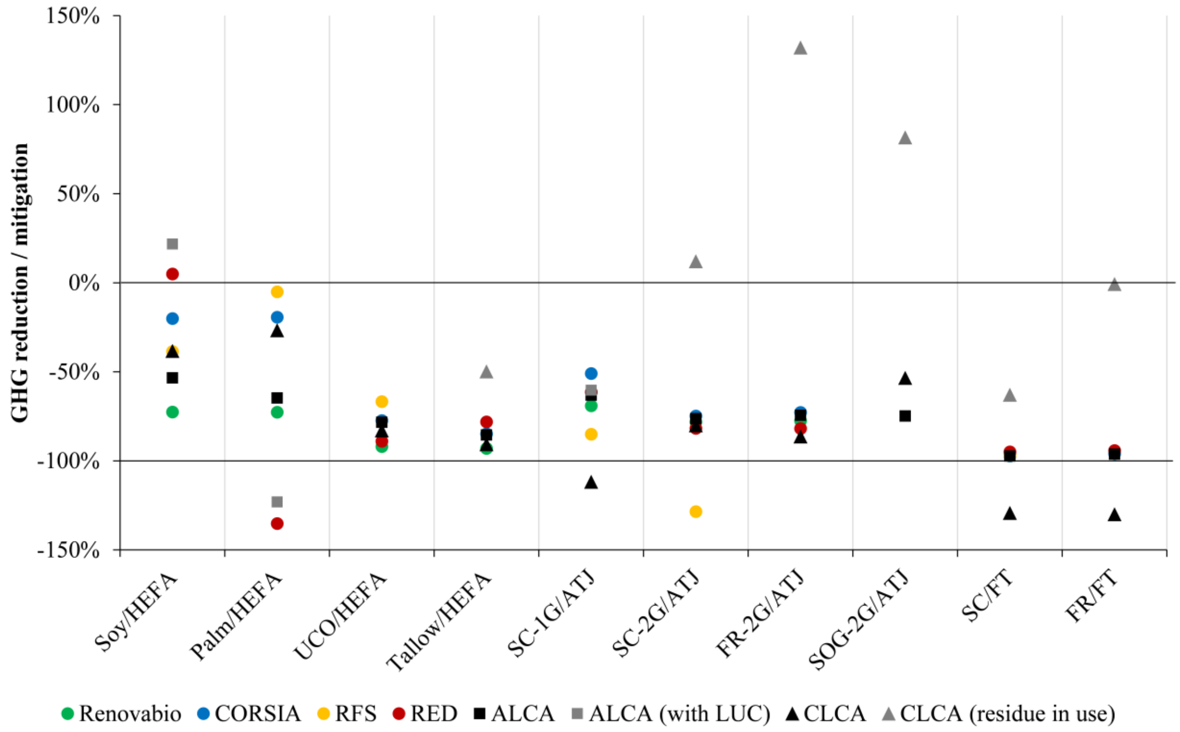

Figure 2.7: GHG reduction/mitigation provided by AJF in comparison with its fossil counterparts, whose emission factor were considered as 87.5 gCO_{2e}/MJ for *Renovabio*; 89.0 gCO_{2e}/MJ for CORSIA, ALCA, and CLCA; 91.0 gCO_{2e}/MJ for RFS; and 94.0 gCO_{2e}/MJ for RED. "ALCA (with LUC)" and "RED" 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.

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 **Figure 3.7**). 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, FT-based pathway potential surpasses 95%, while lignocellulosic-based, waste greases, and SOG-2G/ATJ pathway potential 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 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.

Supplementary Material

1. General assumptions

Table SM.1: Energy content and Economic value assumed in this study

Substance	Energy content	Econ. Value	Reference
Alternative Diesel	43.5 MJ/kg	0.700 USD/L	Energy data: [126]; Density: 0.750 kg/m³. Economic data: Average price (2009-2018) for fossil diesel at Brazilian market [58].
Alternative Jet Fuel	44.1 MJ/kg	0.661 USD/L	Energy data: [126]. Density: 0.757 kg/m³. Economic data: Average price (2009-2018) for fossil kerosene at Brazilian market [58].
Alternative Naphtha	44.4 MJ/kg	0.736 USD/L	Energy data: [126]. Density: 0.700 kg/m³. Economic data: Average price (2009-2018) for gasoline at Brazilian market [58].
Alternative Propane	46.2 MJ/kg	0.549 USD/kg	Energy data: [100] for Liquefied Petroleum Gases (LPG). Economic data: Average price (2009-2018) for LPG at Brazilian market [58].
Anhydrous ethanol	22.4 GJ/m³	0.572 USD/L	Energy data: [100]. Density: 0.790 kg/L. Economic data: Average price (2009-2019) at Brazilian market, [127].
Beef tallow	*n.a.*	0.677 USD/kg	Economic data: Average price (2015-2018) at Brazilian market, [128].
Electricity	*n.a.*	0.085 USD/kWh	Economic data: Average price (2008-2018) at Brazilian market [129].
Hydrated ethanol	21.4 GJ/m³	0.506 USD/L	Energy data: [100]. Density: 0.810 kg/L. Economic data: Average price (2009-2019) at Brazilian market, [127].
Other products from slaughterhouse	*n.a.*	3.941 USD/kg	Economic data: Average price (2014-2017) to meat export from Brazilian market [130].
Palm kernel meal	15.1 MJ/kg	0.142 USD/kg	Energy data: [131]. Economic data: International prices (2015-2019), Export, Unspecified, Palm kernel meal (Expeller pellets, 21/23%, c.i.f. Rotterdam) [132].
Palm kernel oil	39.0 MJ/kg	0.783 USD/kg	Energy data: [131]. Economic data: International prices (2015-2019), Palm kernel oil, c.i.f. Rotterdam [133].
Palm oil	36.5 MJ/kg	0.640 USD/kg	Energy data: [131]. Economic data: International prices (2015-2019), Export, Unspecified, Palm oil (Crude, c.i.f. Rotterdam) [132].
Soybean meal	13.4 MJ/kg	0.331 USD/kg	Energy data: [126]. Economic data: Average price (2009-2019) at Brazilian market [74], without taxes.
Soybean oil	37.2 MJ/kg	0.860 USD/kg	Energy data: [126]. Economic data: Average price (2009-2019) at Brazilian market [74], without taxes.
Sugarcane residues (db)[a]	14.6 MJ/kg	44.8 USD/ton	Mix 85% bagasse / 15% straw [49,134]. Economic data: Opportunity cost [49].
Wood	18.0 MJ/kg	29.39 USD/ton	Energy data: [135]. Economic data: Average price (2008-2011) of eucalyptus to be used in process in Brazil [136].
Wood residues	17.5 MJ/kg	14.38 USD/ton	Mix 90% wood / 10% barks. Energy data: [135]. Economic data: It was assumed 50% discount of average prices (2008-2011) for eucalyptus to be used as energy source [137].

[a] Dry basis (db).

Table SM.2: Process issues investigated in the sensitivity analysis

Process issue		Parameters or variations	Reference and observations
Hydrogen from Water electrolysis (WE)		**Output** Gaseous hydrogen: 1.00 Nm^3 **Input** Electricity: 4.91 kWh Transport > 32 metric ton, EURO4: 0.0045 tkm	[97] Emissions were fully allocated to gaseous hydrogen. Water input was considered without environmental burden.
Refining stage	HEFA design	**Output** AJF: 0.719 kg Naphtha: 0.070 kg Propane fuel mix: 0.102 kg **Input** Feed oil: 1.00 kg Hydrogen: 0.037 kg (for all HEFA-based cases) Electricity: 0.04 kWh Natural gas: 3.36 MJ (use in a boiler)	[62]
	ATJ design	**Output** AJF: 0.411 kg Diesel: 0.049 kg Naphtha: 0.089 kg **Input** Ethanol: 1.00 kg Hydrogen: 0.012 kg Electricity: 0.181 kWh	[62]
	FT design	**Output** AJF: 1.00 kg Diesel: 3.04 kg Gasoline: 1.68 kg Power: 5.51 kWh Propane fuel mix: 0.92 kg **Input** Sugarcane residues (db): 39.60 kg Forestry residues (db): 28.35 kg	[11,138]
Transportation distance		±50%, except for sugarcane and palm oil transportation.	Assumed here.
Upstream yield	Sugarcane	±20%	[51]
	Soybean	±20%	[139]
	Palm	±20%	Assumed here.

2. Life Cycle inventories and results

Table SM.3: Inventory of 1.0 MJ_{AJF} from soybean oil through HEFA technology

Results for reference flow without allocation. Results for ALCA with economic allocation. Results for CLCA with energy allocation in the refining stage. Foreground data are adapted from [9,37,39]. Background inventories are mostly based on [59], while adaptations are pointed out at footnotes.

UPSTREAM STAGE – Soybean crop	Reference flow		ALCA gCO_{2e}/MJ	CLCA gCO_{2e}/MJ
Products				
Soybean [a]	**2.40E-01**	**kg**		
Materials/fuels				
Soybean seed, for sowing {RoW}	3.07E-03	kg	2.75E-01	7.38E-01
Monoammonium phosphate, as N {RoW}	5.38E-04	kg	3.45E-01	9.72E-01
Monoammonium phosphate, as P2O5 {RoW}	2.85E-03	kg	9.30E-01	-2.32E+00
Single superphosphate, as P2O5 {RoW}	8.59E-04	kg	4.62E-01	1.23E+00
Triple superphosphate, as P2O5 {RoW}	1.66E-03	kg	6.83E-01	1.75E+00
Potassium chloride, as K2O {RER}	4.84E-03	kg	5.62E-01	1.56E+00
Limestone, crushed, for mill {RoW}	3.84E-02	kg	2.47E-02	6.86E-02
2,4-dichlorophenol {RoW}	1.23E-05	kg	1.41E-02	3.92E-02
Glyphosate {RoW}	2.31E-04	kg	6.02E-01	1.55E+00
Pesticide, unspecified {RoW}	1.80E-04	kg	4.42E-01	1.19E+00
Diesel use in agricultural operations [b]	1.53E-03	L	1.58E+00	4.45E+00
Inputs transportation, Truck <7.5 metric ton, EURO4 {RoW} [b]	3.21E-07	tkm	1.38E-05	3.88E-05
Inputs transportation, Truck >16 metric ton, EURO4 {RoW} [b]	4.77E-02	tkm	1.57E+00	4.44E+00
Inputs transportation, Transoceanic ship {GLO}	1.98E-01	tkm	5.04E-01	1.42E+00
Emissions to air				
Dinitrogen monoxide [c]	1.59E-04	kg	9.40E+00	2.65E+01
Carbon dioxide, fossil [d]	1.87E-02	kg	4.17E+00	1.18E+01
LUC [e]	7.69E-05	ha	6.69E+01	2.70E+01
TRANSPORTATION for Extraction plant				
Truck >32 metric ton, EURO4 {RoW} [b]	**1.92E-01**	**tkm**	3.49E+00	9.83E+00
INTERMEDIARY STAGE – Extraction plant				
Products				
Soybean oil	**4.60E-02**	**kg**		
Soybean meal	1.92E-01	kg		-5.36E+01 [f]
Materials/fuels				
Soybean, at upstream stage	2.40E-01	kg		
Cyclohexane {RoW}	2.64E-04	kg	1.54E-01	3.73E-01
Electricity/heat				
Electricity [g]	1.16E-02	kWh	4.42E-01	3.38E+00
Natural gas, at boiler [h]	5.95E-02	MJ	8.70E-01	2.23E+00
Wood, at boiler [i]	9.61E-03	MJ	5.83E-03	1.64E-02
TRANSPORTATION for HEFA plant				
Truck >32 metric ton, EURO4 {RoW} [b]	**3.68E-02**	**tkm**	1.74E+00	1.89E+00

REFINING STAGE – HEFA plant				
Products				
AJF	**2.27E-02**	**kg**		
Diesel	1.07E-02	kg		
Naphtha	2.79E-03	kg		
Power surplus	1.57E-02	kWh		-4.59E+00 [j]
Materials/fuels				
Soybean oil, at pre-refining stage	4.60E-02	kg		
Hydrogen (SMR) [k]	1.93E-03	kg	1.21E+01	1.20E+01
Electricity/heat				
Processes gases, at boiler [l]	4.70E-03	kg	1.57E-01	1.70E-01
TRANSPORTATION for use				
Truck >32 metric ton, EURO4 {RoW} [b]	**9.08E-03**	**tkm**	7.39E-01	7.39E-01
USE				
AJF, use [m]	**1.00E+00**	**MJ**	2.09E-01	2.09E-01

[a] Moisture of 11%.

[b] Transportation values of the inputs based on [46]. For all road transportation (by truck) and agricultural operations, it was considered the *biodiesel:diesel* blend of 10%, in volume. It was assumed that soybean oil and tallow are responsible by 82% to 18% of biodiesel produced in Brazil [58]. The inventories related to soybean production and extraction were the same assumed here (see **Tab SI.3**). Tallow was assumed waste, and the distance between slaughterhouse to biodiesel plant was set as 200 km by "*Truck >16 metric ton, EURO4 {RoW}*". Biodiesel production were described in [45,145]. Emissions related to biodiesel use were adjusted for hydrocarbons, nitrogen oxides, particulates and monoxide carbon [146], besides the biogenic carbon and null sulfur emissions.

[c] Direct emissions: 1.0% of nitrogen fertilizer and nitrogen content in crop residues, *i.e.*, 0.032 kg N/kg soybean [46,147]. 100% crop residues is keep on field. Indirect emissions: 1.0% of ammonia and 0.75% nitrogen leached as nitrate are converted into dinitrogen monoxide, according to [89].

[d] From lime use, all carbon content in limestone is converted into carbon dioxide, according to [89], *i.e.*, 0.48 $kgCO_2$/kg limestone.

[e] dLUC for ALCA, considering soybean crop expansion on pasture lands (3.90 tCO_{2e}/ha.year). LUC for CLCA, according to default values reported by [95].

[f] Credits from soybean displacement, as suggested by [83,85], 1.21 $kg_{soybean}/kg_{soy\_meal}$ (0.44 $kgCO_{2e}/kg_{soy\_meal}$).

[g] Brazilian power grid. Average values for ALCA (0.171 $kgCO_{2e}$/kWh), as assumed in [36]. Marginal values for CLCA (0.465 $kgCO_{2e}$/kWh). See Supporting information, **section 3.2**.

[h] Emissions from "*Natural gas, at industrial boiler*" [62]. For ALCA, it was assumed average production of natural gas and transportation in Brazil (0.0655 $kgCO_{2e}$/MJ). For CLCA, the marginal supplier process (0.0596 $kgCO_{2e}$/MJ) was the natural gas produced and transported from Pré-Sal basin in Brazil ("*natural gas production off-shore*"). For specific information about the inventories, see [36].

[i] Based on "*Forest residues, at industrial boiler*" [62], 0.00272 $kgCO_{2e}$/MJ.

[j] Credits from marginal power displacement (0.465 $kgCO_{2e}$/kWh). See Supporting information, **section 3.2**.

[k] Gaseous hydrogen obtained from Steam Methane Reform (SMR) [56], with exergy allocation between gaseous hydrogen (90%) and steam (10%) (10.80 $kgCO_{2e}/kgH_2$). For CLCA, the supply of marginal power and marginal natural gas were considered (9.91 $kgCO_{2e}/kgH_2$).

[l] Based on "*Liquefied Petroleum Gas, at industrial boiler*" considering biogenic carbon emissions, 0.0574 $kgCO_{2e}$/kg.

[m] Based on a typical aircraft operation in an intracontinental trip [59], considering biogenic carbon emissions.

Table SM.4: Inventory of 1.0 MJ_{AJF} from palm oil through HEFA technology

Results for reference flow without allocation. Results for ALCA with economic allocation. Results for CLCA with energy allocation in the refining stage. Foreground data are adapted from [9,40,43,140]. Background inventories are mostly based on [59], while adaptations are pointed out in the footnotes.

UPSTREAM STAGE – Palm crop	**Reference flow**		**ALCA gCO_{2e}/MJ**	**CLCA gCO_{2e}/MJ**
Products				
Palm (FFB)	**2.63E-01**	**kg**		
Materials/fuels				
Ammonium sulfate, as N	1.92E-03	kg	1.93E+00	1.61E+00
Triple superphosphate, as P2O5 {RoW}	4.73E-04	kg	4.36E-01	4.97E-01
Potassium chloride, as K2O {RoW}	3.41E-03	kg	8.90E-01	1.10E+00
Glyphosate {RoW}	0.00E+00	kg	8.95E-02	1.03E-01
Pesticide, unspecified {RoW}	0.00E+00	kg	6.54E-02	7.84E-02
Diesel use in agricultural operations [a]	1.53E-05	L	1.01E+00	1.27E+00
Inputs transportation, Truck <16 ton, EURO4 {RoW} [a, b]	4.54E-04	tkm	3.37E-01	6.72E-01
Inputs transportation, Transoceanic ship {GLO}	4.83E-02	tkm	2.76E-01	3.46E-01
Emissions to air				
Dinitrogen monoxide [c]	8.87E-05	kg	1.18E+01	1.48E+01
LUC [d]	1.48E-05	ha	-5.19E+01	3.91E+01
TRANSPORTATION for Extraction plant				
Truck <7.5 metric ton, EURO4 {RoW} [a]	**1.58E-02**	**tkm**	1.52E+00	1.91E+00
INTERMEDIARY STAGE – Extraction plant				
Products				
Palm oil	**4.60E-02**	**kg**		
Kernel oil	3.52E-03	kg		-3.24E-01 [e]
Kernel cake	5.99E-03	kg		-5.81E-01 [f]
Power surplus [g]	9.70E-03	kWh		-2.84E+00 [h]
Materials/fuels				
Palm (FFB)	2.40E-01	kg		
Electricity/heat				
Fiber/Shells, at boiler [i]	2.92E-02	kg	3.83E-01	4.81E-01
TRANSPORTATION for HEFA plant				
Transoceanic tanker {GLO}	**2.76E-01**	**tkm**	9.64E-01	1.05E+00
REFINING STAGE – HEFA plant				
Products				
AJF	**2.27E-02**	**kg**		
Diesel	1.07E-02	kg		
Naphtha	2.79E-03	kg		
Power surplus	1.88E-02	kWh		-5.51E+00 [f]
Materials/fuels				
Palm oil, at pre-refining stage	4.60E-02	kg		
Hydrogen (SMR) [j]	1.71E-03	kg	1.07E+01	1.07E+01
Electricity/heat				
Processes gases, at boiler [k]	4.70E-03	kg	1.57E-01	1.70E-01

TRANSPORTATION for use				
Truck >32 metric ton, EURO4 {RoW} [a]	**9.08E-03**	**tkm**	7.39E-01	7.39E-01
USE				
AJF, use [l]	**1.00E+00**	**MJ**	2.09E-01	2.09E-01

[a] Transportation values of the inputs based on [140] . For all road transportation (by truck) and agricultural operations, it was considered the *biodiesel:diesel* blend of 10%, in volume. It was assumed that soybean oil and tallow are responsible by 82% to 18% of biodiesel produced in Brazil [58]. The inventories related to soybean production and extraction were the same assumed here (see **Tab SI.3**). Tallow was assumed waste, and the distance between slaughterhouse to biodiesel plant was set as 200 km by "*Truck >16 metric ton, EURO4 {RoW}*". Biodiesel production were described in [45,145]. Emissions related to biodiesel use were adjusted for hydrocarbons, nitrogen oxides, particulates and monoxide carbon [146], besides the biogenic carbon and null sulfur emissions.

[b] It also includes the EFB return to the field.

[c] Besides the nitrogen fertilizer and agricultural use of Empty Fruit Bunches (EFB), the decomposition of pruned fronds and felled trunks at replanting were also considered, as suggested by [148]. Direct emissions: 1.0% of nitrogen fertilizer and nitrogen content in crop residues, *i.e.*, 14.0 kgN/t_{FFB} from EFB and 156.4 kgN/t_{FFB} from pruned fronds [149]. Indirect emissions: 1.0% of ammonia and 0.75% nitrogen leached as nitrate are converted into dinitrogen monoxide, according to [89].

[d] dLUC for ALCA, considering soybean crop expansion on pasture lands (-7.00 tCO_{2e}/ha.year). LUC for CLCA, according to default values reported by [95].

[e] Credits from palm kernel oil displacement, 1.00 $kg_{palm\ oil}/kg_{palm\_kernel\ oil}$ (0.146 $kgCO_{2e}/kg_{soy\ oil}$, without LUC effects).

[f] Credits from palm kernel meal displacement, 0.42 $kg_{soybean}/kg_{palm\_meal}$ (0.154 $kgCO_{2e}/kg_{palm\_meal}$, without LUC effects).

[g] The emissions from POME treatment were assumed to recovered and used for power generation.

[h] Credits from marginal power displacement (0.465 $kgCO_{2e}$/kWh). See Supporting information, **section 3.2**.

[i] Based on "*Bagasse (db), at industrial boiler*" [62], 0.0262 $kgCO_{2e}$/kg.

[j] Gaseous hydrogen obtained from Steam Methane Reform (SMR) [56], with exergy allocation between gaseous hydrogen (90%) and steam (10%) (10.80 $kgCO_{2e}/kgH_2$). For CLCA, the supply of marginal power and marginal natural gas were considered (9.91 $kgCO_{2e}/kgH_2$).

[k] Based on "*Liquefied Petroleum Gas, at industrial boiler*" [62] considering biogenic carbon emissions, 0.0574 $kgCO_{2e}$/kg.

[l] Based on a typical aircraft operation in an intracontinental trip [59], considering biogenic carbon emissions.

Table SM.5: Inventory of 1.0 MJ_{AJF} from UCO through HEFA technology

Results for reference flow without allocation. Results for ALCA with economic allocation. Results for CLCA with energy allocation in the refining stage. Foreground data are adapted from [9,47,48]. Background inventories are mostly based on [59], while adaptations are pointed out in the footnotes.

TRANSPORTATION for Extraction plant	**Reference flow**		**ALCA gCO_{2e}/MJ**	**CLCA gCO_{2e}/MJ**
Truck <7.5 metric ton, EURO4 {RoW} [a]	**5.89E-03**	**tkm**	1.58E+00	1.71E+00
INTERMEDIARY STAGE – Rendering plant				
Products				
UCO, refined	**4.60E-02**	**kg**		
Materials/fuels				
UCO, no refined	5.89E-02	kg		
Electricity/heat				
Electricity [b]	1.93E-03	kWh	1.92E-01	5.65E-01
Natural gas, at boiler [c]	6.72E-02	MJ	2.56E+00	2.52E+00
TRANSPORTATION for HEFA plant				
Truck >32 metric ton, EURO4 {RoW}	**3.68E-02**	**tkm**	1.74E+00	1.89E+00
REFINING STAGE – HEFA plant				
Products				
AJF	**2.27E-02**	**kg**		
Diesel	1.07E-02	kg		
Naphtha	2.79E-03	kg		
Power surplus	1.57E-02	kWh		-4.59E+00 [d]
Materials/fuels				
UCO, at pre-refining stage	**4.60E-02**	**kg**		
Hydrogen (SMR) [e]	1.93E-03	kg	1.21E+01	1.20E+01
Electricity/heat				
Processes gases, at boiler [f]	4.70E-03	kg	1.57E-01	1.70E-01
TRANSPORTATION for use				
Truck >32 metric ton, EURO4 {RoW}	**9.08E-03**	**tkm**	7.39E-01	7.39E-01
USE				
AJF, use [g]	**1.00E+00**	**MJ**	2.09E-01	2.09E-01

[a] Transportation values of the inputs based [48,150]. According to them, it was assumed an average distance of 50 km to collect 1.0 ton of UCO from food service establishments. For all road transportation (by truck), it was considered the *biodiesel:diesel* blend of 10%, in volume. It was assumed that soybean oil and tallow are responsible by 82% to 18% of biodiesel produced in Brazil [58]. The inventories related to soybean production and extraction were the same assumed here (see **Tab SI.3**). Tallow was assumed waste, and the distance between slaughterhouse to biodiesel plant was set as 200 km by "*Truck >16 metric ton, EURO4 {RoW}*". Biodiesel production were described in [45,145]. Emissions related to biodiesel use were adjusted for hydrocarbons, nitrogen oxides, particulates and monoxide carbon [146].

[b] Brazilian power grid. Average values for ALCA (0.171 $kgCO_{2e}$/kWh), as assumed in [36]. Marginal values for CLCA (0.465 $kgCO_{2e}$/kWh). See Supporting information, **section 3.2**.

[c] Based on "*Natural gas, at industrial boiler*" [62]. For ALCA, it was assumed average production of natural gas and transportation in Brazil (0.0655 $kgCO_{2e}$/MJ). For CLCA, the marginal supplier process (0.0596 $kgCO_{2e}$/MJ) was the natural gas produced and transported from Pré-Sal basin in Brazil ("*natural gas production off-shore*"). For specific information about the inventories, see [36].

[d] Credits from marginal power displacement (0.465 $kgCO_{2e}$/kWh). See Supporting information, **section 3.2**.

[e] Gaseous hydrogen obtained from Steam Methane Reform (SMR) [56], with exergy allocation between gaseous hydrogen (90%) and steam (10%) (10.80 $kgCO_{2e}/kgH_2$). For CLCA, the supply of marginal power and marginal natural gas were considered (9.91 $kgCO_{2e}/kgH_2$).
[f] Based "*Liquefied Petroleum Gas, at industrial boiler*" considering biogenic carbon emissions, 0.0574 $kgCO_{2e}/kg$.
[g] Based on a typical aircraft operation in an intracontinental trip [59], considering biogenic carbon emissions.

Table SM.6: Inventory of 1.0 MJ_{AJF} from beef tallow through HEFA technology

Results for reference flow without allocation. Results for ALCA with economic allocation. Results for CLCA with energy allocation in the refining stage. Foreground data are adapted from [9,45,46]. Background inventories are mostly based on [59], while adaptations are pointed out at footnotes.

INTERMEDIARY STAGE – Slaughter/Rendering	**Reference flow**		**ALCA gCO_{2e}/MJ**	**CLCA gCO_{2e}/MJ**
Products				
Beef tallow	**4.60E-02**	**kg**	0.00E+00	0.00E+00 3.64E+01[a]
Carcass	5.22E-01	kg		
Leather	1.11E-01	kg		
Others	1.60E-01	kg		
Materials/fuels				
Cattle head (equivalent carcass)	5.22E-01	kg		
Electricity/heat				
Electricity [b]	4.98E-02	kWh		
Wood, at boiler [c]	1.77E+00	MJ		
TRANSPORTATION for HEFA plant				
Truck >32 metric ton, EURO4 {RoW} [d]	**3.68E-02**	**tkm**	1.74E+00	1.89E+00
REFINING STAGE – HEFA plant				
Products				
AJF	**2.27E-02**	**kg**		
Diesel	1.07E-02	kg		
Naphtha	2.79E-03	kg		
Power surplus	1.64E-02	kWh		-4.80E+00 [e]
Materials/fuels				
Beef tallow, at pre-refining stage	**4.60E-02**	**kg**		
Hydrogen (SMR) [f]	1.62E-03	kg	1.02E+01	1.01E+01
Electricity/heat				
Processes gases, at boiler [g]	4.70E-03	kg	1.56E-01	1.70E-01
TRANSPORTATION for use				
Truck >32 metric ton, EURO4 {RoW} [d]	**9.08E-03**	**tkm**	7.39E-01	7.39E-01
USE				
AJF, use [h]	**1.00E+00**	**MJ**	2.09E-01	2.09E-01

[a] Displacement of soybean oil, when beef tallow is assumed in current use (see **Tab. SM. 3**).
[b] Brazilian power grid. Average values for ALCA (0.171 $kgCO_{2e}/kWh$), as assumed in [36]. Marginal values for CLCA (0.465 $kgCO_{2e}/kWh$). See Supporting information, **section 3.2**.
[c] Based on "*Forest residues, at industrial boiler*" [62], 0.00272 $kgCO_{2e}/MJ$.
[d] For all road transportation (by truck), it was considered the *biodiesel:diesel* blend of 10%, in volume. It was assumed that soybean oil and tallow are responsible by 82% to 18% of biodiesel produced in Brazil [58]. The inventories related to soybean production and extraction were the same assumed here (see **Tab SI.3**). Tallow was assumed waste, and the distance between slaughterhouse to biodiesel plant was set as 200 km by "*Truck >16 metric ton, EURO4 {RoW}*". Biodiesel production were described in [45,145]. Emissions related to biodiesel use were adjusted for hydrocarbons, nitrogen oxides, particulates and monoxide carbon [146], besides the biogenic carbon and null sulfur emissions.
[e] Credits from marginal power displacement (0.465 $kgCO_{2e}/kWh$). See Supporting information, **section 3.2**.

[f] Gaseous hydrogen obtained from Steam Methane Reform (SMR) [56], with exergy allocation between gaseous hydrogen (90%) and steam (10%) (10.80 $kgCO_{2e}/kgH_2$). For CLCA, the supply of marginal power and marginal natural gas were considered (9.91 $kgCO_{2e}/kgH_2$).
[g] Based on "*Liquefied Petroleum Gas, at industrial boiler*" considering biogenic carbon emissions, 0.0574 $kgCO_{2e}/kg$.
[h] Based on a typical aircraft operation in an intracontinental trip [59], considering biogenic carbon emissions.

Table SM.7: Inventory of 1.0 MJ_{AJF} from 1G sugarcane ethanol through ATJ technology

Results for reference flow without allocation. Results for ALCA with economic allocation. Results for CLCA with energy allocation in the refining stage. Foreground data are adapted from [9,49,51]. Background inventories are mostly based on [59], while adaptations are pointed out at footnotes.

UPSTREAM STAGE – Sugarcane crop	Reference flow		ALCA gCO_{2e}/MJ	CLCA gCO_{2e}/MJ
Products				
Sugarcane	**1.12E-03**	**ton**		
Materials/fuels				
Urea, as N {RoW}	1.42E-03	kg	2.15E+00	2.82E+00
Single superphosphate as P2O5 {RoW}	2.16E-04	kg	2.41E-01	3.18E-01
Potassium chloride, as K2O {RoW}	1.52E-03	kg	3.65E-01	5.02E-01
Lime {RoW}	5.59E-03	kg	9.75E-02	1.31E-01
Gypsum, mineral {RoW}	2.80E-03	kg	3.66E-03	5.22E-03
Diesel use in agricultural operations [a]	2.25E-03	l	2.92E+00	4.07E+00
Vinasse aspersion system operation	5.27E-04	m³	1.63E-01	2.27E-01
Glyphosate {RoW}	5.45E-06	kg	2.95E-02	3.76E-02
Pesticide, unspecified {RoW}	1.33E-05	kg	6.76E-02	8.99E-02
Inputs transportation, Truck >16 ton, EURO4 {RoW} [a, b]	1.08E-02	tkm	7.41E-01	1.03E+00
Emissions to air				
Dinitrogen monoxide [c]	5.42E-05	kg	6.64E+00	9.26E+00
Carbon dioxide, fossil [d]	2.68E-03	kg	1.24E+00	1.73E+00
LUC [e]	1.40E-05	ha	2.54E+00	8.70E+00
TRANSPORTATION for Ethanol mill				
Truck >32 metric ton, EURO4 {RoW} [a]	**8.05E-02**	**tkm**	3.03E+00	4.22E+00
Straw bales, transport (wb) [f]	**5.90E-02**	**kg**	1.89E-01	2.63E-01
INTERMEDIARY STAGE – Ethanol mill				
Products				
Hydrated ethanol	**1.04E-01**	**l**		
Power surplus	2.15E-01	kWh		-6.43E+01 [g]
Materials/fuels				
Sugarcane	**1.12E+00**	**kg**		
Straw (db)	5.13E-02	kg		
Quicklime, milled, loose {RoW}	6.82E-04	m3	3.79E-01	5.19E-01
Sulfuric acid {RoW}	4.70E-04	kg	2.39E-02	1.84E-02
Phosphoric acid, industrial grade, 85% {RoW}	1.93E-01	kg	1.31E-01	1.63E-01
Chemical, inorganic {GLO}	2.86E-03	g	2.85E-03	3.73E-03
Chemical, inorganic {GLO}	1.24E-03	g	1.23E-03	1.62E-03
Lubricating oil , at refinery	1.45E-02	g	2.97E-03	4.14E-03
Electricity/heat				
Bagasse (db), at industrial boiler [h]	2.27E-01	kg	2.76E+00	3.84E+00
TRANSPORTATION for ATJ plant				
Truck >32 metric ton, EURO4 {RoW} [a]	**6.75E-02**	**tkm**	3.42E+00	3.54E+00
REFINING STAGE – ATJ plant				
Products				
AJF	**2.27E-02**	**kg**		

Diesel	1.69E-03	kg		
Naphtha	1.10E-02	kg		
Materials/fuels				
Ethanol, at pre-refining stage	**1.07E-01**	**L**		
Hydrogen (SMR) [i]	9.28E-04	kg	6.24E+00	5.93E+00
Electricity/heat				
Electricity [j]	1.65E-02	kWh	1.76E+00	4.95E+00
Processes gases, at boiler [k]	1.22E-02	kg	4.36E-01	4.52E-01
TRANSPORTATION for use				
Truck >32 metric ton, EURO4 {RoW} [a]	**9.08E-03**	**tkm**	7.39E-01	7.39E-01
USE				
AJF, use [l]	**1.00E+00**	**MJ**	2.09E-01	2.09E-01

[a] Transportation values of the inputs based on [46]. For all road transportation (by truck) and agricultural operations, it was considered the *biodiesel:diesel* blend of 10%, in volume. It was assumed that soybean oil and tallow are responsible by 82% to 18% of biodiesel produced in Brazil [58]. The inventories related to soybean production and extraction were the same assumed here (see **Tab SI.3**). Tallow was assumed waste, and the distance between slaughterhouse to biodiesel plant was set as 200 km by "*Truck >16 metric ton, EURO4 {RoW}*". Biodiesel production were described in [45,145]. Emissions related to biodiesel use were adjusted for hydrocarbons, nitrogen oxides, particulates and monoxide carbon [146], besides the biogenic carbon and null sulfur emissions.
[b] It also includes the return of industrial residues to the field.
[c] Direct emissions: 1.0% of nitrogen fertilizer, organic fertilizer (vinasse and filter cake), sugarcane straw and sugarcane roots are emitted as dinitrogen monoxide. Filter cake (14 kgN/ton_db); Vinasse (0.38 kgN/m^3); straw on field (4.70 kgN/ton_db); sugarcane roots (5.14 kg/ton) [51].
Indirect emissions: 1.0% of NH_3 and 0.75% nitrogen leached as nitrate are converted into N_2O, according to [89].
[d] From lime use, all carbon content in limestone is converted into carbon dioxide, according to [89], *i.e.*, 0.48 $kgCO_2$/kg limestone.
[e] dLUC for ALCA, considering sugarcane crop expansion on pasture lands (0.36 tCO_{2e}/ha.year). LUC for CLCA, according to default values reported by [95].
[f] Available in [51].
[g] Credits from marginal power displacement (0.465 $kgCO_{2e}$/kWh). See Supporting information, **section 3.2**.
[h] Emissions from "*Bagasse (db), at industrial boiler*" [62], 0.0262 $kgCO_{2e}$/kg.
[i] Gaseous hydrogen obtained from Steam Methane Reform (SMR) [56], with exergy allocation between gaseous hydrogen (90%) and steam (10%) (10.80 $kgCO_{2e}/kgH_2$). For CLCA, the supply of marginal power and marginal natural gas were considered (9.91 $kgCO_{2e}/kgH_2$).
[j] Brazilian power grid. Average values for ALCA (0.171 $kgCO_{2e}$/kWh), as assumed in [36]. Marginal values for CLCA (0.465 $kgCO_{2e}$/kWh). See Supporting information, **section 3.2**.
[k] Based on "*Liquefied Petroleum Gas, at industrial boiler*" considering biogenic carbon emissions, 0.0574 $kgCO_{2e}$/kg.
[l] Based on a typical aircraft operation in an intracontinental trip [59], considering biogenic carbon emissions.

Table SM.8: Inventory of 1.0 MJ_{AJF} from 2G ethanol from sugarcane residues through ATJ technology

Results for reference flow without allocation. Results for ALCA with economic allocation. Results for CLCA with energy allocation in the refining stage. Foreground data are adapted from [9,49,51]. Background inventories are mostly based on [59], while adaptations are pointed out at footnotes.

INTERMEDIARY STAGE – Ethanol mill	Reference flow		ALCA gCO_{2e}/MJ	CLCA gCO_{2e}/MJ
Products				
Hydrated ethanol	**1.04E-01**	**L**		
Power surplus	3.72E-02	kWh		-1.11E+01 [a]
Materials/fuels				
LCM (db)	**2.91E-04**	**ton**	0.00E+00	0.00E+00 8.24E+01 [b]
Sulfuric acid {RoW}	2.86E-04	kg	1.85E-02	1.12E-02
Enzyme [c]	1.93E-03	kg	3.18E+00	6.78E+00
Ammonia, liquid {RoW}	3.06E-03	kg	3.96E+00	4.40E+00
Sugar, at industrial plant [d]	1.75E-04	kg	2.35E-02	2.58E-02
Electricity/heat				
LCM (db), at industrial boiler [e]	1.18E-01	kg	1.82E+00	2.00E+00
TRANSPORTATION for ATJ plant				
Truck >32 metric ton, EURO4 {RoW} [f]	**6.75E-02**	**tkm**	3.42E+00	3.54E+00
REFINING STAGE – ATJ plant				
Products				
AJF	**2.27E-02**	**kg**		
Diesel	1.69E-03	kg		
Naphtha	1.10E-02	kg		
Materials/fuels				
Ethanol, at pre-refining stage	**1.07E-01**	**L**		
Hydrogen (SMR) [g]	9.28E-04	kg	6.24E+00	5.93E+00
Electricity/heat				
Electricity [h]	1.65E-02	kWh	1.76E+00	4.95E+00
Processes gases, at boiler [i]	1.22E-02	kg	4.36E-01	4.52E-01
TRANSPORTATION for use				
Truck >32 metric ton, EURO4 {RoW} [f]	**9.08E-03**	**tkm**	7.39E-01	7.39E-01
USE				
AJF, use [j]	**1.00E+00**	**MJ**	2.09E-01	2.09E-01

[a] Credits from marginal power displacement (0.465 $kgCO_{2e}/kWh$). See Supporting information, **section 3.2**.
[b] Displacement of marginal power generation (0.465 $kgCO_{2e}/kWh$), see Supporting information, **section 3.2**), when lignocellulosic residue is currently used for power generation in CHP systems (0.944 $kWh/ton_{LCM(db)}$) [51].
[c] Enzyme production according to [151]. For ALCA, average power and natural gas were considered in the inventory (2.80 $kgCO_{2e}/kg$). For CLCA, marginal power and marginal natural gas were considered in the inventory (5.45 $kgCO_{2e}/kg$).
[d] Based on Optimized annex ethanol mill [49] by economic allocation.
[e] Based on "*Bagasse (db), at industrial boiler*" [62], 0.0262 $kgCO_{2e}/kg$.
[f] For all road transportation (by truck) and operation based on diesel, it was considered the *biodiesel:diesel* blend of 10%, in volume. It was assumed that soybean oil and tallow are responsible by 82% to 18% of biodiesel produced in Brazil [58]. The inventories related to soybean production and extraction were the same assumed here (see **Tab SI.3**). Tallow was assumed waste, and the distance between slaughterhouse to biodiesel plant was set as 200 km by "*Truck >16 metric ton, EURO4 {RoW}*". Biodiesel production were described in [45,145]. Emissions

related to biodiesel use were adjusted for hydrocarbons, nitrogen oxides, particulates and monoxide carbon [146], besides the biogenic carbon and null sulfur emissions.

[g] Gaseous hydrogen obtained from Steam Methane Reform (SMR) [56], with exergy allocation between gaseous hydrogen (90%) and steam (10%) (10.80 $kgCO_{2e}/kgH_2$). For CLCA, the supply of marginal power and marginal natural gas were considered (9.91 $kgCO_{2e}/kgH_2$).

[h] Brazilian power grid. Average values for ALCA (0.171 $kgCO_{2e}/kWh$), as assumed in [36]. Marginal values for CLCA (0.465 $kgCO_{2e}/kWh$). See Supporting information, **section 3.2**.

[i] Based on "*Liquefied Petroleum Gas, at industrial boiler*", considering biogenic carbon emissions, 0.0574 $kgCO_{2e}/kg$.

[j] Based on a typical aircraft operation in an intracontinental trip [59], considering biogenic carbon emissions.

Table SM.9: Inventory of 1.0 MJ_{AJF} from 2G ethanol from forestry residues through ATJ technology

Results for reference flow without allocation. Results for ALCA with economic allocation. Results for CLCA with energy allocation in the refining stage. Foreground data are adapted from [9]. Background inventories are mostly based on [59], while adaptations are pointed out at footnotes.

INTERMEDIARY STAGE – Ethanol mill	**Reference flow**		**ALCA gCO_{2e}/MJ**	**CLCA gCO_{2e}/MJ**
Products				
Hydrated ethanol	**1.04E-01**	**L**		
Power surplus	5.34E-02	kWh		-1.60E+01 [a]
Materials/fuels				
LCM (db)	3.38E-04	ton	4.56E-01 [b]	-2.38E+00 [c] 1.93E+02 [d]
Sulfuric acid {RoW}	2.50E-04	kg	1.58E-02	9.81E-03
Enzyme [e]	1.89E-03	kg	3.04E+00	6.65E+00
Ammonia, liquid {RoW}	3.21E-03	kg	4.05E+00	4.55E+00
Sugar, at industrial plant [f]	1.76E-04	kg	2.31E-02	2.60E-02
Electricity/heat				
LCM (db), at industrial boiler [g]	1.16E-01	kg	1.74E+00	1.95E+00
TRANSPORTATION for ATJ plant				
Truck >32 metric ton, EURO4 {RoW} [h]	**6.75E-02**	**tkm**	3.42E+00	3.54E+00
REFINING STAGE – ATJ plant				
Products				
AJF	**2.27E-02**	**kg**		
Diesel	1.69E-03	kg		
Naphtha	1.10E-02	kg		
Materials/fuels				
Ethanol, at pre-refining stage	**1.07E-01**	**L**		
Hydrogen (SMR) [i]	9.28E-04	kg	6.24E+00	5.93E+00
Electricity/heat				
Electricity [j]	1.65E-02	kWh	1.76E+00	4.95E+00
Processes gases, at boiler [k]	1.22E-02	kg	4.36E-01	4.52E-01
TRANSPORTATION for use				
Truck >32 metric ton, EURO4 {RoW} [g]	**9.08E-03**	**tkm**	7.39E-01	7.39E-01
USE				
AJF, use [l]	**1.00E+00**	**MJ**	2.09E-01	2.09E-01

[a] Credits from marginal power displacement (0.465 $kgCO_{2e}/kWh$). See Supporting information, **section 3.2**.
[b] Chipping, harvesting, and transportation of forestry residues to ethanol mill (40 km, one way), as described by Coelho (2018) and reported by Capaz et al. (2020).
[c] Residues available for AJF production. Then, the effects considered were: avoided emissions (13.3 $gCO_{2e}/kg_{LCM(db)}$ from 2.6 $kgN/kg_{LCM(db)}$ [88] or -2.89E+00 gCO_{2e}/MJ) , emissions from collect operations (5.08E-01 gCO_{2e}/MJ), and transportation (1.59E-03 gCO_{2e}/MJ).
[d] Residues in current use as heating source (see Supporting information, **section 3.1**); Then, the effects considered were: marginal heat displacement (0.88 $kgCO_{2e}/kg_{LCM(db)}$, or 1.93E+02 gCO_{2e}/MJ), and emissions from collect (5.08E-01 gCO_{2e}/MJ) and transportation (1.59E-03 gCO_{2e}/MJ). Emission factor for marginal heat was estimated considering the energy parity between wood and natural gas used in a boiler for heat production. The inventories "*heat production from natural gas, at furnace*" and "*heat production from wood chips, at industrial furnace*" [59], were considered.

[e] Enzyme production according to [151]. For ALCA, average power and natural gas were considered in the inventory (2.80 $kgCO_{2e}/kg$). For CLCA, marginal power and marginal natural gas were considered in the inventory (5.45 $kgCO_{2e}/kg$).
[f] Based on Optimized annex ethanol mill [49] by economic allocation.
[g] Based on "*Bagasse (db), at industrial boiler*" [62], 0.0262 $kgCO_{2e}/kg$
[h] For all road transportation (by truck) and operation based on diesel, it was considered the *biodiesel:diesel* blend of 10%, in volume. It was assumed that soybean oil and tallow are responsible by 82% to 18% of biodiesel produced in Brazil [58]. The inventories related to soybean production and extraction were the same assumed here (see **Tab SI.3**). Tallow was assumed waste, and the distance between slaughterhouse to biodiesel plant was set as 200 km by "*Truck >16 metric ton, EURO4 {RoW}*". Biodiesel production were described in [45,145]. Emissions related to biodiesel use were adjusted for hydrocarbons, nitrogen oxides, particulates and monoxide carbon [146], besides the biogenic carbon and null sulfur emissions.
[i] Gaseous hydrogen obtained from Steam Methane Reform (SMR) [56], with exergy allocation between gaseous hydrogen (90%) and steam (10%) (10.80 $kgCO_{2e}/kgH_2$). For CLCA, the supply of marginal power and marginal natural gas were considered (9.91 $kgCO_{2e}/kgH_2$).
[j] Brazilian power grid. Average values for ALCA (0.171 $kgCO_{2e}/kWh$), as assumed in [36]. Marginal values for CLCA (0.465 $kgCO_{2e}/kWh$). See Supporting information, **section 3.2**.
[k] Based on "*Liquefied Petroleum Gas, at industrial boiler*", considering biogenic carbon emissions, 0.0574 $kgCO_{2e}/kg$.
[l] Based on a typical aircraft operation in an intracontinental trip [59], considering biogenic carbon emissions.

Table SM.10: Inventory of 1.0 MJ_{AJF} from 2G ethanol from steel off-gases through ATJ technology

Results for reference flow without allocation. Results for ALCA with economic allocation. Results for CLCA with energy allocation in the refining stage. Foreground data are adapted from [9,55]. Background inventories are mostly based on [59], while adaptations are pointed out at footnotes.

INTERMEDIARY STAGE – Ethanol mill	**Reference flow**		**ALCA gCO_{2e}/MJ**	**CLCA gCO_{2e}/MJ**
Products				
Ethanol	**1.07E-01**	**L**		
Materials/fuels				
Steel off-gases [a]	**5.49E-01**	**kg**	0.00E+00	-4.20E+02 [b] 1.21E+02 [c]
Other inputs	4.29E+00	gCO2e	2.67E+00	2.77E+00
Electricity/heat				
Electricity [d]	7.80E-02	kWh	8.31E+00	2.34E+01
Steam [e]	8.59E+00	gCO2e	0.00E+00	5.54E+00
Emissions to air [f]				
Emissions from anaerobic digestion and waste treatment	1.84E+01	gCO2e	0.00E+00	1.18E+01
Venting gases from fermenter	3.90E-02	kg	0.00E+00	2.90E+02
TRANSPORTATION for ATJ plant				
Truck >32 metric ton, EURO4 {RoW} [g]	**6.75E-02**	**tkm**	3.42E+00	3.54E+00
REFINING STAGE – ATJ plant				
Products				
AJF	**2.27E-02**	**kg**		
Diesel	1.69E-03	kg		
Naphtha	1.10E-02	kg		
Materials/fuels				
Ethanol, at pre-refining stage	**1.07E-01**	**L**		
Hydrogen (SMR) [h]	9.28E-04	kg	6.24E+00	5.93E+00
Electricity/heat				
Electricity [i]	1.65E-02	kWh	1.76E+00	4.95E+00
Processes gases, at boiler [j]	1.22E-02	kg	0.00E+00	2.41E+1
TRANSPORTATION for use				
Truck >32 metric ton, EURO4 {RoW} [e]	**9.08E-03**	**tkm**	7.39E-01	7.39E-01
USE				
AJF, use [k]	**1.00E+00**	**MJ**	2.09E-01	8.90E+1

[a] Total input, assuming theoretical maximum 80% HHV conversion to ethanol [143] and the net off-gases input reported by [55].

[b] When steel off-gases are flared, the avoided emissions were accounted for (1.19 $kgCO_{2e}/kg_{off\text{-}gases}$).

[c] When steel off-gases are currently recovered, the use of natural gas was considered, based on the energy parity (0.206 $Nm^3_{NG}/Nm^3_{off\text{-}gases}$, or 0.341 $kgCO_{2e}/kg_{off\text{-}gases}$).

[d] Based on the sensitivity analysis reported by [55], Table 4. Average values for ALCA (0.171 $kgCO_{2e}/kWh$, Brazilian power grid), as assumed in [36]. Marginal values for CLCA (0.465 $kgCO_{2e}/kWh$), see Supporting information, **section 3.2**.

[e] Based on the electricity consumption and the carbon emissions related to *utilities (heat and power)* as reported by [55], Table 3. For ALCA, since no burden related to steel off-gases was accounted for, the value was assumed zero. For CLCA, it was considered.

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[f] For ALCA, since no burden related to steel off-gases was accounted for, the value was assumed zero. For CLCA, the emissions from venting gases (1.19 $kgCO_{2e}/kg_{off\text{-}gases}$) were estimated, considering theoretical maximum 80% HHV conversion to ethanol [143], the net off-gases input as reported by [55], and the carbon content of steel off-gases (0.324 $kgC/kg_{off\text{-}gas}$ for an average composition (60% CO, 20% CO, and 20% N_2, in %vol)

[g] For all road transportation (by truck) and operation based on diesel, it was considered the *biodiesel:diesel* blend of 10%, in volume. It was assumed that soybean oil and tallow are responsible by 82% to 18% of biodiesel produced in Brazil [58]. The inventories related to soybean production and extraction were the same assumed here (see **Tab SI.3**). Tallow was assumed waste, and the distance between slaughterhouse to biodiesel plant was set as 200 km by "*Truck >16 metric ton, EURO4 {RoW}*". Biodiesel production were described in [45,145]. Emissions related to biodiesel use were adjusted for hydrocarbons, nitrogen oxides, particulates and monoxide carbon [146], besides the biogenic carbon and null sulfur emissions.

[h] Gaseous hydrogen obtained from Steam Methane Reform (SMR) [56], with exergy allocation between gaseous hydrogen (90%) and steam (10%) (10.80 $kgCO_{2e}/kgH_2$). For CLCA, the supply of marginal power and marginal natural gas were considered (9.91 $kgCO_{2e}/kgH_2$).

[i] Brazilian power grid. Average values for ALCA (0.171 $kgCO_{2e}/kWh$), as assumed in [36]. Marginal values for CLCA (0.465 $kgCO_{2e}/kWh$). See Supporting information, **section 3.2**.

[j] Based on "*Liquefied Petroleum Gas, at industrial boiler*", considering biogenic carbon emissions, 0.0574 $kgCO_{2e}/kg$.

[k] Based on a typical aircraft operation in an intracontinental trip [59], considering biogenic carbon emissions..

Table SM.11: Inventory of 1.0 MJ_{AJF} from Fischer-Tropsch of sugarcane residues

Results for reference flow without allocation. Results for ALCA with economic allocation. Results for CLCA with energy allocation in the refining stage. Foreground data are adapted from [9,49,51]. Background inventories are mostly based on [59], while adaptations are pointed out at footnotes.

REFINING STAGE – FT plant	Reference flow		ALCA gCO_{2e}/MJ	CLCA gCO_{2e}/MJ
Products				
AJF	**2.27E-02**	**kg**		
Diesel	1.86E-02	kg		
Naphtha	2.68E-02	kg		
Power surplus	1.83E-01	kWh		-2.84E+01 [a]
Materials/fuels				
LCM (db) [b]	**4.03E-01**	**kg**	0.00E+00	0.00E+00 5.90E+01 [c]
Electricity/heat				
Processes gases, at boiler [d]	1.29E-03	kg	1.81E-02	2.46E-02
TRANSPORTATION for use				
Truck >32 metric ton, EURO4 {RoW} [e]	**2.72E-02**	**tkm**	2.22E+00	2.22E+00
USE				
AJF, use [f]	**1.00E+00**	**MJ**	2.09E-01	2.09E-01

[a] Credits from marginal power displacement (0.465 $kgCO_{2e}$/kWh). See Supporting information, **section 3.2**.
[b] Lignocellulosic material (dry basis). For ALCA, economic allocation at co-product approach (CpA). See **Tab. SM.2** for allocation factor, and [36] for upstream stage description. For CLCA, marginal power displacement (0.465 $kgCO_{2e}$/kWh, see Supporting information, **section 3.2**), when lignocellulosic residue is currently used for power generation in CHP systems (0.944 $kWh/ton_{LCM(db)}$) [51].
[c] Displacement of marginal power generation (0.465 $kgCO_{2e}$/kWh), see Supporting information, **section 3.2**), when lignocellulosic residue is currently used for power generation in CHP systems (0.944 $kWh/ton_{LCM(db)}$) [51].
[d] Based on "*Liquefied Petroleum Gas, at industrial boiler*", considering biogenic carbon emissions, 0.0574 $kgCO_{2e}$/kg.
[e] For all road transportation (by truck) and operation based on diesel, it was considered the *biodiesel:diesel* blend of 10%, in volume. It was assumed that soybean oil and tallow are responsible by 82% to 18% of biodiesel produced in Brazil [58]. The inventories related to soybean production and extraction were the same assumed here (see **Tab SI.3**). Tallow was assumed waste, and the distance between slaughterhouse to biodiesel plant was set as 200 km by "*Truck >16 metric ton, EURO4 {RoW}*". Biodiesel production were described in [45,145]. Emissions related to biodiesel use were adjusted for hydrocarbons, nitrogen oxides, particulates and monoxide carbon [146], besides the biogenic carbon and null sulfur emissions.
[f] Based on a typical aircraft operation in an intracontinental trip [59], considering biogenic carbon emissions.

Table SM.13: Inventory of 1.0 MJ_{AJF} from Fischer-Tropsch of forestry residues

Results for reference flow without allocation. Results for ALCA with economic allocation. Results for CLCA with energy allocation in the refining stage. Foreground data are adapted from [9]. Background inventories are mostly based on [59], while adaptations are pointed out at footnotes.

REFINING STAGE – FT plant	Reference flow		ALCA gCO_{2e}/MJ	CLCA gCO_{2e}/MJ
Products				
AJF	**2.27E-02**	**kg**		
Diesel	1.86E-02	kg		
Naphtha	2.70E-02	kg		
Power surplus	1.83E-01	kWh		-2.84E+01 [a]
Materials/fuels				
LCM (wb)	**4.38E-01**	**kg**	9.79E-01 [b]	-5.97E+00 [c] 1.14E+02 [d]
Electricity/heat				
Processes gases, at boiler [e]	1.23E-03	kg	1.72E-02	2.35E-02
TRANSPORTATION for use				
Truck >32 metric ton, EURO4 {RoW} [f]	**2.72E-02**	**tkm**	2.22E+00	2.22E+00
USE				
AJF, use [g]	**1.00E+00**	**MJ**	2.09E-01	2.09E-01

[a] Credits from marginal power displacement (0.465 $kgCO_{2e}$/kWh). See Supporting information, **section 3.2**.
[b] Collect operation (3.85E-01 gCO_{2e}/MJ) and transportation (9.47E-01 gCO_{2e}/MJ)
[c] Residues available for AJF production. Then, the effects considered were: avoided emissions (13.3 $gCO_{2e}/kg_{LCM(db)}$ from 2.6 $kgN/kg_{LCM(db)}$ [88] or -2.89E+00 gCO_{2e}/MJ), emissions from collect operation (3.86E-01 gCO_{2e}/MJ), and transportation (9.48E-01 gCO_{2e}/MJ).
[d] Residues in current use as heating source (see Supporting information, **section 3.1**). Then, the effects considered were: marginal heat displacement (0.88 $kgCO_{2e}/kg_{LCM(db)}$, or 1.13E+02 gCO_{2e}/MJ), and emissions from collect (3.86E-01 gCO_{2e}/MJ) and transportation (9.48E-01 gCO_{2e}/MJ). Emission factor for marginal heat was estimated considering the energy parity between wood and natural gas used in a boiler for heat production. The inventories "*heat production from natural gas, at furnace*" and "*heat production from wood chips, at industrial furnace*" [59], were considered.
[e] Based on "*Liquefied Petroleum Gas, at industrial boiler*", considering biogenic carbon emissions, 0.0574 $kgCO_{2e}$/kg.
[f] For all road transportation (by truck) and operation based on diesel, it was considered the *biodiesel:diesel* blend of 10%, in volume. It was assumed that soybean oil and tallow are responsible by 82% to 18% of biodiesel produced in Brazil [58]. The inventories related to soybean production and extraction were the same assumed here (see **Tab SI.3**). Tallow was assumed waste, and the distance between slaughterhouse to biodiesel plant was set as 200 km by "*Truck >16 metric ton, EURO4 {RoW}*". Biodiesel production were described in [45,145]. Emissions related to biodiesel use were adjusted for hydrocarbons, nitrogen oxides, particulates and monoxide carbon [146], besides the biogenic carbon and null sulfur emissions.
[g] Based on a typical aircraft operation in an intracontinental trip [59], considering biogenic carbon emissions.

3. Attributional LCA assumptions

Table SM.14: Allocation factors used in ALCA

"Ref.": reference flow; "Econ": economic allocation; "En": energy allocation". For 2G pathways, *i.e.*, residues-based pathways, allocation at upstream stage is used only sensitivity analysis when residual feedstocks is handled as co-product.

Pathways	Upstream stage				Pre-refining stage				Refining stage			
	Ref.	***Econ.***	***Mass***	***En.***	**Ref.**	***Econ.***	***Mass***	***En.***	**Ref.**	***Econ.***	***Mass***	***En.***
Soy/HEFA	Soybean	100%	100%	100%	Soy oil	38%	19%	40%	AJF	58%	63%	61%
Palm/HEFA	Palm	100%	100%	100%	Palm oil	87%	83%	86%				
UCO/HEFA	UCO	n.a.			UCO	100%	100%	100%				
Tallow/HEFA	Tallow	n.a.			Tallow	3%	5%	n.a.				
SC_1G/ATJ	Sugarcane	100%	100%	100%	Ethanol	74%	100%	74%	AJF	60%	64%	64%
SC_2G/ATJ	LCM	15%	63%	46%	n.a.							
FR_2G/ATJ	LCM	7%	7%	7%	n.a.							
SOG_2G/ATJ	SOG	n.a.			Ethanol	100%	100%	100%				
SC/FT	LCM	15%	63%	46%	n.a.				AJF	24%	33%	27%
FR/FT	LCM	7%	7%	7%	n.a.							

4. Consequential LCA assumptions

4.1. Affected suppliers

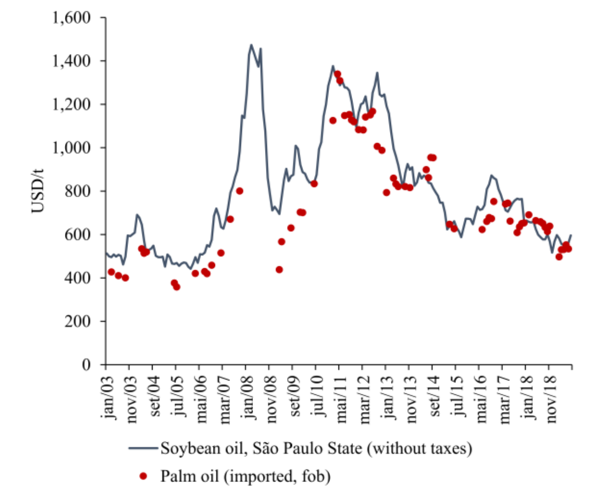

Figure SM.1: Prices of vegetable oils in the Brazilian market, current values, adapted from [73,74]

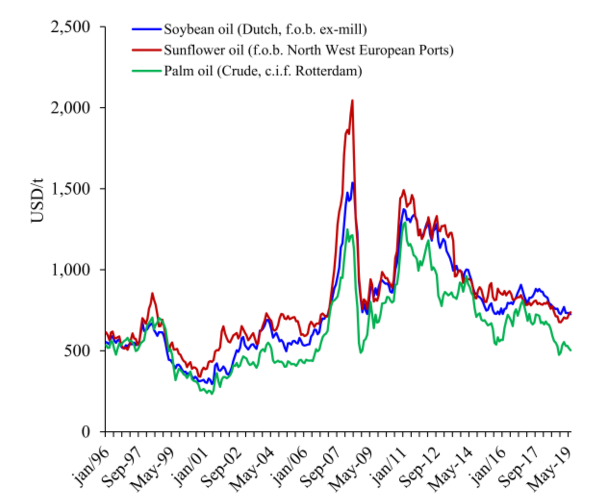

Figure SM.2: Prices of vegetable oils in the international market, current values, adapted from [132]

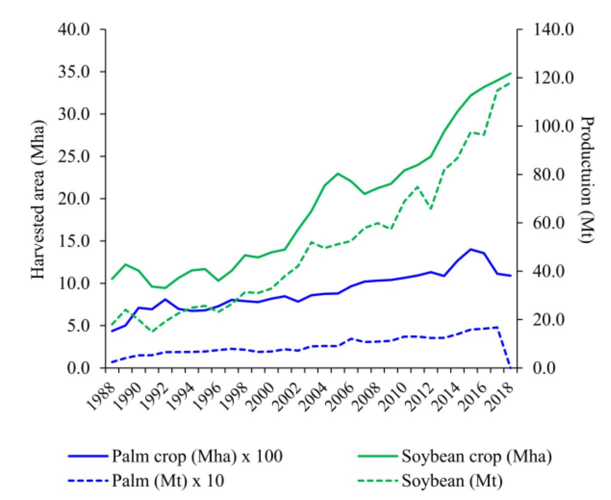

Figure SM.3: Soybean and palm production in Brazil [41]

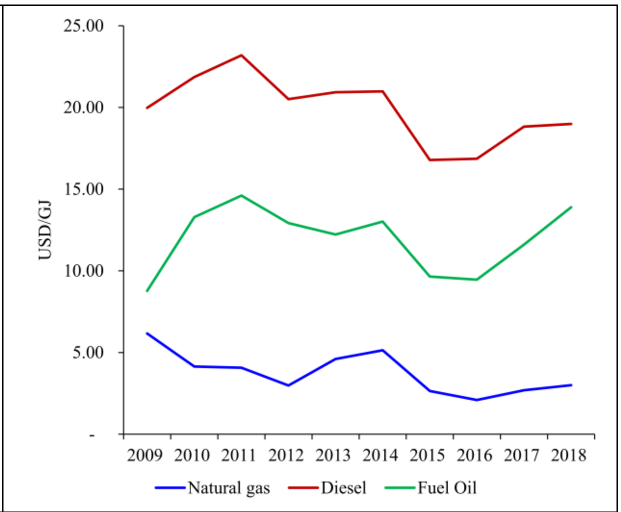

Figure SM.4: Average prices of energy sources in Brazil, typically used for heating, in current values [58]

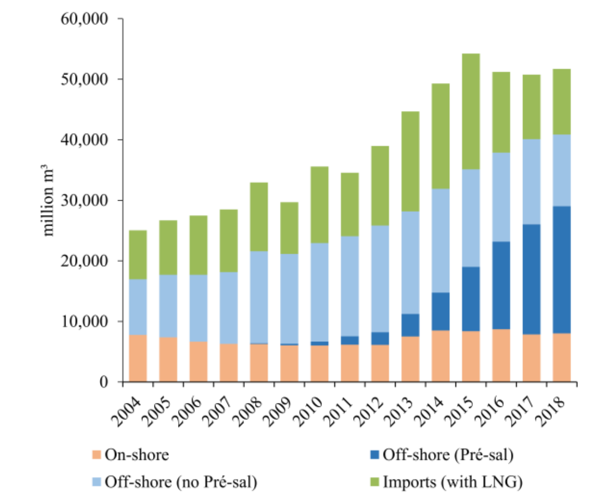

Figure SM.5: Natural gas production and imports in Brazil [58]

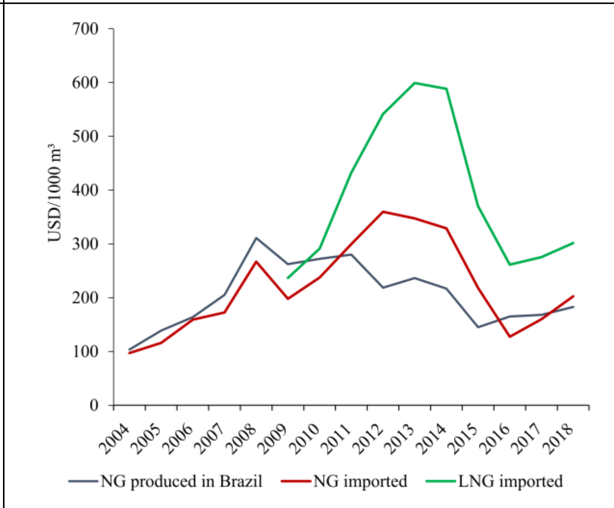

Figure SM.6: Average prices of natural gas in Brazil in current values [58]

4.2. Marginal emissions related to the power grid

According to the current methodology of Clean Development Mechanism (CDM) for electricity systems[84], the marginal emissions related to the power grid are estimated by combining emissions from operation margin (OM) and build margin (BM), as presented in Eq. 4. The total emissions factor used in the present study comprised, on average, the emissions factors for the last three years (2016-2018).

$$EF_y = w_{OM}.EF_{OM,y} + w_{BM}.EF_{BM,y} \qquad \text{(Eq. 4)}$$

EF_y: emission factor at year y ($kgCO_{2e}.kWh^{-1}$); $EF_{OM,y}$: emission factor of operation margin at year y ($kgCO_{2e}.kWh^{-1}$); $EF_{BM,y}$: emission factor of built margin at year y ($kgCO_{2e}.kWh^{-1}$);

w_{OM}: influence of operation margin (%), which is typically assumed 50%; w_{BM}: influence of built margin (%), which is typically assumed 50%.

Operation margin (EF_{OM}): Among the four possible ways to estimate the margin emission factor, as presented by the original methodology[84], the *simple adjusted operation margin method* was assumed here by the following main reasons.

- The power generation in Brazil is mostly provided by hydroelectric plants, which are typically assumed as low-cost/must-run plants. Along the last years, they have been responsible by more than 70% of power generation[100];
- Due to specific policies or hydrologic risks, the dispatch out of the order of merit is legally allowed, *i.e.*, in some situations the dispatch does not follow the economic sense of dispatching firstly low marginal costs plants.

As observed in (Eq. 5), this method quantifies the possible contribution of power generation from low-cost/must-run plants[a] in operation margin.

$$EF_{OM,adjusted,y} = (1-\lambda_y).\frac{\sum_{i,j} F_{i,j,y}.COEF_{i,j}}{\sum_j GEN_{j,y}} + \lambda_y.\frac{\sum_{i,k} F_{i,k,y}.COEF_{i,k}}{\sum_k GEN_{k,y}} \quad \text{(Eq. 5)}$$

$EF_{OM,adjusted,y}$: emission factor adjusted on operation margin ($kgCO_{2e}.kWh^{-1}$); λ_y: time along the year *y* when low-cost/must-run plants dispatch on margin (%); $F_{i,j,y}$: fuel *i* consumed by plant *j* the year *k* (mass or volume); $COEF_{i,j}$: emission factor related to fuel *i* consumed by plant *j*; $GEN_{j,y}$: electricity generation by plant *j* at the year *y*; $F_{i,k,y}$: fuel *i* consumed by low cost/must-run plant *k* at the year *k* (mass or volume); $COEF_{i,k}$: emission factor related to fuel *i* consumed by low-cost/must-run plant *k*; $GEN_{k,y}$: electricity generation by low-cost/must-run plant *k* at the year *y*.

Data related to each power plant are not easily available. Then the power generation from each source in 2016 to 2018, as reported by [100], was taken here (Eq. 6). On the same way, the individual emission factors for each source comprise the life cycle emissions mostly based on [59] with some adaptations to Brazilian context. The life cycle emissions include production and conversions stages (see **Table SM.15**). **Table SM.16** presents the main values estimated here.

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[a] Hydroelectric plants, nuclear plants, windmills, photovoltaic plants, and plants based on biomass, such as sugarcane residues and wood, were assumed here as *low-cost/must-run plants*. *Other plants* comprise power plants from natural gas, coal, diesel, and fuel oil.

$$EF_{OM,adjusted,y} = (1 - \lambda_y).\frac{\sum_j GEN_{j,y}.EF_j}{\sum_j GEN_{j,y}} + \lambda_y.\frac{\sum_k GEN_{k,y}.EF_k}{\sum_k GEN_{k,y}} \quad \text{(Eq. 6)}$$

$EF_{OM,adjusted,y}$: emission factor adjusted on operation margin ($kgCO_{2e}.kWh^{-1}$); λ_y: time along the year *y* when low-cost/must-run plants dispatch on margin (%); $GEN_{j,y}$: total electricity generation by *other plants* from source *j* at year *k* (MWh); EF_j: emission factor according to life cycle assessment of source *j* ($kgCO_{2e}.kWh^{-1}$), see Table SM.15; $GEN_{k,y}$: total electricity generation by *low-cost/must-run plants* from source *k* at year *y* (MWh); EF_j: emission factor according to life cycle assessment of source *k* ($kgCO_{2e}.kWh^{-1}$), see Table SM.15.

Table SM.15: LCI of Electricity from Brazilian grid, based on [100]

Output	**Value**	**Unit**	
Power	1.0	kWh	
Input	**Value**	**Unit**	**Background inventories**
Coal	0.020	kWh	*Electricity, high voltage {BR}| electricity production, hard coal | Rec, U.*
Diesel	0.016	kWh	*Electricity, diesel, at power plant/US U.*
Hydropower	0.802	kWh	*Electricity, high voltage {BR}| electricity production, hydro, reservoir, tropical region | Rec, U.*
Natural gas	0.026	kWh	*Electricity, high voltage {BR}| electricity production, natural gas, combined cycle power plant | Rec, U.* Adapted with natural gas produced in Brazil, as used in [36].
Natural gas	0.047	kWh	*Electricity, high voltage {BR}| electricity production, natural gas, conventional power plant | Rec, U.* Adapted with natural gas produced in Brazil, as used in [36].
Nuclear	0.030	kWh	*Electricity, high voltage {BR}| electricity production, nuclear, pressure water reactor | Rec, U.*
Oil fuel	0.014	kWh	*Electricity, high voltage {BR}| electricity production, oil | Rec, U.*
Sugarcane products	0.022	kWh	*Electricity, high voltage {BR}| cane sugar production with ethanol by-product | Rec, U.* Adapted with sugarcane production (Table SM.7).
Windpower	0.017	kWh	*Electricity, high voltage {BR}| electricity production, wind, 1-3MW turbine, onshore | Rec, U.*
Wood	0.001	kWh	*Electricity, high voltage {BR}| heat and power co-generation, wood chips, 6667 kW, state-of-the-art 2014 | Rec, U.*
Power losses	0.063	kWh	
Transmission	3,17E-10	km	*Transmission network, long-distance {GLO}| market for | Def, U.*
Transmission	6,58E-9	km	*Transmission network, electricity, high voltage {GLO}| market for | Def, U.*
Emission to air	**Value**	**Unit**	**Observation**
Dinitrogen monoxide	0.05	g	
Ozone	4,16	mg	

Table SM.16: Mains values related to operation margin emission factor

Parameters	**2016**	**2017**	**2018**
Total electricity generation (GWh)	522,567	535,242	542,996
Electricity generation (GWh) by *low-cost/must-run* plants	472,936	477,264	501,429
λ	0.271	0.244	0.348
EF_{OM} ($kgCO_{2e}.kWh^{-1}$)	0.503	0.516	0.462

Build margin (EF_{BM}): The emission factor related to build margin (Eq. 7) comprises the five more recent power plants, which started-up in 2019 (see Tab. SM.17)

$$EF_{BM} = \frac{\sum_{i,m} GEN_{i,m}.EF_i}{\sum_m GEN_m} \qquad \text{(Eq. 7)}$$

$EF_{BM,y}$: emission factor of build margin ($kgCO_{2e}.kWh^{-1}$); $GEN_{j,y}$: total electricity generation by plant *m*, from source *i* (MWh); EF_j: emission factor according to life cycle assessment of source *i* ($kgCO_{2e}.kWh^{-1}$), see **Table SM.14**.

Table SM.17: Recent built power plants in Brazil [141]

Type	**Power (MW)**	**Source**
Themal power plant	1238	Natural gas
Themal power plant	1238	Natural gas
Themal power plant	583	Natural gas
Themal power plant	340	Coal
Themal power plant	164	Wood

The total emission factor related to build margin was estimated as 0.436 $kgCO_{2e}.kWh^{-1}$. By Eq. 4 and the previous values, the GHG emissions related to the marginal electricity produced in Brazil were estimated as 0.465 $kgCO_{2e}/kWh^{-1}$.

4.3. Land Use Change

Table SM.18: Values assumed for Land Use Change, LUC (tCO_{2e}/t_{feed}.year)

Feed	When used	LUC (crop expansion in)	Main assumptions
Soybean	**For ALCA**	0.00 (annual cropland) 2.73 (perennial cropland) 1.34 (pasture land) 5.01 (native vegetation)	dLUC based on [122], and average values related to the current land use in the Brazilian States with suitable areas for soybean crop expansion [92], *i.e.*, Maranhão, Tocantins, Piauí, Bahia, Mato Grosso, Mato Grosso do Sul, and Goiás. Direct N_2O emissions by [89].
	For CLCA	0.11	Estimated from default value reported by [95] (27 gCO_{2e}/MJ) for soybean/HEFA in Brazil, and the yields for agricultural and industrial stages assumed in this study.
	For RED2	1.15	dLUC related to soybean expansion in Brazil (1996-2015) [122]. Agricultural yield: 3.00 t/ha.
Sugarcane	**For ALCA**	-0.24 (annual cropland) 0.28 (perennial cropland) 0.02 (pasture land) 0.74 (native vegetation)	dLUC based on [122], and average values related to the current land use in the Brazilian States with suitable areas for sugarcane crop expansion [94], *i.e.*, Goías, Mato Grosso do Sul, São Paulo, and Minas Gearais. Direct N_2O emissions by [89].
	For CLCA	0.008	Estimated from default value reported by [95] (8.7 gCO_{2e}/MJ) for sugarcane/ATJ in Brazil, and the agricultural and industrial yields assumed in this study.
	Alternative LUC for CLCA[21]	0.029	LUC related to an additional demand of 1.74 Mha of sugarcane in Brazil. Agricultural yield of 80.2 tsc/ha. Amortization period of 30 years. Modelling by GATP-BIO-ADV and AEE-AF.
	Alternative LUC for CLCA[96]	0.056	LUC related to an additional demand of 3.5 Mha of sugarcane in Brazil. Amortization period of 20 years. Modelling by MAGNET-PLUC.
	For RED2	0.011	dLUC related to sugarcane expansion in Brazil (1996-2015) [122]. Agricultural yield: 80.0 t/ha.
Palm	**For ALCA**	-0.16 (annual cropland) 0.00 (perennial cropland) -0.09 (pasture land) 0.22 (native vegetation)	dLUC based on [122], and average values related to the current land use in the Brazilian States with suitable areas for palm crop expansion [93] , *i.e.*, Pará, Roraima, and Mato Grosso. Direct N_2O emissions by [89].
	For CLCA	*n.a.*[a]	Estimated from default value reported by [95] (39.1 gCO_{2e}/MJ) for palm/HEFA in Malaysia, and the yields for agricultural and industrial stages assumed in this study.
	For RED2	0.011	dLUC related to palm expansion in Brazil (1996-2015) [122]. Agricultural yield: 18.0 t/ha.

[a] Non-applicable.

Table SM.19: Carbon footprint of AJF using different regulatory schemes

HEFA	Soybean				Palm				UCO				Tallow		
	Renovabio	CORSIA	RFS	RED	Renovabio	CORSIA	RFS	RED	Renovabio	CORSIA	RFS	RED	Renovabio	CORSIA	RED
Upstream	14.40	23.46	4.71	19.00	16.80	17.49	4.24	16.03	0.00	0.00	0.00	0.00	0.00	0.00	
Intermediary stage	0.50	1.60	11.75	1.22	0.10	0.40	21.31	0.32	0.00	2.88	1.47	3.09	0.00	0.00	
Refining stage	3.60	12.82	19.40	1.98	2.50	11.32	20.20	1.76	3.00	12.82	19.40	1.98	2.65	10.78	
Transportation	5.70	6.05	4.70	11.64	3.92	3.27	2.80	6.08	3.44	4.21	2.26	5.32	2.87	2.56	
Use	0.60	0.21	0.00		0.60	0.21			0.60	0.21	0.00		0.60	0.21	
Other effects			-12.23				-0.22								
LUC		27.00	28.8	64.85		39.10	38.9	-57.25			0.00				
TOTAL	**24.00**	**44.13**	**27.69**	**33.84**	**23.91**	**32.69**	**48.34**	**24.19**	**7.04**	**20.12**	**23.13**	**10.39**	**6.12**	**13.54**	**0.00**
TOTAL (with LUC)		***71.13***	***56.46***	***98.69***		***71.79***	***87.26***	***-33.06***							

ATJ	SC-1G				SC-2G				FR-2G		
	Renovabio	CORSIA	RFS	RED	Renovabio	CORSIA	RFS	RED	Renovabio	CORSIA	RED
Upstream	15.90	14.41	41.26	16.22	0.00	0.00	0.00	0.00	0.66	0.47	
Intermediary stage	1.31	3.41	-43.78	2.50	10.50	9.32	-34.45	8.69	9.34	9.18	
Refining stage	3.03	8.73	6.48	2.79	3.07	8.73	6.48	2.79	3.07	8.73	
Transportation	6.47	8.38	3.78	11.33	5.16	4.28	1.77	5.71	6.26	5.74	
Use	0.60	0.21	0.00		0.60	0.21	0.00		0.60	0.21	
Other effects			0.38				0.00				
LUC		8.70	5.65	3.52			0.00				
TOTAL	**27.31**	**35.14**	**8.12**	**32.84**	**19.33**	**22.54**	**-26.20**	**17.20**	**19.92**	**24.33**	**0.00**
TOTAL (with LUC)		***43.84***	***13.77***	***36.37***							

Table SM.19: Carbon footprint of AJF using different regulatory schemes

FT	SC				FR			
	Renovabio	**CORSIA**	**RFS**	**RED**	**Renovabio**	**CORSIA**	**Renovabio**	**CORSIA**
Upstream	0.00	0.00	0.00	0.00	0.34	0.32	0.29	0.41
Intermediary stage	n.a.	n.a.	n.a.		n.a.	n.a.	n.a.	n.a.
Refining stage	0.00	0.02	0.00	0.00	0.00	0.02	0.00	0.00
Transportation	2.50	2.22	2.82	4.74	3.08	2.99	2.26	5.11
Use	0.60	0.21	0.00		0.60	0.21		0.00
Other effects								
LUC								
TOTAL	**3.10**	**2.45**	**2.82**	**4.74**	**4.02**	**3.54**	**2.54**	**5.51**

References

1. ICAO. Assembly Resolutions in Force; A39-2: Consolidated statement of continuing ICAO policies and practices related to environmental protection — Climate change [Internet]. Montreal; 2016. Report No.: Doc 10075. Available from: https://www.icao.int/Meetings/a39/Documents/Resolutions/10075_en.pdf
2. ICAO. Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) [Internet]. *International Civil Aviation Organization.* 2020 [cited 2020 Apr 28]. Available from: https://www.icao.int/environmental-protection/Pages/market-based-measures.aspx
3. ICAO. Sustainable Aviation Fuel Guide [Internet]. 2017. Available from: https://www.icao.int/environmental-protection/GFAAF/Pages/default.aspx
4. European Union. Renewable Energy Directive (EU) 2018/2001 - Promotion of the use of energy from renewable sources [Internet]. 2018. Available from: https://eur-lex.europa.eu/eli/dir/2018/2001/oj
5. EU Science Hub. Renewable Energy – Recast to 2030 (RED II) [Internet]. 2020 [cited 2020 Feb 12]. Available from: https://ec.europa.eu/jrc/en/jec/renewable-energy-recast-2030-red-ii
6. U.S. EPA. Renewable Fuel Standard Program (RFS2) Regulatory Impact Analysis. *EPA-420-R-10-006.* 2010.
7. BRAZIL. Law 13.576 - 26 December 2017 [Internet]. *National Policy of Biofuels (Renovabio).* Brazil; 2017 [cited 2019 May 24]. Available from: http://www.planalto.gov.br/ccivil_03/_ato2015-2018/2017/lei/L13576.htm
8. Staples MD, Malina R, Olcay H, Pearlson MN, Hileman JI, Boies A, et al. Lifecycle greenhouse gas footprint and minimum selling price of renewable diesel and jet fuel from fermentation and advanced fermentation production technologies. *Energy Environ Sci [Internet].* 2014;7(5):1545. Available from: http://xlink.rsc.org/?DOI=c3ee43655a
9. Klein BC, Chagas MF, Junqueira TL, Rezende MCAF, Cardoso T de F, Cavalett O, et al. Techno-economic and environmental assessment of renewable jet fuel production in integrated Brazilian sugarcane biorefineries. *Appl Energy [Internet].* 2018 Jan;209(August 2017):290–305. Available from: https://doi.org/10.1016/j.apenergy.2017.10.079
10. Han J, Tao L, Wang M. Well-to-wake analysis of ethanol-to-jet and sugar-to-jet pathways. *Biotechnol Biofuels [Internet].* 2017 Dec 24;10(1):21. Available from: http://biotechnologyforbiofuels.biomedcentral.com/articles/10.1186/s13068-017-0698-z
11. de Jong S, Antonissen K, Hoefnagels R, Lonza L, Wang M, Faaij A, et al. Life-cycle analysis of greenhouse gas emissions from renewable jet fuel production. *Biotechnol Biofuels [Internet].* 2017 Dec 14;10(1):64. Available from: http://biotechnologyforbiofuels.biomedcentral.com/articles/10.1186/s13068-017-0739-7
12. Santos CI, Silva CC, Mussatto SI, Osseweijer P, van der Wielen LAM, Posada JA. Integrated 1st and 2nd generation sugarcane bio-refinery for jet fuel production in Brazil: Techno-economic and greenhouse gas emissions assessment. *Renew Energy [Internet].* 2018 Dec;129:733–47. Available from: http://dx.doi.org/10.1016/j.renene.2017.05.011
13. Tzanetis KF, Posada JA, Ramirez A. Analysis of biomass hydrothermal liquefaction

and biocrude-oil upgrading for renewable jet fuel production: The impact of reaction conditions on production costs and GHG emissions performance. *Renew Energy [Internet]*. 2017;113:1388–98. Available from: http://dx.doi.org/10.1016/j.renene.2017.06.104
14. Agusdinata DB, Zhao F, Ileleji K, DeLaurentis D. Life cycle assessment of potential biojet fuel production in the United States. *Environ Sci Technol [Internet]*. 2011;45(21):9133–43. Available from: http://www.ncbi.nlm.nih.gov/pubmed/21958200
15. Stratton RW, Wong HM, Hileman JI. Life Cycle Greenhouse Gas Emissions From Alternative Jet Fuels, Partnership for Air Transportation Noise and Emission Reduction [Internet]. Cambridge; 2010. Available from: http://web.mit.edu/aeroastro/partner/reports/proj28/partner-proj28-2010-001.pdf.
16. Wong HM. Life-cycle assessment of greenhouse gas emissions from alternative jet fuels. Massachusetts Institute of Technology; 2008.
17. Fan J, Shonnard DR, Kalnes TN, Johnsen PB, Rao S. A life cycle assessment of pennycress (Thlaspi arvense L.) -derived jet fuel and diesel. *Biomass and Bioenergy [Internet]*. 2013;55:87–100. Available from: http://linkinghub.elsevier.com/retrieve/pii/S0961953413000056
18. Shonnard DR, Williams L, Kalnes TN. Camelina-Derived Jet Fuel and Diesel: Sustainable Advanced Biofuels. *Environ Prog [Internet]*. 2010;29(3):382–92. Available from: http://www3.interscience.wiley.com/journal/122545120/abstract
19. Bailis RE, Baka JE. Greenhouse gas emissions and land use change from Jatropha curcas-based jet fuel in Brazil. *Environ Sci Technol.* 2010;44(22):8684–91.
20. Cox K, Renouf M, Dargan A, Turner C, Klein-Marcuschamer D. Environmental life cycle assessment (LCA) of aviation biofuel from microalgae, Pongamia pinnata , and sugarcane molasses. *Biofuels, Bioprod Biorefining [Internet]*. 2014 Jul;8(4):579–93. Available from: http://doi.wiley.com/10.1002/bbb.1488
21. Moreira M, Gurgel AC, Seabra JEA. Life Cycle Greenhouse Gas Emissions of Sugar Cane Renewable Jet Fuel. *Environ Sci Technol.* 2014;48:14756−14763.
22. Capaz RS, Seabra JEA. Life cycle assessment of biojet fuels. *In: Chuck CJ, editor. Biofuels for aviation: feedstocks, technology and implementation.* Amsterdam: Academic Press is an imprint of Elsevier; 2016. p. 279–94.
23. Sonnemann G, Vigon B. Global Guidance Principles for Life Cycle Assessment Databases. A Basis for Greener Processes and Products. ‘Shonan Guidance Principles. UNEP/SETAP; 2011. 160 p.
24. Guinée JB, Heijungs R, Huppes G, Zamagni A, Masoni P, Buonamici R, et al. Life Cycle Assessment: Past, Present, and Future. *Environ Sci Technol.* 2011 Jan;45(1):90–6.
25. Tillman A-M. Significance of decision-making for LCA methodology. *Environ Impact Assess Rev [Internet]*. 2000 Feb;20(1):113–23. Available from: http://linkinghub.elsevier.com/retrieve/pii/S0195925599000359
26. Finnveden G, Hauschild MZ, Ekvall T, Guinée J, Heijungs R, Hellweg S, et al. Recent developments in Life Cycle Assessment. *J Environ Manage [Internet]*. 2009 Oct;91(1):1–21. Available from: http://linkinghub.elsevier.com/retrieve/pii/S0301479709002345
27. JCR. International Reference Life Cycle Data System (ILCD) Handbook: General guide for Life Cycle Assessment - Detailed guidance. 1st ed. *Joint Research Centre - Institute for Environment and Sustainability, editor.* Luxembourg; 2010. 417 p.

28. Weidema BP. Market information in life cycle assessment [Internet]. *Vol. 863, Danish Ministry of the Environment.* Denmark: Danish Environmental Protection Agency, Danish Ministry of the Environment; 2003. Report No.: Environmental Project No. 863. Available from: http://www.norlca.org/resources/780.pdf
29. Weidema BP, Pizzol M, Schmidt J, Thoma G. Attributional or consequential Life Cycle Assessment: A matter of social responsibility. *J Clean Prod [Internet]*. 2018 Feb;174:305–14. Available from: http://linkinghub.elsevier.com/retrieve/pii/S0959652617325829
30. Thomassen MA, Dalgaard R, Heijungs R, de Boer I. Attributional and consequential LCA of milk production. *Int J Life Cycle Assess [Internet]*. 2008 Jun 1;13(4):339–49. Available from: http://link.springer.com/10.1007/s11367-008-0007-y
31. Khatiwada D, Seabra J, Silveira S, Walter A. Accounting greenhouse gas emissions in the lifecycle of Brazilian sugarcane bioethanol: Methodological references in European and American regulations. *Energy Policy [Internet]*. 2012;47:384–97. Available from: http://dx.doi.org/10.1016/j.enpol.2012.05.005
32. Pereira LG, Cavalett O, Bonomi A, Zhang Y, Warner E, Chum HL. Comparison of biofuel life-cycle GHG emissions assessment tools: The case studies of ethanol produced from sugarcane, corn, and wheat. *Renew Sustain Energy Rev [Internet]*. 2019 Aug;110(October 2017):1–12. Available from: https://doi.org/10.1016/j.rser.2019.04.043
33. Cortez LAB. Roadmap for sustainable aviation biofuels for Brazil. *Blucher, editor.* São Paulo; 2014. 272 p.
34. ASTM. ASTM D7566-20 Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons. West Conshohocken, Pennysilvania, USA; 2020.
35. IPCC. Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Geneva, Switzerland; 2014.
36. Capaz RS, de Medeiros EM, Falco DG, Seabra JEA, Osseweijer P, Posada JA. Environmental trade-offs of renewable jet fuels in Brazil: Beyond the carbon footprint. *Sci Total Environ [Internet]*. 2020 Apr;714:136696. Available from: https://doi.org/10.1016/j.scitotenv.2020.136696
37. IBICT/SICV. National database of Life Cycle Inventories (SICV) [Internet]. 2019 [cited 2019 Feb 5]. Available from: http://sicv.acv.ibict.br/Node/
38. IBGE. Brazilian Institute of Geography and Statistics [Internet]. *SIDRA Database - Consumer Expenditure Survey - POF.* 2019 [cited 2019 Nov 7]. Available from: http://www.sidra.ibge.gov.br/
39. Castanheira ÉG, Grisoli R, Coelho S, Anderi da Silva G, Freire F. Life-cycle assessment of soybean-based biodiesel in Europe: comparing grain, oil and biodiesel import from Brazil. *J Clean Prod [Internet]*. 2015 Sep;102:188–201. Available from: https://linkinghub.elsevier.com/retrieve/pii/S0959652615003972
40. Agropalma. Personal Comunication [Internet]. 2017. Available from: adriano.bastos@agropalma.com.br
41. IBGE. Brazilian Institute of Geography and Statistics [Internet]. *Municipal Agricultural Production.* 2019 [cited 2019 Aug 22]. Available from: https://sidra.ibge.gov.br/pesquisa/pam/tabelas
42. de Souza SP, Pacca S, de Ávila MT, Borges JLB. Greenhouse gas emissions and energy balance of palm oil biofuel. *Renew Energy [Internet]*. 2010 Nov;35(11):2552–

61. Available from: http://dx.doi.org/10.1016/j.renene.2010.03.028
43. Agropalma. Relatório de Sustentabilidade [Internet]. São Paulo; 2017. Available from: https://www.agropalma.com.br/responsabilidade-socioambiental/relatorio-de-sustentabilidade
44. Chin MJ, Poh PE, Tey BT, Chan ES, Chin KL. Biogas from palm oil mill effluent (POME): Opportunities and challenges from Malaysia's perspective. *Renew Sustain Energy Rev.* 2013;26:717–26.
45. Sousa VMZ, Luz SM, Caldeira-Pires A, Machado FS, Silveira CM. Life cycle assessment of biodiesel production from beef tallow in Brazil. *Int J Life Cycle Assess.* 2017;22(11):1837–50.
46. Garcilasso VP. Análise entre processos e matérias-primas para a produção de biodiesel. University of São Paulo; 2014.
47. Seber G, Malina R, Pearlson MN, Olcay H, Hileman JI, Barrett SRH. Environmental and economic assessment of producing hydroprocessed jet and diesel fuel from waste oils and tallow. *Biomass and Bioenergy [Internet].* 2014;67:108–18. Available from: http://linkinghub.elsevier.com/retrieve/pii/S0961953414002189
48. Araujo VKWS, Hamacher S, Scavarda LF. Economic assessment of biodiesel production from waste frying oils. *Bioresour Technol [Internet].* 2010;101(12):4415–22. Available from: http://dx.doi.org/10.1016/j.biortech.2010.01.101
49. Bonomi A, Cavalett O, Pereira da Cunha M, Lima MAP, editors. Virtual Biorefinery [Internet]. 1st ed. Cham: Springer International Publishing; 2016. 285 p. (Green Energy and Technology). Available from: http://link.springer.com/10.1007/978-3-319-26045-7
50. UNICAData. Statistics of Sugarcane Industry Union [Internet]. 2020 [cited 2020 Jul 14]. Available from: http://www.unicadata.com.br/
51. LNBR. Virtual Sugarcane Biorefinery (VSB) [Internet]. Campinas: Brazilian Biorenewables National Laboratory; 2018. Available from: https://lnbr.cnpem.br/
52. Coelho M. Personal Communication of a Brazilian Company of paper and cellulose. 2018.
53. LanzaTech. World's First Commercial Waste Gas to Ethanol Plant Starts Up [Internet]. 2018 [cited 2019 Jul 31]. Available from: https://www.lanzatech.com/2018/06/08/worlds-first-commercial-waste-gas-ethanol-plant-starts/
54. Brooks KP, Snowden-Swan LJ, Jones SB, Butcher MG, Lee G-SJ, Anderson DM, et al. Low-Carbon Aviation Fuel Through the Alcohol to Jet Pathway. *In: Biofuels for aviation: feedstocks, technology and implementation.* London: Elsevier Inc.; 2016. p. 109–50.
55. Handler RM, Shonnard DR, Griffing EM, Lai A, Palou-Rivera I. Life Cycle Assessments of Ethanol Production via Gas Fermentation: Anticipated Greenhouse Gas Emissions for Cellulosic and Waste Gas Feedstocks. *Ind Eng Chem Res [Internet].* 2016 Mar 30;55(12):3253–61. Available from: http://pubs.acs.org/doi/10.1021/acs.iecr.5b03215
56. Spath PL, Mann MK. Life Cycle Assessment of Hydrogen Production via Natural Gas Steam Reforming - NREL/TP-570-27637. Golden, CO (United States); 2001.
57. INRA. INRA-CIRAD-AFZ feed tables [Internet]. *Institut national de la recherche agronomique.* 2018 [cited 2018 Dec 3]. Available from: https://feedtables.com/content/tallow
58. ANP. Oil, Natural Gas and Biofuels Statistical Yearbook 2019 [Internet]. Rio de

Janeiro; 2020. Available from: http://www.anp.gov.br/publicacoes/anuario-estatistico/anuario-estatistico-2020
59. Ecoinvent. Ecoinvent database. Version 3.3 [Internet]. Zurich; 2016 [cited 2017 Jun 6]. Available from: http://www.ecoinvent.ch/
60. Instituto Aço Brasil. Brazil Steel Databook / Anuário estatístico 2018. Rio de Janeiro: Instituto Aço Brasil; 2018.
61. NREL NREL. U.S. Life Cycle Inventory Database [Internet]. 2018 [cited 2018 Jun 29]. Available from: https://uslci.lcacommons.gov/uslci/search
62. ANL. GREET [Internet]. *Greenhouse gases, regulated emissions, and energy use in transportation.* Argonne: Argonne National Laboratory; 2020 [cited 2020 Jan 11]. Available from: https://greet.es.anl.gov/
63. Schmidt JH, Weidema BP. Shift in the marginal supply of vegetable oil. *Int J Life Cycle Assess [Internet]*. 2008 May 11;13(3):235–9. Available from: http://dx.doi.org/10.1065/lca2007.07.351
64. Schmidt JH. System delimitation in agricultural consequential LCA. *Int J Life Cycle Assess [Internet]*. 2008 Jun 15;13(4):350–64. Available from: http://link.springer.com/10.1007/s11367-008-0016-x
65. Reinhard J, Zah R. Global environmental consequences of increased biodiesel consumption in Switzerland: consequential life cycle assessment. *J Clean Prod [Internet]*. 2009;17(SUPPL. 1):S46–56. Available from: http://dx.doi.org/10.1016/j.jclepro.2009.05.003
66. ISO. ISO 14044:2006 Environmental management -- Life cycle assessment -- Requirements and guidelines. 1st ed. *International Organization for Standardization, editor.* 2006 p. 46.
67. Weidema BP, Ekvall T, Heijungs R. Guidelines for application of deepened and broadened LCA. *Final report Co-ordination Action for innovation in Life- Cycle Analysis for Sustainability – Calcas. Project no.037075.* 2009.
68. EPE. PDE 2029 – The Ten-Year Energy Expansion Plan 2029 [Internet]. Brasilia; 2019. Available from: http://www.epe.gov.br/pt/publicacoes-dados-abertos/publicacoes/plano-decenal-de-expansao-de-energia-pde
69. Schmidt JH, Weidema BP, Brandão M. A framework for modelling indirect land use changes in Life Cycle Assessment. *J Clean Prod [Internet]*. 2015 Jul;99:230–8. Available from: https://linkinghub.elsevier.com/retrieve/pii/S0959652615002309
70. Dalgaard R, Schmidt J, Halberg N, Christensen P, Thrane M, Pengue WA. LCA of soybean meal. *Int J Life Cycle Assess.* 2008;13(3):240–54.
71. Schmidt JH. Life cycle assessment of five vegetable oils. *J Clean Prod.* 2015;87(C):130–8.
72. Escobar N, Ribal J, Clemente G, Sanjuán N. Consequential LCA of two alternative systems for biodiesel consumption in Spain, considering uncertainty. *J Clean Prod [Internet]*. 2014 Sep;79:61–73. Available from: https://linkinghub.elsevier.com/retrieve/pii/S0959652614005423
73. BRAZIL/SECEX. Ministry of Industry, Foreign Trade and Services [Internet]. *Statistics of Foreign Trade.* 2020 [cited 2020 Jan 21]. Available from: http://www.mdic.gov.br/index.php/comercio-exterior/estatisticas-de-comercio-exterior/series-historicas
74. ABIOVE. Database of Oil Brazilian Industry [Internet]. *Brazilian Association of Vegetable Oil Industries.* 2020 [cited 2020 Aug 2]. Available from: http://abiove.org.br/en/statistics/

75. Bernstad Saraiva A, Souza RG, Valle RAB. Comparative lifecycle assessment of alternatives for waste management in Rio de Janeiro – Investigating the influence of an attributional or consequential approach. *Waste Manag [Internet]*. 2017 Oct;68(4):701–10. Available from: http://dx.doi.org/10.1016/j.rser.2012.02.072
76. Prapaspongsa T, Musikavong C, Gheewala SH. Life cycle assessment of palm biodiesel production in Thailand: Impacts from modelling choices, co-product utilisation, improvement technologies, and land use change. *J Clean Prod.* 2017;153:435–47.
77. Rehl T, Lansche J, Müller J. Life cycle assessment of energy generation from biogas - Attributional vs. consequential approach. *Renew Sustain Energy Rev [Internet]*. 2012;16(6):3766–75. Available from: http://dx.doi.org/10.1016/j.rser.2012.02.072
78. de Rosa M, Pizzol M, Schmidt J. How methodological choices affect LCA climate impact results: the case of structural timber. *Int J Life Cycle Assess.* 2017;1–12.
79. Ekvall T, Weidema BP. System boundaries and input data in consequential life cycle inventory analysis. *Int J Life Cycle Assess [Internet]*. 2004;9(3):161–71. Available from: http://link.springer.com/10.1007/BF02994190
80. Silalertruksa T, Gheewala SH, Sagisaka M. Impacts of Thai bio-ethanol policy target on land use and greenhouse gas emissions. *Appl Energy [Internet]*. 2009;86(SUPPL. 1):S170–7. Available from: http://dx.doi.org/10.1016/j.apenergy.2009.05.010
81. Hamelin L, Wesnæs M, Wenzel H, Petersen BM. Environmental consequences of future biogas technologies based on separated slurry. *Environ Sci Technol.* 2011;45(13):5869–77.
82. Prapaspongsa T, Gheewala SH. Consequential and attributional environmental assessment of biofuels: implications of modelling choices on climate change mitigation strategies. *Int J Life Cycle Assess.* 2017;22(11):1644–57.
83. Huo H, Wang M, Bloyd C, Putsche V. Life-Cycle Assessment of Energy Use and Greenhouse Gas Emissions of Soybean-Derived Biodiesel and Renewable Fuels. *Environ Sci Technol.* 2009;43(3):750–6.
84. UNFCCC. TOOL07 - Tool to calculate the emission factor for an electricity system. Version 07.0. 2018.
85. Wang M, Huo H, Arora S. Methods of dealing with co-products of biofuels in life-cycle analysis and consequent results within the U.S. context. *Energy Policy [Internet]*. 2011 Oct;39(10):5726–36. Available from: http://dx.doi.org/10.1016/j.enpol.2010.03.052
86. Huo H, Wang M, Bloyd C, Putsche V. Life-Cycle Assessment of Energy and Greenhouse Gas Effects of Soybean-Derived Biodiesel and Renewable Fuels. Argonne; 2008.
87. Han J, Elgowainy A, Cai H, Wang MQ. Life-cycle analysis of bio-based aviation fuels. *Bioresour Technol [Internet]*. 2013;150:447–56. Available from: http://linkinghub.elsevier.com/retrieve/pii/S0960852413012297
88. Bragatto J. Avaliação do potencial da casca de Eucalyptus spp . para a produção de bioetanol. Universidade de São Paulo - Escola Superior de Agricultura “ Luiz de Queiroz ”; 2010.
89. IPCC. IPCC Guidelines for National Greenhouse Gas Inventories - Volume 4 - Agriculture, Forestry and other land use. *Eggleston H., Buendia L, Miwa K, Ngara T, Tanabe K, editors.* Kanagawa, Japan; 2006.
90. ISO. ISO 14067:2018 - Greenhouse gases - Carbon footprint of products - Requirements and guidelines for quantification. 2018.

91. Novaes RML, Pazianotto RAA, Brandão M, Alves BJR, May A, Folegatti-Matsuura MIS. Estimating 20-year land-use change and derived CO2 emissions associated with crops, pasture and forestry in Brazil and each of its 27 states. *Glob Chang Biol [Internet]*. 2017 Sep 9;23(9):3716–28. Available from: https://onlinelibrary.wiley.com/doi/abs/10.1111/gcb.13708
92. Nepstad LS, Gerber JS, Hill JD, Dias LCP, Costa MH, West PC. Pathways for recent Cerrado soybean expansion: extending the soy moratorium and implementing integrated crop livestock systems with soybeans. *Environ Res Lett [Internet]*. 2019 Apr 15;14(4):044029. Available from: https://iopscience.iop.org/article/10.1088/1748-9326/aafb85
93. Ramalho Filho A, Motta PEF. Zoneamento Agroecológico, Produção e Manejo para a Cultura da Palma de Óleo na Amazônia. Rio de Janeiro; 2010.
94. Manzatto CV, Assad ED, Bacca JFM, Zaroni MJ, Pereira SEM. Zoneamento Agroecológico da Cana-de Açúcar. *Documentos 110.* Rio de Janeiro; 2009.
95. ICAO. CORSIA Default Life Cycle Emissions Values for CORSIA Eligible Fuels [Internet]. Montreal; 2019. Available from: https://www.icao.int/environmental-protection/CORSIA/Pages/CORSIA-Eligible-Fuels.aspx
96. van der Hilst F, Verstegen JA, Woltjer G, Smeets EMW, Faaij APC. Mapping land use changes resulting from biofuel production and the effect of mitigation measures. *GCB Bioenergy [Internet]*. 2018 Nov;10(11):804–24. Available from: http://doi.wiley.com/10.1111/gcbb.12534
97. James B, Colella W, Moton J, Saur G, Ramsden T. PEM Electrolysis H2A Production Case Study Documentation. *PEM Electrolysis H2A Production Case Study Documentation.* Arlington; 2013.
98. IPCC. IPCC Guidelines for National Greenhouse Gas Inventories Volume 2 – Energy. *Eggleston S, Buendia L, Miwa K, Ngara T, Tanabe K, editors.* Kanagawa, Japan; 2006.
99. Hanssen S V., Huijbregts MAJ. Assessing the environmental benefits of utilising residual flows. *Resour Conserv Recycl [Internet].* 2019 Nov;150(July 2019):104433. Available from: https://linkinghub.elsevier.com/retrieve/pii/S0921344919303283
100. EPE. National Energy Balance [Internet]. Brasilia; 2020 [cited 2019 Oct 26]. Available from: https://ben.epe.gov.br/BENSeriesCompletas.aspx
101. ABM. Seminário de Balanço Energético Global e Utilidades [Internet]. *Seminar on Global Energy Balances and Utiliities.* Belo Horizonte, Brazil: Brazilian Mettalurgy, Materials and Mining Association; 2017 [cited 2019 Oct 20]. Available from: https://www.abmbrasil.com.br/
102. ANP. Renovacalc - v.6.1 [Internet]. *National Agency of Petroleum Natural Gas and Biofuels - Renovabio.* 2020 [cited 2020 Feb 16]. Available from: http://www.anp.gov.br/producao-de-biocombustiveis/renovabio/renovacalc
103. ANP. RenovaCalcMD: Método e ferramenta para a contabilidade da Intensidade de Carbono de Biocombustíveis no Programa RenovaBio [Internet]. *National Agency of Petroleum Natural Gas and Biofuels - Renovacalc.* 2018 [cited 2020 Feb 16]. Available from: http://www.anp.gov.br/images/Consultas_publicas/2018/n10/CP10-2018_Nota-Tecnica-Renova-Calc.pdf
104. ANP. CP10-2018_Calculadora [Internet]. *National Agency of Petroleum Natural Gas and Biofuels - Renovacalc.* 2018 [cited 2020 Feb 16]. Available from: http://www.anp.gov.br/images/Consultas_publicas/2018/n10/CP10-2018_Calculadora.xlsm
105. U. S. EPA. Lifecycle Greenhouse Gas Results [Internet]. *Fuels Registration,*

Reporting, and Compliance Help. 2020 [cited 2020 Jan 16]. Available from: https://www.epa.gov/fuels-registration-reporting-and-compliance-help/lifecycle-greenhouse-gas-results

106. Edwards R, O'Connell A, Padella M, Giuntoli J, Koeble R, Bulgheroni C, et al. Definition of input data to assess GHG default emissions from biofuels in EU legislation - Version 1d. Luxembourg; 2019.
107. ArcellorMittal Tubarão. ArcelorMittal no Espírito Santo [Internet]. Tubarão; 2016. Available from: https://brasil.arcelormittal.com/sala-imprensa/publicacoes-relatorios/
108. Vásquez MC, Martínez A, Castillo EF, Silva EE. Holistic approach for sustainability enhancing of hydrotreated aviation biofuels, through life cycle assessment: A Brazilian case study. *J Clean Prod [Internet]*. 2019 Nov;237(2019):117796. Available from: https://linkinghub.elsevier.com/retrieve/pii/S0959652619326563
109. Cavalett O, Cherubini F. Contribution of jet fuel from forest residues to multiple Sustainable Development Goals. *Nat Sustain [Internet]*. 2018 Dec 19;1(12):799–807. Available from: http://www.nature.com/articles/s41893-018-0181-2
110. ABRA. Anuário ABRA - Setor de Reciclagem Animal [Internet]. Brasilia; 2019. Available from: https://abra.ind.br/
111. ANP. Renovabio - National Policy of Biofuels [Internet]. *National Agency of Petroleum Natural Gas and Biofuels.* 2018 [cited 2018 Dec 16]. Available from: http://www.anp.gov.br/producao-de-biocombustiveis/renovabio
112. JRC. GNOC - Global Nitrous Oxide Calculator [Internet]. *European Commission - Joint Research Centre.* 2020 [cited 2020 Mar 22]. Available from: https://gnoc.jrc.ec.europa.eu/
113. ICAO. CORSIA - Methodology for Calculating Actual Life Cycle Emissions Values. Montreal; 2019.
114. FAO. FAOSTAT [Internet]. *Food and Agriculture Organization.* 2018 [cited 2018 Jan 10]. Available from: http://faostat.fao.org/site/339/default.aspx
115. Pirker J, Mosnier A, Kraxner F, Havlík P, Obersteiner M. What are the limits to oil palm expansion? *Glob Environ Chang [Internet]*. 2016 Sep;40:73–81. Available from: http://dx.doi.org/10.1016/j.gloenvcha.2016.06.007
116. Branford S, Torres M. Brazilian Amazon oil palm deforestation under control, for now [Internet]. *Mongabay Series: Amazon Agribusiness.* 2018 [cited 2020 Sep 7]. Available from: https://news.mongabay.com/2018/05/brazilian-amazon-oil-palm-deforestation-under-control-for-now/
117. Waha K, Dietrich JP, Portmann FT, Siebert S, Thornton PK, Bondeau A, et al. Multiple cropping systems of the world and the potential for increasing cropping intensity. *Glob Environ Chang [Internet]*. 2020 Sep;64(May):102131. Available from: https://doi.org/10.1016/j.gloenvcha.2020.102131
118. Batista VV, Adami PF, Moraes PVD de, Oligini KF, Giacomel CL, Link L. Row Arrangements of Maize and Soybean Intercrop on Silage Quality and Grain Yield. *J Agric Sci [Internet]*. 2019 Jan 15;11(2):286. Available from: http://www.ccsenet.org/journal/index.php/jas/article/view/0/38103
119. Xu Z, Li C, Zhang C, Yu Y, van der Werf W, Zhang F. Intercropping maize and soybean increases efficiency of land and fertilizer nitrogen use; A meta-analysis. *F Crop Res [Internet]*. 2020 Feb;246(2):107661. Available from: https://doi.org/10.1016/j.fcr.2019.107661
120. Balbinot Junior AA, Franchini JC, Debiasi H, Mandarino JMG, Sichieri F. Desempenho da soja em sistemas agroflorestais com eucalipto em solo arenoso e clima

tropical. *Rev Ciências Agroveterinárias [Internet]*. 2018 Nov 21;17(4):556–63. Available from: http://revistas.udesc.br/index.php/agroveterinaria/article/view/10069
121. Werner F, Balbinot Junior AA, Franchini JC, Ferreira AS, Silva MA de A e. Agronomic performance of soybean cultivars in an agroforestry system1. *Pesqui Agropecuária Trop [Internet]*. 2017 Sep;47(3):279–85. Available from: http://www.scielo.br/scielo.php?script=sci_arttext&pid=S1983-40632017000300279&lng=en&tlng=en
122. EMBRAPA. BRLUC - Method for estimating land use change and CO2 emissions associated to agriculture in Brazil [Internet]. Jaguariúna: Brazilian Agricultural Research Corporation; 2018. Available from: http://www.cnpma.embrapa.br/forms/BRLUC.php
123. ABIOVE. Soy Moratorium -Twelth Year. São Paulo; 2020.
124. European Union. Comission Delegated Regulation (EU) 2019/807 of 13 March 2019 [Internet]. 2019. Available from: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32019R0807&from=EN
125. European Commission. Report from the Comission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the regions on the status of production expansion of relevant food and feed crops worldwide. Brussels; 2019.
126. Elgowainy A, Dieffenthaler D, Sokolov V, Sabbisetti R, Cooney C, Anjum A. GREET - Greenhouse gases, Regulated Emissions, and Energy use in Transportation [Internet]. Chicago: Argonne National Laboratory; 2013. Available from: https://greet.es.anl.gov/
127. CEPEA C for AS on AE. Ethanol Index [Internet]. 2020 [cited 2020 Jan 10]. Available from: https://www.cepea.esalq.usp.br/en/indicator/ethanol.aspx
128. Scot Consultoria. Beef Tallow - Market price (Brazil Central region) [Internet]. 2018 [cited 2018 Nov 20]. Available from: https://www.scotconsultoria.com.br/
129. CCEE. Chamber of Electric Energy Commercialization [Internet]. *Preço de Liquidação das Diferenças - PLD, SE/CO regions*. 2018 [cited 2018 Nov 25]. Available from: https://www.ccee.org.br/portal/faces/pages_publico/o-que-fazemos/como_ccee_atua/precos/precos_medios
130. MDIC. COMEX-STAT Brazilian foreign trade statistics [Internet]. *Ministry of Industry, Foreign Trade and Services*. 2019 [cited 2019 Dec 8]. Available from: http://comexstat.mdic.gov.br/en/home
131. Castanheira ÉG, Freire F. Environmental life cycle assessment of biodiesel produced with palm oil from Colombia. *Int J Life Cycle Assess [Internet]*. 2017 Apr 22;22(4):587–600. Available from: http://link.springer.com/10.1007/s11367-016-1097-6
132. FAO. Food and Agriculture Organization - Food prices [Internet]. 2019 [cited 2019 Aug 21]. Available from: http://www.fao.org/giews/food-prices/tool/public/#/dataset/international
133. Index Mundi. Palm Kernel Oil Monthly Price [Internet]. *Commodities Prices Indices.* 2020 [cited 2020 Feb 13]. Available from: https://www.indexmundi.com/commodities/?commodity=palm-kernel-oil&months=120
134. Seabra JEA, Tao L, Chum HL, Macedo IC. A techno-economic evaluation of the effects of centralized cellulosic ethanol and co-products refinery options with sugarcane mill clustering. *Biomass and Bioenergy [Internet]*. 2010;34(8):1065–78.

Available from: http://dx.doi.org/10.1016/j.biombioe.2010.01.042
135. ECN. Database for biomass and waste [Internet]. 2018 [cited 2017 Jun 12]. Available from: https://phyllis.nl/
136. IEA. Market of eucalyptus products in São Paulo - Mercado de Produtos de Eucalipto em São Paulo, 2011/2012 [Internet]. *Análises e indicadores do Agronegócio.* 2012 [cited 2020 Feb 29]. Available from: http://www.iea.sp.gov.br/out/TerTexto.php?codTexto=12366
137. SEAB S of A and S. Forestry Prices [Internet]. 2018 [cited 2018 Dec 8]. Available from: http://www.agricultura.pr.gov.br/modules/conteudo/conteudo.php?conteudo=129
138. Swanson RM, Satrio JA, Brown RC, Platon A, Hsu DD. Techno-economic analysis of biomass-to-liquids production based on gasification. *Technical Report NREL/TP-6A20-46587.* 2010.
139. Raucci GS, Moreira CS, Alves PA, Mello FFC, Frazão L de A, Cerri CEP, et al. Greenhouse gas assessment of Brazilian soybean production: A case study of Mato Grosso State. *J Clean Prod [Internet].* 2015 Jun;96:418–25. Available from: http://dx.doi.org/10.1016/j.jclepro.2014.02.064
140. Queiroz AG, França L, Ponte MX. The life cycle assessment of biodiesel from palm oil (“dendê”) in the Amazon. *Biomass and Bioenergy [Internet].* 2012 Jan;36:50–9. Available from: https://linkinghub.elsevier.com/retrieve/pii/S0961953411005150
141. ANEEL. Results of power generation auctions [Internet]. *National Agency of Electric Energy.* 2019 [cited 2019 Oct 26]. Available from: https://www.aneel.gov.br/pt/resultados-de-leiloes
142. Klein B. Personal Communication of Brazilian Bioethanol Science and Technology Laboratory. 2019.
143. LanzaTech. Syngas to Fuels and Chemicals: Closing the Loop [Internet]. 2019 [cited 2020 Mar 21]. Available from: https://arpa-e.energy.gov/sites/default/files/2.2_Haynes_LanzaTech.pdf
144. IPCC. IPCC Reports [Internet]. *Assessment reports.* 2020 [cited 2020 Feb 17]. Available from: https://www.ipcc.ch/reports/
145. Sugawara ET. Comparação dos desempenhos ambientais do B5 etílico de soja e do óleo diesel, por meio da Avaliação do Ciclo de Vida (ACV). [Internet]. [São Paulo]: Universidade de São Paulo; 2012. Available from: http://www.teses.usp.br/teses/disponiveis/3/3137/tde-16072013-122953/en.php
146. U. S. EPA. A comprehensive analysis of Biodiesel Impacts on Exhaust Emissions. *United States Air and Radiation Environmental Protection Agency.* 2002.
147. EMBRAPA. Tecnologias de Produção de Soja: Região Central do Brasil 2014. Londrina; 2013.
148. Castanheira ÉG, Acevedo H, Freire F. Greenhouse gas intensity of palm oil produced in Colombia addressing alternative land use change and fertilization scenarios. *Appl Energy [Internet].* 2014 Feb;114:958–67. Available from: http://dx.doi.org/10.1016/j.apenergy.2013.09.010
149. Schmidt J. Life cycle assessment of rapeseed oil and palm oil, Part 3: Life cycle inventory of rapeseed oil and palm oil [Internet]. Aalborg University; 2007. Available from: https://lca-net.com/publications/show/life-cycle-assessment-rapeseed-oil-palm-oil-ph-d-thesis-part-3-life-cycle-inventory-rapeseed-oil-palm-oil/
150. Caldeira C, Queirós J, Noshadravan A, Freire F. Incorporating uncertainty in the life cycle assessment of biodiesel from waste cooking oil addressing different collection

systems. *Resour Conserv Recycl [Internet]*. 2016 Sep;112:83–92. Available from: http://dx.doi.org/10.1016/j.resconrec.2016.05.005

151. Humbird D, Davis R, Tao L, Kinchin C, Hsu D, Aden A, et al. Process Design and Economics for Biochemical Conversion of Lignocellulosic Biomass to Ethanol: Dilute-Acid Pretreatment and Enzymatic Hydrolysis of Corn Stover [Internet]. *Technical Report NREL/TP-5100-47764.* Golden, CO (United States); 2011. Available from: http://www.nrel.gov/biomass/pdfs/47764.pdf

3 Mitigating carbon emissions through sustainable aviation fuels: costs and potential

This chapter was published as *Rafael S. Capaz*[1,2*], *Elisa Guida*[2], *Joaquim E. A. Seabra*[2], *Patricia Osseweijer*[1], *John A. Posada*[1]. **Mitigating carbon emissions through sustainable aviation fuels: costs and potential.** Biofuels, Bioproducts, and Biorefining. (Available online 16 November 2020).
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It is worth mentioning that, in this chapter, the *alternative jet fuel* (AJF) was referred to as *sustainable aviation fuel (SAF)*, according to the suggestion of the journal's editor.

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Abstract

In general, the certified pathways to produce sustainable aviation fuels (SAFs) are still far from being competitive with fossil kerosene, although they have potential for reducing greenhouse gases (GHG) emissions. However, the mitigation costs related to SAFs and how they compete with the carbon credits market are yet unclear. The present study addressed these issues, evaluating SAF pathways based on hydrotreatment (HEFA process) of soybean oil, palm oil, used cooking oil (UCO) and beef tallow; dehydration and oligomerization of ethanol (ATJ technology) obtained from sugarcane, lignocellulosic residues, and steel off-gases; and, the thermochemical conversion of lignocellulosic residues using the Fischer-Tropsch (FT) and Hydrothermal Liquefaction (HTL). Residue-based pathways had lower mitigation costs. UCO/HEFA had the lowest value (185 USD/tCO_{2e}), followed by the thermochemical conversion of forest residues (234 - 263 USD/tCO_{2e}). Of the 1G pathways, SAF production from 1G sugarcane ethanol (SC-1G/ATJ) had a better performance (495 USD/tCO_{2e}) than oil-based ones. In comparison with the carbon market, the mitigation costs of SAFs are much higher than the current prices or even future ones. However, several concerns about the credibility of the emissions units and their effective mitigation effects indicate that SAFs could play an important role in aviation sector goals. Considering both the potentials of supplying SAF and mitigate emissions, SC-1G/ATJ was suggested as a preferred alternative in the short-term. Of the residues-based pathways, Tallow/HEFA and FT of forest residues are pointed out as strategic alternatives.

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

3.1. Introduction

The aviation sector is responsible for around 2.5% of all Greenhouse Gases (GHG) emissions and 3% of the oil products consumed in the world[1]. Still, the average energy intensity of aircraft operations (1.8 MJ/passenger.km), which is exclusively supplied by fossil resources, is 3-fold higher than buses and rails, and similar to passenger cars, which already have consolidated initiatives for biofuels use. Ambitious goals for the aviation sector were set for the next years[2], such as: improve the CO_2 efficiency, achieve carbon-neutral growth from 2020, and reduce carbon emissions by 50% in 2050 compared to 2005 levels.

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

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

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

Until now, seven pathways have already been approved to produce alternative jet fuels, which can be eligible as sustainable aviation fuels (SAFs) if they fill the CORSIA requirements[9]: i) hydrotreating of oil-based feedstocks (hydroprocessed esters and fatty acids, HEFA); ii) dehydration and oligomerization of iso-butanol or ethanol (alcohol-to-jet, ATJ); iii) direct conversion of sugar to hydrocarbons (DCSH); iv) Fischer-Tropsch (FT) process of renewable or fossil feedstock; v) Fischer-Tropsch (FT) process plus alkylation of light aromatics; vi) Catalytic Hydrothermolysis of oil-based feedstocks (CH); and vii) hydrotreating of bio-derived hydrocarbons, which at present only include the tri-terpenes produced by the *Botryococcus braunii* species of algae[10]. It is worth mentioning that all alternative jet fuels are allowed to be used within specific blending restrictions (v/v) with fossil kerosene

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

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

3.2. Methodology

The mitigation costs related to SAF, which would be obtained through the pathways described in **section 3.2.1**, were estimated according to **Eq. 1**, as suggested by some authors[33,34].

$$MC_i = \frac{P_i - P_{ref}}{ER_i} \qquad \text{(Eq. 1)}$$

Where: MC_i (USD/ton CO_{2e}) is the mitigation cost related to the SAF obtained through the pathway i. P_i (USD/GJ) is the minimum selling price of SAF obtained through the pathway i, see **section 3.2.2**. P_{ref} (15.8 USD_{2019}/GJ) is the reference price of the fossil kerosene based on the average price paid to the producer in Brazil between 2017-2019[35]. ER_i ($kgCO_{2e}$/GJ) is the carbon emissions reduction by pathway i according to CORSIA guidelines[4].

The original equation for calculating emissions reduction (ER) from the use of SAFs is based on the total mass consumed of SAF, the GHG reduction provided by SAF compared with fossil kerosene on life cycle basis, and a fuel conversion factor related to fossil kerosene. Since the carbon emission reduction is expressed in $kgCO_{2e}$/GJ in **Eq. 1**, we adapted the original equation with a factor basing on SAF density and its low heating value (see **Eq. 2**).

$$ER_i = 3.16 \ x \ 23.0 \ x \ \left(1 - \frac{EF_i}{89.0}\right) \quad \text{(Eq. 2)}$$

Where: 3.16 ($kgCO_{2e}/kg_{fuel}$) is the fuel conversion factor according to CORSIA. 23.0 (kg/GJ), taking 0.735 ton/m^3_{SAF} and 32.0 GJ/m^3_{SAF}[36]. EF_i is the life cycle carbon emissions related to SAF produced through the pathway i (gCO_{2e}/MJ), see **section 3.2.3**. 89.0 (gCO_{2e}/MJ) is the baseline life cycle emissions for fossil kerosene[4].

The results were also explored considering the potential SAF production from each pathway (**section 3.2.4**) and their sensitivity to the main parameters (**section 3.2.5**). Finally, the feasibility of the SAFs was compared with the emission units traded on the carbon market, considering current and future scenarios (see **section 3.2.6**).

3.2.1. Description of the SAF pathways

The SAF would be obtained from 1G and 2G pathways. 1G pathways are food-based, *i.e.*, obtained from soybean, palm, and sugarcane. 2G pathways are residues-based, *i.e.*, produced from used cooking oil (UCO), beef tallow, lignocellulosic residues, and steel off-gases. In general, the pathways comprise four stages: feedstock procurement – *i.e.*, the agricultural stage for 1G pathways, or feedstock management and collection for 2G pathways – intermediary processes, when deemed necessary, SAF conversion, and the transportation among the stages (see **Figure 3.1**).

For the Soy/HEFA pathway, soybean oil production was described by a representative monoculture system[37] placed in the central region of Brazil – which is responsible for more than half of all Brazilian production of soybeans[38] – with a further oil extraction by hexane[39]. The crop-to-mill and mill-to-refinery distances were at 200 km and 600 km (one-way), respectively, considering possible distances in Brazil.

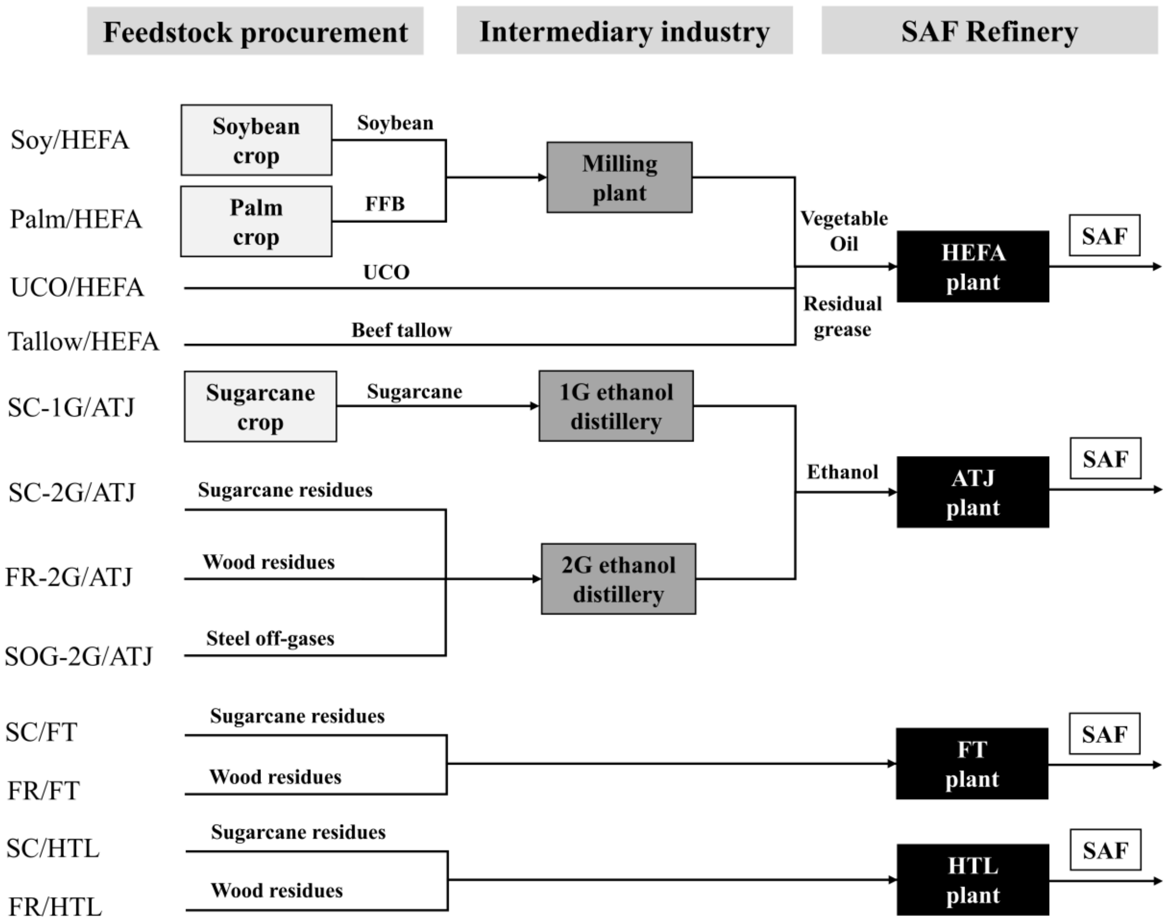

Figure 3.1: SAF pathways considered in this study. 1G: First-generation; 2G: Second-generation; SAF: Sustainable Aviation Fuel; ATJ: Alcohol-to-Jet; FFB: Fresh Fruit Bunches; FR: Forestry residues; FT: Fischer-Tropsch; HEFA: Hydroprocessed Esters and Fatty Acids; HTL: Hydrothermal Liquefaction; SC: Sugarcane; SOG: Steel off-gases; UCO: Used Cooking Oil.

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

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

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

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

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

2G ethanol from sugarcane residues would be produced using steam explosion and enzymatic hydrolysis, according to the advanced configuration reported by Bonomi *et al.*[46] The enzyme would be purchased from suppliers, and the plant would be self-supplied by cellulignin burning in a CHP system. The industrial yields for forestry residues were estimated using the VSB model with the proper adjustments made to the feed composition.[51] The mill-to-refinery distance was also set at 600 km (one-way).

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

Finally, the SAF conversion processes and the related yields for HEFA technology[55,56] were assumed to be similar for all oil-feedstocks[11,14,31]. The ATJ plant was fed by hydrated ethanol[22], and the yields for FT and HTL were based on de Jong *et al.*[20] and Tzanetis *et al.*,[32] respectively. For both of these latter pathways, the collect point-to-refinery distance was 100 km (one-way). **Table 3.1** shows the main yields. The hydrogen demand in HEFA and ATJ processes would be supplied by an external plant of Steam Methane Reform (SMR). For FT and HTL processes, the hydrogen is internally produced.

3.2.2. Minimum Selling Price of SAF

The minimum selling price of SAF (USD_{2019}/GJ) was set when the cash flow results in a net present value equal to zero and when the internal return rate (IRR) of the investment attains the Minimum Attractive Rate of Return (MARR), which was 12% as also assumed in other studies[22,26,46].

The capital expenditures (CAPEX) for SAF technologies (HEFA, ATJ, FT, and HTL) were scaled up to an annual distillate production of 0.20 million m^3, based on typical values found in the literature[22,25,31]. The intermediary processes were scaled up considering typical commercial plants. In both cases, the scaling factor of 0.6 was used[26,31]. Furthermore, a location factor of 1.14 was assumed for SAF technologies built in Brazil[57].

In turn, besides the material/utilities, the operational expenditures (OPEX) comprised labor, maintenance, and general taxes, which were set at 3.5%[26], 3.0%[21], and 0.7%[21] of the CAPEX, respectively. In general, transportation costs were based on the current tables for the minimum freight prices in Brazil[58]. All the assumptions are summarized in **Table 3.2**. See **Table SM.1** in Supplementary Material for more details.

Table 3.1: Overall yields for SAF pathway

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

[a] FFB: Fresh Fruit Bunches; tsc: ton sugarcane.
[b] SAF: Sustainable Aviation Fuel (0.735 ton/m³, 32.00 GJ/m³ [36]); Diesel (0.757 ton/m³, 31.99 GJ/m³ [36]); Naphtha (0.678 ton/m³, 29.66 GJ/m³ [36]). LPG: Liquefied Petroleum Gases (0.552 ton/m³, 46.34 GJ/ton [126]).
[c] Ethanol density: 0.810 ton/m³.
[d] Ethanol density: 0.810 ton/m³; LCM (db): sugarcane residues as lignocellulosic material, dry basis (14.4 MJ/kg, 45% moisture) composed by 85% of sugarcane bagasse and 15% of sugarcane straw [46,127].
[e] Ethanol density: 0.810 ton/m³; LCM (db): forestry residues as lignocellulosic material, dry basis (17.5 MJ/kg, 12% moisture)[128].
[f] Total off-gases input, assuming a theoretical maximum 80% HHV conversion to ethanol[129], and the net off-gases input (0.936 L_{ethanol} /$\text{Nm}^3_{\text{off-gases}}$)[54], *i.e.*, the total off-gases input minus the venting gases from the process.

Average off-gas generation from steel refining process through BOF technology: 100 $Nm^3_{off\text{-}gases}$ / ton crude steel[80]. Average off-gases composition (60% CO, 20% CO_2 and 20% N_2, in %vol.); LHV: 7.58 MJ/Nm^3; density: 1.392 kg/Nm^3. Ethanol density 0.789 ton/m^3. Only in this pathway, SAF would be produced from anhydrous ethanol, as reported by the original reference. It was assumed that anhydrous ethanol input would not influence the overall conversion yields, since the ethylene production, which is the first stage of the ATJ-based process, does not present relevant discrepancies if an input of hydrated ethanol was assumed[130]. Even though, lower costs for producing hydrated ethanol instead of anhydrous ethanol could slightly influence the economic analysis of the whole process.

[g] The yields were estimated according to the lower heating value (LHV) of the feedstocks[20]. LCM (db): sugarcane residues as lignocellulosic material, dry basis (14.6 MJ/kg, 45% moisture) composed by 85% of sugarcane bagasse and 15% of sugarcane straw[46,127].

[h] The yields were estimated according to the lower heating value (LHV) of the feedstocks[20]. LCM (db): forestry residues as lignocellulosic material, dry basis (17.5 MJ/kg, 12% moisture)[128].

[i] The yields were estimated according to the lower heating value (LHV) of the feedstocks[32]. LCM (db): sugarcane residues as lignocellulosic material, dry basis (14.6 MJ/kg, 45% moisture) composed by 85% of sugarcane bagasse and 15% of sugarcane straw[46,127].

[j] The yields were estimated according to the lower heating value (LHV) of the feedstocks[32]. LCM (db): forestry residues as lignocellulosic material, dry basis (17.5 MJ/kg, 12% moisture)[128].

The total costs were economically allocated to the volume of SAF produced, considering the market values of the products (see **Table 3.3**). The cash flow considered a period of 25 years[22,25,46] with full capacity, 100% equity[26,46], a linear annual depreciation of 10%[22,26], and 34% income taxes[22,46].

Table 3.2: Economic description of the SAF pathways (N^{th} plant)

Pathways	Intermediary industry			SAF refinery		
	Scale *Mt_{feed}* [a]	CAPEX [b] *M USD*	OPEX+T[c] *USD/t_{feed}*	Scale *Mt_{feed}*	CAPEX *M USD*	OPEX+T *USD/t_{feed}*
Soy oil/HEFA	0.83	158.7	30.1	0.16	403.5	316.7
Palm oil/HEFA	0.65	76.4	20.5	0.16	403.5	312.8
UCO/HEFA				0.16	403.5	493.0
Tallow/HEFA				0.16	403.5	316.7
SC-1G/ATJ	4.00	473.8	11.2	0.34	86.1	98.9
SC-2G/ATJ	0.22	149.8	121.3	0.34	86.1	98.9
FR-2G/ATJ	0.26	163.7	108.4	0.34	86.1	98.9
SOG-2G/ATJ	0.058	79.6	329.9	0.34	86.1	98.9
SC/FT				1.14	1,084.1	96.0
FR/FT				0.95	972.4	103.6
SC/HTL				0.68	933.8	175.7
FR/HTL				0.56	933.8	196.2

[a] "Scale" refers to the production scale of one industrial plant as assumed here. Specifically for SOG-2G/ATJ, the production scale for the intermediary industry was expressed in 10^6 $m^3_{ethanol}$ produced.

[b] CAPEX: capital expenditures, including working capital (5% of the CAPEX).

[c] OPEX: operational expenditures; T: transportation.

Greenfield plants and mature technologies (N^{th} plant) were considered in the reference scenario. Furthermore, the industrial stages were integrated, which means that the primary feedstocks – soybean, fresh fruit bunches, sugarcane stalks, agro/forest residues, and waste greases – were assumed to be purchased from suppliers at average market prices (**Table 3.3**). All economic values were corrected to 2019 by the Brazilian inflation rate (IGP-DI[59]), taking the average exchange rate of 3.86 BRL/USD.

The minimum selling price of SAF was also explored considering pioneer plants, according to **Eq. 3.**

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

Where: $CAPEX_p$, are the capital expenditures for the pioneer plant (USD). $CAPEX_{N^{th}}$, are the capital expenditures for the N^{th} plant (USD). GF, growth factor.

Table 3.3: Market values for the primary feedstocks

Products	Market value		Ref.	Description
Soybean	374.0	(USD/ton)	38	Average price (2017-2019) in Rondonópolis market (Mato Grosso State).
Palm, FFB	84.5	(USD/ton)	41	Average production costs of fresh fruit bunches (FFB) in Brazil, (2016-2018).
UCO	166.2	(USD/ton)	48	Based on the acquisition cost, according to a survey carried out in bars and restaurants in Rio de Janeiro (Brazil).
Beef tallow	665.3	(USD/ton)	60	Average price (2017-2019) in Brazil for Center and South regions.
Sugarcane	18.1	(USD/ton)	61	Average price (2017-2019) of sugarcane stalks on the field.
Sugarcane residues	26.6	(USD/ton)	46	Based on the opportunity costs for lignocellulosic material, wet basis (45% moisture content), assuming mix (85%/15%) of sugarcane bagasse and sugarcane trash from the field.
Forestry residues	9.0	(USD/ton)	62	Based on firewood market, wet basis (12% moisture content).
Steel off-gases, at flares	0.0	(USD/1000 Nm^3)		Null cost was assumed for off-gases available on flares.

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

HEFA technology, 0.42 for ATJ, 0.45 for FT, and 0.40 for HTL. A similar factor for 2G ethanol via enzymatic hydrolysis (0.53 [25]) was taken for ethanol production via syngas fermentation.

3.2.3. Carbon emissions of SAF

The carbon emissions along the SAF life cycle were estimated considering the CORSIA guidelines[63] and the description of the pathways presented in **section 3.2.1**. Therefore, an attributional life cycle assessment was performed from feedstock procurement to SAF combustion in an aircraft engine. Only emissions of CH_4, N_2O, and non-biogenic CO_2 were accounted for, according to the 5th AR IPCC[64]. Co-production was handled by energy allocation. Residual feedstocks, such as UCO, agricultural/forestry residues, sugarcane bagasse, and beef tallow, were deemed wastes. Thus, only emissions related to collection and transportation were accounted for. The default values for land use change (LUC) suggested by CORSIA[65] for 1G pathways were taken here.

Databases Ecoinvent v3.3[66], USCLI[67], and GREET[68] were used for background systems with some adaptations to the Brazilian context. See **Table SM.2** in Supplementary Material for more details about the inventories. The total values assumed here are presented in **Table 3.4**.

Table 3.4: GHG emissions ($kgCO_{2e}$/GJ) related to SAF production and use

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

[a] Default values according to CORSIA[65] for Brazil.
[b] For palm production in Malaysia, due to a lack of information for Brazil[65].

3.2.4. Potential SAF supply and carbon mitigation

The pathways were also evaluated by their potential production of SAFs and carbon mitigation in Brazil[35,69], considering the availability of feedstocks and conversion yields assumed here (**Table 3.1**).

The potential areas for biomass expansion (soybean, palm, and sugarcane) were taken from Cervi *et al.*[25] That study evaluated the potential SAF production in Brazil through thirteen pathways from food-based biomasses and wood-based ones. According to their economic feasibility and the agro-ecological suitability of the available areas for biomass growth, a spatially explicit economic optimization was carried out in order to supply the nearest airport. Biomass expansion was assumed only onto "residual lands", *i.e.*, areas not in use for other function in those years, such as croplands, pasture, rangeland, forest planted, natural forest, urban areas, and conservation areas. Hence, those authors considered SAF production only from abandoned agricultural land, shrublands, and grasslands. Under these conditions, in 2015, Soy/HEFA, Palm/HEFA, and SC-1G/ATJ could supply 4.9, 36.5, 13.1 million m^3 of SAF, respectively, from the cultivation of 19.1 Mha of soybean, 23.5 Mha of palm, and 3.9 Mha of sugarcane.

The potential of 2G pathways was estimated based on Brazilian databases, literature, and specific criteria, as presented in **Table 3.5**. Finally, the total carbon mitigation for each pathway was estimated from their potential production and the respective potential emission reductions.

3.2.5. Sensitivity analysis for mitigation costs

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

i) Feedstock prices were set at ±20%, according to their market variations over the last years[38,41,61,62,79]. Specifically for SOG-2G/ATJ, since several steel mills have recovered steel off-gases for internal use[80], an opportunity cost of the steel off-gases (117.5 USD/1000 Nm^3) was taken according to the average price of natural gas (2016-2018) by energy parity (0.21 Nm^3 off-gas/Nm^3 natural gas).

ii) Fossil kerosene prices were set at ±30%, according to the national market variations in 2004-2019[35].

iii) Processes scales were set at ±50%, which comprise possible scales for soybean mills [38]; for 1G ethanol distilleries[46]; and for SAF plants[11,22,25]. Similar ranges were taken for palm mills and 2G ethanol distilleries.

iv) The MAAR was set at 8% to 12%, comprising possible investment scenarios.

v) Transportation distances were set at ±50%, taking into account some possible varying distances in Brazil. The "crop-to-mill" distance for palm and sugarcane was kept the same, due to the limitations reported by some authors[46,81].

vi) Finally, considering the relevant role of the hydrogen input for SAF conversion, we took an external hydrogen supply from a water electrolysis plant (6.31 USD_{2019}/t[82] and 9.31 $kgCO_{2e}/kg$[83]).

Table 3.5: Residual feedstock availability for SAF production in Brazil

Feedstock	Annual potential	Description
UCO	0.30 Mt	Used cooking oil collected from households and food services. For UCO from households, it was assumed that 35%[70] of the annual acquisition of vegetable oils per capita in Brazil[71] would be available for recycling. From this amount, only 10% would be collected, basing on the initiatives in Europe[70]. The potential UCO from food services was assumed equivalent to 67% of the UCO available from households[70].
Beef tallow	1.02 Mt	Total supply of beef tallow, considering the generation of 31.5 kg_{tallow}/cattle head[49] and the slaughtering of 32.4 million cattle head (only bovine) in 2019[72].
Sugarcane residues	100.1 Mt 55.3 $Mt_{(db)}$	Total residues available in ethanol distilleries after to guarantee the self-supply, and assuming that 7.5 $t_{straw(db)}/ha$[73,74] are kept on the field for ecological purposes. Sugarcane production in 2018[75]. Bagasse yield, 0.28 $t_{bagasse}/t_{sugarcane}$ (50% moisture, 7.2 MJ/kg). Total straw yield, 0.14 $t_{straw(db)}/t_{sugarcane}$ (15% moisture, 13.3 MJ/kg). Internal energy demand and losses in ethanol distillery, 1,445 $MJ/t_{sugarcane}$[76,77].
Forest residues	16.6 Mt 14.6 $Mt_{(db)}$	Average annual generation of wood residues (barks, branches, and leaves) during the harvesting operations (167 $kg_{residues}/m^3_{wood}$.cycle)[78]. The potential availability of wood residues from eucalyptus crops was estimated considering: average yield of eucalyptus (35 m^3/ha.year), crop cycle (7 years), area with eucalyptus in Brazil in 2018 (5.67 Mha), and 50% recovery of residues.
Steel off-gases	2.15 10^9 Nm^3	Total availability of steel off-gases considering steel refining through BOF/LD technology and a generation of 100 Nm^3/t_{crude_steel}. Only steel mills with a minimum generation of 280 10^6 Nm^3 off-gases/year were considered, which would be suitable to supply an ethanol plant on a commercial scale.

3.2.6. Alternative offsetting market-measures

Finally, the mitigation costs of SAF's were compared with current and future prices of the emissions units traded on the carbon market, since the latter is one possible way for achieving the emission targets in the short-term, according to CORSIA.

The current prices of the emissions units were retrieved from[84–86], which correspond to the values from 2016-2018. The values were also disaggregated by project category (forestry and land use, renewable energy, household devices, chemical processes, industrial manufacturing, waste disposal, energy efficiency/fuel switching, and transportation); by region (North America, Latin America & Caribbean, Asia, Africa, Europe, and Oceania); and by Program (American Carbon Registry - ACR, Clean Development Mechanism - CDM, Climate Action Reserve - CAR, Gold Standard - GS, and Verified Carbon Standard - VCS).

The future prices of the emission units were retrieved from Piris-Cabezas *et al.* (2018)[87]. That study addressed the carbon price variation on the market by applying a partial equilibrium model due to the coexistence of the Nationally Determined Contribution (NDC), according to the Paris Agreement, and CORSIA. It is worth mentioning that the Paris Agreement[88] is a bottom-up climate change-related international compromise in which each Party has presented its NDC. A NDC determines the national goals for emissions measures that are aligned with the global effort for holding the increase in global average temperatures below 2ºC.

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

3.3. Results and Discussion

3.3.1. Techno-economic assessment of SAF

In general, none of the pathways were competitive with fossil kerosene (Jet A) (see **Figure 3.2**), as already pointed out in previous studies[20,21,23,26]. The MSP of SAFs ranged from 26.7 - 44.6 USD/GJ, while fossil kerosene had an average price of 15.8 USD/GJ in 2017-2019 in Brazil, reaching 20.9 USD/GJ in the top ten percentile for 2004-2019.

The MSP related to 1G pathways remained in a narrow range of 33.7 USD/GJ (SC-1G/ATJ) to 36.4 USD/GJ (Soy/HEFA), where the feedstock was the major contributor responsible for 43% of the total costs in Soy/HEFA and around 32% in Palm/HEFA and SC-1G/ATJ. The capital expenditures contributed to roughly 30% of the total costs, mostly led by HEFA technology and ethanol distilleries in oil-based pathways and SC-1G/ATJ, respectively. The lower overall yield of SC-1G/ATJ (27.6 $L_{SAF}/t_{sugarcane}$) with respect to oil-based pathways (131.1 $L/t_{soybean}$ or 117.8 L_{SAF}/t_{FFB}) resulted in the relevant contribution of transportation (13% of the total costs) for that pathway.

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

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

The MSP values are close for both FT and HTL technologies, given that the benefits of the higher HTL conversion yields (178 L_{SAF}/t_{db} for FR/HTL and 149 L_{SAF}/t_{db} for SC/HTL) are counterbalanced by power demand and natural gas consumption for hydrogen production. On the other hand, the self-supply of utilities in FT and the low expenditures with other inputs are compensated for by the low conversion yields (40 L_{SAF}/t_{db} and 34 L_{SAF}/t_{db} for forest and sugarcane residues, respectively).

Beef tallow price brought the MSP of Tallow/HEFA to similar values as 1G pathways. Beef tallow is a valuable co-product in Brazil, and it is mostly used for biodiesel production, corresponding to around 15% of the total volume of biodiesel produced.[35] Because of competition with soybean oil for the biodiesel market, beef tallow price directly follows the up-down trends of that vegetable oil. Over the last years, the prices of beef tallow have been reported 5% to 22% lower than soybean oil[60,89], both taken from the Central-region of Brazil, without taxes. A different trend or even decreasing prices for beef tallow should not be expected if this residual feedstock was also demanded by a SAF new market.

ATJ-based pathways via 2G ethanol had the highest MSP. Even with a higher overall yield (90-100 L_{SAF}/t_{db}) than FT-based pathways, the capital costs – which are mostly related to ethanol conversion (around 85% of the CAPEX) – and operational expenditures mostly related to enzyme purchase in SC-2G/ATJ and FR-2G/ATJ, or power demand for steel off-gas compression (SOG-2G/ATJ) pushed up the total costs. Regarding this later pathway, the power surplus generation from an optimized steel mill, as already on some plants[80,90], could eventually supply the integrated ethanol plant. If this were to happen, the MSP of SOG-2G/ATJ would decrease by around 33%, reaching 33.5 USD/GJ, but still two times higher than the average price of fossil kerosene.

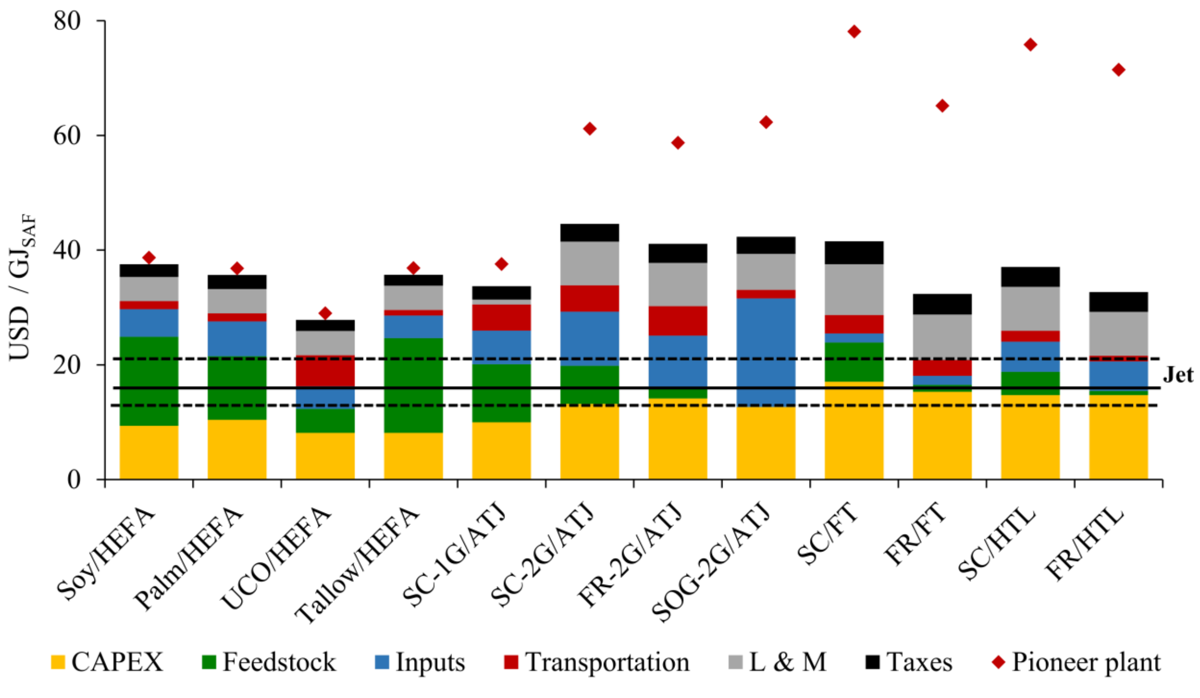

Figure 3.2: Breakdown of the Minimum Selling Price (MSP) of SAFs. Integrated supply-chain for 1G-pathways. Fossil kerosene (Jet A) price in Brazil[79] average values (2017-2019), top and bottom ten percentile values (2004-2019). ATJ: Alcohol-to-Jet; FT: Fischer-Tropsch; HEFA: Hydroprocessed Esters and Fatty Acids; HTL: Hydrothermal Liquefaction.

The possible risks related to a new plant increased the total costs for capital-intensive technologies. Therefore, the technological immaturity of hydrothermal liquefaction or the complexity of Fischer-Tropsch technology led to a MSP 100-105% and 89-100% higher than

N^h plants for HTL and FT-based pathways, respectively. The values for the ATJ-based pathways could increase by 30-35%, mostly due to the technological immaturity of 2G-ethanol production. Even so, it is worth mentioning that values for pioneer plant were estimated from an aggressive approach since it was assumed a full-plant capacity availability in the first year.

Some trends reported here were also observed in other studies, such as the low MSP related to SAF obtained from used cooking oil, and the high values for SAF production from lignocellulosic residues via 2G ethanol (see **Table 3.6**).

The low values reported by Klein *et al.*[22], which were also estimated in Brazilian conditions, highlighted the benefits of considering SAF production in an integrated biorefinery. Those authors proposed several integrated designs between an optimized autonomous ethanol distillery and SAF technologies, assuming the internal supply of utilities – which includes hydrogen production by water electrolysis – the ethanol and power surplus revenues, when it was the case, and the use of alternative diesel in agricultural operations. The MSP of SAF obtained via FT technology could even present negative values due to the great profits from ethanol revenues, although the authors pointed out the complexity of the integration of these technologies, considering the high requirement of mass and energy integration.

Santos *et al.*[26] also evaluated possible designs for SAF production in a sugarcane-based biorefinery in Brazil, including several pretreatment methods for lignocellulosic material, revenues of high-value co-products, fast pyrolysis of bagasse, or gasification followed by Fischer-Tropsch processing of lignin. The values reported by these authors for SAF production from 1G ethanol and fast pyrolysis of sugarcane bagasse were a bit lower than what was estimated here for SAF from 1G ethanol. However, the MSP increases if the integrated SAF production from 2G ethanol is also considered.

Finally, de Jong *et al.*[31] evaluated only residue-based pathways and pointed out some trends as observed here, albeit with some discrepancies. The feedstock price of UCO taken by those authors was around 6 times more expensive than that was taken here, which led to a higher MSP. Furthermore, they estimate lower values for HTL-based pathways, mainly led by CAPEX, which was roughly 40% cheaper than calculated here.

Table 3.6: Economic feasibility and life cycle carbon emissions of SAF according to other studies

Feedstock	SAF technology	MSP (USD/GJ)		GHG emission ($kgCO_{2e}/GJ$) [a]	
		This study	Other ref. [b]	This study	Other ref.
Soybean	HEFA	36.4	23.1 [22] 37.2 [23]	69.9 (*42.9*)	67.4 *(40.4)* [65] *(22.0)* [22] *(40.1)* [91]
Palm	HEFA	34.5	18.4 [22]	73.5 (*34.4*)	76.5 *(37.4)* [65] *(17.0)* [22] *(14.2)* [91]
UCO	HEFA	26.7	28.4 [23] 33.3 [31]	17.2	13.9 [65] 27.0 [11]
Beef tallow	HEFA	34.5	33.1 [23]	18.5	22.5 [65] 29.8 [14]
Sugarcane	ATJ (via 1G ethanol)	33.7	51.8 [21] 27.2 [22] 44.9 [26]	44.7 (*36.0*)	32.8 *(24.1)* [65] *(20.5)* [22] *(26.0)* [11]
Lignocellulosic residues	ATJ (via 2G ethanol)	44.6 (SC) 41.1 (FR)	78.8 [21] 36.6 [22] 64.0 - 67.7 [26] 55.5 [31]	27.6 (SC) 27.4 (FR)	35.0 [11] 28.4 [15] 24.8 [22]
Steel off-gases	ATJ (via 2G ethanol)	41.5	n.a.	24.8	n.a.
Lignocellulosic residues	FT	41.5 (SC) 32.4 (FR)	56.0 [21] -6.9 to 11.2 [22] 46.6 [31]	3.9 (SC) 2.4 (FR)	7.7 to 8.3 [65] 6.0 [11] 6.8 [15] 8.6 [22]
Lignocellulosic residues	HTL	37.1 (SC) 32.7 (FR)	24.4 [31]	11.0 (SC) 10.3 (FR)	18 to 20 [11]

[a] Only for 1G pathways, the values in parenthesis represent the GHG emissions related to the life cycle without land use change (LUC). All the values retrieved of other references were estimated considering allocation approach for co-products, preferably energy allocation, as set out by CORSIA guidelines[63].
[b] When necessary, the MSP were converted in USD/GJ taking the exchange rate, density and heating value assumed in the original reference. It was assumed 32.0 GJ/m^3 and 0.735 t/m^3, as LHV and density of SAF[36], respectively, when these data are not available in the original reference.

3.3.2. Mitigation costs of SAF

According to **Figure 3.3.A**, there is a clear trend of low mitigation costs related to residues-based pathways. UCO/HEFA had the lowest value (185 USD/tCO_{2e}), followed by thermochemical conversion of forest residues (234 - 263 USD/tCO_{2e}), hydrotreating of beef tallow (326 USD/tCO_{2e}) and the thermochemical conversion of sugarcane residues (334 -

370 USD/tCO_{2e}). The SAF obtained from 2G ethanol were related to high mitigation costs (504 - 575 USD/tCO_{2e}) led by the high MSP, despite providing an emission reduction of approximately 70% compared to fossil kerosene.

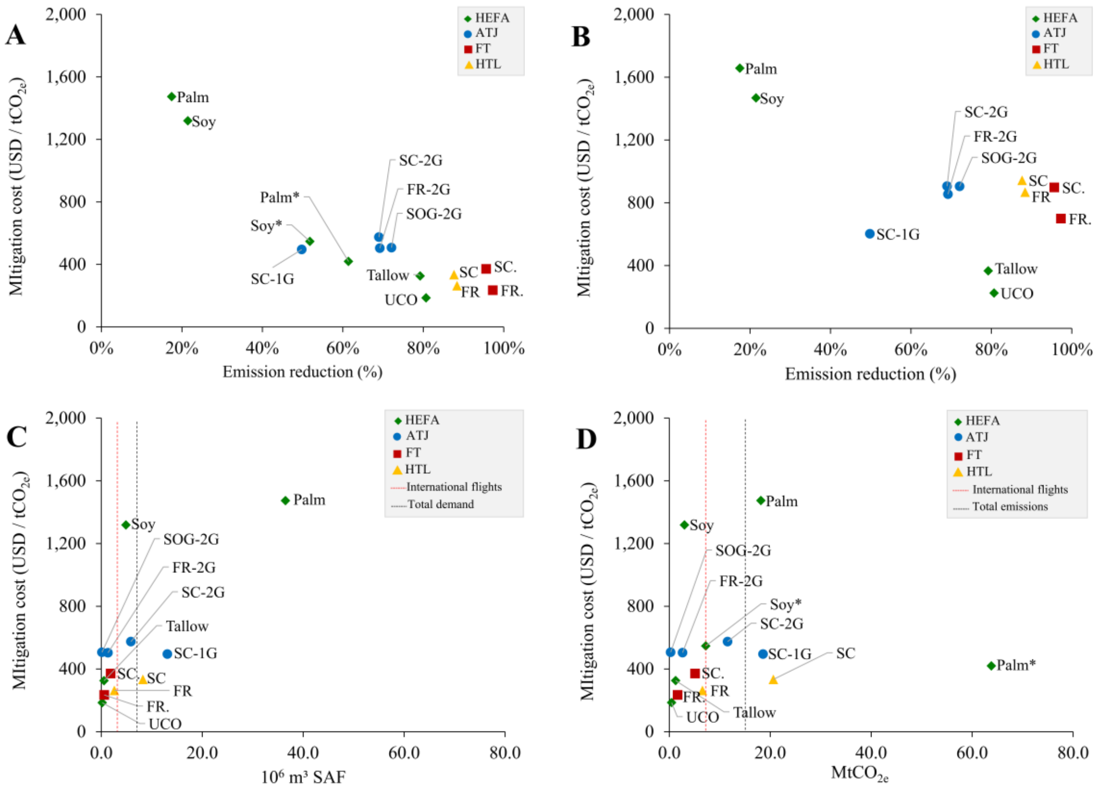

Figure 3.3: Mitigation costs of SAF considering the potential emission reduction by an Nth plant (A); the potential emission reduction by a Pioneer plant (B); the potential production of SAF assuming an Nth plant (C); and the potential carbon reduction assuming an Nth plant (D). Soy* and Palm* means SAF produced from soybean and palm if areas with low-risks for LUC. "International flights" mean the fuel demand or GHG emissions related to international flights originating in Brazil. "Total values" mean the fuel demand or GHG emissions related to international and domestic flights in Brazil[69].

Of the 1G pathways, the mitigation costs ranged from 495 - 1,474 USD/tCO_{2e}, where the SAF production via 1G sugarcane ethanol (SC-1G/ATJ) had better performance than oil-based pathways mostly due to the low emission reduction provided by soybean (21%) and palm (17%) (see **Figure 3.2.A**).

It is worth stressing that the GHG emissions related to Palm/HEFA comprised a default value for emissions related to land use change (39.1 $kgCO_{2e}$/GJ) – which has been suggested for palm crop in Malaysia & Indonesia (see **Table 3.4**) – due to the lack of specific data for Brazil. Since this value is not based on Brazilian data, and it corresponds to more than half of the emissions for the whole life cycle, it could lead to overestimations of the mitigation costs related to this pathway in Brazilian conditions.

Even so, SAFs produced via Palm/HEFA and Soy/HEFA could be strategic options under CORSIA guidelines if they were obtained from certified areas with low-risks for land use change. In that case, iLUC emissions could be assumed zero[63], and the mitigation costs of these pathways could decrease substantially by 58% and 72%, respectively, achieving 550 USD/tCO_{2e} (Soy/HEFA) and 420 USD/tCO_{2e} (Palm/HEFA). Low-risks for land use change are possible when the feedstock is produced in unused lands or by management practices that provide an increase of the agricultural yield without land expansion.

Variations on the life cycle emissions from different studies are expected due to inventory aspects and methodological issues, which can influence the mitigation costs. Although it is reasonable to suppose that techno-economic evaluations and GHG emissions estimations are based on the same pathway description, an airline operator can use the default values for life cycle emissions suggested by CORSIA[65] to report its inventory emissions. These default values are considerably different than what was estimated here for SC-1G/ATJ and Fischer-Tropsch pathways (see **Table 3.4**). In comparison with the studies that supported the CORSIA values[92], the major differences are the GHG emissions estimated for the conversion processes, such as ethanol and SAF production, and the feedstock procurement/transportation for Fischer-Tropsch processing of lignocellulosic residues. Furthermore, if these default values were assumed here, the mitigation costs could decrease by 25% for SC-1G/ATJ (391 USD/tCO_{2e}) or increase by around 10% for FR/FT and SC/FT (252 and 388 USD/tCO_{2e}, respectively). Relevant discrepancies were not observed in other pathways.

Pioneer plants (**Figure 3.3.B**) of waste grease-based pathways (UCO/HEFA and Tallow/HEFA) had the best performance (225 and 366 USD/tCO_{2e}, respectively) followed by SC-1G/ATJ (602 USD/tCO_{2e}), while Palm/HEFA (1657 USD/tCO_{2e}) and Soy/HEFA (1468 USD/tCO_{2e}) still reported the highest values. On the other hand, the mitigation costs related to immature or complex technologies, such as ATJ via 2G ethanol and thermochemical processes, ranged in 854-943 USD/tCO_{2e}, except the Fischer-Tropsch processing of forest residues, which achieved roughly 700 USD/tCO_{2e}.

The effective feasibility of each pathway is better evaluated by considering the potential of each to produce SAF or provide carbon emission reductions in view of mitigation costs. According to **Figure 3.3.C**, the potential SAF production of 1G pathways based on palm or sugarcane would exceed the total demand of SAF in Brazil (around 7.0 million m^3 [69]) at expenses of 33.7 - 34.8 USD/GJ, *i.e.*, two times higher than the current average price of Jet A. Hydrothermal liquefaction of sugarcane residues also exceeded the total demand, but this pathway is under development and it is not approved yet.

It is worth mentioning that the potential availability of feedstocks for 1G pathways was based on specific conditions (see **section 3.2.4**). Basing on the agro-ecological zoning for sugarcane in Brazil[93] and the recent expansion of the crop[75,94], around 9.5 Mha would be highly suitable for sugarcane expansion in the Center-South region, potentially providing 32.0 million m^3 of SAF. Here, sugarcane expansion into only 3.9 Mha was assumed.

In addition, here the palm expansion was assumed into 23.5 Mha of residual lands according to Cervi *et al.*[25], while Ramalho Filho *et al.*[95] reported that 7.4 Mha of deforested areas in the Amazon region would be highly suitable for palm expansion, with possible benefits in recovering degraded areas, providing income for family farmers, and improving the carbon balance. Palm/HEFA could provide 11.8 million m^3 of SAF, assuming the potential area reported by these latter authors.

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

Finally, according to **Figure 3.3.D**, the potential carbon reduction of each pathway, especially the ones based on sugarcane via 1G ethanol or thermochemical conversion of sugarcane residues, could eventually provide a reduction equivalent to the total emissions estimated for the Brazilian aviation sector in 2018 (16.7 $MtCO_{2e}$ [69]), at the expenses of 334 to 575 USD/tCO_{2e}. Alternatively, the thermochemical conversion of forest residues or Tallow/HEFA could provide an abatement of 25% (FR/FT), 17% (Tallow/HEFA), and 94% (FR/HTL) of related emissions to international flights originating in Brazil, respectively.

In turn, if the residual areas assumed here for palm expansion were certified as low-risk for land use change, Palm/HEFA* could provide great mitigation of around 63.8 $MtCO_{2e}$. However, this potential should be evaluated carefully. According to the CORSIA sustainability criteria[9], SAFs shall not be produced from areas whose previous use to 2008 was related to a high carbon stock, such as primary forests. Furthermore, to be certified as low-risk for LUC[63], an eligible unused land must fulfill specific criteria related to the previous use or the degradation level. Even so, the potential carbon mitigation by Palm/HEFA* could achieve 20.6 $MtCO_{2e}$, assuming palm expansion into degraded areas in Amazon[95].

Ranking the pathways by their mitigation costs – which seems to be reasonable considering the ICAO goals – it is possible to draw the supply and abatement curves presented in **Fig 3.4**. Since the HTL technology is not approved yet, it was not considered in the following graphs. Furthermore, pathways based on ATJ of 2G ethanol were disregarded, as they compete for feedstock with pathways based on Fischer-Tropsch technologies, which presented lower mitigation costs than those.

According to **Figure 3.4.A**, residues-based pathways (FR/FT, SC/FT, Tallow/HEFA, and a tiny contribution of UCO/HEFA) could supply the Jet A demand by international flights originating in Brazil by costs ranging from 26.4 to 34.5 USD/GJ. Furthermore, the total volume estimated here from approved pathways (57.9 10^6 m^3) – which was led mainly by Palm/HEFA – could supply roughly 13% of the global demand by fossil kerosene, or even 22% of demand by international flights[96]. These figures just point out the general potential of the pathways, since that the SAFs produced from the pathways evaluated here are allowed to be used in the maximum blend (v/v) of 50% with fossil kerosene.

Regarding the potential carbon reduction (**Figure 3.4.B**), waste grease-based pathways (UCO/HEFA and Tallow/HEFA) and thermochemical conversion of lignocellulosic residues could provide carbon mitigation equivalent to the emission from the international flights originating in Brazil (around 7.6 $MtCO_{2e}$) with moderate costs (185 - 371 USD/tCO_{2e}).

On the other hand, the costs increased assuming pioneer plants (**Figure 3.4.C**), and the pathway based on 1G ethanol (SC-1G/ATJ, 602 USD/tCO_{2e}) gained prominence providing carbon mitigation correspondent to all emissions from the Brazilian aviation sector. In contrast, the waste-grease pathways could provide a carbon reduction close to 20% of the emissions from the international flights originating in Brazil with the lowest costs (225 - 266 USD/tCO_{2e}).

In a wider perspective, the pathways evaluated here could provide a total reduction of 48.5 $MtCO_{2e}$, which means 8% of the carbon emissions related to the international flights in the world, or 29% for international flights originating in Europe, or even 41% of the international flights originating in the American continent[97]. Excluding oil-based 1G pathways due to their high costs, the pathways could reduce roughly 23% of the carbon emissions related to the international flights in the American continent, at expenses of 185 - 495 USD/tCO_{2e}.

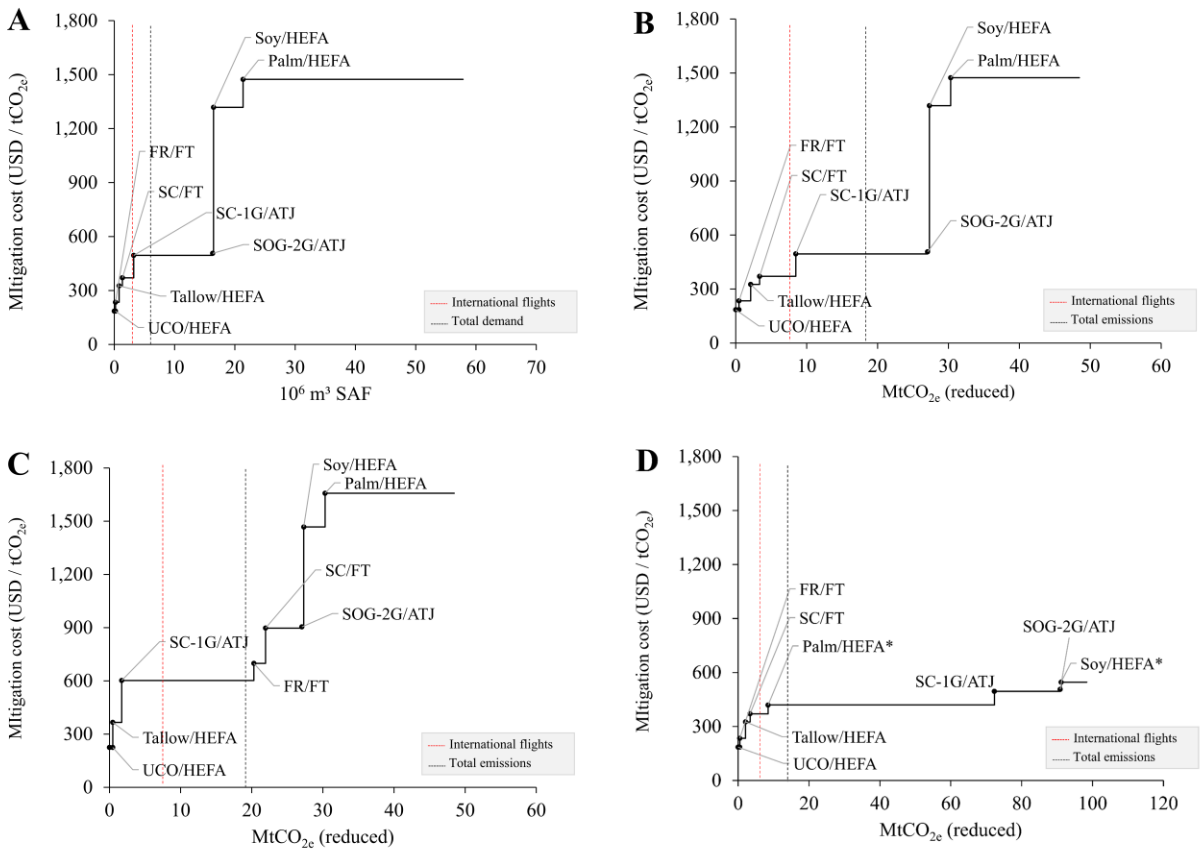

Figure 3.4: Supply curve of SAF assuming an Nth plant (A); Carbon mitigation curve by SAF assuming an Nth plant (B); Carbon mitigation curve assuming a pioneer plant (C). Carbon mitigation curve by SAF assuming an Nth plant, with SAF produced from soybean (Soy*) and palm (Palm*) obtained in areas with low-risks for LUC (D). "International flights" mean the fuel demand or GHG emissions related to international flights originating in Brazil. "Total values" mean the fuel demand or GHG emissions related to international and domestic flights in Brazil[69].

However, if Soy/HEFA and Palm/HEFA were proven to be obtained from low-risks areas for land use change (**Figure 3.4.D**), SAF produced in Brazil could mitigate 18% of the carbon emissions related to international aviation operations (98.4 $MtCO_{2e}$) at expenses of 185-547 USD/tCO_{2e}. It is worth remembering that the CORSIA criteria for eligible areas, as mentioned previously, must be taken into account, which could reduce this potential.

3.3.3. Sensitivity analysis

In general, the fossil fuel price is a relevant parameter for the feasibility of any biofuel program. Here (see **Figure 3.5**), the mitigation costs of SAF pathways ranged similarly to the variations of the Jet A price (±30%), except for pathways based on 2G ethanol, whose values vary (±15%). The variation of the MARR (±30%) also implied close variations on 2G pathways (±30%), while led to (±20%) in 1G-based ones.

The sensitivity of the scale of industrial plants (±50%) was more relevant in capital-intensive pathways, such as those based on 2G ethanol (-30% to +80%) and thermochemical processes (-20% to +50%). In turn, variations on the feedstock price (±20%) were relevant for Soy/HEFA (±30%) and less than 20% for other pathways, including residue-based ones, except for SOG-2G/ATJ. In this latter, if steel-off gases – which have been recovered for energy purposes in several steel mills[80] – were priced by natural gas, the mitigation costs related to SOG-2G/ATJ would increase by 103% (1,031 USD/tCO_{2e}).

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

In turn, the variation on transportation distances (±50%) could lead to variations of ±25% in UCO/HEFA, and less than 5% in the other pathways. Finally, the mitigation costs of each pathway could be reduced by around 80% and be increased two-fold for 1G pathways assuming the cumulative variations. The range of the cumulative variations is a bit narrow (-70% to 120%) for 2G pathways, except for UCO/HEFA and SOG-2G/ATJ, which total values could increase 3-fold to 5-fold, respectively.

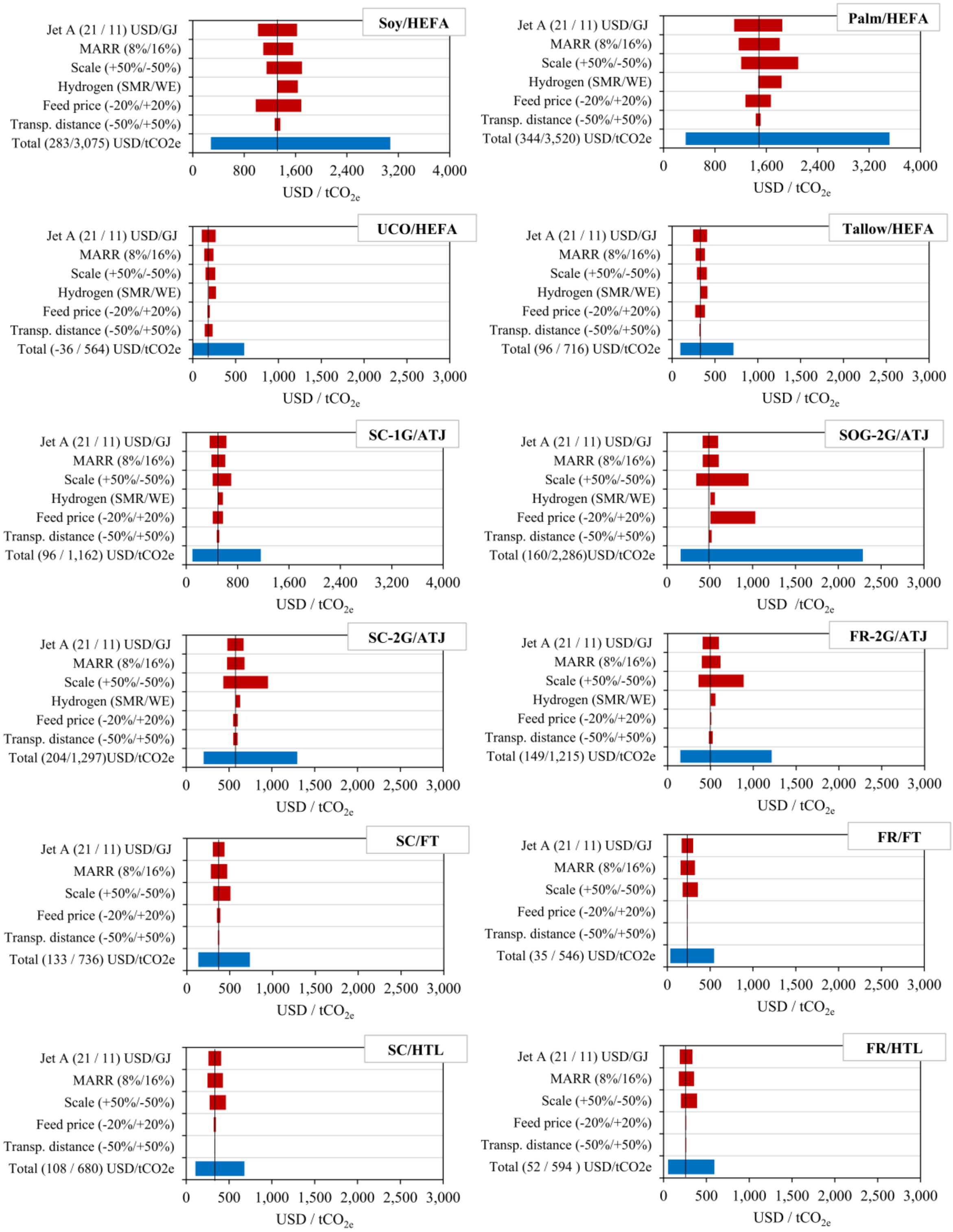

Figure 3.5: Sensitivity analysis of the mitigation costs of SAF

3.3.5. Alternative offsetting market-measures

In comparison with the emission units traded in the carbon market, the mitigation costs of SAFs – considering the possible range from the sensitivity analysis (see **Figure 3.5**) – are much higher than current prices (1.02 - 3.13 USD/tCO_{2e}) or even the future ones (5.90 - 55.2 USD/tCO_{2e}) (see **Figure 3.6**). Some competitiveness is observed in UCO/HEFA and in the thermochemical conversion of forest residues. Of the 1G pathways, only SAF production from sugarcane (SC-1G/ATJ) had a minimum value close to the maximum carbon price reported for future scenarios. It is important to highlight that the mitigation costs of Palm/HEFA are considerably influenced by the default factor related to land use change emissions. Thus, this pathway can eventually be competitive with the carbon market for a different LUC factor estimated in Brazil.

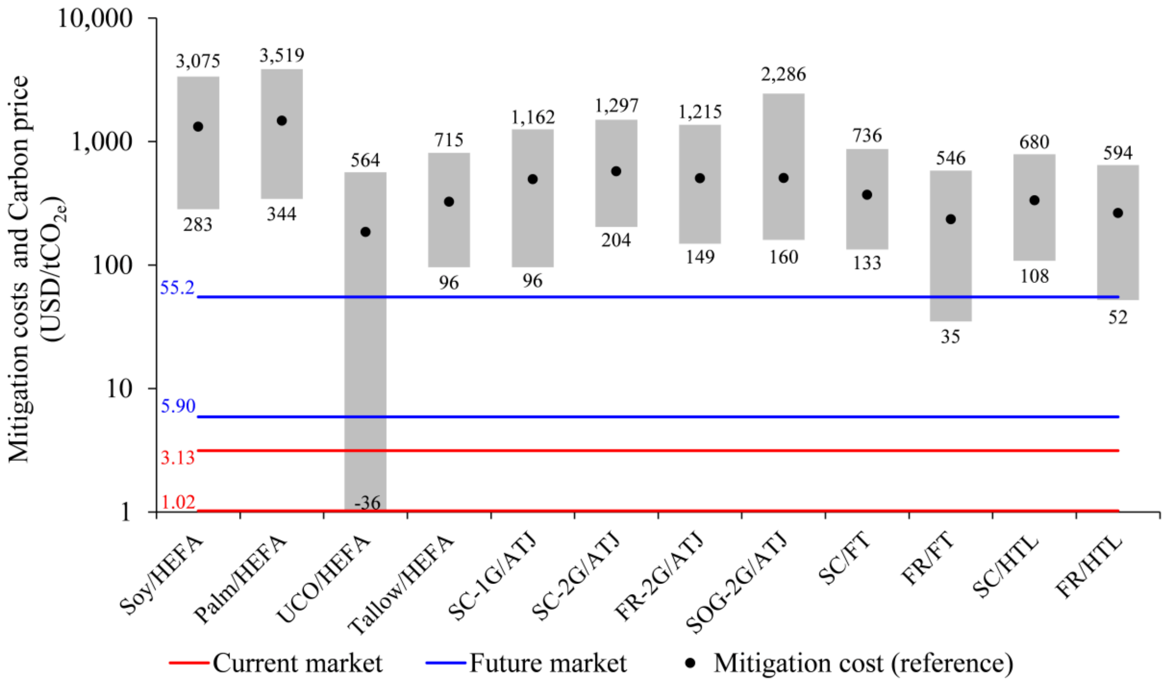

Figure 3.6: Comparison between the mitigation costs of SAF and the price of the emission units according to the carbon market.

The current prices of the emission units can be presented in different ranges: i) by program (1.02 - 3.13 USD/tCO_{2e}), as reported in **Figure 3.6**, where the minimum and maximum values are related to CDM and Gold Standard; ii) by the project category (1.67 - 5.01 USD/tCO_{2e}), where the minimum and maximum values are related to projects of renewable energy/industrial manufacturing and household devices, respectively; and iii) by region (0.70 - 4.20 USD/tCO_{2e}) where the minimum and maximum values are related to European projects and African projects, respectively.

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

Furthermore, the availability of the emission units in the carbon market is also a relevant parameter in this discussion. Ecosystem MarketPlace[98] has compared the CORSIA demand by emissions units for the first cycle (2021-2023) with the existing and potential emissions units supply, based on the six approved Programs, within the 2016-2020 timeframe. Results have shown that the existing supply is roughly 4.0 to 5.5-fold higher than CORSIA demand. Fearnehough *et al.*[99] extended the analysis to the complete CORSIA duration (2021-2035), by considering data from the four largest Programs: CDM, VCS, GS, and CAR. They estimated a potential supply of 18 billion tCO_{2e} against a predicted demand of 2.7 billion tCO_{2e} for the aviation sector.

These absolute results reaffirm that purchasing emission units is currently more feasible than direct investments in biofuels, since carbon offset prices are much lower (see **Figure 3.6**), and there is high availability in the market. An important question thus arises: do SAFs on GHG reduction still make sense?

First, it is worth stressing that the production and use of biofuels, *e.g.,* SAFs, could directly or indirectly provide benefits beyond GHG mitigation, such as the development of national industry, possible socio-economic improvements to farmers and local communities, and energy security[46,100–103].

Secondly, it is necessary to take a closer look at the particularities of the carbon market to assess the effective benefits of carbon offsetting in order to understand whether the emissions units can really serve the mitigation purpose.

Although a potential supply of emission units was reported approximately 7 times higher than CORSIA's demand[99], that study has defined different restriction scenarios, which could significantly reduce the availability of the emissions units.

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

That study[99] also added scenarios not related to vintage: (i) double claiming scenarios, in which emission reductions could only come from projects that were not included in any mitigation targets from NDCs or should only consider emissions reductions from countries without listed NDC mitigation targets; (ii) vulnerability scenarios, where only projects with high or variable vulnerability would be accepted for discontinuing GHG abatement without emission reductions revenues; and (iii) a scenario comprising only projects developed in Less Developed Countries (LDCs) and Small Island Developing States (SIDs).

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

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

Discussions on more restrictive rules for carbon offsetting are not new in the carbon market. The most widespread market mechanisms related to GHG mitigation were those defined by the Kyoto Protocol, especially the Clean Development Mechanism, which served as the most well-known case. Among those experiences, some lessons learned have been shared by different authors[104–110], mainly to support decisions for future protocols, such as the proposed market in Article 6 from the Paris Agreement.

Although CORSIA is not included at the Paris Agreement's goals, discussions and trends regarding perceptions of the market players should be considered. Some studies have expressed concerns about additionality, environmental integrity, and double counting of the emissions units[111–113]. According to these authors, special attention should be given to additionality, which means that reductions must occur against a baseline scenario that would continue to happen without that project intervention. Then a project activity must surpass financial, technological, and institutional barriers[114].

In this context, Cames *et al.*[115], who evaluated CDM projects with the potential emissions reductions within 2013-2020, indicated that at least 73% of the emissions were either unlikely to be additional or had been overestimated. This corroborates the scenario depicted by Fearnehough *et al.*[99] for project vulnerability, when it was concluded that most of the existing carbon projects would continue to operate without carbon revenues and, therefore, the effective mitigation could be questionable.

At the moment, emissions units could properly supply the CORSIA demand for the first cycle (2021-2023). On the other hand, taking into account the doubts related to the credibility of the emission units and uncertainties related to mitigation effects, different scenarios should be expected after 2023, when more restrictive guidelines would lead to lower availability. In this almost certain gap, the SAFs could play an important role if the development of this new biofuel sector is supported by robust carbon policies. These policies could tackle the current disadvantages incorporated by CORSIA, which handle emissions reduction as equivalent to emission offsetting[29].

Some existing policies already have supported biofuels, including SAFs. In 2017, the Brazilian Government launched the National Policy on Biofuels *Renovabio*[116], seeking to promote biofuel expansion. Of the determined instruments in Renovabio are the "Decarbonization credits" (CBIOs), that can be claimed by biofuel producers or importers, properly authorized by the national agency. Because those credits have just been implemented, price projections are still uncertain, even though they have already reached around 10.0 USD/tCO_{2e} at the first negotiations held in June 2020[117]. The program also covers compulsory additions of biofuels to fossil fuels, taxes, financial and credit incentives. Only HEFA-based pathways are currently considered in the program scope[118], but biofuel producers can request the incorporation of new pathways.

The Renewable Fuel Standard (RFS), which has been implemented in the United States since 2005[119,120], sets a minimum volume for renewable fuels for transportation.[121] Currently, only four pathways based on HEFA and FT technologies are approved by RFS.[122] The latest RIN prices ranged from 2.65 - 820 USD/m³ (0.01- 3.50 USD/gallon)[123]. Although RSF assess is based on the environmental performance of fuels, unlike Renovabio it does not put a direct price on carbon emissions.

In California, the Low Carbon Fuel Standard (LCFS) has been implemented since 2011, aiming at reducing carbon intensity (CI) of fuels used in transportation by 10% until

2020, compared with a 2010 base year[124]. Adjusted goals will improve overall CI fuel benchmarks until 2030. LCFs below benchmark generate credits and LCFs above the benchmark generate deficits. Currently, three “alternative jet fuels” pathways based on HEFA/Tallow are approved. LCFs prices ranged from 160 - 217 USD/tCO_{2e}, according to July 2020 report[125].

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

3.5. Conclusion

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

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

In general, residue-based pathways had lower mitigation costs. UCO/HEFA had the lowest value (185 USD/tCO_{2e}), followed by the thermochemical conversion of forest residues (234 - 263 USD/tCO_{2e}), hydrotreating of beef tallow (326 USD/tCO_{2e}) and the thermochemical conversion of sugarcane residues (334 - 370 USD/tCO_{2e}). SAF from 2G ethanol had high values (500 - 570 USD/tCO_{2e}). Of the 1G pathways, SAF production using 1G sugarcane ethanol (SC-1G/ATJ) had a better performance than oil-based pathways. While the former resulted in 495 USD/tCO_{2e}, the latter ranged from 1,320 - 1,470 USD/tCO_{2e}. However, if Soy/HEFA and Palm/HEFA were obtained from certified areas with low-risks for land use change, the mitigation costs of these pathways could decrease to 550 USD/tCO_{2e} and 420 USD/tCO_{2e}, respectively.

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

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

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

Finally, SC-1G/ATJ as the most suitable alternative in the short-term, considering both the potential to supply SAF and mitigate emissions. Palm/HEFA could also be included after confirmation of the potential lower emissions related to land use change in Brazilian conditions. Of the residues-based pathways, Tallow/HEFA and FR/FT are pointed out as strategic alternatives. However, the commercial risks for Tallow/HEFA due to the possible competition with the biodiesel market and technological risks related to thermochemical conversion must be taken into account.

Supplementary Material

Table SM. 1: Economic description of the SAF pathways (Nth plant)

Pathways	Intermediary industry			SAF refinery		
	Scale (Ref.) (Mt_{feed}) [a]	CAPEX [b] (M USD)	OPEX+T (USD/t_{feed})	Scale (Ref.) (Mt_{feed})	CAPEX [b] (M USD)	OPEX+T (USD/t_{feed})
Soy/HEFA [c]	0.83 (0.66)	158.7	30.1	0.16 (0.83)	403.5	316.7
Palm/HEFA [d]	0.65	76.4	20.5	0.16 (0.83)	403.5	312.8
UCO/HEFA [e]				0.16 (0.83)	403.5	493.0
Tallow/HEFA [f]				0.16 (0.83)	403.5	316.7
SC-1G/ATJ [g]	4.00	473.8	11.2	0.34 (0.29)	86.1	98.9
SC-2G/ATJ [h]	0.22 (0.46)	149.8	121.3	0.34 (0.29)	86.1	98.9
FR-2G/ATJ [i]	0.26 (0.46)	163.7	108.4	0.34 (0.29)	86.1	98.9
SOG-2G/ATJ [j]	0.058 (0.124)	79.6	329.9	0.34 (0.29)	86.1	98.9
SC/FT [k]				1.14 (0.89)	1,084.1	96.0
FR/FT [l]				0.95 (0.74)	972.4	103.6
SC/HTL [m]				0.68 (0.32)	933.8	175.7
FR/HTL [n]				0.56 (0.27)	933.8	196.2

[a] "Scale" refers to the production scale of one industrial plant as assumed here. (Ref) refers the reference scale based on the literature. Specifically for SOG-2G/ATJ, the production scale for the intermediary industry was expressed in 10^6 $m^3_{ethanol}$ produced.

[b] Including working capital (5% of the CAPEX).

[c] **Intermediary industry:** soybean as feedstock; Reference (Ref.) plant of 2,500 t_{feed}/day, like the most soybean mills in Brazil [38]; Reference (Ref.) plant, CAPEX, and OPEX (20.2 USD/t_{feed}, without feedstock) based on [25]; transportation (T) *crop-to-mill* (0.050 USD/tkm [131]); economic allocation factor for soybean oil (31%). **SAF refinery:** soybean oil as feedstock; HEFA technology; Reference (Ref.) plant and CAPEX based on [31]; OPEX (278.6 USD/t_{feed}, without feedstock), including power demand (0.044 MWh/t_{feed}, 190.7 USD/MWh [126]), hydrogen (0.040 t/t_{feed}, 1,395 USD/t_{H2} [132]), and natural gas (3.0 GJ/t_{feed}, 15.5 USD/GJ [126]); transportation (T) *mill-to-refinery* (0.064 USD/tkm [133]); economic allocation factor for SAF (54%).

[d] **Intermediary industry:** fresh fruit bunches (FFB) of palm as feedstock; Reference (Ref.) plant of a typical palm milling plant in Brazil (82 t_{FFB}/h or 0.114 $Mt_{palm\ oil}$/year) [43]; Reference (Ref.) plant, CAPEX, and OPEX (17.0 USD/t_{feed}, without feedstock) based on [25]; POME treatment and power generation systems (capital costs of 6.2 M USD for a power plant of 3.50 MW [45]); transportation (T) *crop-to-mill* (0.107 USD/tkm) [134]); economic allocation factor for palm oil (89%). **SAF refinery:** soybean oil as feedstock; HEFA technology; Reference (Ref.) plant and CAPEX based on [31]; OPEX (278.6 USD/t_{feed}, without feedstock), including power demand (0.044 MWh/t_{feed}, 190.7 USD/MWh [126]), hydrogen (0.037 t/t_{feed}, 1,395 USD/t_{H2} [132]), and natural gas (3.0 GJ/t_{feed}, 15.5 USD/GJ [126]); transportation (T) *mill-to-refinery* (0.064 USD/tkm [133]); economic allocation factor for SAF (54%).

[e] **UCO collect and transportation** (0.254 USD/tkm) [48], considering a medium-duty commercial vehicle (1,500 kg) which travelled 844 km/week to collect 14,900 L/week from bars and restaurant in a big-size city in Brazil. **SAF refinery:** UCO as feedstock; HEFA technology; Reference (Ref.) plant and CAPEX based on [31]; OPEX (270.1 USD/t_{feed}, without feedstock), including power demand (0.044 MWh/t_{feed}, 190.7 USD/MWh [126]), hydrogen (0.040 t/t_{feed}, 1,395 USD/t_{H2} [132]), and natural gas (3.0 GJ/t_{feed}, 15.5 USD/GJ [126]); transportation (T) *mill-to-refinery* (0.064 USD/tkm [133]); economic allocation factor for SAF (54%).

[f] Transportation *slaughterhouse-to-refinery* (0.064 USD/tkm [133]), based on soybean oil transportation. **SAF refinery:** beef tallow as feedstock; HEFA technology; Reference (Ref.) plant and CAPEX based on [31]; OPEX (278.6 USD/t_{feed}, without feedstock), including power demand (0.044 MWh/t_{feed}, 190.7 USD/MWh [126]), hydrogen (0.040 t/t_{feed}, 1,395 USD/t_{H2} [132]), and natural gas (3.0 GJ/t_{feed}, 15.5 USD/GJ [126]); transportation (T) *mill-to-refinery* (0.064 USD/tkm [133]); economic allocation factor for SAF (54%).

[g] **Intermediary industry:** processing scale of 4.0 Mt sugarcane/year; CAPEX and OPEX (5.7 USD/$t_{sugarcane}$, without feedstock) based on [46]; transportation (T) *crop-to-mill* (0.107 USD/tkm [134]); economic allocation factor for 1G ethanol (82%). **SAF refinery:** ethanol as feedstock; ATJ technology; Reference (Ref.) plant and CAPEX based on [22]; OPEX (69.2 USD/t_{feed}, without feedstock), including power demand (0.196 MWh/t_{feed}, 190.7 USD/MWh [126]), and hydrogen (0.011 t/t_{feed}, 1,395 USD/t_{H2} [132]); transportation (T) *mill-to-refinery* (0.050 USD/tkm [133]); economic allocation factor for SAF (59%).

[h] **Intermediary industry:** sugarcane residues (45% moisture [46,127]) as feedstock; Reference (Ref.) plant (input capacity in dry basis) based on a commercial plant in Brazil (80,000 m³ ethanol/year) [135]; Reference (Ref.) plant (dry basis), CAPEX, and OPEX (98.8 USD/$t_{feed\ (db)}$, without feedstock) based on [46]; transportation (T) *field-to-mill* (0.103 USD/tkm [136]); economic allocation factor for 2G ethanol (97%). **SAF refinery:** ethanol as feedstock; ATJ technology; Reference (Ref.) plant and CAPEX based on [22]; OPEX (69.2 USD/t_{feed}, without feedstock), including power demand (0.196 MWh/t_{feed}, 190.7 USD/MWh [126]), and hydrogen (0.011 t/t_{feed}, 1,395 USD/t_{H2} [132]); transportation (T) *mill-to-refinery* (0.050 USD/tkm [133]); economic allocation factor for SAF (59%).

[i] **Intermediary industry:** forestry residues (12% moisture [128]) as feedstock; Reference (Ref.) plant (input capacity in dry basis) based on a commercial plant in Brazil (80,000 m³ ethanol/year) [135]; Reference (Ref.) plant (dry basis), CAPEX, and OPEX (85.2 USD/$t_{feed\ (db)}$, without feedstock) based on [46]; transportation (T) *field-to-mill* (0.103 USD/tkm [136]); economic allocation factor for 1G ethanol (96%). **SAF refinery:** ethanol as feedstock; ATJ technology; Reference (Ref.) plant and CAPEX based on [22]; OPEX (69.2 USD/t_{feed}, without feedstock), including power demand (0.196 MWh/t_{feed}, 190.7 USD/MWh [126]), and hydrogen (0.011 t/t_{feed}, 1,395 USD/t_{H2} [132]); transportation (T) *mill-to-refinery* (0.050 USD/tkm [133]); economic allocation factor for SAF (59%).

[j] **Intermediary industry**: steel off-gases as feedstock; Reference (Ref.) plant (10^6 m³ ethanol/year) was based on a commercial plant [53]; Reference (Ref.) and CAPEX based on [137], assuming the minimum selling price for Pareto optimum solutions; OPEX (342.8 USD/$m^3_{ethanol}$, without feedstock), including power demand (730 MWh/$m^3_{ethanol}$, 190.7 USD/MWh [126]) based on [54], considering self-supply of steam, electricity from Brazilian grid and labor and maintenance as defined here (section 2.2). **SAF refinery:** ethanol as feedstock; ATJ technology; Reference (Ref.) plant and CAPEX based on [22]; OPEX (69.2 USD/t_{feed}, without feedstock), including power demand (0.196 MWh/t_{feed}, 190.7 USD/MWh [126]), and hydrogen (0.011 t/t_{feed}, 1,395 USD/t_{H2} [132]); transportation (T) *mill-to-refinery* (0.050 USD/tkm [133]); economic allocation factor for SAF (59%).

[k] **FT technology:** sugarcane residues (45% moisture, 14.6 MJ/kg_{db} [46,127]) as feedstock; Reference (Ref.) plant (dry basis) and CAPEX based on [31], for input capacity of 454 MW; OPEX (73.5 USD/$t_{feed\ (db)}$, without feedstock); transportation (T) *field-to-mill* (0.103 USD/tkm [136]); economic allocation factor for SAF (15%).

[l] **FT technology:** forestry residues (12% moisture, 17.5 MJ/kg_{db} [128]) as feedstock; Reference (Ref.) plant (dry basis) and CAPEX based on [31], for input capacity of 454 MW; OPEX (80.4 USD/$t_{feed\ (db)}$, without feedstock); transportation (T) *field-to-mill* (0.103 USD/tkm [136]); economic allocation factor for SAF (15%).

[m] **HTL technology:** sugarcane residues (45% moisture, 14.6 MJ/kg_{db} [46,127]) as feedstock; Reference (Ref.) (dry basis) plant and CAPEX based on [32], , for input capacity of 454 MW; OPEX (153.1 USD/$t_{feed\ (db)}$, without feedstock), including power demand (1.90 MWh/ t_{SAF}, 190.7 USD/MWh [126]), natural gas (220 m³/t_{SAF}, 0.570 USD/m³ [126]), and other chemicals (65.5 USD/t_{SAF}); transportation (T) *field-to-mill* (0.103 USD/tkm [136]); economic allocation factor for SAF (40%).

[n] **HTL technology:** forestry residues (12% moisture, 17.5 MJ/kg_{db} [128]) as feedstock; Reference (Ref.) plant (dry basis) and CAPEX based on [32], for input capacity of 164 MW; OPEX (182.1 USD/$t_{feed\ (db)}$, without feedstock), including power demand (1.90 MWh/ t_{SAF}, 190.7 USD/MWh [126]), natural gas (220 m³/t_{SAF}, 0.570 USD/m³ [126]), and other chemicals (58.4 USD/t_{SAF}); transportation (T) *field-to-mill* (0.103 USD/tkm [136]); economic allocation factor for SAF (40%).

Table SM. 2: Life Cycle emissions for SAF pathways, without emissions from land use change ($kgCO_{2e}/GJ$)

Life cycle stages [b]	HEFA [c]				ATJ [d]				FT [e]		HTL [f]	
	Soybean	Palm [g]	UCO	Tallow	SC-1G	SC-2G	FR-2G	SOG-2G [h]	SC	FR	SC	FR
Feedstock procurement	**21.2**	**16.0**	**0.0**	**0.0**	**15.1**	**0.0**	**0.5**	**0.0**	**0.0**	**0.3**	**0.0**	**0.2**
Inputs	6.3	3.9			3.2							
Energy	1.6	1.0			3.8		0.5			0.3		0.2
Other emissions	13.4	11.2			8.1							
Intermediary industry	**1.4**	**0.4**	**0.0**	**0.0**	**3.4**	**9.3**	**9.1**	**11.3**	**0.0**	**0.0**	**0.0**	**0.0**
Inputs	0.2	0.0	0.0	0.0	0.6	7.4	7.3	2.8				
Energy	1.3	0.4	0.0	0.0	2.8	1.9	1.8	8.6				
SAF refinery	**15.8**	**15.8**	**15.8**	**15.8**	**8.7**	**8.7**	**8.7**	**8.2**	**0.0**	**0.0**	**8.8**	**8.8**
Inputs	10.1	10.1	10.1	10.1	6.4	6.4	6.4	6.4	0.0	0.0	5.2	5.2
Energy	5.7	5.7	5.7	5.7	2.3	2.3	2.3	1.8	0.0	0.0	3.5	3.5
Transportation	**4.2**	**2.0**	**1.2**	**2.5**	**8.6**	**9.4**	**8.9**	**5.3**	**3.7**	**1.9**	**2.0**	**1.2**
Use	**0.2**	**0.2**	**0.2**	**0.2**	**0.2**	**0.2**	**0.2**	**0.0**	**0.2**	**0.2**	**0.2**	**0.2**
TOTAL	**42.9**	**34.4**	**17.2**	**18.5**	**36.0**	**27.6**	**27.4**	**24.8**	**3.9**	**2.4**	**11.0**	**10.3**

[a] The most life cycle inventories are described in [18]: soybean oil production, sugarcane production, and ethanol production from sugarcane and lignocellulosic material (sugarcane residues and forest residues). The background data and the emission factors also assumed in 18 were used in all pathways.
[b] 'Inputs" comprise chemicals in general, fertilizers, pesticides, hydrogen, etc. "Energy" comprise diesel in agricultural operations and utilities use (power/steam). "Other emissions" comprise direct emissions from field from fertilizers use, including organic fertilizers.
[c] Hydrotreating of oil-based feedstock is described in [55,56].
[d] Upgrading ethanol to jet fuel via ATJ technology is described in [22,138].
[e] Fisher-Tropsch technology is described in [11,20].
[f] Hydrothermal Liquefaction is described in [32].
[g] Palm crop and palm oil extraction are described in [40,43].
[h] Ethanol production from steel off-gases are described in [54,137].

References

1. IEA. Data and Statistics [Internet]. 2020 [cited 2020 Apr 28]. Available from: https://www.iea.org/data-and-statistics
2. ICAO. Resolutions 37th Assembly [Internet]. 2010. Available from: http://www.icao.int/Meetings/AMC/Assembly37/Documents/ProvisionalEdition/a37_res_prov_en.pdf
3. ICAO. Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) [Internet]. *International Civil Aviation Organization.* 2020 [cited 2020 Apr 28]. Available from: https://www.icao.int/environmental-protection/Pages/market-based-measures.aspx
4. ICAO. Annex 16 - Environmental Protection, Volume IV - Carbon Offsetting and Reduction Scheme for Internationl Aviation (CORSIA) [Internet]. Montreal; 2018. Available from: https://www.icao.int/environmental-protection/CORSIA/Pages/SARPs-Annex-16-Volume-IV.aspx
5. ICAO. Doc 9501, Envinronmental Technical Manual Volume IV, Procedures for demonstrating compliance with the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) [Internet]. Montreal, Canada; 2019. Available from: https://www.icao.int/environmental-protection/CORSIA/Pages/ETM-V-IV.aspx
6. ICAO. Doc 9 -CORSIA Emissions Unit Eligibility Criteria [Internet]. Montreal; 2019. Available from: https://www.icao.int/environmental-protection/CORSIA/Pages/implementation-elements.aspx
7. ICAO. Doc 8 - CORSIA Eligible Emission Units [Internet]. Montreal; 2020. Available from: https://www.icao.int/environmental-protection/CORSIA/Pages/implementation-elements.aspx
8. ICAO. Sustainable Aviation Fuel Guide [Internet]. 2017. Available from: https://www.icao.int/environmental-protection/GFAAF/Pages/default.aspx
9. ICAO. CORSIA - Sustainability Criteria for CORSIA Eligible Fuels. Montreal; 2019.
10. ASTM. ASTM D7566-20 Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons. West Conshohocken, Pennsylvania, USA; 2020.
11. de Jong S, Antonissen K, Hoefnagels R, Lonza L, Wang M, Faaij A, et al. Life-cycle analysis of greenhouse gas emissions from renewable jet fuel production. *Biotechnol Biofuels [Internet]*. 2017 Dec 14;10(1):64. Available from: http://biotechnologyforbiofuels.biomedcentral.com/articles/10.1186/s13068-017-0739-7
12. Li X, Mupondwa E. Life cycle assessment of camelina oil derived biodiesel and jet fuel in the Canadian Prairies. *Sci Total Environ [Internet]*. 2014;481(1):17–26. Available from: http://dx.doi.org/10.1016/j.scitotenv.2014.02.003
13. Han J, Elgowainy A, Cai H, Wang MQ. Life-cycle analysis of bio-based aviation fuels. *Bioresour Technol [Internet]*. 2013;150:447–56. Available from: http://linkinghub.elsevier.com/retrieve/pii/S0960852413012297
14. Seber G, Malina R, Pearlson MN, Olcay H, Hileman JI, Barrett SRH. Environmental and economic assessment of producing hydroprocessed jet and diesel fuel from waste oils and tallow. *Biomass and Bioenergy [Internet]*. 2014;67:108–18. Available from: http://linkinghub.elsevier.com/retrieve/pii/S0961953414002189
15. Cavalett O, Cherubini F. Contribution of jet fuel from forest residues to multiple Sustainable Development Goals. *Nat Sustain [Internet]*. 2018 Dec 19;1(12):799–807.

Available from: http://www.nature.com/articles/s41893-018-0181-2

16. Cox K, Renouf M, Dargan A, Turner C, Klein-Marcuschamer D. Environmental life cycle assessment (LCA) of aviation biofuel from microalgae, Pongamia pinnata , and sugarcane molasses. *Biofuels, Bioprod Biorefining [Internet]*. 2014 Jul;8(4):579–93. Available from: http://doi.wiley.com/10.1002/bbb.1488
17. Staples MD, Malina R, Olcay H, Pearlson MN, Hileman JI, Boies A, et al. Lifecycle greenhouse gas footprint and minimum selling price of renewable diesel and jet fuel from fermentation and advanced fermentation production technologies. *Energy Environ Sci [Internet]*. 2014;7(5):1545. Available from: http://xlink.rsc.org/?DOI=c3ee43655a
18. Capaz RS, de Medeiros EM, Falco DG, Seabra JEA, Osseweijer P, Posada JA. Environmental trade-offs of renewable jet fuels in Brazil: Beyond the carbon footprint. *Sci Total Environ [Internet]*. 2020 Apr;714:136696. Available from: https://doi.org/10.1016/j.scitotenv.2020.136696
19. Bwapwa JK, Anandraj A, Trois C. Possibilities for conversion of microalgae oil into aviation fuel: A review. *Renew Sustain Energy Rev [Internet]*. 2017;80(August):1345–54. Available from: http://dx.doi.org/10.1016/j.rser.2017.05.224
20. de Jong S, Hoefnagels R, Faaij A, Slade R, Mawhood R, Junginger M. The feasibility of short-term production strategies for renewable jet fuels - a comprehensive techno-economic comparison. *Biofuels, Bioprod Biorefining [Internet]*. 2015 Nov;9(6):778–800. Available from: http://doi.wiley.com/10.1002/bbb.1613
21. Diederichs GW, Ali Mandegari M, Farzad S, Görgens JF. Techno-economic comparison of biojet fuel production from lignocellulose, vegetable oil and sugar cane juice. *Bioresour Technol [Internet]*. 2016 Sep;216:331–9. Available from: http://dx.doi.org/10.1016/j.biortech.2016.05.090
22. Klein BC, Chagas MF, Junqueira TL, Rezende MCAF, Cardoso T de F, Cavalett O, et al. Techno-economic and environmental assessment of renewable jet fuel production in integrated Brazilian sugarcane biorefineries. *Appl Energy [Internet]*. 2018 Jan;209(August 2017):290–305. Available from: https://doi.org/10.1016/j.apenergy.2017.10.079
23. Bann SJ, Malina R, Staples MD, Suresh P, Pearlson M, Tyner WE, et al. The costs of production of alternative jet fuel: A harmonized stochastic assessment. *Bioresour Technol [Internet]*. 2017 Mar;227:179–87. Available from: https://linkinghub.elsevier.com/retrieve/pii/S0960852416316911
24. Bittner A, Tyner WE, Zhao X. Field to flight: A techno-economic analysis of the corn stover to aviation biofuels supply chain. *Biofuels, Bioprod Biorefining [Internet]*. 2015 Mar;9(2):201–10. Available from: http://doi.wiley.com/10.1002/bbb.1536
25. Cervi WR, Lamparelli RAC, Seabra JEA, Junginger M, de Jong S, van der Hilst F. Spatial modeling of techno-economic potential of biojet fuel production in Brazil. *GCB Bioenergy [Internet]*. 2020 Feb 14;12(2):136–57. Available from: https://onlinelibrary.wiley.com/doi/abs/10.1111/gcbb.12659
26. Santos CI, Silva CC, Mussatto SI, Osseweijer P, van der Wielen LAM, Posada JA. Integrated 1st and 2nd generation sugarcane bio-refinery for jet fuel production in Brazil: Techno-economic and greenhouse gas emissions assessment. *Renew Energy [Internet]*. 2018 Dec;129:733–47. Available from: http://dx.doi.org/10.1016/j.renene.2017.05.011
27. Baral NR, Kavvada O, Mendez-Perez D, Mukhopadhyay A, Lee TS, Simmons BA, et

al. Techno-economic analysis and life-cycle greenhouse gas mitigation cost of five routes to bio-jet fuel blendstocks. *Energy Environ Sci [Internet]*. 2019;12(3):807–24. Available from: http://xlink.rsc.org/?DOI=C8EE03266A

28. Carvalho F, Silva FTF, Szklo A, Portugal-Pereira J. Potential for biojet production from different biomass feedstocks and consolidated technological routes: a georeferencing and spatial analysis in Brazil. *Biofuels, Bioprod Biorefining [Internet]*. 2019 Nov 27;13(6):1454–75. Available from: https://onlinelibrary.wiley.com/doi/abs/10.1002/bbb.2041
29. Pavlenko AN, Searle S, Christensen A. The cost of supporting a lternative jet fuels in the European Union. 2019. (2019-5).
30. Cortez LAB. Roadmap for sustainable aviation biofuels for Brazil. *Blucher, editor.* São Paulo; 2014. 272 p.
31. de Jong S, Hoefnagels R, Faaij A, Slade R, Mawhood R, Junginger M. The feasibility of short-term production strategies for renewable jet fuels - a comprehensive techno-economic comparison. *Biofuels, Bioprod Biorefining [Internet]*. 2015 Nov;9(6):778–800. Available from: http://doi.wiley.com/10.1002/bbb.1613
32. Tzanetis KF, Posada JA, Ramirez A. Analysis of biomass hydrothermal liquefaction and biocrude-oil upgrading for renewable jet fuel production: The impact of reaction conditions on production costs and GHG emissions performance. *Renew Energy [Internet]*. 2017;113:1388–98. Available from: http://dx.doi.org/10.1016/j.renene.2017.06.104
33. Tomaschek J, Özdemir ED, Fahl U, Eltrop L. Greenhouse gas emissions and abatement costs of biofuel production in South Africa. *GCB Bioenergy [Internet]*. 2012 Nov;4(6):799–810. Available from: http://doi.wiley.com/10.1111/j.1757-1707.2011.01154.x
34. Sterner M, Fritsche U. Greenhouse gas balances and mitigation costs of 70 modern Germany-focused and 4 traditional biomass pathways including land-use change effects. *Biomass and Bioenergy [Internet]*. 2011 Dec;35(12):4797–814. Available from: http://dx.doi.org/10.1016/j.biombioe.2011.08.024
35. ANP. Oil, Natural Gas and Biofuels Statistical Yearbook 2019 [Internet]. Rio de Janeiro; 2020. Available from: http://www.anp.gov.br/publicacoes/anuario-estatistico/anuario-estatistico-2020
36. ANP. Renovacalc - v.6.1 [Internet]. *National Agency of Petroleum Natural Gas and Biofuels - Renovabio.* 2020 [cited 2020 Feb 16]. Available from: http://www.anp.gov.br/producao-de-biocombustiveis/renovabio/renovacalc
37. IBICT/SICV. National database of Life Cycle Inventories (SICV) [Internet]. 2019 [cited 2019 Feb 5]. Available from: http://sicv.acv.ibict.br/Node/
38. ABIOVE. Database of Oil Brazilian Industry [Internet]. *Brazilian Association of Vegetable Oil Industries.* 2020 [cited 2020 Aug 2]. Available from: http://abiove.org.br/en/statistics/
39. Castanheira ÉG, Grisoli R, Coelho S, Anderi da Silva G, Freire F. Life-cycle assessment of soybean-based biodiesel in Europe: comparing grain, oil and biodiesel import from Brazil. *J Clean Prod [Internet]*. 2015 Sep;102:188–201. Available from: https://linkinghub.elsevier.com/retrieve/pii/S0959652615003972
40. Agropalma. Personal Comunication [Internet]. 2017. Available from: adriano.bastos@agropalma.com.br
41. IBGE. Brazilian Institute of Geography and Statistics [Internet]. *Municipal Agricultural Production.* 2019 [cited 2019 Aug 22]. Available from:

https://sidra.ibge.gov.br/pesquisa/pam/tabelas
42. de Souza SP, Pacca S, de Ávila MT, Borges JLB. Greenhouse gas emissions and energy balance of palm oil biofuel. *Renew Energy [Internet]*. 2010 Nov;35(11):2552–61. Available from: http://dx.doi.org/10.1016/j.renene.2010.03.028
43. Agropalma. Relatório de Sustentabilidade [Internet]. São Paulo; 2017. Available from: https://www.agropalma.com.br/responsabilidade-socioambiental/relatorio-de-sustentabilidade
44. Chin MJ, Poh PE, Tey BT, Chan ES, Chin KL. Biogas from palm oil mill effluent (POME): Opportunities and challenges from Malaysia's perspective. *Renew Sustain Energy Rev.* 2013;26:717–26.
45. Rahayu AS, Karsiwulan D, Yuwono H, Trisnawati I, Rahardjo SM, Paramita S, et al. Handbook POME-to-Biogas. Jakarta; 2015.
46. Bonomi A, Cavalett O, Pereira da Cunha M, Lima MAP, editors. Virtual Biorefinery [Internet]. 1st ed. Cham: Springer International Publishing; 2016. 285 p. (Green Energy and Technology). Available from: http://link.springer.com/10.1007/978-3-319-26045-7
47. LNBR. Virtual Sugarcane Biorefinery (VSB) [Internet]. Campinas: Brazilian Biorenewables National Laboratory; 2018. Available from: https://lnbr.cnpem.br/
48. Araujo VKWS, Hamacher S, Scavarda LF. Economic assessment of biodiesel production from waste frying oils. *Bioresour Technol [Internet]*. 2010;101(12):4415–22. Available from: http://dx.doi.org/10.1016/j.biortech.2010.01.101
49. Sousa VMZ, Luz SM, Caldeira-Pires A, Machado FS, Silveira CM. Life cycle assessment of biodiesel production from beef tallow in Brazil. *Int J Life Cycle Assess.* 2017;22(11):1837–50.
50. Canto JL do, Machado CC, Seixas F, Souza AP de, Sant' Anna C de M. Avaliação de um sistema de cavaqueamento de ponteiras de eucalipto para aproveitamento energético. *Rev Árvore [Internet]*. 2011 Dec;35(6):1327–34. Available from: http://www.scielo.br/scielo.php?script=sci_arttext&pid=S0100-67622011000700019&lng=pt&tlng=pt
51. Bragatto J. Avaliação do potencial da casca de Eucalyptus spp . para a produção de bioetanol. Universidade de São Paulo - Escola Superior de Agricultura " Luiz de Queiroz "; 2010.
52. Brooks KP, Snowden-Swan LJ, Jones SB, Butcher MG, Lee G-SJ, Anderson DM, et al. Low-Carbon Aviation Fuel Through the Alcohol to Jet Pathway. *In: Biofuels for aviation: feedstocks, technology and implementation.* London: Elsevier Inc.; 2016. p. 109–50.
53. LanzaTech. World's First Commercial Waste Gas to Ethanol Plant Starts Up [Internet]. 2018 [cited 2019 Jul 31]. Available from: https://www.lanzatech.com/2018/06/08/worlds-first-commercial-waste-gas-ethanol-plant-starts/
54. Handler RM, Shonnard DR, Griffing EM, Lai A, Palou-Rivera I. Life Cycle Assessments of Ethanol Production via Gas Fermentation: Anticipated Greenhouse Gas Emissions for Cellulosic and Waste Gas Feedstocks. *Ind Eng Chem Res [Internet]*. 2016 Mar 30;55(12):3253–61. Available from: http://pubs.acs.org/doi/10.1021/acs.iecr.5b03215
55. Pearlson MN. A Techno-economic and Environmental Assessment of Hydroprocessed Renewable Distillate Fuels [Internet]. *Department of Aeronautics and Astronautics.* Massachusetts Institute of Technology; 2011. Available from:

http://dspace.mit.edu/bitstream/handle/1721.1/65508/746766700.pdf?sequence=1
56. Pearlson M, Wollersheim C, Hileman J. A techno-economic review of hydroprocessed renewable esters and fatty acids for jet fuel production. *Biofuels, Bioprod Biorefining [Internet]*. 2013 Jan;7(1):89–96. Available from: http://doi.wiley.com/10.1002/bbb.1378
57. Towler G, Sinnott R. Chemical engineering design : principles, practice, and economics of plant and process design [Internet]. 2nd Editio. Waltham: Elsevier; 2013. 1320 p. Available from: https://linkinghub.elsevier.com/retrieve/pii/B9780080966595000018
58. ANTT. Resolução Nº 5.867, de 14 de janeiro de 2020 [Internet]. Brazil: National Agency of Terrestrial Transportation; 2020. Available from: https://anttlegis.datalegis.inf.br/
59. IpeaData. IGP-DI - General price index domestic supply [Internet]. *Institute for Applied Economic Research.* 2020 [cited 2020 May 5]. Available from: http://www.ipeadata.gov.br/
60. Scot Consultoria. Beef Tallow - Market price (Brazil Central region) [Internet]. 2018 [cited 2018 Nov 20]. Available from: https://www.scotconsultoria.com.br/
61. UDOP. Valores de ATR e Preço da Tonelada de Cana-de-açúcar [Internet]. 2020 [cited 2020 May 4]. Available from: https://www.udop.com.br/consecana/?route=consecana_index
62. IBGE. Brazilian Institute of Geography and Statistics [Internet]. *Production of Vegetable Extraction and Silviculture.* 2020 [cited 2020 May 5]. Available from: https://sidra.ibge.gov.br/pesquisa/pevs/tabelas
63. ICAO. CORSIA - Methodology for Calculating Actual Life Cycle Emissions Values. Montreal; 2019.
64. IPCC. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. *Stocker TF, Qin D, Plattner G-K, Tignor M, Allen SK, Boschung J, et al., editors.* Cambridge: Cambridge University Press; 2013. 1535 p.
65. ICAO. CORSIA Default Life Cycle Emissions Values for CORSIA Eligible Fuels [Internet]. Montreal; 2019. Available from: https://www.icao.int/environmental-protection/CORSIA/Pages/CORSIA-Eligible-Fuels.aspx
66. Ecoinvent. Ecoinvent database. Version 3.3 [Internet]. Zurich; 2016 [cited 2017 Jun 6]. Available from: http://www.ecoinvent.ch/
67. NREL NREL. U.S. Life Cycle Inventory Database [Internet]. 2018 [cited 2018 Jun 29]. Available from: https://uslci.lcacommons.gov/uslci/search
68. ANL. GREET [Internet]. *Greenhouse gases, regulated emissions, and energy use in transportation.* Argonne: Argonne National Laboratory; 2020 [cited 2020 Jan 11]. Available from: https://greet.es.anl.gov/
69. ANAC. National Inventory of the atmospheric emissions of civil aviation - Base 2018. Brasilia; 2019.
70. Hillairet F, Allemandou V, Golab K. Analysis of the current development of household UCO collection systems in the EU [Internet]. Coivert; 2016. Available from: https://theicct.org/sites/default/files/publications/Greenea Report Household UCO Collection in the EU_ICCT_20160629.pdf
71. IBGE. Brazilian Institute of Geography and Statistics [Internet]. *SIDRA Database - Consumer Expenditure Survey - POF.* 2019 [cited 2019 Nov 7]. Available from: http://www.sidra.ibge.gov.br/

72. IBGE. Brazilian Institute of Geoghaphy and Statistics [Internet]. *SIDRA Database - Quarterly Survey of Animal Slaughter.* 2020 [cited 2020 Aug 21]. Available from: https://www.ibge.gov.br/en/statistics/economic/agriculture-forestry-and-fishing/21163-first-results-1abate-2.html?=&t=o-que-e
73. Hassuani SJ, Leal MRLV, Macedo I de C. Biomass Power Generation: Sugar Cane Bagasse and Trash. São Paulo; 2005 Mar.
74. Cervi WR, Lamparelli RAC, Seabra JEA, Junginger M, van der Hilst F. Bioelectricity potential from ecologically available sugarcane straw in Brazil: A spatially explicit assessment. *Biomass and Bioenergy [Internet]*. 2019 Mar;122(January):391–9. Available from: https://doi.org/10.1016/j.biombioe.2019.02.001
75. UNICAData. Statistics of Sugarcane Industry Union [Internet]. 2020 [cited 2020 Jul 14]. Available from: http://www.unicadata.com.br/
76. Seabra JEA, Macedo IC. Comparative analysis for power generation and ethanol production from sugarcane residual biomass in Brazil. *Energy Policy.* 2011 Jan;39(1):421–8.
77. Seabra JEA, Macedo IC, Chum HL, Faroni CE, Sarto CA. Life cycle assessment of Brazilian sugarcane products: GHG emissions and energy use. *Biofuels, Bioprod Biorefining [Internet].* 2011 Sep;5(5):519–32. Available from: http://doi.wiley.com/10.1002/bbb.289
78. IBA. Annual Report - Brazilian Tree Industry [Internet]. 2019 [cited 2020 Jul 14]. p. 80. Available from: http://iba.org/images/shared/Biblioteca/IBA_RelatorioAnual2017.pdf
79. ANP. Fuel Prices Survey [Internet]. *National Oil, Natural Gas and Biofuels Agency.* 2020 [cited 2020 Jan 20]. Available from: http://www.anp.gov.br/precos-e-defesa-da-concorrencia/precos?view=default
80. ABM. Seminário de Balanço Energético Global e Utilidades [Internet]. *Seminar on Global Energy Balances and Utiliities.* Belo Horizonte, Brazil: Brazilian Mettalurgy, Materials and Mining Association; 2017 [cited 2019 Oct 20]. Available from: https://www.abmbrasil.com.br/
81. Souza SP, de Ávila MT, Pacca S. Life cycle assessment of sugarcane ethanol and palm oil biodiesel joint production. *Biomass and Bioenergy [Internet]*. 2012 Sep;44:70–9. Available from: https://linkinghub.elsevier.com/retrieve/pii/S0961953412001894
82. U.S.DRIVE. Hydrogen Production Tech Team Roadmap [Internet]. Washington; 2017. Available from: https://www.energy.gov/eere/vehicles/vehicle-technologies-office
83. James B, Colella W, Moton J, Saur G, Ramsden T. PEM Electrolysis H2A Production Case Study Documentation. *PEM Electrolysis H2A Production Case Study Documentation.* Arlington; 2013.
84. Hamrick K, Gallant M. Voluntary Carbon Markets Insights: 2018 Outlook and First-Quarter Trends. Washington; 2018.
85. Donofrio S, Maguire P, Merry W, Zwick S. Financing Emissions Reductions for the Future [Internet]. Washington; 2019. Available from: https://www.ecosystemmarketplace.com/carbon-markets/
86. Hamrick K, Gallant M. Unlocking Potential: State of the Voluntary Carbon Markets 2017 [Internet]. *Forest Trends's Ecosystem Marketplace.* Washington; 2017. Available from: https://www.forest-trends.org/publications/unlocking-potential/
87. Piris-Cabezas P, Lubowski R, Leslie G. Carbon prices under carbon market scenarios consistent with the Paris Agreement: Implications for the Carbon Offsetting and

Reduction Scheme for International Aviation (CORSIA). New York; 2018.
88. UNFCCC. Conference of the Parties [Internet]. *Adoption of a protocol, another legal instrument, or an agreed outcome with legal force under the Convention applicable to all Parties.* Paris; 2015 [cited 2020 Sep 29]. p. 32. Available from: https://unfccc.int/resource/docs/2015/cop21/eng/l09r01.pdf
89. CRFEBio. Centro de Referência da Cadeia de Biocombustíveis para Agricultura Familiar [Internet]. *Biomercado - Cotações Nacionais.* 2020 [cited 2020 Jul 15]. Available from: http://www.biomercado.com.br/
90. ArcellorMittal Tubarão. ArcelorMittal no Espírito Santo [Internet]. Tubarão; 2016. Available from: https://brasil.arcelormittal.com/sala-imprensa/publicacoes-relatorios/
91. Vásquez MC, Martínez A, Castillo EF, Silva EE. Holistic approach for sustainability enhancing of hydrotreated aviation biofuels, through life cycle assessment: A Brazilian case study. *J Clean Prod [Internet]*. 2019 Nov;237(2019):117796. Available from: https://linkinghub.elsevier.com/retrieve/pii/S0959652619326563
92. ICAO. CORSIA Supporting Document: Eligible Fuels – Life Cycle Assessment Methodology [Internet]. Montreal; 2019. Available from: https://www.icao.int/environmental-protection/CORSIA/Documents/CORSIA Supporting Document_CORSIA Eligible Fuels_LCA Methodology.pdf
93. Manzatto CV, Assad ED, Bacca JFM, Zaroni MJ, Pereira SEM. Zoneamento Agroecológico da Cana-de Açúcar. *Documentos 110.* Rio de Janeiro; 2009.
94. Novaes RML, Pazianotto RAA, Brandão M, Alves BJR, May A, Folegatti-Matsuura MIS. Estimating 20-year land-use change and derived CO2 emissions associated with crops, pasture and forestry in Brazil and each of its 27 states. *Glob Chang Biol [Internet].* 2017 Sep 9;23(9):3716–28. Available from: https://onlinelibrary.wiley.com/doi/abs/10.1111/gcb.13708
95. Ramalho Filho A, Motta PEF. Zoneamento Agroecológico, Produção e Manejo para a Cultura da Palma de Óleo na Amazônia. Rio de Janeiro; 2010.
96. IEA. IEA Sankey Diagram [Internet]. 2020 [cited 2020 Jul 25]. Available from: https://www.iea.org/sankey/
97. IEA. CO2 Emissions from Fuel Combustion: Overview [Internet]. Paris; 2020 [cited 2020 Aug 27]. Available from: https://www.iea.org/reports/co2-emissions-from-fuel-combustion-overview
98. Ecosystem Marketplace. Carbon Markets Are Well- Positioned To Meet Corsia Demand Projections [Internet]. *Ecosystem Marketplace Insights Brief.* 2020 [cited 2020 May 14]. p. 8. Available from: https://app.hubspot.com/documents/3298623/view/69866075?accessId=fe65d3
99. Fearnehough H, Warnecke C, Schneider L, Broekhoff D, La Hoz Theuer S. Offset credit supply potential for CORSIA [Internet]. Berlin; 2019. Available from: https://newclimate.org/2019/11/05/offset-credit-supply-potential-for-corsia/
100. Cortez LAB, Nigro FEB, Nassar AM, Cantarella H, Nogueira LAH, Moraes MAFD de, et al. Roadmap for sustainable aviation biofuels for Brazil — A Flightpath to Aviation Biofuels in Brazil [Internet]. São Paulo: Edgard Blücher; 2014. 272 p. Available from: http://openaccess.blucher.com.br/article-list/roadmap-aviation-272/list
101. Augusto Horta Nogueira L, Silva Capaz R. Biofuels in Brazil: Evolution, achievements and perspectives on food security [Internet]. *Vol. 2, Global Food Security.* Elsevier; 2013. p. 117–25. Available from: http://dx.doi.org/10.1016/j.gfs.2013.04.001

102. Brinkman MLJ, da Cunha MP, Heijnen S, Wicke B, Guilhoto JJM, Walter A, et al. Interregional assessment of socio-economic effects of sugarcane ethanol production in Brazil. *Renew Sustain Energy Rev [Internet]*. 2018;88(February):347–62. Available from: https://doi.org/10.1016/j.rser.2018.02.014
103. Capaz RS, Carvalho VSB, Nogueira LAH. Impact of mechanization and previous burning reduction on GHG emissions of sugarcane harvesting operations in Brazil. *Appl Energy [Internet]*. 2013 Feb;102:220–8. Available from: https://linkinghub.elsevier.com/retrieve/pii/S0306261912006903
104. Ellis J, Winkler H, Corfee-Morlot J, Gagnon-Lebrun F. CDM: Taking stock and looking forward. *Energy Policy [Internet]*. 2007 Jan;35(1):15–28. Available from: https://linkinghub.elsevier.com/retrieve/pii/S030142150500248X
105. Boyd E, Hultman N, Timmons Roberts J, Corbera E, Cole J, Bozmoski A, et al. Reforming the CDM for sustainable development: lessons learned and policy futures. *Environ Sci Policy [Internet]*. 2009 Nov;12(7):820–31. Available from: https://linkinghub.elsevier.com/retrieve/pii/S1462901109000847
106. Subbarao S, Lloyd B. Can the Clean Development Mechanism (CDM) deliver? *Energy Policy [Internet]*. 2011 Mar;39(3):1600–11. Available from: http://dx.doi.org/10.1016/j.enpol.2010.12.036
107. Cormier A, Bellassen V. The risks of CDM projects: How did only 30% of expected credits come through? *Energy Policy [Internet]*. 2013 Mar;54:173–83. Available from: http://dx.doi.org/10.1016/j.enpol.2012.11.016
108. Michaelowa A, Shishlov I, Brescia D. Evolution of international carbon markets: lessons for the Paris Agreement. *Wiley Interdiscip Rev Clim Chang [Internet]*. 2019 Nov 16;10(6). Available from: https://onlinelibrary.wiley.com/doi/abs/10.1002/wcc.613
109. Benites-Lazaro LL, Andrade C. Clean Development Mechanism: Key Lessons and Challenges in Mitigating Climate Change and Achieving Sustainable Development. *In: Reference Module in Earth Systems and Environmental Sciences [Internet]*. Elsevier; 2019. Available from: https://linkinghub.elsevier.com/retrieve/pii/B9780124095489118639
110. Frangetto FW, Veiga APB, Luedemann G. Legacy of the CDM: lessons learned and impacts from the Clean Development Mechanism in Brazil as insights for new mechanisms [Internet]. *IPEA, editor.* Brasilia; 2019. 417 p. Available from: http://www.ipea.gov.br/portal/publicacoes
111. Nylander J. Carbon trading in a Paris Agreement [Internet]. Stockholm, SE; 2015. Available from: https://fores.se/wp-content/uploads/2015/10/Carbontrading-Paris-Nylander-webb.pdf
112. Michaelowa A, Hoch S. How to transition from the CDM to the Sustainable Development. *Carbon Mech Rev.* 2016;(1):28–31.
113. Michaelowa A. The Paris market mechanisms' contribution to global greenhouse gas mitigation: complementarities and tensions between article 6.2 and article 6.4. *In: Stavins RN, Stowe RC, editors. Market Mechanisms and the Paris Agreement.* Cambridge: Harvard College; 2017. p. 63–6.
114. UNFCCC. Clean Development Mechanism - Methodological tool Tool for the demonstration and assessment of additionality Version 07.0.0. 2014.
115. Cames M, Harthan RO, Füssler J, Lazarus M, Lee CM, Erickson P, et al. How additional is the Clean Development Mechanism? [Internet]. Berlin; 2016. Available from:

https://ec.europa.eu/clima/sites/clima/files/ets/docs/clean_dev_mechanism_en.pdf
116. BRAZIL. Law 13.576 - 26 December 2017 [Internet]. *National Policy of Biofuels (Renovabio).* Brazil; 2017 [cited 2019 May 24]. Available from: http://www.planalto.gov.br/ccivil_03/_ato2015-2018/2017/lei/L13576.htm
117. Chiappini G. Preços dos créditos de carbono do RenovaBio ainda são incertos [Internet]. *EPBR.* 2019 [cited 2020 Jul 15]. Available from: https://epbr.com.br/precos-do-creditos-de-carbono-do-renovabio-ainda-sao-incertos/
118. ANP. RenovaCalcMD: Método e ferramenta para a contabilidade da Intensidade de Carbono de Biocombustíveis no Programa RenovaBio [Internet]. *National Agency of Petroleum Natural Gas and Biofuels - Renovacalc.* 2018 [cited 2020 Feb 16]. Available from: http://www.anp.gov.br/images/Consultas_publicas/2018/n10/CP10-2018_Nota-Tecnica-Renova-Calc.pdf
119. USA. Energy Policy Act [Internet]. United States of America; 2005. Available from: https://www.congress.gov/109/plaws/publ58/PLAW-109publ58.pdf
120. USA. Energy Independence and Security Act of 2007 [Internet]. United Stated of America; 2007. Available from: https://www.govinfo.gov/content/pkg/PLAW-110publ140/pdf/PLAW-110publ140.pdf
121. U.S.DOE. Renewable Identification Numbers [Internet]. *Alternative Fuel Data Center - Laws and Incentives.* [cited 2020 Jun 22]. Available from: https://afdc.energy.gov/laws/RIN.html
122. U.S. EPA. Approved Pathways for Renewable Fuel. *Renewable Fuel Standard Program.* 2020.
123. U.S. EPA. Rin Trades and Prices Information [Internet]. 2020 [cited 2020 Jul 15]. Available from: https://www.epa.gov/fuels-registration-reporting-and-compliance-help/rin-trades-and-price-information
124. CARB. Low Carbon Fuel Standard [Internet]. *California Air Resources Board.* 2020 [cited 2020 Aug 20]. Available from: https://ww2.arb.ca.gov/our-work/programs/low-carbon-fuel-standard
125. CARB. Monthly LCFS Credit Transfer Activity Reports [Internet]. *Credit trading activity reports.* 2020 [cited 2020 Aug 20]. Available from: https://ww3.arb.ca.gov/fuels/lcfs/credit/lrtmonthlycreditreports.htm
126. EPE. National Energy Balance [Internet]. Brasilia; 2020 [cited 2019 Oct 26]. Available from: https://ben.epe.gov.br/BENSeriesCompletas.aspx
127. Seabra JEA, Tao L, Chum HL, Macedo IC. A techno-economic evaluation of the effects of centralized cellulosic ethanol and co-products refinery options with sugarcane mill clustering. *Biomass and Bioenergy [Internet].* 2010;34(8):1065–78. Available from: http://dx.doi.org/10.1016/j.biombioe.2010.01.042
128. ECN. Database for biomass and waste [Internet]. 2018 [cited 2017 Jun 12]. Available from: https://phyllis.nl/
129. LanzaTech. Syngas to Fuels and Chemicals: Closing the Loop [Internet]. 2019 [cited 2020 Mar 21]. Available from: https://arpa-e.energy.gov/sites/default/files/2.2_Haynes_LanzaTech.pdf
130. Salardani LSF, Albuquerque LP, da Costa JMJ, da Silva WB, Dutra JCS. Particle filter-based monitoring scheme for simulated bio-ethylene production process. *Inverse Probl Sci Eng [Internet].* 2019 May 4;27(5):648–68. Available from: https://doi.org/10.1080/17415977.2018.1493726
131. ESALQ-LOG. Yearbooks [Internet]. *Group of Research and Extension in Agroindustrial Logistics.* 2020 [cited 2020 May 30]. Available from:

https://esalqlog.esalq.usp.br/en/category/yearbooks
132. Axelsson L, Franzén M, Ostwald M, Berndes G, Lakshmi G, Ravindranath NH. Perspective: Jatropha cultivation in southern India: Assessing farmers' experiences. *Biofuels, Bioprod Biorefining.* 2012;6(3):246–56.
133. SIFRECA. System of Freight Information [Internet]. *Mensal indicators.* 2020 [cited 2020 May 20]. Available from: https://sifreca.esalq.usp.br/
134. Françoso RF, Bigaton A, Silva HJT da, Marques PV. Relação do custo de transporte da cana-de-açúcar em função da distância. *Rev iPecege [Internet].* 2017 Feb 16;3(1):100. Available from: https://revista.ipecege.org.br/Revista/article/view/123
135. NovaCana Website. GranBio starts production of second generation ethanol [Internet]. 2014 [cited 2020 Jul 9]. Available from: https://www.novacana.com/n/etanol/2-geracao-celulose/granbio-producao-etanol-segunda-geracao-240914
136. Hoffmann BS, Szklo A, Schaeffer R. An evaluation of the techno-economic potential of co-firing coal with woody biomass in thermal power plants in the south of Brazil. *Biomass and Bioenergy [Internet].* 2012 Oct;45:295–302. Available from: http://dx.doi.org/10.1016/j.biombioe.2012.06.016
137. de Medeiros EM, Noorman H, Maciel Filho R, Posada JA. Production of ethanol fuel via syngas fermentation: Optimization of economic performance and energy efficiency. *Chem Eng Sci X [Internet].* 2020 Jan;5:100056. Available from: https://linkinghub.elsevier.com/retrieve/pii/S2590140020300022

4 Environmental trade-offs of renewable jet fuels in Brazil: beyond the carbon footprint

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It is worth mentioning that, in this chapter, the *alternative jet fuel* (AJF) was referred to as *renewable jet fuel (RJF)*, according to the suggestion of the journal's editor.

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Abstract:

The use of renewable jet fuels (RJFs) is an option for meeting the greenhouse gases (GHG) reduction targets of the aviation sector. Therefore, most of the studies have focused on climate change indicators, but other environmental impacts have been disregarded. In this paper, an attributional life cycle assessment is performed for ten RJF pathways in Brazil, considering the environmental trade-offs between climate change and seven other categories, *i.e.,* fossil depletion, terrestrial acidification, eutrophication, human and environmental toxicity, and air quality-related categories, such as particulate matter and photochemical oxidant formation. The scope includes sugarcane and soybean for first-generation (1G) pathways and residual materials (wood and sugarcane residues, beef tallow, and used cooking oil-UCO) for second-generation (2G) pathways. Three certified technologies to produce RJF are considered: hydroprocessed esters and fatty acids (HEFA), alcohol-to-jet (ATJ), and Fischer-Tropsch (FT). Assuming the residual feedstocks as wastes or by-products, the 2G pathways are evaluated by two different approaches, in which the biomass sourcing processes are either accounted for or not. Results show that 1G pathways lead to significant GHG reductions compared to fossil kerosene from 55% (soybean/HEFA) to 65% (sugarcane/ATJ). However, the sugarcane-based pathway generated three-fold higher values than fossil kerosene for terrestrial acidification and air quality impacts, and seven-fold for eutrophication. In turn, soybean/HEFA caused five-fold higher levels of human toxicity. For 2G pathways, when the residual feedstock is assumed to be waste, the potential GHG emission reduction is over 74% with no relevant trade-offs. On the other hand, if the residual feedstocks are assumed as valuable by-products, tallow/HEFA becomes the worst option and pathways from sugarcane residues, even providing a GHG reduction of 67% to 94%, are related to higher impacts than soybean/HEFA for terrestrial acidification and air quality. FT pathways represent the lowest impacts for all categories within both approaches, followed by UCO/HEFA.

Keywords: environmental trade-offs; life cycle assessment; aviation biofuels; sugarcane; soybean; residual feedstocks.

4.1. Introduction

The international civil aviation sector has set ambitious targets to achieve carbon-neutral growth from 2020 and reduce its greenhouse gas (GHG) emissions by 50% by 2050 relative to 2005 levels[1]. The renewable jet fuels (RJFs) are an important means of achieving these targets[2], being used as drop-in fuels blended with fossil kerosene. The technologies used to produce RJFs fall into three groups[3]: lipid conversion[4], thermochemical[5], and biochemical processes[6,7]. From these three groups, five technologies have been approved by the ASTM[8] with different blending restrictions: hydrotreating oil-based feedstocks (hydroprocessed esters and fatty acids, HEFA), dehydration and oligomerization of iso-butanol or ethanol (alcohol-to-jet, ATJ), direct conversion of sugar to hydrocarbons (DCSH), and the Fischer-Tropsch (FT) process.

According to Dodd[9], more than 140 thousand commercial flights have been supplied by RJF since 2011. It corresponds to a sharp increase of RJF production, which achieved 13 million liters in 2018, and accounts for 6 billion liters in future purchased agreements. However, an accelerated deployment of sustainable biofuels is required to reach low carbon scenarios in the coming decades[10], with competitive costs and meeting sustainability standards. In this context, Brazil is considered as a potential supplier of RJF because of its large biomass production and technical experience in bioenergy[3]. Currently, sugarcane ethanol represents almost 20% of the country's road transport fuel consumption, while biodiesel, mostly from soybean oil, accounts for 10% of diesel consumption[11]. At the same time, the use of residues, such as crop residues and waste greases, as energy source is already in place in Brazil. These promising feedstocks are well accepted as GHG mitigation strategy due to no relevant concerns related to land use change (LUCs) and food competition aspects[12,13]. For example, sugarcane bagasse supplies around 6% of Brazil's electricity demand (*i.e.*, 35 GWh) and waste greases, such as used cooking oil (UCO) and beef tallow, represents 18% of Brazilian biodiesel production[11]. Furthermore, the 33.5 million tons of wood residue available in 7.7 million ha of planted forests[14], along with bagasse surplus and sugarcane cane straw, are potentially relevant feedstocks for bioenergy production in Brazil, including RJF.

With respect to the environmental performance of products, the life cycle assessment (LCA) has been a frequently employed tool for the evaluation of different environmental impact categories[15,16]. Specifically for the aviation industry, the GHG reduction potential of several RJF pathways has been widely reported in the literature[7,17–22] due to the current sectorial goals However, the environmental effects and the possible trade-offs between different environmental impact categories along the RJF life cycle remain rather unexplored Staples *et al.*[23] evaluated the water footprint of middle distillate fuels in the United States. In Australia, Cox *et al.*[24] reported the environmental performance of RJF from microalgae, Pongamia oil, and sugarcane molasses by eutrophication, water, land, and fossil energy use. In turn, Li and Mupondwa[25] evaluated the jet fuel and biodiesel from camelina oil in Canadian Praires under endpoint impact categories, such as global warming potential, human health, ecosystem quality, and energy resource consumption. On the other hand, Klein *et al.*[17] discussed the benefits of different routes for producing RJF by integrated designs to sugarcane mills in Brazil, considering environmental aspects related to human toxicity, terrestrial acidification, agricultural land occupation, fossil depletion, and climate change. Finally, Cavalett and Cherubini[21] analyzed RJF production from forest residues in Norway for climate change mitigation and other environmental issues, which are embraced within the context of the Sustainable Development Goals (SDGs)[26].

Even so, these analyses are scope-limited by either considering few categories or a small number of technical options, making it difficult to assess the environmental trade-offs of RJF production in different technical contexts.

In this sense, this paper aims to contribute to this research gap carrying out a harmonized and detailed LCA of ten strategic RJF pathways in Brazilian conditions and pointing out the possible trade-offs between the different impact categories. The pathways, which were represented by literature, modeling, first hand-data, and local-specific life cycle inventories, comprised three ASTM-approved jet fuel-technologies (HEFA, ATJ, and FT) and six different feedstocks. The production systems were categorized as first-generation (1G) pathways – *i.e.*, food-based feedstocks, such as soybean oil and sugarcane – and second-generation (2G) pathways, *i.e.*, residue-based feedstocks, such as beef tallow, UCO, sugarcane residues and forestry residues, which were compared with each other and with fossil kerosene (Jet A).

4.2. Methods

The LCA was carried out considering the following steps, as recommended by the ISO[27].

4.2.1. Goal and scope definition

A *well-to-wake* analysis – *i.e.*, from feedstock production to RJF use in aircraft – was performed by attributional approach, which focuses on the environmentally-relevant physical flows described by averaged data to and from the product-system [28]. The functional unit was 1.0 MJ_{RJF} of energy supplied to aircraft.

System boundaries

The product-system for each RJF pathway was depicted in four stages, as presented in **Figure 4.1** and detailed in **section 4.2.2**. The "upstream stage" is related to the feedstock sourcing and its treatment (*e.g.*, agricultural processes, feedstock collection, cattle management, and slaughterhouse). The "midstream stage" refers to feedstock processing into intermediary products for RJF conversion, which takes place at the "downstream stage". Finally, the "use stage" involves RJF combustion in aircraft engines. The transportation between each stage is also considered. Jet A is used as the benchmark for comparative purposes.

Notwithstanding the environmentally sound appeal of using waste as a feedstock, it is frequently argued that whether such materials should still be regarded as waste as their utilization gains relevance, while, in some instances, alternative uses may already be in place. In the face of the rather arbitrary definitions around waste and by-products, two different approaches were considered for the residue-based pathways.

In System 1 (S1), residual feedstocks are deemed as waste, hence sugarcane and wood residues, beef tallow, and UCO do not carry a burden related to their generation. This approach has already been applied in low-carbon policies – such as the Renewable Energy Directive[13] in Europe and the Renovabio in Brazil[29]. The methodology of the Renewable Fuel Standard program[30] in the United States accounts for only the environmental burdens of the upstream stages related to nutrient compensation due to the crop residues' removal from the field and those related to the rendering process for tallow. Here, nutrient compensation was considered as a consequence of a decision, then it is not accounted for within a strict attributional approach. For tallow-based pathways, the rendering plant was assumed to be attached and integrated into the slaughterhouse, as is usually the case in Brazil [31]. Hence, no burdens were considered for this pathway in the upstream stage of S1. Finally, UCO was treated as an end-of-life product, *i.e.,* product at the end of its useful life that could potentially undergo reuse, recycling, or recovery[28]. Therefore, no upstream burden was included.

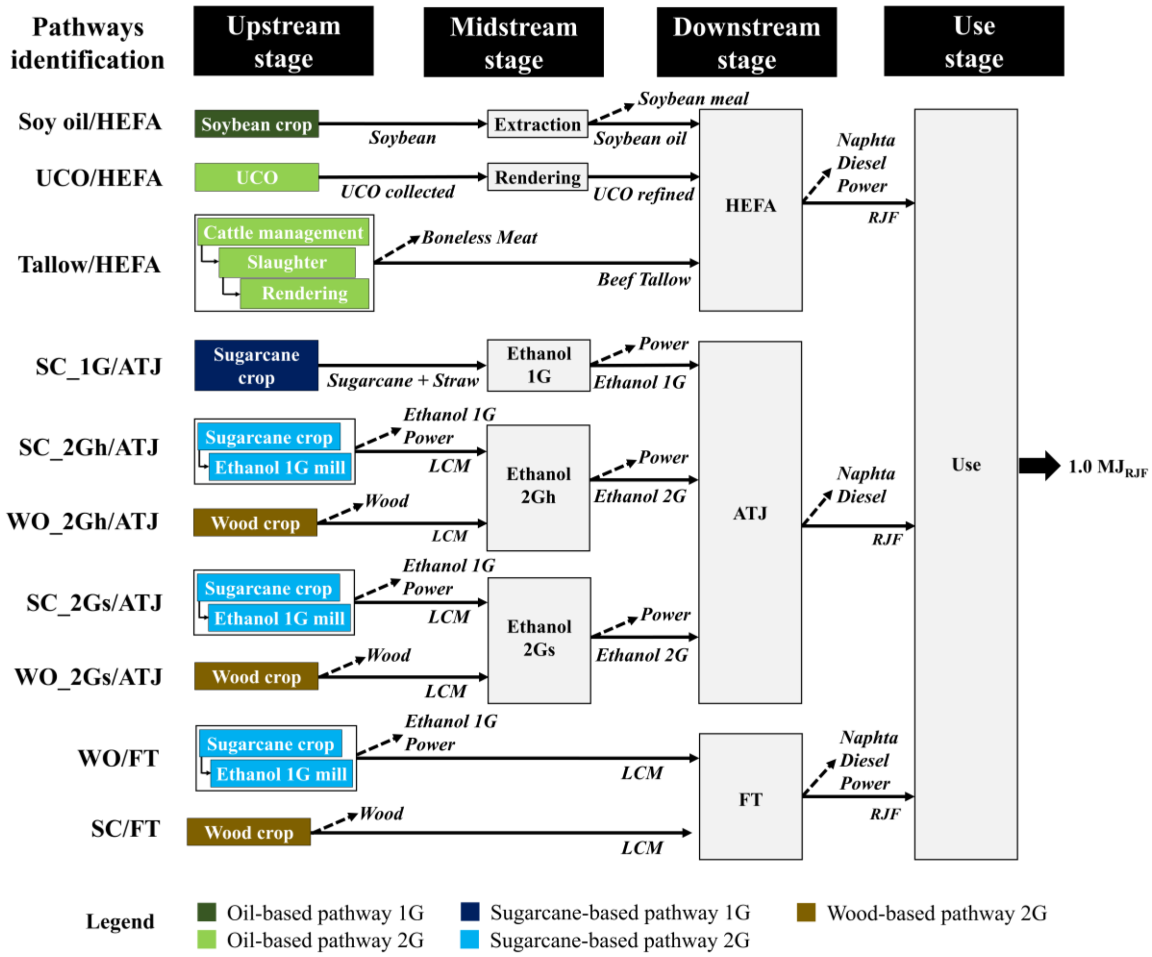


Figure 4.1: Life Cycle stages for RJF production. Feedstocks: UCO, used cooking oil; SC, sugarcane; LCM: lignocellulosic material. Midstream stage: 1G, first-generation ethanol mill; 2Gh: second-generation ethanol mill from enzymatic hydrolysis; and 2Gs: second-generation ethanol mill from syngas fermentation. Downstream stage: HEFA, Hydroprocessed esters and fatty acids; ATJ, Alcohol-to-Jet; and FT: Fisher-Tropsch. Dotted lines for by-products.

On the other hand, System 2 (S2) treats the residual feedstock as a valuable product from the upstream stage, considering the increasing use and market for biomass residues. According to the JCR[28], "if the market value of the waste/end-of-life product at its point of origin is above zero, in the LCA perspective it would be considered as a co-product, and the multifunctionality is to be solved by allocation." Likewise, the Roundtable on Sustainable

Biomaterials[32] methodology uses this approach when the economic value of an output is greater than 5% of the total value of the other products generated in the same production process[32]. This approach has also been adopted in some LCA studies for lignocellulosic ethanol[33] and RJF from tallow[22].

As cut-off criteria, the environmental burden related to the production and assembling of machinery and processing equipment, as well as building construction, 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.

Allocation procedures

The environmental burdens of each life cycle stage were partitioned among the multi-products as represented in **Figure 4.1**, which is a more consistent approach for cause-oriented analyses, such as attributional studies[28,34]. In this study, economic allocation was applied as a default method, *i.e.*, the partitioning was based on the market prices of each product. The allocation factors are presented in Supplementary Material (**Table SM.2**), from the values informed in **Table SM.1.**

Land use change (LUC)

One of the motivations to use residual feedstocks for biofuel production is that, presumably, there would not be any additional land requirements. As a matter of fact, direct and indirect LUC (dLUC and iLUC) – which accounts for the carbon emissions from the conversion of the original land use and rebound effects in other locations, respectively – have been raised as a concern for biofuel production in general.

Despite the relevant influence of the LUC on GHG emissions[6,7,20,35], LUC impacts were not accounted for. Given the methodological approach used here (attributional LCA), the present study focuses on the environmental performance of each RJF pathway rather than evaluating the consequences outside of the system boundaries. Then iLUC would be out of the scope. In turn, dLUC was not also considered, since deforestation for the production of biofuels is very unlikely in Brazil due to the current legislation in the country (*e.g.*, Forest Code[36] and RenovaBio[29]) as well as the international sustainability requirements on biofuels (*e.g.*, CORSIA[37] and European's Renewable Energy Directive[13]). Nevertheless, the conversion of croplands and pasturelands may still lead to relevant carbon emissions or sequestration, which must be addressed on case by case basis.

Environmental impact categories

The life cycle impact assessment was performed according to the ReCiPe (H) midpoint method v.1.13 [38] and included the following categories: climate change, terrestrial acidification, eutrophication, human and environmental toxicities, photochemical oxidant formation, particulate matter formation, and fossil fuel depletion. Here, the results for eutrophication category corresponds to the sum of freshwater and marine eutrophication values. Likewise, results for freshwater, marine, and terrestrial toxicity are combined in environmental toxicity category.

Database

The foreground systems were assembled using primary, secondary, and modeled data, as indicated in **section 4.2.2**. For the background systems (*e.g.*, production of chemicals and utilities), inventories were taken from Ecoinvent v3.3 [39], USCLI [40], and GREET databases[41] and adapted to the Brazilian context whenever possible. SimaPro 8.3® (PRé-Sustainability, The Netherlands) was used as an auxiliary tool for the analysis.

4.2.2. Life cycle inventory (LCI)

Upstream stage

Among the oil-based pathways, the soybean production and harvesting conditions are fully described in **Table SM.5**, adapted from SICV[42] and based on 2012-2014 averaged data for Mato Grosso State, which is the major Brazilian producer[43].

The upstream stages for beef tallow production comprise the cattle management, slaughter, beef production, and rendering process. The full description of the LCI under Brazilian conditions was adapted from Sousa *et al.*[31] and available in **Table SM.6**. According to them, for simplification purposes, boneless meat and beef tallow are the only products considered at the slaughterhouse, while leather, edible offal, blood, and condemned parts were considered wastes.

The agricultural stage of the sugarcane-based pathways was described according to the *Virtual Sugarcane Biorefinery (VSB)* tool[44] from averaged data of São Paulo State, which is the current major Brazilian producer[43]. The *VSB* model covers the whole supply chain of Brazilian sugarcane with validated data. A complete mechanized harvesting process was assumed with 50% recovery of straw by bailing/loading systems and the agricultural use of vinasse and filter-cake returned from ethanol distillery (see **Table SM.7**). A general description and the main aspects found in VSB are presented in Bonomi *et al.*[33].

The sugarcane residue-based pathways, *i.e.,* via 2G-ethanol and Fisher-Tropsch (FT) were modeled considering a mix of bagasse and straw as feedstock. This material is provided by an optimized 1G autonomous mill[33], which burns only the amount of biomass required to supply its steam demand. Hence, the upstream stage is composed of the sugarcane cultivation and harvesting and 1G-ethanol mill. A detailed LCI is presented in the Supplementary Material. (**Table SM.8**).

Finally, for the pathways involving wood residues, the upstream inventory was based on a Brazilian company that manufactures cellulose and paper from eucalyptus. The LCI represents the common practices for this crop[45], listed in **Table SM.9**. The branches, top, and bark are chopped by a diesel-electric machine in a "full-tree" harvesting operation and transported to the plant.

Midstream stage

At this stage, only soybean extraction, UCO rendering, and the production of hydrated ethanol were considered. Soybean oil extraction using hexane was described by Sugawara[46] and the corresponding LCI is provided in **Table SM.10**. The LCI for collecting and rendering UCO is based on Seber *et al.*[22] (**Table SM.11**).

For the sugarcane-based pathways, via 1G ethanol, an optimized autonomous mill was considered, as represented by the *VSB* [33,44] and adjusted to produce hydrated ethanol. A detailed LCI is in **Table SM.12**.

The 2G processes from sugarcane residues were modeled as stand-alone plants – *i.e.,* physically separated from the 1G process, to allow for an independent evaluation – considering two different technologies: enzymatic hydrolysis (2Gh) and gasification of lignocellulosic material with subsequent syngas fermentation (2Gs). The former is based on an advanced 2G technology, as described by the *VSB* models[33,44], and further adjusted to produce hydrated ethanol. The *VSB* model considers that solid residues (*i.e.*, cellulignin) are used as an energy source in the Combined Heat and Power (CHP) system. The industrial effluents, such as vinasse and pre-treatment flash, could alternatively be used for biogas production, as suggested by Humbird *et al.*[47]. However, the presence of inhibitory agents, such as phenolic compounds, may cause difficulties in the biodigestion of stillage [48,49], but this was not considered as an obstacle for its application on the field, as suggested by [44]. Detailed LCIs for sugarcane and wood residues are available in **Table SM.13** and **Table SM.16**, respectively. For wood residues, the 2Gh models in *VSB* were adapted to the composition presented in **Table SM.3**. Furthermore, the production process of the enzyme was based on Da Silva *et al.*[50] considering the sugar input from an optimized annexed ethanol mill[33], as presented in **Table SM.14**.

The pathways from syngas fermentation were based on the models developed by de Medeiros *et al.*[51] and adapted to the composition of both biomass sources, sugarcane residues and wood residues (for details, see **Table SM.13**). The process modeling considers steam generation by heat recovered from hot gases and power generation from unreacted syngas. The syngas fermentation parameters and liquid media composition are in line with those of Gaddy *et al.*[52]. The make-up media nutrients for syngas fermentation were simplified to account for the most relevant components, which are also available in Ecoinvent database[39]. The wastewater leaving the process is assumed to undergo treatment before disposal or reuse, and the ashes from the gasification process are returned to the field to be used as fertilizers. Detailed LCIs are gathered in **Table SM.15** for sugarcane residues and **Table SM.17** for wood residues.

The main overall yields related to the upstream and midstream processes, for all pathways depicted in **Figure 4.1**, are presented in **Table SM.18**.

Downstream stage

Three certified technologies, according to ASTM[8], were considered for RJF production, whose LCIs were mostly based on the modeling performed by Klein *et al.*[17], with some adaptations, as described below. A major difference from Klein *et al.*[17] is that the hydrogen is supplied by an external plant (*i.e.,* the H_2 production system is outside of the system's boundaries), except for the FT process in which hydrogen is produced internally via gasification.

Here, the HEFA model considered the self-supply of utilities by the internal burning of light streams (*e.g.,* propane), which are produced at 102 kg/t_{oil}[53]. This differs from Pearlson[4] who reported external power and natural gas inputs and the light stream outputs. The airborne emissions were considered similar to the liquefied petroleum gases in an industrial boiler[41], assuming biogenic carbon. The wastewater undergoes treatment before disposal or reuse.

For the UCO pathway, the conversion performance was assumed to be similar to soybean oil in HEFA technology – as also assumed by Seber *et al.*[22] and de Jong *et al.*[18] – because of the high consumption of soybean oil in Brazilian cuisine, *i.e.,* around 90% of vegetable oil consumed in 2008 [54]. This assumption was deemed appropriate for the scope of this study, although the influence of UCO composition on HEFA yields should be further investigated. On the other hand, it is reasonable to suppose that the use of UCO for RJF production in large scales would not be feasible because of the constraints related to the logistics of its collection. In this sense, UCO is expected to be used as a co-feedstock with other oil-based materials, hence lowering the influence of its composition on the overall industrial yields.

However, for beef tallow, the hydrogen demand was adjusted according to Pearlson[4] and Klein *et al.*[17] and considering the different compositions of the feedstock [55]. Utilities and conversion yields for the tallow-based pathway were kept the same as reported by Klein *et al.*[17].

In ATJ technology, the steam demand is supplied by burning light hydrocarbons produced throughout the process (around 146 kg/$t_{ethanol}$), according to Klein *et al.*[17] and Klein[53]. The wastewater was also assumed as properly treated without environmental burden to the reference flow.

Finally, the FT process was also based on Klein *et al.*[17] and considered sugarcane residues and eucalyptus as feedstocks, on-site hydrogen production, and the use of light hydrocarbons (around 3.2 kg/$t_{lignocellulosic\_material}$) as self-energy source. For practical purposes, the conversion yields from eucalyptus were assumed to be the same as eucalyptus residues. Wastewater treatment was also assumed, as no additional environmental burdens to the system occur.

The overall yields and hydrogen input of the processes within RJF conversion processes are summarized in **Table SM.19**.

The LCI for hydrogen production was based on a Brazilian company[56], assuming steam methane reform (SMR) with a platinum catalyst. A detailed inventory can be found in **Table SM.20**.

Transportation and use

One-way distance was considered to evaluate transportation stage. In oil-based pathways, the distance between the soybean crop in Mato Grosso State to the extraction plant (Midstream) was set at 400 km. Collection and transportation of UCO to the rendering plant were set at 50 km, based on the average distance for recyclables collection by two cooperative units in a medium-sized city in Brazil[57]. For sugarcane-based pathways, an average distance of 36 km was assumed to transport straw and stalks to the ethanol mill[44] or FT plant. For wood-based pathways, this distance was defined as 40 km, which corresponds to the current economically feasible value to collect wood residues for use as an energy source[45].

A default distance of midstream and slaughterhouse to downstream was set at 400 km. This considered possible values between a rendering plant, an extraction plant, or an ethanol distillery to the RJF plant, which was assumed to be near an oil refinery in São Paulo State.

Likewise, to supply the airport, 200 km was set for all pathways, which corresponds to the weighted distance between the three major Brazilian refineries of Jet A production — *i.e.,* REVAP (São Paulo State), REPLAN (São Paulo State), and REDUC (Rio de Janeiro State)[58] — to Guarulhos International Airport that is responsible for around 30% of kerosene consumption in Brazil[58]. Specifically, for the FT pathways, with no midstream processes, a one-way distance of 600 km between the FT plant and the airport was assumed.

Transportation was considered to be entirely based on heavy trucks that meet the EUR04 emission standards[39]. This inventory was adapted to the most commonly diesel consumed in Brazil and the current biodiesel blend (B10). Diesel S500, *i.e.*, with 500 ppm of sulfur content, corresponded to around 70% of the diesel consumed in Brazil in 2016, but the current efforts for S10 expansion is expected to decrease S500 contribution to 42% in 2026 [59]. For biodiesel, it was assumed that 82%, on average, of Brazilian biodiesel is derived from soybean oil and 18% from tallow[58]. The inventories related to biodiesel production were reported by Sousa *et al.*[31] and Sugawara[46], while the airborne emissions from its use were adjusted considering: no sulfur, 20% increase of nitrogen dioxides, and decreases of 75%, 15%, and 40% for hydrocarbons, particulates, and carbon monoxide, respectively, as reported by the EPA[60].

Finally, the emissions related to RJF use were assumed similar to a typical aircraft operation in an intracontinental trip, as reported by Ecoinvent[39], with the following adjustments: reduction of 2% and 5% in carbon dioxide and nitrogen oxide emissions, respectively, due to lower heating, cetane number, and density of RJF in comparison with fossil kerosene; increase of 11% in water emissions; and no emissions of particulate matter and sulfur. The carbon emissions from RJF use were considered biogenic. These adjustments were made according to Moore *et al.*[61], Stratton *et al.*[62], Donohoo[63], and Cavalett and Cherubini[21] (**Table SM.22**).

Fossil kerosene (Jet A)

The fossil kerosene production was assumed to be similar to a typical oil refinery in the United States[40], as suggested by Sugawara[46]. The split of the multiple oil-products was adapted to the average production profile 2007-2017 of the three major Brazilian refineries: REVAP, REPLAN, and REDUC[58], which are responsible for around 40% of Brazilian oil products. The extraction of crude oil was taken from Ecoinvent[39] and adapted to Brazilian conditions, as described in **Table SM.23**. The transportation of Jet A between refinery and airport was set in 200 km (one-way) by the same assumptions presented previously.

4.2.3. Uncertainty and Sensitivity analysis

The uncertainties of the model and the significance of the results were assessed through a Monte Carlo analysis with 1000 trials. The parameter distributions related to the foreground systems were based on the original databases and adaptations from similar inventories in the literature. When data was not available, uncertainties were estimated according to the Pedigree Matrix[64,65]. All the assumptions and uncertainty data for the 44 parameters considered here for the foreground systems are indicated in **Table SM.4A**. For the background systems, it was assumed the uncertainty data already available on the Ecoinvent database [39].

Additionally, the sensitivity of the environmental trade-offs with respect to relevant parameters and methodological choices were evaluated as well. Conversion yields were varied according to the ranges reported in the literature (**Table SM.4B**). Given the relevance of the hydrogen supply for most pathways, the alternative route based on water electrolysis (WE) was also investigated, whose inventory is available in **Table SM.24**. The effect of different locations of the conversion plants with respect to the biomass sources and airports was assessed through a ±50% allowance on transportation distances, except for the transportation of sugarcane and wood residues to the ethanol plant, which are already a well-established in the country[33,45]. As for the methodological choices, the effect of energy-based allocation (instead of economic allocation) was analyzed, following the parameters given in **Table SM.2**.

4.3. Results and Discussion

This section is divided into four parts: in the first, the pathways are analyzed per impact category, considering the contribution of each life cycle stage; subsequently, the combination of these results are analyzed per pathway, when trade-offs between the climate change and the other impact categories are discussed; in the third part, a sensitivity analysis is carried out; and finally, the environmental impacts estimated here are compared to other reports from the literature.

4.3.1. Environmental impacts assessment of RJF

In general, RJF from 1G pathways (*i.e.*, Soy oil/HEFA and SC_1G/ATJ) lead to higher impacts along its life cycle than 2G pathways at S1 (*i.e.*, waste-based pathways), mainly due to the environmental burden related to the upstream stage. On the other hand, the opposite is observed in some cases when the residual feedstock is assumed to be a valuable by-product (S2). The results are presented in **Figure 4.2**. **Table SM.26** in Supporting Information presents the contribution of each stage and related activities, which supports specific investigations.

Specifically at S2, the pathways based on sugarcane residues present higher values than wood residues-based ones in all impact categories. It is justified by the different system boundaries of wood and sugarcane residues (see **Figure 4.1**), and different allocation factors (see **Table SM.2**). Furthermore, sugarcane crop presents a relative higher environmental impacts than wood crop. In other words, while at S1, the "upstream" of wood residues comprises only their collection and transport operations, no burden is allocated for sugarcane residues, which is assumed to be totally carried by ethanol. Otherwise, at S2, the wood residues take up 7.0% of the burden related to the eucalyptus crop by economic allocation and sugarcane residues bear 15% of the total burden estimated for the sugarcane crop and ethanol mill.

In turn, FT pathways tend to present the best environmental performance of all categories for the S1 and S2 approaches, even with the lowest overall yield (56 and 59 g RJF/kg $feed_{(db)}$ for sugarcane and wood residues, respectively) compared to other lignocellulosic-based processes, such as 77 - 59 g RJF/kg $feed_{(db)}$ for enzymatic hydrolysis (2Gh) and 71 - 64 g RJF/kg $feed_{(db)}$ for syngas fermentation (2Gs). FT pathways do not require a midstream stage and their downstream stage is self-supplied with hydrogen and utilities, which explains their environmental performance.

Regarding specific impact categories, around half of the GHG emissions related to RJFs from the 1G pathways (see **Figure 4.2.A**) are associated with the upstream stage and can be explained by the combined effect of the use of nitrogen fertilizers (2.1% and 13.5% of the total GHG emissions for Soy oil/HEFA and SC_1G/ATJ, respectively), emissions from crops and industrial residues on the fields (22% and 9.8%), and diesel use in agricultural operations and input transportation (around 10% for both pathways). However, for 2G pathways when the upstream stage is taken into consideration (S2), GHG emissions reach 3.1 in WO/FT to 150 g CO_{2e}/MJ in tallow/HEFA. For the latter, the methane from the enteric digestion of cattle (4.6 kg CH_4/MJ_{RJF}) is responsible for around 70% of the GHG emissions assigned to the feedstock, even assuming a low allocation factor for tallow (3%) at the slaughterhouse gate.

The midstream stage is relevant in 2Gh pathways and corresponds to around half of the total GHG emissions at S1, *i.e.*, 11 g CO_{2e}/MJ. In this case, enzyme use, which demands natural gas and sugar for its production, is responsible for 25% of the total emissions of these pathways.

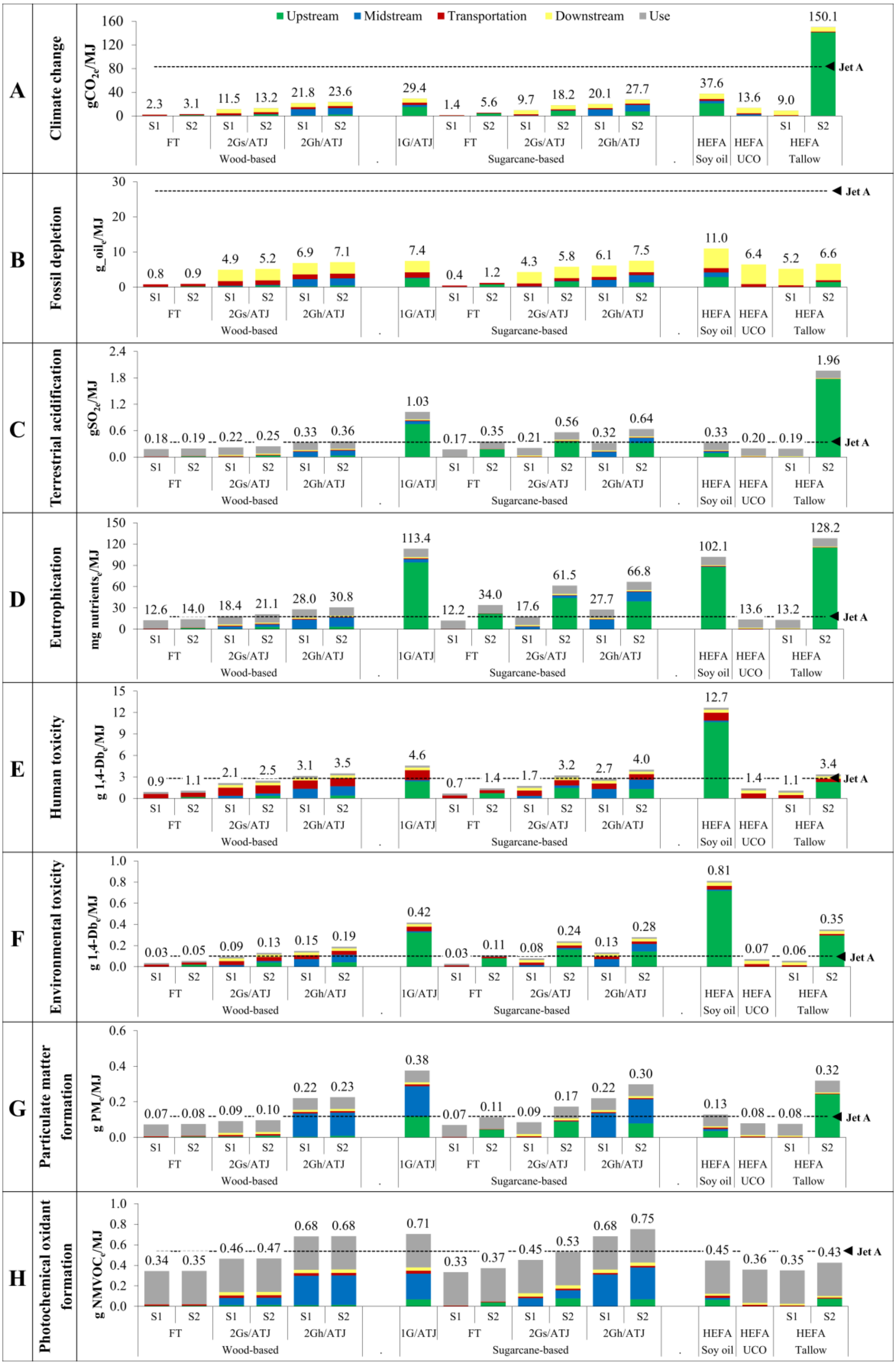


Figure 4.2: LCA of RJF and Jet A (S1, residual feedstock as waste; S2, residual feedstock as by-product)

Despite similar ethanol yields, 2Gs pathways present lower values than 2Gh because of the low environmental burden related to the industrial inputs at the midstream stage, which corresponds to around 6.0% of the total GHG emissions (0.55 g CO_{2e}/MJ) (**Table SM.16** and **SM.17**). Even with the contribution of the industrial inputs reported by Handler et al. (2016) – but not detailed by them (*i.e.*, 1.30 g $CO_{2e}/MJ_{ethanol}$) – the GHG emissions of WO_2Gs/ATJ and SC_2Gs/ATJ would increase by 16% on average but would still be lower than the 2Gh pathways.

At the downstream stage, HEFA processes usually require three-to-four-fold more hydrogen in kg H_2/kg_{feed} [4,17,41] than ATJ technology[7,17,20]. Therefore, the GHG emissions related to hydrogen input in the HEFA pathways – *i.e.,* 7.4 g CO_{2e}/MJ for tallow and 8.8 g CO_{2e}/MJ for soybean and UCO – in contrast to ATJ pathways, where the hydrogen input results in 4.6 g CO_{2e}/MJ. In general, hydrogen use contributes 15% (SC_1G/ATJ) and 23% (Soy oil/HEFA) of the total emissions in 1G pathways. For 2G pathways at S1, the contribution is around 20% for 2Gh-based pathways, 30-40% for 2Gs-based, and more than 60% for oil-based.

The fossil depletion category (**Figure 4.2.B**) presents similar trends to those of the climate change results, except for Tallow/HEFA at S2, due to its biogenic methane emissions. In this category, hydrogen use is the main contributor. In HEFA-based pathways, this corresponds to 5.6. g_oil_e/MJ (soybean and UCO) and 4.7 g_oil_e/MJ for tallow, *i.e.,* more than 50% of the total environmental impact. In ATJ pathways, its contribution (2.9 g_oil_e/MJ) corresponds to 39% (SC_1G) to 68% (SC_2Gs at S1) of the total impact. Likewise, 1G pathways have a greater impact than the 2G ones in both approaches (S1 and S2), exclusively because of the upstream accounting. At the upstream stage, diesel use in agricultural operations, including inputs transportation, corresponds to around 20% of the total values in SC_1G and Soy oil/HEFA. At the midstream stage, around 20% of the total values in 2Gh pathways are related to ammonia input.

Terrestrial acidification is mostly related to NH_3, NO_x, and SO_x emissions, while eutrophication is related to the nutrient (nitrate and phosphorous) emissions into water bodies. Therefore, the relevant contribution of the upstream stage in 1G and 2G pathways at S2 (see **Figures 4.2.C** and **4.2.D**) is, in general, mostly associated with the nitrogen input from chemical fertilizers and from organic substances (*e.g.*, industrial effluents or crop residues).

According to the LCA inventories (**Tables SM.5** and **SM.7**), the total nitrogen input for sugarcane is lower (1.26 g N/MJ_{RJF}) than for soybean (1.88 g N/MJ_{RJF}). However, in sugarcane, over 60% of the nitrogen is obtained from chemical fertilizers (0.67g N/MJ_{RJF}) and industrial residues (0.15 g N/MJ_{RJF}) (vinasse and filter cake); in soybean crops, the major contributor is biological nitrogen fixation by the plant (1.76 g N/MJ_{RJF}). In this context, despite that the nitrate emissions are estimated from the total nitrogen input, ammonia emissions are estimated only from chemical fertilizers and manure [67], which explains the higher values for SC_1G/ATJ than Soy oil/HEFA regarding terrestrial acidification and their similar values for eutrophication. Likewise, even 2G pathways from sugarcane residues at S2 present higher values than Soy oil/HEFA for terrestrial acidification. In turn, the considerable contribution from the upstream stage in Tallow/HEFA at S2 (around 90% of the total values) is mostly related to ammonia emitted from cattle urine, as reported by Seber *et al.*[22].

For both categories, the contribution of the midstream stage in 2Gh pathways is mostly related to the enzyme input, which bears the impact of sugar production and corresponds to 20% and 30% of the total terrestrial acidification and eutrophication results at S1, respectively

Regarding the eutrophication category, although some inventories[42,68,69] have accounted for phosphorous emissions from fertilizers use based on general assumptions, none were considered here. As set out by Bonomi *et al.*[33] and Cavalett *et al.*[70], phosphorous leaching and loss by water erosion in Brazilian soil are not verified due to the high phosphorus-binding capacity of the soils and the flat landscape in the producing regions, which reduce this risk[71].

Human and environmental toxicities are directly linked to the use of agrochemicals, including fertilizers and pesticides, at the upstream stage, which again explains the higher values of the 1G pathways than for the 2G pathways for both approaches (S1 and S2) (**Figures 4.2.E** and **4.2.F**). In general, direct emissions from use of agrochemicals represent 11% and 50% of the environmental burden related to human toxicity in SC_1G/ATJ and Soy oil/HEFA, respectively; and less than 10% for residues-based pathways (S2). On the other hand, these emissions correspond to 60% of the environmental toxicity for 1G pathways, and 15 to 40% for 2G pathways (S2).

As stated by Macedo[72], the more intense application of pesticides to soybean crops (estimated at 1.76 kg/$t_{soybean}$ or 96.9 mg/MJ_{RJF}) than sugarcane (0.02 kg/$t_{sugarcane}$ or 8.8 mg/MJ_{RJF}) confirms the considerable toxicity of Soy oil/HEFA. Likewise, the upstream accounting (S2) results in a significant increase in the values for pathways based on sugarcane residues and tallow, because of the allocated burden of the sugarcane crop and animal feed, respectively. Substantial variations for wood-based pathways between S1 and S2 are not seen due to the low allocation factor of wood residues compared to sugarcane residues and the relatively low use of pesticides (0.03 kg/t_{wood}).

The split of pesticides emissions to air/water/soil, which considerably influences toxicity impact categories, has been commonly simplified or omitted in several LCAs through the application of different arbitrary assumptions on splitting fractions[33,67,68,73]. Here, the split of pesticide emissions to soil, air, and water is assumed to be same for soybean, sugarcane, and wood – *i.e.*, 90% to soil; 9% to air, and 1% to water (**Tables SI.5, SI.7,** and **SI.9**) – as suggested by the European Commission[74]. However, it is worth noting that different modeling options of pesticide emissions can influence the environmental assessment of barley production as concluded by Schmidt Rivera *et al.*[75]. On the same way, Nordborg[76] reported a different split for pesticide emissions in Brazilian crops based on computational modeling, and considering different application techniques, climate conditions, and types of pesticides. In that study, for soybean, 0.4% of the pesticides would be emitted into air and 0.002% into surface water, for sugarcane, 10.5% would go into air and 0.4% into surface water. This discrepancy should be analyzed in future investigations.

The contribution of the transportation stage to human toxicity is related to brake wear emissions. They are relevant for SC_1G/ATJ (around 30% of the total environmental impact) and wood-based pathways (more 35% at S1), for which the transportation from field to ethanol mills was fully considered.

Particulate matter and photochemical oxidant formation are related to possible impacts on local air quality. For these categories, the burning of lignocellulosic material in the midstream stage of the SC_1G (0.17 g PM_e/MJ) and 2Gh pathways (0.10 g PM_e/MJ) contributes with around 50% of particulate matter formation at S1 (**Figure 4.2.G**). Likewise, process emissions (e.g., ethanol releasing) contribute around 20% of the photochemical oxidant formation of these pathways (**Figure 4.2.G**).

Specifically, for particulate matter formation, the contribution of the upstream stage in sugarcane-based pathways is mostly related to nitrogen oxide emissions from fertilizer use, *i.e.,* around of 25% (0.42 g NO_x/MJ_{RJF}) and 15% (0.17 g NO_x/MJ_{RJF}) of the total values in the SC_1G and 2G pathways at S2, respectively. For tallow/HEFA at S2, ammonia emissions from cattle urine (0.69 g NH_3/ MJ_{RJF}) in the upstream stage are responsible for around 70% of the total environmental impact.

Regarding to photochemical oxidant formation, RJF use is responsible for, at least, 45% of the total results of each pathway (**Figure 4.2.H**). However, it provides only 8% lower impact than those related to fossil fuel use for this category. According to the RJF use inventory (**Table SM.22**), a large reduction in combustion-generated particles and low or no sulfur emissions are related to RJF use; no relevant reductions in carbon monoxide, hydrocarbons, and nitrogen oxides emissions – which influences this impact category – have been reported[61,62]. Nevertheless, Benosa *et al.*[77] confirmed the benefits of alternative kerosene in reducing aviation emissions in the boundary layer (up to 1000 m). According to their report, the 50/50 blend of RJF and fossil kerosene provided lower sulfur dioxide emission and particulate matter impact on the ground-level than other strategies to improve air quality in airports, such as taxi out time reduction and ground support equipment electrification.

In general, in this study, assessment of the local impact, such as air quality, toxicity, acidification, and eutrophication was conducted by general characterization factors, which can be refined in future investigations considering a specific description of the region where the supply chain is to be implanted.

4.3.2. Uncertainty analysis

Considering the uncertainties related to the life cycle inventories, all base case values (deterministic results) presented in **Figure 4.2** are within the 95% confidence interval generated by the Monte Carlo analysis, *i.e.*, 2.5th percentile to 97.5th percentile (see "Base case" in **Figure 4.3**). Furthermore, most of the base case values are near the median and mean values. Some discrepancies are observed when the upstream stage is accounted for, such as in SC_1G/ATJ, Soy oil/HEFA, and Tallow/HEFA (S2) for climate change and toxicity categories.

GHG emissions in the base case (see **Figure 4.2.A**) are more optimistic than the median values from Monte Carlo simulations. While the base case reported 37.6 gCO_{2e}/MJ and 29.4 gCO_{2e}/MJ for Soy oil/HEFA and SC_1G/ATJ, respectively, the median emissions for these pathways are 42.6 gCO_{2e}/MJ (varying in 34.2 to 54.4 gCO_{2e}/MJ) and 32.6 gCO_{2e}/MJ (27.4 - 38.6 gCO_{2e}/MJ). In turn, the median emissions of Tallow/HEFA (S2) are 189 gCO_{2e}/MJ (146 - 521 gCO_{2e}/MJ) compared to 150 gCO_{2e}/MJ as reported in **Figure 4.2.A**. The range related to N_2O emissions from fertilizers[78] and CH_4 emissions from cattle management[79] are the main underlying reasons for this gap. Similarly, the uncertainty on pesticides application in soybean crop[80] leads to median values for human and environmental toxicity of 14.4 $g1,4Db_e$/MJ (10.3 - 22.8 $g1,4Db_e$/MJ) and 1.2 $g1,4Db_e$/MJ (0.5 - 2.0 $g1,4Db_e$/MJ), respectively, while base case results are 12.7 and 0.8 $g1,4Db_e$/MJ (see **Figure 4.2.E** and **4.2.F**).

In addition, the uncertainty range of the results for each pathway can lead to no significant differences among them. Then, by Monte Carlo analysis, which was run in SimaPro 8.3®, it was possible to estimate the frequency when two compared pathways are different from each other during the trials. If the frequency of the difference is observed in more than 95% of the trials, it was assumed there is a significant difference among the pathways[65]. These comparisons are illustrated in **Figure SM.1**.

For instance, the small difference observed between the results of eutrophication and environmental toxicity in SC_1G/ATJ and Soy oil/HEFA (see **Figure 4.2.D**) are not considered significant, which means that during the trials Soy oil/HEFA can present higher values than SC_1G/ATJ, and vice-versa. Likewise, the differences between Soy oil/HEFA and Tallow/HEFA (S2) are not significant for eutrophication and photochemical oxidant formation.

Finally, wood-based pathways in comparison with sugarcane residues at S1 are significantly different only for Fischer-Tropsch (FT). On the other hand, when the upstream is accounted for, *i.e.*, in S2, the sugarcane residues-based pathways are significantly higher than wood-based pathways in climate change, terrestrial acidification, eutrophication, and particulate matter formation.

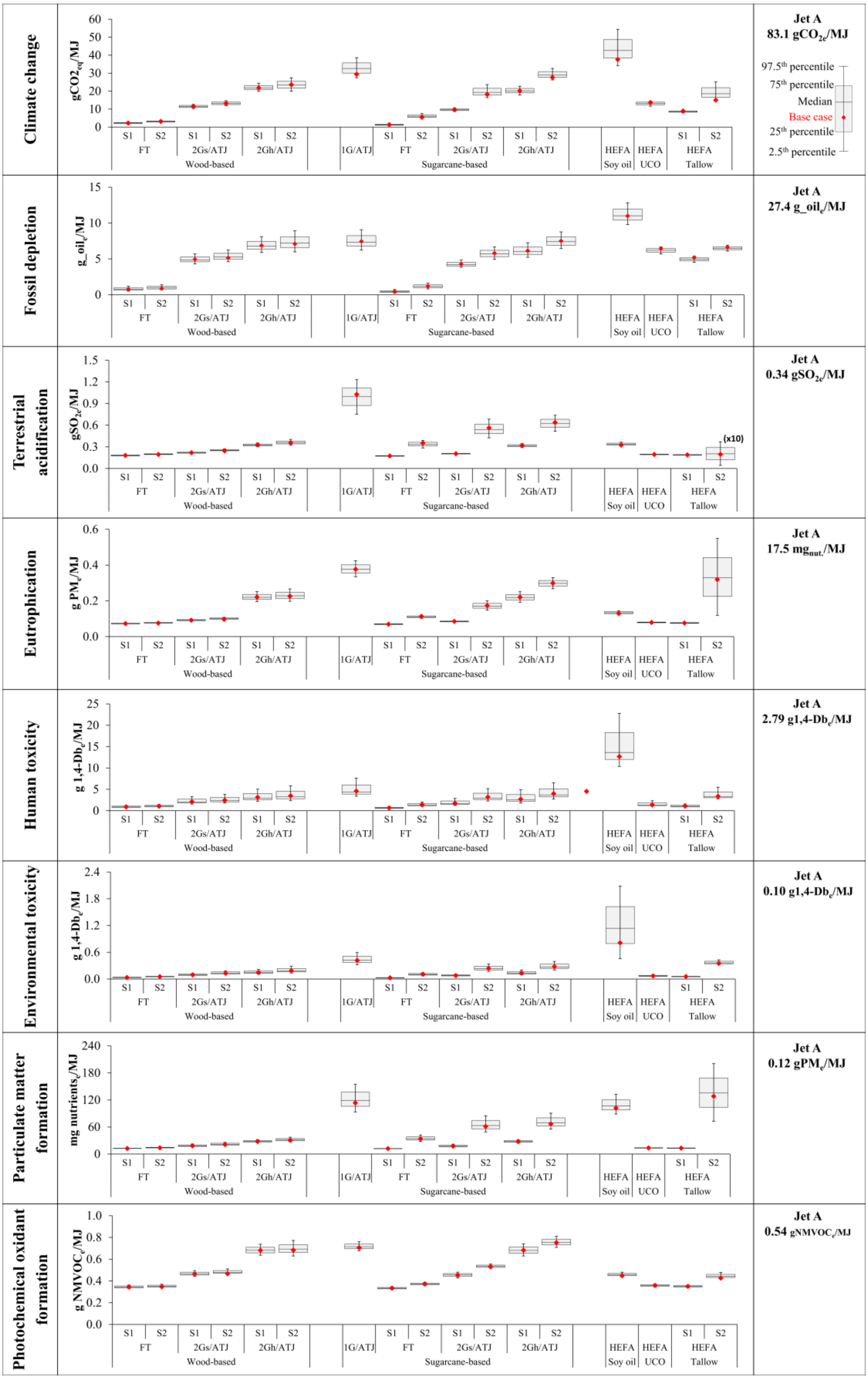


Figure 4.3: Uncertainty analysis of LCA of RJF (S1, feedstock as waste; S2, feedstock as by-product). Climate change and terrestrial acidification results for Tallow/HEFA (S2) were adjusted to better fit to the graph scale.

4.3.3. Environmental trade-offs

All pathways reported a possible reduction in GHG emissions compared to fossil kerosene (Jet A), but this does not occur in the other impact categories (see **Figure 4.4**). By the deterministic results (base case values),1G pathways – *i.e.,* Soy oil/HEFA and SC_1G/ATJ – provide a GHG reduction of 55% and 65%, respectively, compared to Jet A. However, they present relevant values for local impacts. For example, the Soy oil/HEFA reports human toxicity impacts three-fold higher than those for the sugarcane-based pathway and around five-fold higher than those for Jet A (**Figure 4.4.A**), mainly due to agrochemicals use. On the other hand, the SC_1G/ATJ pathway (**Figure 4.4.D**) presents two-fold higher terrestrial acidification impacts than for soybean-based (and six-fold higher than Jet A. Similarly, higher particulate matter and photochemical oxidant formation impacts (around three-fold and 30% higher, respectively, than Jet A) are seen for SC_1G/ATJ. In turn, the results related to eutrophication for Soy oil/HEFA and SC_1G/ATJ, which are not significantly different from each other, are around six-fold higher than Jet A.

Some of these trade-offs are discussed by Cox *et al.*[24], who reported low GHG emissions and fossil fuel dependency for the sugarcane-based pathway and high values for eutrophication and water consumption. Similarly, Klein *et al.*[17] highlighted the benefits of RJF produced in integrated sugarcane biorefineries for global-scale impact categories, such as climate change and fossil depletion, which contrasted with high local impact (human toxicity, terrestrial acidification, and agricultural land occupation), mostly observed at the agricultural stage.

When residual feedstock is treated as waste (S1), some trade-offs are observed but only in 2Gh pathways (**Figure 4.4.E** and **4.4.G**). While these pathways provide a GHG reduction of 74% (WO_2Gh) to 76% (SC_2Gh), photochemical oxidant and particulate matter formation impacts are 30% and 90% higher than Jet A, on average, respectively. Pathways based on wood residues lead to slightly higher environmental impacts than those obtained for sugarcane residues in all assessed categories at S1, and this may be explained by the difference in ethanol production yield and the boundaries of the LCA, as mentioned previously (**section 4.3.1**). However, as mentioned previously, these differences are significant only when FT technology is considered.

Furthermore, no trade-offs are observed for the other pathways at S1, whose potential GHG reduction is estimated around 97% for the FT pathways, 89% for Tallow/HEFA, 86%

for 2Gs pathways, and 84% for UCO/HEFA. These pathways lead to the fewest environmental impacts, following this order, for all categories except fossil fuel depletion, in which Jet A presents the highest values compared with all pathways in both approaches (S1 and S2).

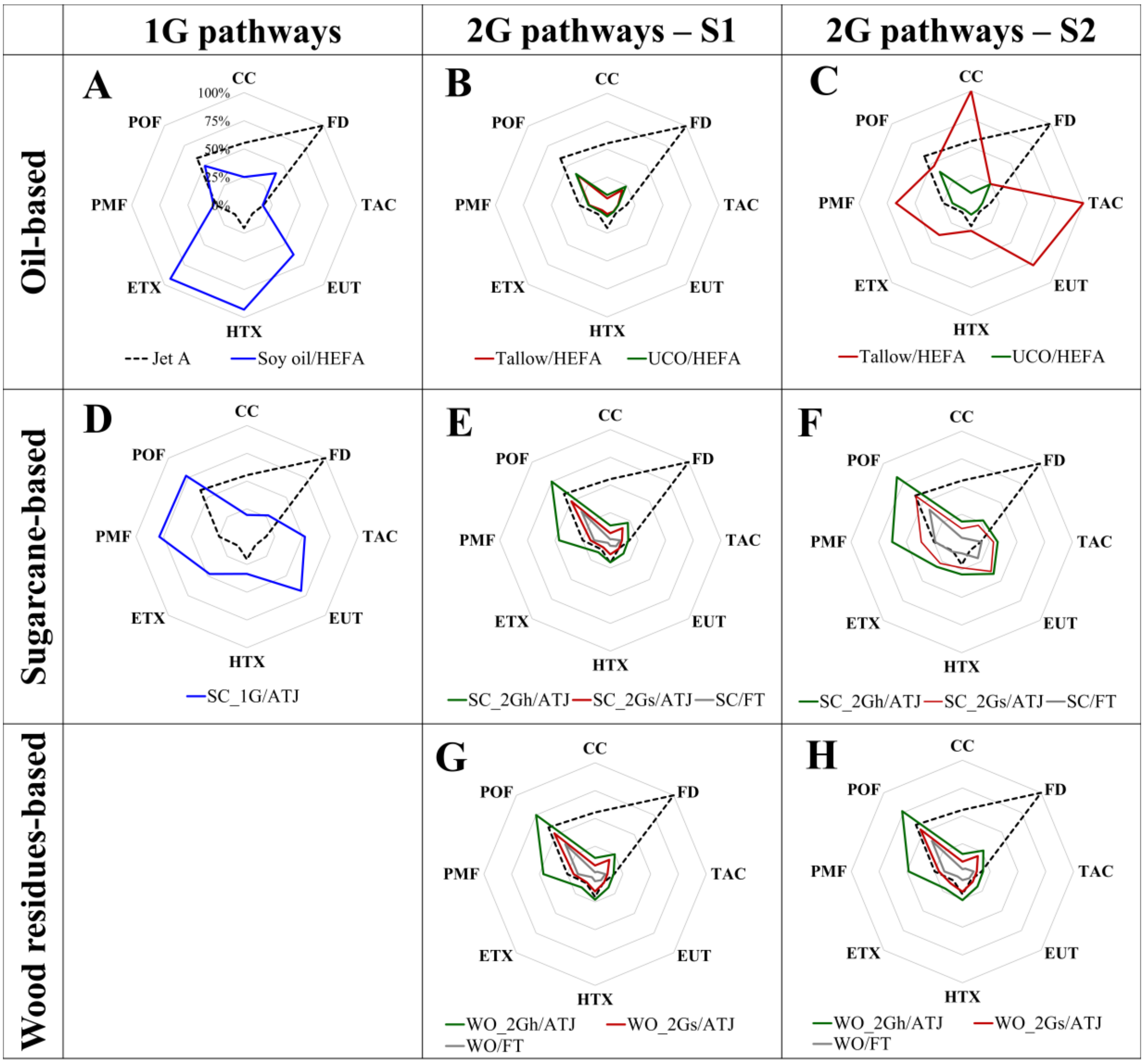


Figure 4.4: Environmental trade-offs of RJF pathways normalized by the highest values in each impact category according to the deterministic results (base case values) presented in Fig. 2. CC, climate change; FD, fossil depletion; TAC, terrestrial acidification; EUT, eutrophication; HTX, human toxicity; ETX, environmental toxicity; PMF, particulate material formation; POF, photochemical oxidant formation. S1, residual feedstock as waste; S2, residual feedstock as by-product.

On the other hand, when the residual feedstock is treated as a by-product (S2), relevant trade-offs take place in 2G pathways. For pathways based on sugarcane residues (**Figure 4.4.F**), while providing a GHG reduction of 67% (SC_2Gh) to 78% (SC_2Gs), terrestrial acidification and eutrophication become, on average, 77% and four-fold higher than Jet A, respectively. The aspects related to sugarcane crop inventory, such as nitrogen use, and the high allocation factor applied to sugarcane residues at the upstream stage explain these values.

Otherwise, no relevant differences are observed for wood-based pathways between S1 (**Figure 4.4.G**) and S2 (**Figure 4.4.H**). With a potential GHG reduction of 72% (WO_2Gh) and 84% (WO_2Gs), the results in S2 are significantly different from S1 only for some categories, such as terrestrial acidification and eutrophication.

At S2, the largest discrepancy compared to the values estimated in S1 is observed for Tallow/HEFA (**Figure 4.4.C**), which confirms the high impacts related to pasture activities. For climate change, the values become 80% higher than Jet A in base case, or 128% higher (mean value) by Monte Carlo analysis. Even compared to 1G pathways (**Figure 4.4.A and 4.4.D**), the results for terrestrial acidification and eutrophication are 90% and 12% higher than SC_1G/ATJ, respectively.

4.3.4. Sensitivity analysis

In general, the results of terrestrial acidification, eutrophication, and toxicity range in the same order as the upstream yield variations. In turn, climate change, fossil depletion, and toxicity impacts vary similarly to the range of the downstream yields. Hydrogen production via water electrolysis (WE) would imply increasing GHG emissions of up to 13% in Soy oil/HEFA (4.7 gCO_{2e}/MJ), as well as decreasing fossil depletion in 30% of the same pathway (**Figure 4.5**). Pathways based on sugarcane residues at S2 are considerably sensitive to the energy allocation method. They would present higher impacts even than the 1G pathways, and trade-offs would be observed even in FT pathway. The sensitivity analysis is detailed in Supplementary Material **(Fig. SM.2)**.

4.3.5. Comparison with other studies

The GHG emissions related to the RJF life cycle are the primary impact category discussed in the literature. In this context, comparing the results achieved here to those reported in other studies can help to identify trends and differences. In the case of the soy oil/HEFA pathway, the results are similar to those published by Han *et al.*[19], who considered soybean production in the United States by energy allocation, and within the range of other oil-bearing feedstocks, such as jatropha, rapeseed, camelina, and palm (**Figure 4.6**).

According to the authors, the main differences between soy oil/HEFA and the other oil-based pathways are explained by the high fertilizer consumption of jatropha, camelina, and rapeseed crops and the high palm oil yield. Camelina oil as feedstock was also studied by Li and Mupondwa[25] under five endpoints environmental impacts. Different designs for HEFA process and different demand of fertilizers and crop yields also explain the range of the results reported by them. The direct comparison of their results for climate change to those reported here would not be correct, because they accounted credits to the co-products, while here, in an attributional approach, it was not assumed.

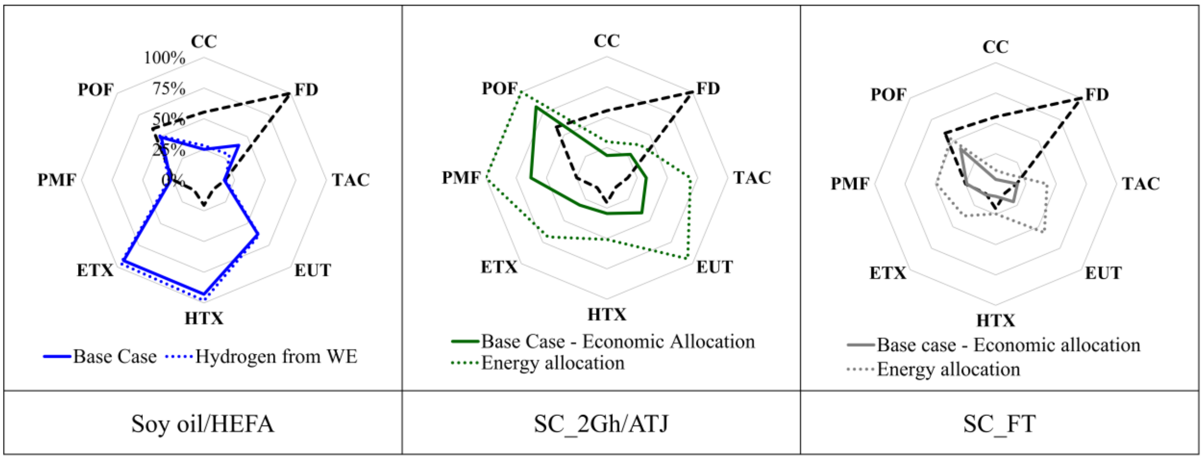


Figure 4.5: Sensitive analysis for some key parameters. S2, residual feedstock as by-product.

For UCO and tallow, the results described here are lower than those published in other studies mainly because of inventory aspects and system boundaries. For example, in the tallow inventory, Seber *et al.*[22] considered the rendering process separately to the slaughter process. Likewise, when tallow is assumed to be a by-product of meat production, the discrepancy between the results estimated here (148 g CO_{2e}/MJ) with respect to those from Seber *et al.*[22] (87 g CO_{2e}/MJ) is explained mainly by the estimations of methane emissions during the animal's lifespan. According to the pastoral system of beef production (assumed here), around 174 kg CH_4/cattle head are emitted along the three years required for the cattle to reach a weight of 450 kg [31]. Seber *et al.*[22] is based on a feedlot system, in which, 57 kg CH_4/cattle head are emitted along the 1.5 years required for the cattle to be ready for slaughter.

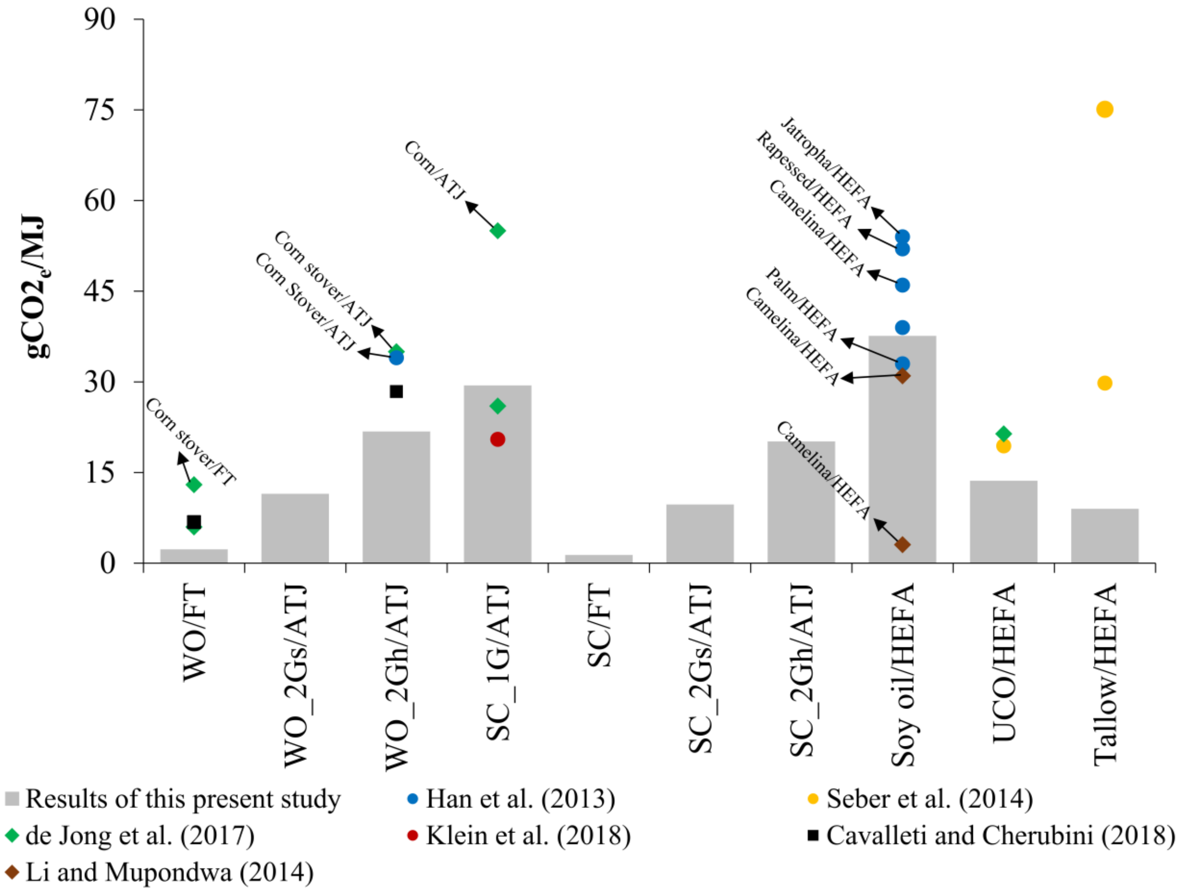


Figure 4.6: GHG emissions for RJF production and use in comparison with other studies [7,17–19,21]; residues-based pathways by S1 approach; allocation was used in all the studies and none LUC aspects were considered; dots without label indicate results for the same pathway (feedstock and conversion technologies) as here analyzed.

Other differences among the oil-based pathways derive from the design of RJF conversion technology: while other studies[4,18,19,22] assumed external utilities' demand and light hydrocarbons, such as propane, the internal use of this light stream was considered here, with power surplus generation. As mentioned previously, the HEFA process modeled by Klein *et al.*[17] – and adopted here – aims to assure the self-supply of utilities, which commonly result in good performance from an LCA perspective. However, an economic assessment will indicate the best design of a HEFA plant.

In the case of ATJ pathways, Klein *et al.*[17] considered an integrated plant (to the ethanol mill) with on-site hydrogen production from water electrolysis. This leads to lower emissions. In turn, for SC_1G/ATJ, de Jong *et al.*[18] assumed lower values for chemical fertilizer input for the sugarcane crop (0.80 kg N/ton sugarcane) than those considered here (1.26 kg N/ton sugarcane). The higher GHG emissions for Corn/ATJ [18] than those for the sugarcane-based pathway can be explained by the significant nitrogen (15 kg N/ton corn) and diesel demand (5 L/ton corn) at the upstream stage, added to the overall performance of the conversion process, which also accounted for external utilities.

For the residue-based pathways, such as corn stover, de Jong *et al.*[18] and Han *et al.*[20] considered additional fertilizer demand as nutrient compensation due to crop residue removal (around 30 kg NPK/ton corn stover), which explains the difference between their results and those presented here. Cavalett and Cherubini[21] reported slightly higher values for RJF from forest residues in Norway, due, most likely, to different agricultural inputs, transportation distances, and operations (e.g., harvesting, chipping, and processing) for forest residues.

Other impact categories are briefly discussed in some studies. According to Klein *et al.*[17], the performance of RJF from 1G ethanol for terrestrial acidification is around two-fold higher than the fossil kerosene, which is similar to what is estimated here. On the other hand, relative to Jet A, RJF provides less fossil depletion (-85% vs. -73% in this study) and human toxicity (27% vs. 64% in this study), due to inventory aspects, such as on-site hydrogen production by water electrolysis.

Regarding pathways from wood-residues, Cavalett and Cherubini[21] recommended the FT pathway as the most interesting option in terms of environmental performance. However, in contrast to what is estimated here, they reported higher impact in some categories compared to Jet A: terrestrial acidification (-24% vs. -46% in this study), particulate matter formation (-11% vs. -38% in this study), and photochemical oxidant formation (-6% vs. -36% in this study). For these same categories, those authors reported that RJF from 2G ethanol provided greater impact relative to Jet A, such as terrestrial acidification (13% vs. -35% in this study), particulate material (34% vs. -22% in this study), and photochemical oxidant formation (30% vs. -14% in this study). The description of the whole supply chain in Norway – which included field and industrial operations, transportation, and RJF use – can explain these differences.

4.4. Conclusions

An attributional life cycle assessment of 10 different pathways to produce RJF in Brazil was carried out in the present study. Potential 1G pathways from soybean and sugarcane and residue-based pathways, *i.e.*, 2G pathways from wood, sugarcane, UCO, and tallow, were evaluated through eight impact categories.

In general, while RJF pathways provide lower global-scale impact than fossil kerosene (Jet A), such as climate change and fossil depletion, relevant trade-offs are observed in categories related to local impacts, such as eutrophication, toxicity and air quality-related categories. The 1G pathways have potential to provide a GHG emission reduction of over 50% with respect to fossil kerosene (Jet A), even considering the uncertainties related to the life cycle inventories. However, sugarcane-based pathway (SC_1G/ATJ) is related to high impacts in terms of eutrophication and air quality, mostly because of fertilizer use and bagasse burning at the ethanol mill. Furthermore, the soybean-based pathway (Soy oil/HEFA) causes large impacts on human and environmental toxicity, because of agrochemical applications. The GHG emission reductions are estimated to be around 70% in the 2G pathways, when the residual feedstock is treated as waste and, consequently, the environmental burden of the upstream stage is not considered. In these cases, no relevant trade-offs are observed, except for air quality impacts observed in hydrolysis-based pathways with wood and sugarcane residues, due to biomass burning at the ethanol mill.

However, when treating residual feedstocks as by-products, the environmental performance of some pathways changes considerably and relevant trade-offs take place. For instance, the beef tallow pathway (Tallow/HEFA) leads to 80% higher GHG emissions than Jet A, as well as larger impacts regarding terrestrial acidification and eutrophication than 1G pathways. Similarly, pathways based on sugarcane residues, although providing a potential GHG reduction of 67% (SC_2Gh/ATJ) to 94% (SC/FT), feature higher impacts than Soy oil/HEFA for terrestrial acidification, particulate matter, and photochemical oxidant formation. In this context, wood-based pathways perform better than sugarcane residues, due to the relatively low environmental burden of the upstream stage allocated to this feedstock.

The definition of what is considered waste (or not), as already observed in low carbon policies, can support (or not) the use of residues for biofuel production. Nevertheless, several of these residual materials have been used in specific markets and are treated as valuable products by their sector. This study does not intend to advocate for a specific pathway, but, rather, indicates what values could be achieved for different impact categories depending on how the feedstock is treated in the LCA.

Pathways with low dependency on industrial inputs featured the best performances. Then, FT pathways in both approaches, followed by syngas fermentation-based ones, represent the highest potential reduction in GHG emissions (over 75%) with no relevant environmental trade-offs. UCO/HEFA is also an interesting option, but the considerable demand for hydrogen poses some limitations. Further, the effective potential of the feedstock supply and maturity of these technologies can be obstacles to their quick start-up.

It must be noted that the findings of the present analysis are based inventories that reflect the conditions of Brazilian agriculture and the forecasted performances of promising RJFs production routes. As such, the results obtained here cannot be simply extrapolated to other scopes given the relevance of the upstream stages for 1G pathways. Nevertheless, future analyses may benefit from the detailed life cycle inventories assembled in this work, whereas the findings for residues-based pathways tend to be less sensitive to the geographical scope.

Supplementary Material

1. General assumptions

Table SM.1: Energy content and Economic value for specific substances

Substance	Energy content (GJ/)	Economic Value (R$/)	Reference
Hydrated ethanol (m³)	21.4	1,218	[11]; Average price (2008-2018) at Brazilian market, [81].
Anhydrous ethanol (m³)	22.4	1,376	[11]; Average price (2008-2018) at Brazilian market, [81].
Electricity (MWh)	3.6	218.6	Average price (2008-2018) at Brazilian market [82].
Sugarcane residues (ton, db) [a]	14.6	188.2	Mix 85% bagasse / 15% straw [33,83]; Opportunity cost US$ 44.8/ton (db), exchange rate of 4.2, [33].
Wood (ton, db)	18.0	49.58	[84]; Average price (2013-2017) of eucalyptus to be used in process in Brazil [85].
Wood residues (ton, db)	17.5	47.50	Mix 90% wood / 10% barks [84]; Average prices (2013-2017) for eucalyptus clean residues to be used as energy source in Brazil [85].
Boneless meat (ton)	n.a.	13,127	Average price (2014-2017) to export from Brazilian market, [86].
Beef tallow (ton)	n.a.	2,310	Average price (2015-2018) at Brazilian market, [87].
Renewable Naphtha (ton)	44.9	1,703	[88]; Average price (2008-2017) for gasoline at Brazilian market [58].
Renewable Diesel (ton)	43.2	1,648	[88]; Average price (2008-2017) for fossil diesel at Brazilian market [58].
Renewable Jet Fuel (ton)	44.0	1,541	[88]; Average price (2008-2017) for fossil kerosene at Brazilian market [58].
Soybean oil (ton)	37.2	2,131	[88]; Average price (2008-2018) at Brazilian market [89].
Soybean meal (ton)	13.4	814.6	[88]; Average price (2008-2018) at Brazilian market [89].

[a] Dry basis (db).

Table SM.2: Allocation factors in each stage for the different system boundaries[a]

Pathway	Upstream	Mid-Industry	Jet-Industry
Soy oil/HEFA	Soybean: 100%	Soy oil: 35.0% (*36.4%*)	RJF: 58.3% (*60.9%*)
Tallow/HEFA	Tallow: System 1 (S1): 0% System 2 (S2): 3.1% *(n.a.)*	n.a.	RJF: 58.2% (*60.8%*)
UCO/HEFA	UCO: n.a.	UCO refined: 100%	RJF: 58.3% (*60.9%*)
SC_1G/ATJ	Sugarcane: 100%	Ethanol: 73.0% (*75.1%*)	RJF: 63.2% (*64.9%*)
SC/FT	Sugarcane residues: System 1 (S1): 0% System 2 (S2): 14.9% *(46.6%)*	n.a.	RJF: 23.9% (*27.4%*)
SC_2Gh/ATJ		Ethanol: 94.0% (*94.3%*)	RJF: 63.2% (*64.9%*)
SC_2Gs/ATJ		Ethanol: 96.6% (*96.8%*)	
WO/FT	Wood residues: System 1 (S1): 0% System 2 (S2): 6.7% *(6.5%)*	n.a.	RJF: 24.6% (*27.4%*)
WO_2Gh/ATJ		Ethanol: 91.6% (*92.0%*)	RJF: 63.2% (*64.9%*)
WO_2Gs/ATJ		Ethanol: 93.7 (*94.1%*)	

[a] Values in parenthesis refer to Energy allocation, which was assumed in the sensitivity analysis.

Table SM.3: Feedstock composition of lignocellulosic feedstocks for process modeling

Analysis	Composition	Sugarcane residues[a]	Wood residues[b]
Ultimate (db) [c]	Carbon	46.69%	48.55%
	Hydrogen	5.72%	5.72%
	Oxygen	44.03%	45.22%
	Nitrogen	0.32%	0.26%
	Sulphur	0.05%	0.04%
	Chlorine	0.40%	0.21%
Proximate (db)	Fixed Carbon	16.79%	17.05%
	Volatile Material	80.06%	79.44%
	Ash	3.15%	3.52%
Moisture content		45.00%	11.58%
Compound description (db)	Acetyl group	2.45%	2.08%
	Ash	2.20%	3.26%
	Cellulose	42.28%	31.64%
	Glucose	0.18%	3.88%
	Lignin	23.42%	13.88%
	Organic acids	0.23%	14.62%
	Phosphate	0.01%	0.75%
	Soil (SiO2)	1.26%	1.27%
	Sucrose	4.06%	1.90%
	Xylan	23.88%	14.74%

[a] Ultimate and Proximate analysis, Moisture content and Compound description from [33] as required for both 2G process from sugarcane residues.
[b] Ultimate, Proximate analysis and Moisture content from [84] for wood residues gasification/fermentation; Compound description from [97] for wood residues hydrolysis.
[c] Dry basis.

Table SM.4.A: Uncertainty parameters used for Monte Carlo analysis. Emission factor (EF)

Parameters	Unit	Distrib.[a]	Best value[b]	MIN	MAX	SD	References and comments
General issues							
EF (CO_{2e} from liming)	$kgCO_{2e}/kg$	Triang.	4.80E-01	2.40E-01	4.80E-01		[78]
EF (NH_3 converted in N_2O)	%	Triang.	1.00E-02	2.00E-03	5.00E-02		[78]
EF (nitrogen leached converted in N_2O)	%	Triang.	7.50E-03	5.00E-04	2.50E-02		[78]
EF (N fertilizer converted in N_2O)	%	Triang.	1.00E-02	3.00E-03	3.00E-02		[78]
EF (N fertilizer converted in NH_3)	%	Triang.	3.00E-01	1.50E-01	4.00E-01		[44]
EF (N fertilizer converted in NH_3)	%	Triang.	4.00E-02	2.00E-02	5.33E-02		For sugarcane and soybean.
EF (N fertilizer converted in NO3)	%	Triang.	5.00E-02	2.00E-02	1.00E-01		[44]
EFs related to lignocellulosic burning on boiler (uncertainty range)	all emissions	Triang.	-	-25%	25%		[44]
Relative NO_x emission for RJF combustion	RJF/Jet A	Triang.	9.50E-01	9.00E-01	1.00E+00		[21]
Relative black carbon for RJF combustion	RJF/Jet A	Triang.	3.70E-01	3.00E-01	5.00E-01		[21]
Upstream stage for soybean-based pathway							
Agricultural yield	m^2/kg	Log normal	3.21E+00			1.20E+00	[42]
Nitrogen input	kg/ha	Log-normal	7.00E+00			1.09E+00	[42]
Glyphosate input	kg/ha	Triang.	3.00E+00	1.14E-01	6.49E+00		Adapted from[80] for herbicides use.
Lime input	kg/ha	Triang.	4.99E+02	1.51E+02	1.05E+03		[80]
Upstream stage for sugarcane-based pathways							
Agricultural yield	t/ha	Triang.	8.00E+01	7.00E+01	1.00E+02		Cardoso (2017)
Nitrogen input	kg/ha	Triang.	1.01E+02	9.13E+01	1.11E+02		Adapted from[50]
Lime input	kg/ha	Triang.	6.00E+02	1.43E+01	1.21E+03		Adapted from[90]

[a] Triangular distribution (best guess value; minimum value – maximum value, “MIN – MAX”); Normal distribution (best guess value; 2*standard deviation, “2*SD”); Lognormal distribution (best guess value, standard deviation², “SD²”).
[b] Best guess value was used in deterministic analysis (base case).

Parameters	**Unit**	**Distrib.**[c]	**Best value**[d]	**MIN**	**MAX**	**SD**	**References and comments**
Diesel input, agri. Operations	L/ha	Normal	1.61E+02			6.38E+01	Adapted from[50]
Glyphosate input	kg/ha	Triang.	3.90E-01	3.68E-01	4.12E-01		Adapted from[50]
Carbofuran input	kg/ha	Triang.	4.20E-01	2.10E-01	6.30E-01		Adapted from[50]
Diuron input	kg/ha	Triang.	9.80E-02	7.70E-02	1.19E-01		Adapted from[50]
Upstream stage for sugarcane residues-based pathways							
LCM (db)	kg/tsc	Triang.	1.16E+02	1.04E+02	1.27E+02		Assumed according to [44]
Upstream stage for tallow-based pathway							
Tallow production	kg_tallow/ cattle head	Log-normal	2.66E+01			1.07E+00	Based on Pedrigree matrix (2,2,na,1,1,na)
Ammonia emission	kg_NH_3/ catlle head	Normal	2.30E+01			1.27E+01	Adapted from[91]
Methane emission	kg_CH_4/ catlle head	Triang.	1.74E+02	1.54E+02	3.53E+02		Adapted from[79]
Upstream stage for wood-based pathways							
Agricultural yield	t/ha	Log-normal	3.85E+02			1.07E+00	Pedigree matrix (1,3,1,2,1,na)
Wood residues, yield	kg/ha	Log-normal	2.80E+01			1.07E+00	Pedigree matrix (1,3,1,2,1,na)
Nitrogen input	kg/ha	Log-normal	5.30E+01			1.07E+00	Pedigree matrix (1,3,1,2,1,na))
Lime input	kgha	Log-normal	1.50E+03			1.07E+00	Pedigree matrix (1,3,1,2,1,na)
Glyphosate input	kg/ha	Log-normal	7.50E+00			1.07E+00	Pedigree matrix (1,3,1,2,1,na)
Midstream stage for SC_1G pathway							
Hydrated ethanol yield	L/tsc	Triang.	9.32E+01	8.85E+01	9.55E+01		[44]
Power surplus	kWh/tsc	Triang.	1.93E+02	1.69E+02	1.98E+02		[44]

[c] Triangular distribution (best guess value; minimum value – maximum value, "MIN – MAX"); Normal distribution (best guess value; 2*standard deviation, "2*SD"); Lognormal distribution (best guess value, standard deviation², "SD²").
[d] Best guess value was used in deterministic analysis (base case).

Parameters	Unit	Distrib.[e]	Best value[f]	MIN	MAX	SD	References and comments
Midstream stage for SC_2Gh pathway							
Ethanol yield	L_ethanol / t_LCM(db)	Triang.	3.57E+02	2.86E+02	4.28E+02		Adapted from[44]
Midstream stage for WO_2Gh pathway							
Ethanol yield	L_ethanol / t_LCM(db)	Triang.	3.24E+00	2.59E+00	3.89E+00		Adapted from[44]
Midstream stage for SC_2Gs pathway							
Ethanol yield	$kg_{LCM(db)}$ / L_ethanol	Log-normal	3.06E+00			1.29E+00	Pedigree matrix (4,na,na,na,3,na)
Midstream stage for WO_2Gs pathway							
Ethanol yield	$kg_{LCM(db)}$ / L_ethanol	Log-normal	3.42E+00			1.29E+00	Pedigree matrix (4,na,na,na,3,na)
Midstream stage for UCO-based pathway							
UCO rendering (NG)	MJ/kg	Triang.	1.46E+00	2.90E-01	2.24E+00		[22]
UCO rendering (Power)	kWh/kg	Triang.	4.17E-02	1.75E-02	6.94E-02		[22]
Collect distance	km	Normal	5.00E+01			2.52E+01	[57]
Downstream stage for HEFA-based pathway							
HEFA yield	kg fuel / kg_feed	Triang.	7.86E-01	6.68E-01	7.94E-01		Adapted from[18]
Downstream stage for ATJ-based pathway							
ATJ yield	kg fuel / kg_feed	Triang.	4.18E-01	4.09E-01	4.47E-01		Adapted from[18]
Downstream stage for FT-based pathway							
FT yield_SC	kg fuel / kg_feed	Triang.	1.69E-01	1.22E-01	2.06E-01		Adapted from[18]
FT yield_WO	kg fuel / kg_feed	Triang.	1.77E-01	1.28E-01	2.16E-01		
Transportation stage							
Relative range for all distances		Triang.		-50%	50%		Except for "field-to-mill" for sugarcane-based pathways and collection of UCO.

[e] Triangular distribution (best guess value; minimum value – maximum value, "MIN – MAX"); Normal distribution (best guess value; 2*standard deviation, "2*SD"); Lognormal distribution (best guess value, standard deviation², "SD²").
[f] Best guess value was used in deterministic analysis (base case).

Table SM.4.B: Parameters variations investigated in Sensitivity analysis

Parameter	Pathways	Min	Max	Reference
Upstream yield	Sugarcane-based	-20%	+20%	[44]
	Sugarcane residues-based	-10%	+10%	[44]
	Soybean-based	-20%	+20%	[80]
	Wood residues-based	-20%	+20%	Assumed here
	Tallow-based	-10%	+10%	Assumed here
Downstream yield	HEFA	-15%	+1%	Adapted from [18]
	ATJ	-2%	+7%	Adapted from [18]
	FT	-28%	+22%	Adapted from [18]

2. Life Cycle inventories

Table SM.5: LCI for Soybean production and harvesting, adapted from [42].

Output	Value	Unit	
Soybean	3,120.00	kg	
Input	**Value**	**Unit**	**Background inventories and adaptations**
Soybean seed	39.94	kg	*Soybean seed, for sowing {RoW}| production | Rec, U* Adapted to Brazilian power grid (Table SM.21) and Soybean production in Brazil.
MAP, as N	7.00	kg	Nitrogen fertilizer, as N {RoW}| monoammonium phosphate production.
MAP, as P2O5	37.13	kg	*Phosphate fertilizer, as P2O5 {RoW}| monoammonium phosphate production | Rec, U* It corresponds to 53% of total P2O5 input, as suggested by [92].
SSP, as P2O5	11.17	kg	*Phosphate fertilizer, as P2O5 {RoW}| single superphosphate production | Rec, U* It corresponds to 16% of total P2O5 input, as suggested by [92]
TSP, as P2O5	21.65	kg	*Phosphate fertilizer, as P2O5 {RoW}| triple superphosphate production | Rec, U* It corresponds to 31% of total P2O5 input, as suggested by [92]
KCl, as K2O	63.02	kg	*Potassium chloride, as K2O {RER}| potassium chloride production | Rec, U*
Lime	499.20	kg	*Limestone, crushed, for mill {RoW}| production | Rec, U*
Diesel	19.95	L	From agricultural operations in soybean crop reported by [92], based on [67]. Adapted to B10 [a].
2,4-D	0.16	kg	*2,4-dichlorophenol {RoW}| production | Rec, U*
Glyphosate	3.00	kg	*Glyphosate {RoW}| production | Rec, U*
Pesticide	2.34	kg	*Pesticide, unspecified {RoW} | Rec, U*
Cobalt	1.37	g	*Cobalt {GLO}| production | Rec, U*
Input transportation	2577.12	tkm	*Transport, freight, sea, transoceanic ship {GLO}| processing | Rec, U*
Input transportation	0.004	tkm	*Transport, freight, lorry 3.5-7.5 metric ton, EURO4 {RoW} | Rec, U* Adapted to B10 [a].
Input transportation	11.48	tkm	*Transport, freight, lorry 16-32 metric ton, EURO4 {RoW} | Rec, U* Adapted to B10 [a].
Input transportation	608.40	tkm	*Transport, freight, lorry 16-32 metric ton, EURO4 {RoW} | Rec, U* Adapted to B10 [a].
Emission to air	**Value**	**Unit**	**Adaptations**
Ammonia	0.345	kg	From nitrogen fertilizer use. It was assumed 4.0% of nitrogen fertilizer is emitted as ammonia, according to [67].
Dinitrogen monoxide	1.72	kg	Direct emissions: 1.0% of nitrogen fertilizer and nitrogen content in crop residues (0.032 kg N/kg soybean, [93]) emitted as dinitrogen monoxide. It was assumed that 100% of the crop residues is kept on the field. Indirect emissions: 1.0% of ammonia and 0.75% nitrogen leached as nitrate are converted into dinitrogen monoxide, according to [78].

Carbon dioxide, fossil	243.00	kg	From lime use, all carbon content in limestone is converted into carbon dioxide, according to [78], i.e., 0.48 $kgCO_2/kg$ limestone.
Nitrogen oxides	0.34	kg	From nitrogen fertilizer use. It was assumed the amount related to 21% of dinitrogen monoxide is emitted as nitrogen oxides, according to [67].
2,4-D	14.45	g	It was assumed 9% of pesticides application is emitted to air [74].
Acephate	13.39	g	
Azoxystrobin	5.39	g	
Chlorimuron-ethyl	0.92	g	
Cyfluthrin	0.79	g	
Cyproconazole	4.32	g	
Diuron	8.09	g	
Fipronil	2.25	g	
Glyphosate	269.57	g	
Imidacloprid	6.29	g	
Lambda-cyhalothrin	3.96	g	
Mineral oil	112.32	g	
Molybdenum	1.24	g	
Paraquat	16.20	g	
Prothioconazol	6.29	g	
Pyraclostrobin (prop)	0.22	g	
Teflubenzuron	1.08	g	
Thiamethoxam	9.58	g	
Thiophanate-methyl	2.02	g	
Trifloxystrobin	5.39	g	
Emission to water	**Value**	**Unit**	**Adaptations**
Nitrate	17.3	kg	From nitrogen fertilizer use and Biological Nitrogen Fixation (0.08 kgN/kg soybean, [93]), it was assumed 5% of nitrogen fertilizer is leached as nitrate, according to [33].
2,4-D	1.61	g	It was assumed 1% of pesticides application is emitted to water [74].
Acephate	1.49	g	
Azoxystrobin	0.60	g	
Chlorimuron-ethyl	0.10	g	
Cyfluthrin	0.09	g	
Cyproconazole	0.48	g	
Diuron	0.90	g	
Fipronil	0.25	g	
Glyphosate	29.95	g	
Imidacloprid	0.70	g	
Lambda-cyhalothrin	0.44	g	
Mineral oil	12.48	g	
Molybdenum	0.14	g	
Paraquat	1.80	g	
Prothioconazol	0.59	g	
Pyraclostrobin (prop)	0.70	g	
Teflubenzuron	0.02	g	
Thiamethoxam	0.12	g	

Thiophanate-methyl	1.06	g	
Trifloxystrobin	0.22	g	
Emission to soil	**Value**	**Unit**	**Adaptations**
2,4-D	144.53	g	It was assumed 90% of pesticides application is emitted to soil [74].
Acephate	133.94	g	
Azoxystrobin	53.91	g	
Chlorimuron-ethyl	9.24	g	
Cyfluthrin	7.86	g	
Cyproconazole	43.24	g	
Diuron	80.87	g	
Fipronil	22.49	g	
Glyphosate	2695.68	g	
Imidacloprid	62.90	g	
Lambda-cyhalothrin	39.59	g	
Mineral oil	1123.20	g	
Molybdenum	12.41	g	
Paraquat	162.02	g	
Pesticides, unspecified	53.07	g	
Picoxystrobin	53.91	g	
Prothioconazol	62.90	g	
Pyraclostrobin (prop)	2.25	g	
Teflubenzuron	10.81	g	
Thiamethoxam	95.75	g	
Thiophanate-methyl	20.25	g	
Trifloxystrobin	53.91	g	
Cobalt	1.38	g	From agrochemicals use, as mineral fertilizers, limestone and gypsum. It was assumed the heavy metals contained on these materials are totally emitted to the soil, according to [33].
Cadmium	18.19	g	
Copper	29.34	g	
Zinc	10.74	g	
Lead	16.48	g	
Nickel	64.31	g	
Chromium	2.59	g	

[a] It was considered the biodiesel:diesel blend of 10%, in volume basis. For biodiesel use in Brazil, it was assumed that 82%, on average, of Brazilian biodiesel derive from soybean oil and 18% from tallow [58]. The inventories related to soybean production and extraction were from Table SM.5 and Table SM.10. Assuming tallow as waste, the upstream processes had no burden, and the distance between slaughterhouse and biodiesel plant was set as 200 km by "*Transport, freight, lorry 16-32 metric ton, EURO4 {RoW} | Rec, U.* Biodiesel production as reported in [31,46]. Emissions related to biodiesel use were adjusted for hydrocarbons, nitrogen oxides, particulates and monoxide carbon [60], besides the biogenic carbon and null sulfur emissions.

Table SM.6: LCI for Beef tallow production, adapted from [31].

Output	Value	Unit	
Beef tallow	1.00	kg	
Meat	5.53	kg	
Residues	7.74	kg	
Input	**Value**	**Unit**	**Background inventories and adaptations**
Urea, as N	0.254	kg	*Urea, as N {RoW}| production | Rec, U*
TSP, as P2O5	0.242	kg	*Phosphate fertilizer, as P2O5 {RoW}| triple superphosphate production | Rec, U*
Animal feed	18.60	kg	Feed composition based on [94] Corn: 0.78 kg/kg animal feed (*Sweet corn {GLO} | market for | Rec, U*) Soybean meal: 0.20 kg/kg animal feed (Table SM.10).
Sodium Chloride	0.643	kg	*Sodium chloride, powder {RoW} | production | Rec, U*
Cattle transportation	0.94	tkm	*Transport, freight, lorry 16-32 metric ton, EURO4 {RoW} | Rec, U* Adapted to B10[a]. It was assumed 50 km (one-way) between the pasture land and the slaughter house; 500 kg/cattle head; 26.6 kg tallow/cattle head.
Electricity	0.18	kWh	From Brazilian grid (Table SM.25).
Natural gas	7.37	MJ	Natural gas, at industrial boiler [88], adapted to natural gas production and transportation in Brazil (Table SM.21).
Emission to air	**Value**	**Unit**	**Adaptations**
Ammonia	0.73	kg	
Methane, biogenic	5.53	kg	
Dinitrogen monoxide	0.12	kg	
Emission to soil	**Value**	**Unit**	**Adaptations**
Manure, as nitrate	1.40	kg	Nitrogen content in manure is leached as nitrate [95].

[a] It was considered the biodiesel:diesel blend of 10%, in volumetric values. For biodiesel use in Brazil, it was assumed that 82%, on average, of Brazilian biodiesel derive from soybean oil and 18% from tallow [58]. The inventories related to soybean production and extraction were from Table SM.5 and Table SM.10. Assuming tallow as waste, the upstream processes had null burden, and the distance between slaughterhouse and biodiesel plant was set as 200 km by "*Transport, freight, lorry 16-32 metric ton, EURO4 {RoW} | Rec, U.* Biodiesel production were reported in [31,46]. Emissions related to biodiesel use were adjusted for hydrocarbons, nitrogen oxides, particulates and monoxide carbon [60], besides the biogenic carbon and null sulfur emissions.

Table SM.7: LCI for Sugarcane production, adapted from [33,44]

Output	**Value**	**Unit**	
Sugarcane	80.0	ton	
Input	**Value**	**Unit**	**Background inventories and adaptations**
Urea, as N	101.25	kg	*Urea, as N {RoW}| production | Rec, U*
SST, as P2O5	15.48	kg	*Phosphate fertiliser, as P2O5 {RoW}| single superphosphate production | Rec, U*
KCl, as K2O	108.57	kg	*Potassium chloride, as K2O {RoW}| potassium chloride production | Rec, U*
Lime	400.0	kg	*Lime {RoW}| production, milled, loose | Rec, U*
Gypsum	200.0	kg	*Gypsum, mineral {RoW}| gypsum quarry operation | Rec, U*
Diesel	160.97	L	From agricultural operations and straw loading/bailing in sugarcane crop, as reported by [44]. Adapted to B10 [a].
Glyphosate	0.39	kg	*Glyphosate {RoW}| production | Rec, U*
Diuron	0.10	kg	*Pesticide, unspecified {RoW}| production | Rec, U*
Carbofuran	0.42	kg	*Pesticide, unspecified {RoW}| production | Rec, U*
Pesticide	0.95	kg	*Pesticide, unspecified {RoW}| production | Rec, U*
Inputs transportation	775	tkm	*Transport, freight, lorry 16-32 metric ton, EURO4 {RoW}| EURO4 | Rec, U.* Adapted to B10 [a].
Vinasse	40.15	m^3	
Vinasse aspersion	313.8	MJ	*Diesel, burned in diesel-electric generating set, 10MW {GLO}| Rec, U*
Filter cake (db)[b] and ash	1026.00	kg	570.1 kg filter cake (db); 456.0 kg ash
Straw on field (db)[b]	5.26	ton	
Sugarcane roots (db)	7.82	ton	
Emission to air	**Value**	**Unit**	**Adaptations**
Ammonia	42.5	kg	It was assumed 30% of nitrogen fertilizer and vinasse, is emitted as ammonia, according to [67].
Dinitrogen monoxide	3.49	kg	Direct emissions: 1.0% of nitrogen fertilizer, organic fertilizer (vinasse and filter cake), sugarcane straw and sugarcane roots are emitted as dinitrogen monoxide. Filter cake (14 kgN/ton db); vinasse (0.38 kgN/m^3); straw on field (4.7 kgN/ton db); sugarcane roots (5.14 kg/ton) [44]. Indirect emissions: 1.0% of NH_3 and 0.75% nitrogen leached as nitrate are converted into N_2O, according to [78].
Carbon dioxide, fossil	192.00	kg	From lime use, all carbon content in limestone is converted into carbon dioxide, according to [78], i.e., 0.48 $kgCO_2$/kg limestone.
Nitrogen oxides	0.73	kg	From nitrogen fertilizer use. It was assumed the amount related to 21% of dinitrogen monoxide is emitted as nitrogen oxides, according to [67].
Carbofuran	37.80	g	It was assumed 9% of pesticides application is emitted to air [74].
Diuron	8.73	g	
Fipronil	3.60	g	
Glyphosate	35.10	g	
Hexazinone	2.61	g	
Tebuthiuron	9.00	g	

Emission to water	Value	Unit	Adaptations
Nitrate	41.66	kg	From nitrogen input, it was assumed 5% of nitrogen fertilizer and organic fertilizer (vinasse and filter cake), sugarcane straw in field and sugarcane root are leached as nitrate, according to [33].
Carbofuran	4.20	g	It was assumed 1% of pesticides application is emitted to water [74].
Diuron	0.97	g	
Fipronil	4.00	g	
Glyphosate	3.90	g	
Hexazinone	0.29	g	
Pesticides, unspec.	1.40	g	
Tebuthiuron	1.00	g	
Emission to soil	**Value**	**Unit**	**Adaptations**
Carbofuran	378.00	kg	It was assumed 90% of pesticides application is emitted to soil [74].
Diuron	87.30	kg	
Fipronil	36.00	kg	
Glyphosate	351.00	kg	
Hexazinone	26.10	kg	
Imazapic	126.00	kg	
Tebuthiuron	90.00	kg	
Cadmium	0.47	g	From agrochemicals use, as mineral fertilizers, limestone and gypsum. It was assumed the heavy metals contained on these materials are totally emitted to the soil, according to [33].
Copper	8.40	g	
Zinc	32.63	g	
Lead	10.55	g	
Nickel	5.53	g	
Chromium	9.23	g	

[a] It was considered the biodiesel:diesel blend of 10%, in volumetric values. For biodiesel use in Brazil, it was assumed that 82%, on average, of Brazilian biodiesel derive from soybean oil and 18% from tallow [58]. The inventories related to soybean production and extraction were from Table SM.5 and Table SM.10. Assuming tallow as waste, the upstream processes had null burden, and the distance between slaughterhouse and biodiesel plant was set as 200 km by "*Transport, freight, lorry 16-32 metric ton, EURO4 {RoW} | Rec, U.* Biodiesel production as reported in [31,46]. Emissions related to biodiesel use were adjusted for hydrocarbons, nitrogen oxides, particulates and monoxide carbon [60], besides the biogenic carbon and null sulfur emissions.
[b] Dry basis (db).

Table SM.8: LCI of Sugarcane residues production, adapted from [33]

Output	Value	Unit	
LCM (db) [a,b]	116.0	kg	
Ethanol [c]	85.3	L	
Electricity	31.6	kWh	
Input	**Value**	**Unit**	**Background inventories and adaptations**
Sugarcane	1.00	ton	From Table SM.7.
Straw bales (wb) [d] transportation	1.89	tkm	Transportation 36 km one-way (*Transport, freight, lorry 7.5-16 metric ton, EURO4 {RoW}| Rec, U).* Adapted to B10 [e].
Sugarcane transportation	36.0	tkm	Transportation 36 km one-way (*Transport, freight, lorry > 32 metric ton, EURO4 {RoW}| Rec, U).* Adapted to B10.
Lime	0.61	kg	*Quicklime, milled, loose {RoW}| production | Rec, U*
Sulfuric acid	0.42	kg	*Sulfuric acid {RoW}| production | Rec, U*
Phosphoric acid	172.4	g	*Phosphoric acid, industrial grade, without water, in 85% solution state {RoW}| purification of wet-process phosphoric acid to industrial grade, product in 85% solution state | Rec, U*
Chemicals	3.66	g	*Chemical, inorganic {GLO}| production | Rec, U*
Lubricant oil	13.00	g	From Brazilian refinery (Table SM.23)
Hexane	27.380	g	*Zeolita, powder {RoW} | production | Rec, U*
LCM [a] in cogeneration system	84.4	kg	Bagasse, at industrial boiler [88].
Emission to air	**Value**	**Unit**	**Adaptations**
Carbon dioxide, biog.	66.6	kg	
Carbon dioxide, biog.	1,124.0	kg	
Carbon dioxide, biog.	339.2	kg	
Ethanol	116.1	g	

[a] Dry basis (db).
[b] LCM, lignocellulosic material (85% sugarcane bagasse, 15% sugarcane straw).
[c] Anhydrous ethanol.
[d] Wet basis (wb), 15% moisture.
[e] It was considered the biodiesel:diesel blend of 10%, in volumetric values. For biodiesel use in Brazil, it was assumed that 82%, on average, of Brazilian biodiesel derive from soybean oil and 18% from tallow [58]. The inventories related to soybean production and extraction were from Table SM.5 and Table SM.10. Assuming tallow as waste, the upstream processes had null burden, and the distance between slaughterhouse and biodiesel plant was set as 200 km by "*Transport, freight, lorry 16-32 metric ton, EURO4 {RoW} | Rec, U.* Biodiesel production were reported in [31,46]. Emissions related to biodiesel use were adjusted for hydrocarbons, nitrogen oxides, particulates and monoxide carbon [60], besides the biogenic carbon and null sulfur emissions.

Table SM.9: LCI of Wood residues production. Output and Input data was provided by [45]; emissions to air, water and soil are estimated in this study.

Output	**Value**	**Unit**	
Wood	385.00	ton	
Wood residues	28.00	ton	
Input	**Value**	**Unit**	**Background inventories and adaptations**
Urea, as N	53.00	kg	*Urea, as N {RoW}| production | Rec, U*
SST, as P2O5	140.00	kg	*Phosphate fertilizer, as P2O5 {RoW}| single superphosphate production | Rec, U*
KCl, as K2O	150.00	kg	*Potassium chloride, as K2O {RoW}| potassium chloride production | Rec, U*
Lime	1500.00	kg	Lime {RoW}| production, milled, loose | Rec, U
Gypsum	7.50	kg	Gypsum, mineral {RoW}| gypsum quarry operation| Rec, U
Diesel	614.75	L	From agricultural operations, as reported by [44]. Adapted to B10 [a].
Glyphosate	7.50	kg	*Glyphosate {RoW}| production | Rec, U*
Pesticide	0.56	kg	*Pesticide, unspecified {RoW}| production | Rec, U*
Emission to air	**Value**	**Unit**	**Adaptations**
Ammonia	19.30	kg	It was assumed 30% of nitrogen fertilizer, is emitted as ammonia, according to [67].
Dinitrogen monoxide	1.05	kg	Direct emissions: 1.0% of nitrogen fertilizer is emitted as dinitrogen monoxide [78]. It was assumed that 100% of crop residues are removed from the field. Indirect emissions: 1.0% of NH_3 and 0.75% nitrogen leached as nitrate are converted into N_2O, according to [78].
Carbon dioxide, fossil	726.00	kg	From lime use, all carbon content in limestone is converted into carbon dioxide, according to [78], i.e., 0.48 $kgCO_2$/kg limestone.
Nitrogen oxides	0.22	kg	From nitrogen fertilizer use. It was assumed the amount related to 21% of dinitrogen monoxide is emitted as nitrogen oxides, according to [67].
Glyphosate	675.00	g	It was assumed 9% of pesticides application is emitted to air [74].
Flumioxazina	18.00	g	
Isoxaflutole	32.40	g	
Emission to water	**Value**	**Unit**	**Adaptations**
Nitrate	2.63	kg	From nitrogen input, it was assumed 5% of nitrogen fertilizer are leached as nitrate, according to [33].
Glyphosate	75.00	g	It was assumed 1% of pesticides application is emitted to water [74].
Flumioxazina	2.00	g	
Isoxaflutole	3.60	g	
Emission to soil	**Value**	**Unit**	**Adaptations**
Glyphosate	6.75	kg	It was assumed 90% of pesticides application is emitted to soil [74].
Flumioxazina	0.18	kg	
Isoxaflutole	0.32	kg	
Cd	0.49	g	From agrochemicals use, as mineral fertilizers, limestone and gypsum. It was assumed the heavy metals contained on these materials are emitted to the soil, according to [33].
Cu	1.36	g	
Zn	4.22	g	
Pb	1.30	g	
Ni	0.67	g	

Cr	1.95	g	

[a] It was considered the biodiesel:diesel blend of 10%, in volumetric values. For biodiesel use in Brazil, it was assumed that 82%, on average, of Brazilian biodiesel derive from soybean oil and 18% from tallow [58]. The inventories related to soybean production and extraction were from Table SM.5 and Table SM.10. Assuming tallow as waste, the upstream processes had null burden, and the distance between slaughterhouse and biodiesel plant was set as 200 km by "*Transport, freight, lorry 16-32 metric ton, EURO4 {RoW} | Rec, U.* Biodiesel production were reported in [31,46]. Emissions related to biodiesel use were adjusted for hydrocarbons, nitrogen oxides, particulates and monoxide carbon [60], besides the biogenic carbon and null sulfur emissions.

Table SM.10: LCI of Soybean extraction, adapted from [46].

Output	**Value**	**Unit**	
Soy oil	1.00	kg	
Soy meal	4.85	kg	
Input	**Value**	**Unit**	**Background inventories and adaptations**
Soybean	5.85	kg	Table SM.5
Water	4.24	Kg	*Tap water {RER} | market group for | Rec, U*
Cyclohexane	7.08	g	*Cyclohexane {RoW} | production | Rec, U*
Inputs transportation	0.01	tkm	*Transport, freight, lorry 7.5 - 16 metric ton, EURO4 {RoW}| EURO4 | Rec, U.* Adapted to B10 [a].
Inputs transportation	0.10	tkm	*Transport, freight, lorry 16 - 32 metric ton, EURO4 {RoW}| EURO4 | Rec, U.* Adapted to B10
Soybean transportation	2.34	tkm	Transportation 400 km one-way (*Transport, freight, lorry > 32 metric ton, EURO4 {RoW}| Rec, U).* Adapted to B10.
Electricity	0.181	kWh	From Brazilian grid (Table SM.25).
Heavy oil	4.21	MJ	Residual oil, at industrial boiler [88], adapted to heavy oil production in Brazilian refinery (Table SM.23).
Emission to water	**Value**	**Unit**	**Adaptations**
Cyclohexane	7.08	g	

[a] It was considered the biodiesel:diesel blend of 10%, in volumetric values. For biodiesel use in Brazil, it was assumed that 82%, on average, of Brazilian biodiesel derive from soybean oil and 18% from tallow [58]. The inventories related to soybean production and extraction were from Table SM.5 and Table SM.10. Assuming tallow as waste, the upstream processes had null burden, and the distance between slaughterhouse and biodiesel plant was set as 200 km by "*Transport, freight, lorry 16-32 metric ton, EURO4 {RoW} | Rec, U.* Biodiesel production were reported in [31,46]. Emissions related to biodiesel use were adjusted for hydrocarbons, nitrogen oxides, particulates and monoxide carbon [60], besides the biogenic carbon and null sulfur emissions.

Table SM.11: LCI for UCO collection and rendering, adapted from [22].

Output	**Value**	**Unit**	
UCO refined	1.00	kg	
Input	**Value**	**Unit**	**Background inventories and adaptations**
UCO transportation	0.064	tkm	*Transport, freight, lorry 3.5 – 7.5 metric ton, EURO4 {RoW}| EURO4 | Rec, U.* Adapted to B10 [a]. It was assumed 50 km (one-way) for UCO collect; 1.28 UCO no-refined/kg UCO_refined.
Electricity	0.042	kWh	From Brazilian grid (Table SM.25).
Natural gas	1.46	MJ	Natural gas, at industrial boiler [88], adapted to natural gas production and transportation in Brazil (Table SM.21).

[a] It was considered the biodiesel:diesel blend of 10%, in volumetric values. For biodiesel use in Brazil, it was assumed that 82%, on average, of Brazilian biodiesel derive from soybean oil and 18% from tallow [58]. The inventories related to soybean production and extraction were from Table SM.5 and Table SM.10. Assuming tallow as waste, the upstream processes had null burden, and the distance between slaughterhouse and biodiesel plant was set as 200 km by "*Transport, freight, lorry 16-32 metric ton, EURO4 {RoW} | Rec, U.* Biodiesel production were reported in [31,46]. Emissions related to biodiesel use were adjusted for hydrocarbons, nitrogen oxides, particulates and monoxide carbon [60], besides the biogenic carbon and null sulfur emissions.

Table SM.12: LCI of 1G ethanol production from an optimized mill, adapted from [33a].

Output	Value	Unit	
Ethanol [b]	93.2	L	
Electricity	192.0	kWh	
Input	**Value**	**Unit**	**Background inventories and adaptations**
Sugarcane	1.00	ton	From Table SM.7.
Straw bales (wb) [c] transportation	1.89	tkm	Transportation 36 km one-way (*Transport, freight, lorry 7.5-16 metric ton, EURO4 {RoW}| Rec, U).* Adapted to B10 [d].
Sugarcane transportation	36.0	tkm	Transportation 36 km one-way (*Transport, freight, lorry > 32 metric ton, EURO4 {RoW}| Rec, U).* Adapted to B10.
Lime	0.61	kg	*Quicklime, milled, loose {RoW}| production | Rec, U*
Sulfuric acid	0.42	kg	*Sulfuric acid {RoW}| production | Rec, U*
Phosphoric acid	172.40	g	*Phosphoric acid, industrial grade, without water, in 85% solution state {RoW}| purification of wet-process phosphoric acid to industrial grade, product in 85% solution state | Rec, U*
Chemicals	3.67	g	*Chemical, inorganic {GLO}| production | Rec, U*
Lubricant oil	13.00	g	From Brazilian refinery (Table SM.25)
LCM (db) [e,f] in cogeneration system	0.197	ton	Bagasse, at industrial boiler [88].
Emission to air	**Value**	**Unit**	**Adaptations**
Carbon dioxide, biog.	66.60	kg	
Carbon dioxide, biog.	320.45	kg	
Ethanol	379.08	g	

[a] Milling capacity of 4.0 million ton sugarcane per year, dry cleaning, electric mill engines, 90% fermentation efficiency, 20% steam reduction, and CHP system of 65 bar/extraction-condensing turbines. Vinasse, filter-cake and ash returned to field.
[b] Hydrated ethanol.
[c] Wet basis (wb), 15% moisture.
[d] It was considered the biodiesel:diesel blend of 10%, in volumetric values. For biodiesel use in Brazil, it was assumed that 82%, on average, of Brazilian biodiesel derive from soybean oil and 18% from tallow [58]. The inventories related to soybean production and extraction were from Table SM.5 and Table SM.10. Assuming tallow as waste, the upstream processes had null burden, and the distance between slaughterhouse and biodiesel plant was set as 200 km by "*Transport, freight, lorry 16-32 metric ton, EURO4 {RoW} \| Rec, U.* Biodiesel production were reported in [31,46]. Emissions related to biodiesel use were adjusted for hydrocarbons, nitrogen oxides, particulates and monoxide carbon [60], besides the biogenic carbon and null sulfur emissions.
[e] Dry basis (db).
[f] LCM, lignocellulosic material (85% sugarcane bagasse, 15% sugarcane straw).

Table SM.13: LCI of 2G ethanol production by enzymatic hydrolysis of sugarcane residues, adapted from [44a].

Output	**Value**	**Unit**	
Ethanol [b]	357.37	L	
Electricity	127.58	kWh	
Input	**Value**	**Unit**	**Background inventories and adaptations**
LCM (db) [c,d]	1.00	ton	From Table SM.8.
Sulfuric acid	0.98	kg	*Sulfuric acid {RoW}| production | Rec, U*
Enzyme	6.63	kg	[44]. LCI from Table SM.14.
Ammonia	10.51	kg	Ammonia production mix, based on [96] 71% of *Ammonia, liquid {RoW}| ammonia production, steam reforming, liquid | Alloc Rec, U*, 29% of *Ammonia, liquid {RoW}| ammonia production, partial oxidation, liquid | Alloc Rec, U*
Sugar	0.60	kg	Based on Optimized annex ethanol mill [33].
LCM (db) [e] in CHP system	405.70	kg	Bagasse, at industrial boiler [88].
Emission to air	**Value**	**Unit**	**Adaptation**
CO2, biogenic	271.12	kg	
CO2, biogenic	577.66	kg	
Ethanol	1,781.07	g	

[a] Pre-treatment by steam explosion (210ºC, 5 min); enzymatic hydrolysis (25% solid content, 80% conversion of cellulose and xylan); neutralization, deoligomerization and separated fermentation of C5 stream by genetically modified organisms (GMO) (85% conversion); and fermentation of C6 (90% conversion). The solids residues, i.e. cellulignin, are sent to CHP system (65 bar/back-pressure turbines).
[b] Hydrated ethanol.
[c] Dry basis (db).
[d] LCM, lignocellulosic material (85% sugarcane bagasse, 15% sugarcane straw).
[e] Cellulignin.

Table SM.14: LCI for Enzyme production, adapted from [50].

Output	**Value**	**Unit**	
Enzyme	1.0	kg	
Input	**Value**	**Unit**	**Background inventories**
Ammonia	0.14	kg	Ammonia production mix, based on [96] 71% (*Ammonia, liquid {RoW}| ammonia production, steam reforming, liquid | Rec, U);* 29% of *(Ammonia, liquid {RoW}| ammonia production, partial oxidation, liquid | Alloc Rec, U).*
Ammonium sulfate	0.028	kg	*Ammonium sulfate, as N {RoW}| ammonium sulfate production | Rec, U.*
Calcium Chloride	0.008	kg	*Calcium chloride {GLO}| market for | Rec, U.*
Inorganic chemicals	0.004	kg	*Chemical, inorganic {GLO}| production | Rec, U.*
Magnesium sulfate	0.006	kg	*Magnesium sulfate {RoW}| production | Rec, U.*
Natural gas	52.1	MJ	Natural gas, at industrial boiler [88], adapted to natural gas production and transportation in Brazil (Table SM.21).
Saltpeter	0.040	kg	*Potassium nitrate {RoW}| production | Alloc Rec, U.*
Soy oil	0.016	kg	From Table SM.10.
Sugar	4.2	kg	Based on Optimized annex ethanol mill [33].
Sulfur dioxide	0.012	kg	*Sulfur dioxide, liquid {RoW}| production | Rec, U.*
Emission to soil	**Value**	**Unit**	**Observation**
Phosphate	0,009	kg	

Table SM.15: LCI for 2G ethanol production by syngas fermentation of sugarcane residues, adapted from [51a].

Output	**Value**	**Unit**	
Ethanol [b]	327.10	L	
Electricity	64.10	kWh	
Input	**Value**	**Unit**	**Background inventories and adaptations**
LCM (db) [c,d]	1.00	ton	From Table SM.8.
Nutrients	1.33	kg	Nutrient composition: *0.91 kg/kg Ammonium chloride {GLO}| market for | Rec, U* *0.09 kg/kg Sodium chloride, powder {RoW}| production | Rec, U*
Emission to air	**Value**	**Unit**	**Adaptation**
Hydrogen	6.86	g	
Methane, biog.	0.06	g	
Carbon dioxide, biog.	1.22	ton	
Carbon monox., biog.	20.59	g	
Ammonia	0.58	g	
Hydrogen sulfide	0.02	kg	
Hydrogen chloride	0.71	kg	
Carbonyl sulfide	19.47	g	
Ethane	0.08	mg	
Hydrogen cyanide	0.10	g	
Ethanol	0.60	kg	
Acetic acid	0.01	g	

[a] Indirectly-heated gasification; steam generation by heat recovery from hot gases; syngas fermentation in bubble columns with cell and water recycle (90% CO conversion, 60% H_2 conversion); power generation with unreacted syngas; and multi-effect ethanol distillation. The water that is recycled from the distillation bottoms to the bioreactor contains small amounts of acetic acid, as well as liquid media nutrients.
[b] Hydrated ethanol.
[c] Dry basis (db).
[d] LCM, lignocellulosic material (85% sugarcane bagasse, 15% sugarcane straw).

Table SM.16: LCI of 2G ethanol production by enzymatic hydrolysis of wood residues, adapted from [44]**[a]**.

Output	Value	Unit	
Ethanol [b]	308.36	L	
Electricity	158.55	kWh	
Input	**Value**	**Unit**	**Background inventories and adaptations**
LCM (db) [c,d]	1.00	ton	From Table SM.9.
LCM (wb) [e], collect	38.31	MJ	*Diesel-electric generation set, 10MW {GLO} | diesel, burned | Rec, U.* Adapted to B10 [f].
LCM (wb), transport	44.85	tkm	*Transport, freight, lorry > 32 metric ton, EURO4 {RoW}| EURO4 | Rec, U.* Adapted to B10. It was assumed 40 km (one-way) between eucalyptus crop and ethanol mill.
Sulfuric acid	0.74	kg	*Sulfuric acid {RoW}| production | Rec, U*
Enzyme	5.60	kg	From Table SM.12.
Ammonia	9.49	kg	Ammonia production mix, based on [96] 71% of *Ammonia, liquid {RoW}| ammonia production, steam reforming, liquid | Alloc Rec, U*, 29% of *Ammonia, liquid {RoW}| ammonia production, partial oxidation, liquid | Alloc Rec, U*
Sugar	0.52	kg	Based on Optimized annex ethanol mill [33].
LCM (db)[g] used in CHP system	342.30	kg	Bagasse, at industrial boiler [88].
Emission to air	**Value**	**Unit**	**Adaptation**
CO2, biogenic	226.35	kg	
CO2, biogenic	473.18	kg	
Ethanol	1,431.82	g	

[a] Same design plant reported in Table SM.13.
[b] Hydrated ethanol.
[c] Dry basis (db).
[d] LCM, lignocellulosic material (wood residues).
[e] Wet basis (db), 11.6% moisture.
[f] It was considered the biodiesel:diesel blend of 10%, in volumetric values. For biodiesel use in Brazil, it was assumed that 82%, on average, of Brazilian biodiesel derive from soybean oil and 18% from tallow [58]. The inventories related to soybean production and extraction were from Table SM.5 and Table SM.10. Assuming tallow as waste, the upstream processes had null burden, and the distance between slaughterhouse and biodiesel plant was set as 200 km by "*Transport, freight, lorry 16-32 metric ton, EURO4 {RoW} \| Rec, U.* Biodiesel production were reported in [31,46]. Emissions related to biodiesel use were adjusted for hydrocarbons, nitrogen oxides, particulates and monoxide carbon [60], besides the biogenic carbon and null sulfur emissions.
[g] Cellulignin.

Table SM.17: LCI of 2G ethanol production by syngas fermentation of wood residues, adapted from [51a].

Output	**Value**	**Unit**	
Ethanol [b]	332.60	L	
Electricity	123.90	kWh	
Input	**Value**	**Unit**	**Background inventories and adaptations**
LCM (db) [c,d]	1.00	ton	From Table SM.9..
LCM (wb) [e], collect	38.31	MJ	*Diesel-electric generation set, 10MW {GLO} | diesel, burned | Rec, U.* Adapted to B10 [f].
LCM (wb), transport	44.85	tkm	*Transport, freight, lorry > 32 metric ton, EURO4 {RoW}| EURO4 | Rec, U.* Adapted to B10. It was assumed 40 km (one-way) between eucalyptus crop and ethanol mill.
Nutrients	1.19	kg	0.91 kg/kg Ammonium chloride {GLO}| market for | Alloc Rec, U 0.09 kg/kg Sodium chloride, powder {RoW}| production | Alloc Rec, U
Emission to air	**Value**	**Unit**	**Adaptation**
Hydrogen	6.35	g	
Methane, biog.	53.94	g	
Carbon dioxide, biog.	1.24	ton	
Carbon monox., biog.	19.06	g	
Ammonia	0.56	g	
Hydrogen sulfide	1.91	kg	
Hydrogen chloride	12.97	kg	
Carbonyl sulfide	76.57	g	
Ethane	0.13	mg	
Hydrogen cyanide	0.09	g	
Ethanol	0.55	kg	
Acetic acid	0.01	g	

[a] Same design plant reported in Table SM.15.
[b] Hydrated ethanol.
[c] Dry basis (db).
[d] LCM, lignocellulosic material (wood residues).
[e] Wet basis (db), 11.6% moisture.
[f] It was considered the biodiesel:diesel blend of 10%, in volumetric values. For biodiesel use in Brazil, it was assumed that 82%, on average, of Brazilian biodiesel derive from soybean oil and 18% from tallow [58]. The inventories related to soybean production and extraction were from Table SM.5 and Table SM.10. Assuming tallow as waste, the upstream processes had null burden, and the distance between slaughterhouse and biodiesel plant was set as 200 km by "*Transport, freight, lorry 16-32 metric ton, EURO4 {RoW} \| Rec, U.* Biodiesel production were reported in [31,46]. Emissions related to biodiesel use were adjusted for hydrocarbons, nitrogen oxides, particulates and monoxide carbon [60], besides the biogenic carbon and null sulfur emissions.

Table SM.18: Overall yields from Upstream and Midstream stages[a]

Pathway	Upstream	Mid-Industry	Reference
Soy oil/HEFA	Soybean crop 3.1 $ton_{soybean}$/ha	Oil extraction plant: 0.17 $ton_{soy\_oil}/ton_{soybean}$ 0.83 $ton_{soy\_meal}/ton_{soybean}$	Upstream [42] Mid-Industry [46]
Tallow/HEFA	Cattle/Slaughter/Rendering 26.6 kg_{tallow}/cattle head 147.0 kg_{meat}/cattle head	n.a.	[31]
UCO/HEFA	n.a.	Rendering plant: 0.78 $kg_{refined}$ /kg_{crude}	[22]
SC_1G/ATJ	Sugarcane crop 80 $ton_{sugarcane}$/ha	Ethanol 1G mill: 85.6 $L_{ethanol}/ton_{sugarcane}$ 192.0 kWh//$ton_{sugarcane}$	[33]
SC_2Gh/ATJ	Sugarcane/Ethanol 1G mill 115.6 $kg_{residues(db)}/ton_{sugarcane}$ 85.4 $L_{ethanol}/ton_{sugarcane}$ 31.6 kWh/$ton_{sugarcane}$	Ethanol 2Gh mill: 357.4 $L_{ethanol}/ton_{residues(db)}$ 127.6 kWh/$ton_{residues(db)}$	[33]
SC_2Gs/ATJ		Ethanol 2Gs mill: 327.1 $L_{ethanol}/ton_{residues(db)}$ 64.1 kWh/$ton_{residues(db)}$	This study.
WO_2Gh/ATJ	Wood crop 28.0 $ton_{residues}$/ha.cycle 385.0 ton_{wood}/ha.cycle	Ethanol 2Gh mill: 308.4 $L_{ethanol}/ton_{residues(db)}$ 158.5 kWh $ton_{residues(db)}$	Upstream [45] Mid-Industry (This study)
WO_2Gs/ATJ		Ethanol 2Gs mill: 332.6 $L_{ethanol}/ton_{residues(db)}$ 123.9 kWh $ton_{residues(db)}$	Upstream [45] Mid-Industry (This study)

[a] (db): dry-basis. 1G: first-generation ethanol; 2Gh: second-generation ethanol from enzymatic hydrolysis; 2Gs: second-generation ethanol from syngas fermentation.

Table SM.19: LCI for Downstream stage, based on [17]

Pathways related	Technology	Input	Output
Soy oil/HEFA UCO/HEFA	HEFA	Soybean oil; UCO H_2: 41.9 kg/$t_{feedstock}$	RJF: 493.0 kg/$t_{feedstock}$ Diesel: 232.6 kg/$t_{feedstock}$ Naphta: 60.5 kg/$t_{feedstock}$ Power: 341.4 kWh/$t_{feedstock}$
Tallow/HEFA	HEFA	Tallow H_2: 35.2 kg/$t_{feedstock}$ (estimated)	RJF: 493.0 kg/$t_{feedstock}$ Diesel: 232.6 kg/$t_{feedstock}$ Naphta: 60.5 kg/$t_{feedstock}$ Power: 356.3 kWh/$t_{feedstock}$
SC_1G/ATJ SC_2Gh/ATJ SC_2Gs/ATJ WO_2Gh/ATJ WO_2Gs/ATJ	ATJ	Hydrated ethanol H_2: 11.0 kg/$t_{ethanol}$ Power: 196.0 kWh/$t_{ethanol}$	RJF: 269.2 kg/$t_{ethanol}$ Diesel: 126.4 kg/$t_{ethanol}$ Naphta: 22.0 kg/$t_{ethanol}$
SC_FT	FT	Sugarcane residues H_2 (on-site production) Power (on-site production)	RJF: 56.3 kg/$t_{feedstock\ (db)}$[a] Diesel: 46.2 kg/$t_{feedstock\ (db)}$ Naphta: 66.4 kg/$t_{feedstock\ (db)}$ Power: 454.9 kWh/$t_{feedstock\ (db)}$
WO_FT	FT	Wood residues H_2 (on-site production) Power (on-site production)	RJF: 58.9 kg/$t_{feedstock\ (db)}$ Diesel: 48.3 kg/$t_{feedstock\ (db)}$ Naphta: 70.1 kg/$t_{feedstock\ (db)}$ Power: 476.3 kWh/$t_{feedstock\ (db)}$

[a] (db): dry-basis.

Table SM.20: LCI of Hydrogen production by Steam Methane Reform process (SMR), according to [56].

Output	Value	Unit	
H2	1.0	kg	
Input	**Value**	**Unit**	**Background inventories**
Natural gas	5.40	m³	From natural gas production and transportation in Brazil (Table SM.21).
Power	3.00	kWh	From Brazilian grid (Table SM.25).
Emission to air	**Value**	**Unit**	**Observation**
Water	4.10	kg	
Oxygen	11.07	kg	
Carbon dioxide, fossil	5.58	kg	
Nitrogen, total	61.11	kg	

Table SM.21: LCI of Natural gas production in Brazil, adapted from [58], average values 2007-2017.

Output	Value	Unit	
Natural gas	1.00	m³	
Input	**Value**	**Unit**	**Background inventories and observations**
Liquefied Natural Gas (LPG)	0.095	m³	Natural gas, liquefied {RoW}| production | Rec, U
National production on-shore	0.134	m³	*Natural gas, high pressure {RoW}| petroleum and gas production, on-shore | Rec, U* National on-shore production.
National production off-shore	0.393	m³	*Natural gas, high pressure {RoW}| petroleum and gas production, off-shore | Rec, U* National off-shore production
International production on-shore	0.371	m³	*Natural gas, high pressure {RoW}| petroleum and gas production, on-shore | Rec, U.* Imported share from Bolivia and Argentina.
LPG transportation	0.498	tkm	*Transport, freight, sea, liquefied natural gas {GLO}| market for | Rec, U* Average distance (7,100 km) from the three major exporters at this period (Nigeria, Catar and Trinidade&Tobago).
On-shore transportation from imported share	0.467	tkm	*Transport, pipeline, onshore, long distance, natural gas {GLO}| market for | Rec, U* Transportation of imported share through GASBOL (Bolivia-Brazil); 1,700km.
On-shore transportation from national share	0.545	tkm	*Transport, pipeline, onshore, long distance, natural gas {GLO}| market for | Rec, U* Transportation of national share (Fortaleza-São Paulo); 3,000km.
Off-shore transportation	0.162	tkm	*Transport, pipeline, long distance, natural gas {DZ}| market for | Rec, U* Transportation of national share (Santos's Basin - São Paulo); 300 km

Table SM.22: EFs related to RJF use adapted from the inventory "*Transport, passenger, aircraft {RoW} | Rec, U.*" [39]

EFs	$RJF_{use}/Jet\ A_{use}$	Observations
Carbon dioxide	0.98	[62], biogenic emissions.
Carbon monoxide	1.0	[62], biogenic emissions.
Methane emission	1.0	Biogenic emissions.
Nitrogen oxides	0.95	[62].
Particulates < 2.5 um	0.00	Moore et al. (2017) reported for RJF/Jet A blend (50/50, by volume) a reduction of 50-70% related to particle matter (PM) emissions in comparison to Jet A use. Then, it was assumed null PM emission related to use of 1.0 MJ of the RJF (functional unit), without blend.
Sulfur dioxide	0.00	[62].
Water	1.11	[62].

Table SM.23: Normalized output of average Brazilian oil refineries [58], adapted from "Crude oil, in refinery/kg/US" [40]**.**

Output	Value	Unit	Energy allocation (%) by energy content reported in [11]
Diesel, at refinery	0.347	kg	36.7
Gasoline, at refinery	0.185	kg	18.6
Asphalt, at refinery	0.021	kg	2
Kerosene, at refinery	0.084	kg	8.5
Petroleum coke, at refinery	0.06	kg	4.8
Naphtha, at refinery	0.048	kg	4.9
Petroleum refining coproduct, unspecified, at refinery	0.035	kg	3.5
LPG, at refinery	0.048	kg	5.1
Fuel oil, at refinery	0.158	kg	14.6
Lubricant oil, at refinery	0.013	kg	1.3
Input	**Value**	**Unit**	**Observation**
Crude oil	1.00	t	Based on "Petroleum {GLO} [39], 7.7% petroleum on-shore "*Petroleum {RoW} | petroleum and gas production, on-shore | Rec U*"; 92.3% petroleum off-shore "*Petroleum {RoW} | petroleum and gas production, off-shore | Rec U*"

Table SM.24: LCI of Hydrogen production by Water Electrolysis (WE) process, according to [56].

Output	Value	Unit	
H2 (99.5%)	1.00	kg	
O2	4.00	kg	Estimated by stoichiometry analysis
Input	**Value**	**Unit**	**Background inventories**
Water	11.20	kg	
Power	71.16	kWh	From Brazilian grid (Table SM.25).

Table SM.25: LCI of Electricity from Brazilian power grid, based on [11]

Output	**Value**	**Unit**	
Power	1.0	kWh	
Input	**Value**	**Unit**	**Background inventories**
Coal	0.020	kWh	*Electricity, high voltage {BR}| electricity production, hard coal | Rec, U.*
Diesel	0.016	kWh	*Electricity, diesel, at power plant/US U.* Adapted with diesel (Table SM.23)
Hydropower	0.802	kWh	*Electricity, high voltage {BR}| electricity production, hydro, reservoir, tropical region | Rec, U.*
Natural gas	0.026	kWh	*Electricity, high voltage {BR}| electricity production, natural gas, combined cycle power plant | Rec, U.* Adapted with Natural gas in Brazil (Table SM.21).
Natural gas	0.047	kWh	*Electricity, high voltage {BR}| electricity production, natural gas, conventional power plant | Rec, U.* Adapted with Natural gas in Brazil (Table SM.21)
Nuclear	0.030	kWh	*Electricity, high voltage {BR}| electricity production, nuclear, pressure water reactor | Rec, U.*
Oil fuel	0.014	kWh	*Electricity, high voltage {BR}| electricity production, oil | Rec, U.*
Sugarcane bagasse	0.022	kWh	*Electricity, high voltage {BR}| cane sugar production with ethanol by-product | Rec, U.* Adapted with sugarcane production (Table SM.5).
Windpower	0.017	kWh	*Electricity, high voltage {BR}| electricity production, wind, 1-3MW turbine, onshore | Rec, U.*
Wood	0.001	kWh	*Electricity, high voltage {BR}| heat and power co-generation, wood chips, 6667 kW, state-of-the-art 2014 | Rec, U.*
Power losses	0.063	kWh	
Transmission	3,17E-10	km	*Transmission network, long-distance {GLO}| market for | Def, U.*
Transmission	6,58E-9	km	*Transmission network, electricity, high voltage {GLO}| market for | Def, U.*
Emission to air	**Value**	**Unit**	**Observation**
Dinitrogen monoxide	0.05	g	
Ozone	4,16	mg	

3. Contributional analysis at System 2 (S2) – Tables SM.26

CLIMATE CHANGE ($g\ CO_{2e}/MJ$)	Wood-residues based			Sugarcane-based pathways				Oil-based pathways		
	FT	2Gs/ ATJ	2Gh/ ATJ	1G/ ATJ	FT	2Gs/ ATJ	2Gh/ ATJ	Soy-oil/ HEFA	UCO/ HEFA	Tallow/ HEFA
Fertilizers (NPK)	1.47E-01	2.86E-01	3.01E-01	2.81E+00	6.34E-01	1.28E+00	1.14E+00	2.96E+00	n.a.	1.06E+00
Chemicals	3.74E-02	7.31E-02	7.69E-02	2.03E-01	1.82E-01	3.67E-01	3.28E-01	1.40E+00	n.a.	4.96E+00
Agric. operations[15]	7.21E-01	1.41E+00	1.48E+00	3.18E+00	7.16E-01	1.44E+00	1.29E+00	1.61E+00	n.a.	n.a.
Other operations[16]	n.a.[17]	n.a.	n.a.	7.64E-01	5.67E-01	1.14E+00	1.02E+00	2.14E+00	n.a.	1.16E-01
Industrial utilities	n.a.	n.a.	n.a.	n.a.	1.83E+00	5.46E-01	4.87E-01	0.00E+00	n.a.	3.73E-01
Direct emissions	2.59E-01	5.05E-01	5.32E-01	8.12E+00	2.71E-01	3.69E+00	3.29E+00	1.31E+01	n.a.	1.35E+02
Upstream Total	**1.16E+00**	**2.27E+00**	**2.39E+00**	**1.51E+01**	**4.20E+00**	**8.46E+00**	**7.55E+00**	**2.12E+01**	**n.a.**	**1.42E+02**
Enzyme	n.a.	n.a.	4.86E+00	n.a.	n.a.	n.a.	5.10E+00	0.00E+00	n.a.	n.a.
Chemicals	n.a.	5.39E-01	4.09E+00	5.47E-01	n.a.	5.56E-01	4.01E+00	1.86E-01	n.a.	n.a.
Utilities	n.a.	n.a.	1.79E+00	2.89E+00	n.a.	n.a.	1.88E+00	4.02E+00	2.41E+00	n.a.
Other emissions	n.a.	2.22E-04	n.a.	n.a.	n.a.	2.41E-04	n.a.	0.00E+00	n.a.	n.a.
Midstream Total	**n.a.**	**5.39E-01**	**1.07E+01**	**3.43E+00**	**n.a.**	**5.56E-01**	**1.10E+01**	**4.21E+00**	**2.41E+00**	**n.a.**
Hydrogen	n.a.	4.57E+00	4.57E+00	4.57E+00	n.a.	4.57E+00	4.57E+00	8.79E+00	8.79E+00	7.36E+00
Utilities	n.a.	1.76E+00	1.76E+00	1.76E+00	n.a.	1.76E+00	1.76E+00	0.00E+00	n.a.	n.a.
Other emissions	1.94E-02	4.93E-01	4.93E-01	4.93E-01	1.97E-02	4.93E-01	4.93E-01	1.76E-01	1.76E-01	1.76E-01
Downst. Total	**1.94E-02**	**6.82E+00**	**6.82E+00**	**6.82E+00**	**1.97E-02**	**6.82E+00**	**6.82E+00**	**8.97E+00**	**8.97E+00**	**7.54E+00**
Transportation	**1.74E+00**	**3.35E+00**	**3.41E+00**	**3.85E+00**	**1.11E+00**	**2.10E+00**	**2.10E+00**	**3.03E+00**	**2.03E+00**	**1.24E+00**
Use	**2.28E-01**	**2.28E-01**	**2.28E-01**	**2.28E-01**	**2.28E-01**	**2.28E-01**	**2.28E-01**	**2.28E-01**	**2.28E-01**	**2.28E-01**
TOTAL	**3.16E+00**	**1.32E+01**	**2.36E+01**	**2.94E+01**	**5.55E+00**	**1.82E+01**	**2.77E+01**	**3.76E+01**	**1.36E+01**	**1.51E+02**

FOSSIL DEPLETION ($g\ oil_e/MJ$)	Wood-residues based			Sugarcane-based pathways				Oil-based pathways		
	FT	2Gs/ ATJ	2Gh/ ATJ	1G/ ATJ	FT	2Gs/ ATJ	2Gh/ ATJ	Soy-oil/ HEFA	UCO/ HEFA	Tallow/ HEFA
Fertilizers (NPK)	5.08E-02	9.93E-02	1.05E-01	1.07E+00	2.41E-01	4.86E-01	4.34E-01	1.16E+00	n.a.	4.08E-01
Chemicals	1.10E-02	2.16E-02	2.27E-02	5.98E-02	4.66E-02	9.40E-02	8.38E-02	3.99E-01	n.a.	9.75E-01
Agric. operations	2.44E-01	4.77E-01	5.02E-01	1.08E+00	2.43E-01	4.90E-01	4.37E-01	5.03E-01	n.a.	n.a.
Other operations	n.a.	n.a.	n.a.	2.97E-01	2.24E-01	4.51E-01	4.02E-01	7.99E-01	n.a.	4.51E-02
Industrial utilities	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	4.99E-03
Direct emissions	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Upstream Total	**3.06E-01**	**5.98E-01**	**6.29E-01**	**2.51E+00**	**7.55E-01**	**1.52E+00**	**1.36E+00**	**2.86E+00**	**n.a.**	**1.43E+00**
Enzyme	n.a.	n.a.	3.43E-01	n.a.	n.a.	n.a.	3.60E-01	n.a.	n.a.	n.a.
Chemicals	n.a.	1.69E-01	1.71E+00	1.38E-01	n.a.	1.74E-01	1.68E+00	1.22E-01	n.a.	n.a.
Utilities	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	1.18E+00	3.76E-02	n.a.
Other emissions	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Midstream Total	**n.a.**	**1.69E-01**	**2.05E+00**	**1.38E-01**	**n.a.**	**1.74E-01**	**2.04E+00**	**1.30E+00**	**3.76E-02**	**n.a.**
Hydrogen	n.a.	2.92E+00	2.92E+00	2.92E+00	n.a.	2.92E+00	2.92E+00	5.61E+00	5.61E+00	4.70E+00
Utilities	n.a.	3.46E-01	3.46E-01	3.46E-01	n.a.	3.46E-01	3.46E-01	n.a.	n.a.	n.a.
Other emissions	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Downst. Total	**n.a.**	**3.26E+00**	**3.26E+00**	**3.26E+00**	**n.a.**	**3.26E+00**	**3.26E+00**	**5.61E+00**	**5.61E+00**	**4.70E+00**
Transportation	**6.91E-01**	**1.33E+00**	**1.35E+00**	**1.54E+00**	**4.42E-01**	**8.41E-01**	**8.41E-01**	**1.21E+00**	**7.93E-01**	**4.96E-01**
Use	**n.a.**	**n.a.**	**n.a.**	**n.a.**	**n.a.**	**n.a.**	**n.a.**	**n.a.**	**n.a.**	**n.a.**
TOTAL	**9.97E-01**	**5.36E+00**	**7.29E+00**	**7.44E+00**	**1.20E+00**	**5.80E+00**	**7.50E+00**	**1.10E+01**	**6.44E+00**	**6.63E+00**

[15] For wood-based pathways at S1, the harvesting operations for wood residues are accounted here.
[16] Other operations include input transportation at the upstream stage.
[17] Non-applicable or null environmental burden for this impact category.

TERREST. ACIDIFICAT. (mg SO_{2e}/MJ)	Wood-residues based			Sugarcane-based pathways				Oil-based pathways		
	FT	2Gs/ ATJ	2Gh/ ATJ	1G/ ATJ	FT	2Gs/ ATJ	2Gh/ ATJ	Soy-oil/ HEFA	UCO/ HEFA	Tallow/ HEFA
Fertilizers (NPK)	1.20E-03	2.34E-03	2.46E-03	1.95E-02	4.39E-03	8.85E-03	7.89E-03	3.21E-02	n.a.	9.11E-03
Chemicals	2.04E-04	3.98E-04	4.19E-04	1.39E-03	1.25E-03	2.52E-03	2.24E-03	8.82E-03	n.a.	8.30E-02
Agric. operations	7.62E-03	1.49E-02	1.57E-02	3.03E-02	6.82E-03	1.37E-02	1.23E-02	1.34E-02	n.a.	n.a.
Other operations	n.a.	n.a.	n.a.	3.55E-03	2.62E-03	5.27E-03	4.70E-03	1.76E-02	n.a.	5.40E-04
Industrial utilities	n.a.	n.a.	n.a.	n.a.	1.56E-01	1.19E-02	1.06E-02	0.00E+00	n.a.	1.88E-04
Direct emissions	1.19E-02	2.32E-02	2.44E-02	6.94E-01	5.90E-03	3.15E-01	2.81E-01	1.82E-02	n.a.	1.69E+00
Upstream Total	**2.09E-02**	**4.09E-02**	**4.30E-02**	**7.49E-01**	**1.77E-01**	**3.58E-01**	**3.19E-01**	**9.00E-02**	**n.a.**	**1.78E+00**
Enzyme	n.a.	n.a.	5.20E-02	n.a.	n.a.	n.a.	5.46E-02	0.00E+00	n.a.	n.a.
Chemicals	n.a.	2.94E-03	2.15E-02	3.85E-03	n.a.	3.03E-03	2.13E-02	7.93E-04	n.a.	n.a.
Utilities	n.a.	n.a.	3.89E-02	6.28E-02	n.a.	n.a.	4.09E-02	3.51E-02	1.28E-03	n.a.
Other emissions	n.a.	2.56E-04	n.a.	n.a.	n.a.	2.74E-04	n.a.	0.00E+00	n.a.	n.a.
Midstream Total	**n.a.**	**3.19E-03**	**1.12E-01**	**6.66E-02**	**n.a.**	**3.30E-03**	**1.17E-01**	**3.59E-02**	**1.28E-03**	**n.a.**
Hydrogen	n.a.	5.98E-03	5.98E-03	5.98E-03	n.a.	5.98E-03	5.98E-03	1.15E-02	1.15E-02	9.64E-03
Utilities	n.a.	4.72E-03	4.72E-03	4.72E-03	n.a.	4.72E-03	4.72E-03	0.00E+00	n.a.	n.a.
Other emissions	5.20E-04	1.32E-02	1.32E-02	1.32E-02	5.29E-04	1.32E-02	1.32E-02	4.71E-03	4.71E-03	4.70E-03
Downst. Total	**5.20E-04**	**2.39E-02**	**2.39E-02**	**2.39E-02**	**5.29E-04**	**2.39E-02**	**2.39E-02**	**1.62E-02**	**1.62E-02**	**1.43E-02**
Transportation	**8.08E-03**	**1.55E-02**	**1.58E-02**	**1.78E-02**	**5.11E-03**	**9.71E-03**	**9.71E-03**	**1.40E-02**	**9.22E-03**	**5.73E-03**
Use	**1.69E-01**	**1.69E-01**	**1.69E-01**	**1.69E-01**	**1.69E-01**	**1.69E-01**	**1.69E-01**	**1.69E-01**	**1.69E-01**	**1.69E-01**
TOTAL	**1.99E-01**	**2.53E-01**	**3.64E-01**	**1.03E+00**	**3.52E-01**	**5.63E-01**	**6.38E-01**	**3.25E-01**	**1.96E-01**	**1.97E+00**

EUTROPHIC. (mg nutri.$_e$/MJ)	Wood-residues based			Sugarcane-based pathways				Oil-based pathways		
	FT	2Gs/ ATJ	2Gh/ ATJ	1G/ ATJ	FT	2Gs/ ATJ	2Gh/ ATJ	Soy-oil/ HEFA	UCO/ HEFA	Tallow/ HEFA
Fertilizers (NPK)	1.69E-01	3.31E-01	3.48E-01	1.73E+00	3.90E-01	7.86E-01	7.01E-01	3.54E+00	n.a.	1.00E+00
Chemicals	4.96E-02	9.70E-02	1.02E-01	2.30E-01	1.29E-01	2.60E-01	2.32E-01	3.11E+00	n.a.	4.04E+01
Agric. operations	5.13E-01	1.00E+00	1.06E+00	2.07E+00	4.68E-01	9.42E-01	8.40E-01	1.24E+00	n.a.	n.a.
Other operations	n.a.	n.a.	n.a.	2.45E-01	1.80E-01	3.63E-01	3.23E-01	8.66E-01	n.a.	3.72E-02
Industrial utilities	n.a.	n.a.	n.a.	n.a.	2.02E+01	8.27E-01	7.38E-01	0.00E+00	n.a.	1.35E-02
Direct emissions	1.12E+00	2.19E+00	2.30E+00	8.98E+01	4.11E-01	4.08E+01	3.64E+01	7.89E+01	n.a.	7.41E+01
Upstream Total	**1.85E+00**	**3.62E+00**	**3.81E+00**	**9.41E+01**	**2.18E+01**	**4.40E+01**	**3.92E+01**	**8.76E+01**	**n.a.**	**1.15E+02**
Enzyme	n.a.	n.a.	9.30E+00	n.a.	n.a.	n.a.	9.77E+00	0.00E+00	n.a.	n.a.
Chemicals	n.a.	3.38E+00	9.54E-01	2.95E-01	n.a.	3.48E+00	9.45E-01	1.07E-01	n.a.	n.a.
Utilities	n.a.	n.a.	2.71E+00	4.37E+00	n.a.	n.a.	2.85E+00	4.93E-01	9.21E-02	n.a.
Other emissions	n.a.	9.60E-03	n.a.	n.a.	n.a.	1.03E-02	n.a.	0.00E+00	n.a.	n.a.
Midstream Total	**n.a.**	**3.39E+00**	**1.30E+01**	**4.67E+00**	**n.a.**	**3.49E+00**	**1.36E+01**	**6.01E-01**	**9.21E-02**	**n.a.**
Hydrogen	n.a.	4.13E-01	4.13E-01	4.13E-01	n.a.	4.13E-01	4.13E-01	7.95E-01	7.95E-01	6.65E-01
Utilities	n.a.	3.62E-01	3.62E-01	3.62E-01	n.a.	3.62E-01	3.62E-01	0.00E+00	n.a.	n.a.
Other emissions	3.62E-02	9.19E-01	9.19E-01	9.19E-01	3.68E-02	9.19E-01	9.19E-01	3.28E-01	3.28E-01	3.27E-01
Downst. Total	**3.62E-02**	**1.69E+00**	**1.69E+00**	**1.69E+00**	**3.68E-02**	**1.69E+00**	**1.69E+00**	**1.12E+00**	**1.12E+00**	**9.93E-01**
Transportation	**5.54E-01**	**1.06E+00**	**1.08E+00**	**1.22E+00**	**3.49E-01**	**6.63E-01**	**6.63E-01**	**9.55E-01**	**6.56E-01**	**3.91E-01**
Use	**1.18E+01**	**1.18E+01**	**1.18E+01**	**1.18E+01**	**1.18E+01**	**1.18E+01**	**1.18E+01**	**1.18E+01**	**1.18E+01**	**1.18E+01**
TOTAL	**1.42E+01**	**2.15E+01**	**3.13E+01**	**1.13E+02**	**3.40E+01**	**6.16E+01**	**6.69E+01**	**1.02E+02**	**1.36E+01**	**1.29E+02**

HUMAN TOXICITY (g 1,4-Db$_e$/MJ)	Wood-residues based			Sugarcane-based pathways				Oil-based pathways		
	FT	2Gs/ ATJ	2Gh/ ATJ	1G/ ATJ	FT	2Gs/ ATJ	2Gh/ ATJ	Soy-oil/ HEFA	UCO/ HEFA	Tallow/ HEFA
Fertilizers (NPK)	1.09E-01	2.14E-01	2.25E-01	1.26E+00	2.83E-01	5.70E-01	5.09E-01	2.72E+00	n.a.	5.80E-01
Chemicals	1.57E-02	3.08E-02	3.24E-02	8.03E-02	7.17E-02	1.44E-01	1.29E-01	7.52E-01	n.a.	1.67E+00
Agric. operations	5.14E-02	1.00E-01	1.06E-01	2.69E-01	6.07E-02	1.22E-01	1.09E-01	5.90E-01	n.a.	n.a.
Other operations	n.a.	n.a.	n.a.	2.33E-01	1.93E-01	3.88E-01	3.46E-01	5.53E-01	n.a.	3.55E-02
Industrial utilities	n.a.	n.a.	n.a.	n.a.	1.17E-01	n.a.	n.a.	n.a.	n.a.	2.11E-03
Direct emissions	1.88E-02	3.67E-02	3.86E-02	5.17E-01	n.a.	2.35E-01	2.10E-01	6.04E+00	n.a.	n.a.
Upstream Total	**1.95E-01**	**3.81E-01**	**4.01E-01**	**2.36E+00**	**7.25E-01**	**1.46E+00**	**1.30E+00**	**1.07E+01**	**n.a.**	**2.29E+00**
Enzyme	n.a.	n.a.	3.16E-01	n.a.	n.a.	n.a.	3.32E-01	n.a.	n.a.	n.a.
Chemicals	n.a.	3.17E-01	9.93E-01	1.95E-01	n.a.	3.27E-01	9.78E-01	6.19E-02	n.a.	n.a.
Utilities	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	1.63E-01	1.59E-02	n.a.
Other emissions	n.a.	3.20E-03	3.91E-04	2.90E-03	n.a.	3.77E-03	4.31E-04	1.38E-03	n.a.	n.a.
Midstream Total	**n.a.**	**3.20E-01**	**1.31E+00**	**1.98E-01**	**n.a.**	**3.31E-01**	**1.31E+00**	**2.26E-01**	**1.59E-02**	**n.a.**
Hydrogen	n.a.	2.18E-01	2.18E-01	2.18E-01	n.a.	2.18E-01	2.18E-01	4.19E-01	4.19E-01	3.51E-01
Utilities	n.a.	1.46E-01	1.46E-01	1.46E-01	n.a.	1.46E-01	1.46E-01	n.a.	n.a.	n.a.
Other emissions	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Downst. Total	**n.a.**	**3.64E-01**	**3.64E-01**	**3.64E-01**	**n.a.**	**3.64E-01**	**3.64E-01**	**4.19E-01**	**4.19E-01**	**3.51E-01**
Transportation	**5.97E-01**	**1.14E+00**	**1.16E+00**	**1.38E+00**	**4.02E-01**	**7.63E-01**	**7.63E-01**	**1.10E+00**	**6.74E-01**	**4.50E-01**
Use	**2.73E-01**	**2.73E-01**	**2.73E-01**	**2.73E-01**	**2.73E-01**	**2.73E-01**	**2.73E-01**	**2.73E-01**	**2.73E-01**	**2.73E-01**
TOTAL	**1.07E+00**	**2.48E+00**	**3.51E+00**	**4.57E+00**	**1.40E+00**	**3.19E+00**	**4.01E+00**	**1.27E+01**	**1.38E+00**	**3.36E+00**

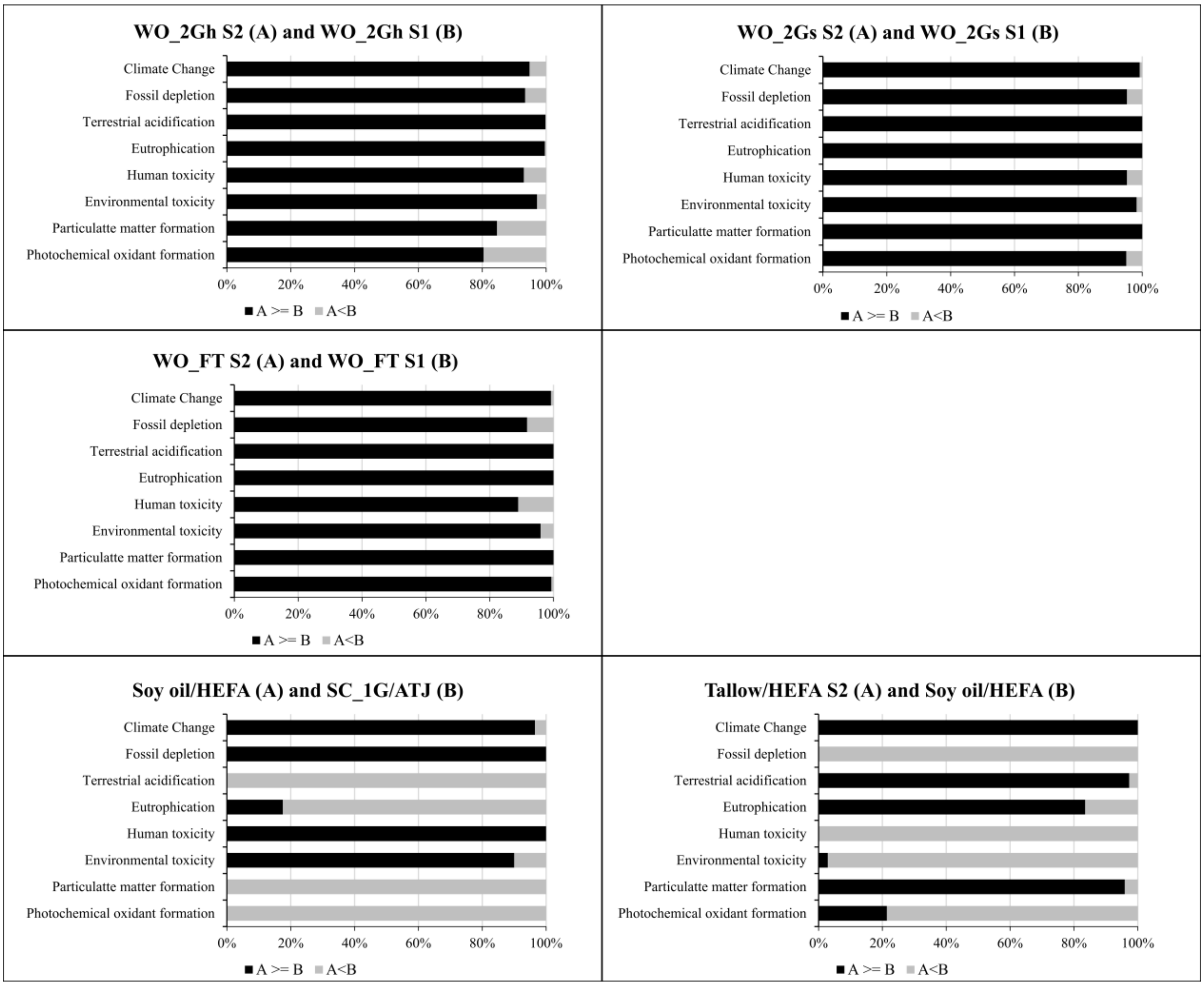
ENVIRON. TOXICITY (g 1,4-Db$_e$/MJ)	Wood-residues based			Sugarcane-based pathways				Oil-based pathways		
	FT	2Gs/ ATJ	2Gh/ ATJ	1G/ ATJ	FT	2Gs/ ATJ	2Gh/ ATJ	Soy-oil/ HEFA	UCO/ HEFA	Tallow/ HEFA
Fertilizers (NPK)	5.10E-03	9.96E-03	1.05E-02	5.81E-02	1.31E-02	2.64E-02	2.35E-02	1.26E-01	n.a.	2.71E-02
Chemicals	8.24E-04	1.61E-03	1.69E-03	4.09E-03	4.31E-03	8.68E-03	7.74E-03	3.98E-02	n.a.	2.68E-01
Agric. operations	1.50E-03	2.92E-03	3.07E-03	6.56E-03	1.48E-03	2.98E-03	2.65E-03	3.68E-02	n.a.	n.a.
Other operations	n.a.	n.a.	n.a.	8.08E-03	6.29E-03	1.27E-02	1.13E-02	2.25E-02	n.a.	1.23E-03
Industrial utilities	n.a.	n.a.	n.a.	n.a.	5.52E-02	n.a.	n.a.	n.a.	n.a.	1.14E-04
Direct emissions	1.34E-02	2.61E-02	2.75E-02	2.45E-01	n.a.	1.11E-01	9.92E-02	4.94E-01	n.a.	n.a.
Upstream Total	**2.08E-02**	**4.06E-02**	**4.27E-02**	**3.22E-01**	**8.04E-02**	**1.62E-01**	**1.44E-01**	**7.20E-01**	**n.a.**	**2.97E-01**
Enzyme	n.a.	n.a.	2.71E-02	n.a.	n.a.	n.a.	2.85E-02	n.a.	n.a.	n.a.
Chemicals	n.a.	1.39E-02	4.34E-02	1.24E-02	n.a.	1.43E-02	4.28E-02	3.06E-03	n.a.	n.a.
Utilities	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	6.06E-03	8.62E-04	n.a.
Other emissions	n.a.	9.18E-04	1.58E-05	1.32E-05	n.a.	1.10E-03	1.75E-05	3.74E-03	n.a.	n.a.
Midstream Total	**n.a.**	**1.48E-02**	**7.05E-02**	**1.24E-02**	**n.a.**	**1.54E-02**	**7.12E-02**	**1.29E-02**	**8.62E-04**	**n.a.**
Hydrogen	n.a.	1.65E-02	1.65E-02	1.65E-02	n.a.	1.65E-02	1.65E-02	3.17E-02	3.17E-02	2.65E-02
Utilities	n.a.	7.94E-03	7.94E-03	7.94E-03	n.a.	7.94E-03	7.94E-03	n.a.	n.a.	n.a.
Other emissions	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Downst. Total	**n.a.**	**2.44E-02**	**2.44E-02**	**2.44E-02**	**n.a.**	**2.44E-02**	**2.44E-02**	**3.17E-02**	**3.17E-02**	**2.65E-02**
Transportation	**1.93E-02**	**3.70E-02**	**3.78E-02**	**4.36E-02**	**1.26E-02**	**2.39E-02**	**2.39E-02**	**3.44E-02**	**2.37E-02**	**1.41E-02**
Use	**1.50E-02**	**1.50E-02**	**1.50E-02**	**1.50E-02**	**1.50E-02**	**1.50E-02**	**1.50E-02**	**1.50E-02**	**1.50E-02**	**1.50E-02**
TOTAL	**5.51E-02**	**1.32E-01**	**1.90E-01**	**4.17E-01**	**1.08E-01**	**2.41E-01**	**2.79E-01**	**8.14E-01**	**7.13E-02**	**3.52E-01**

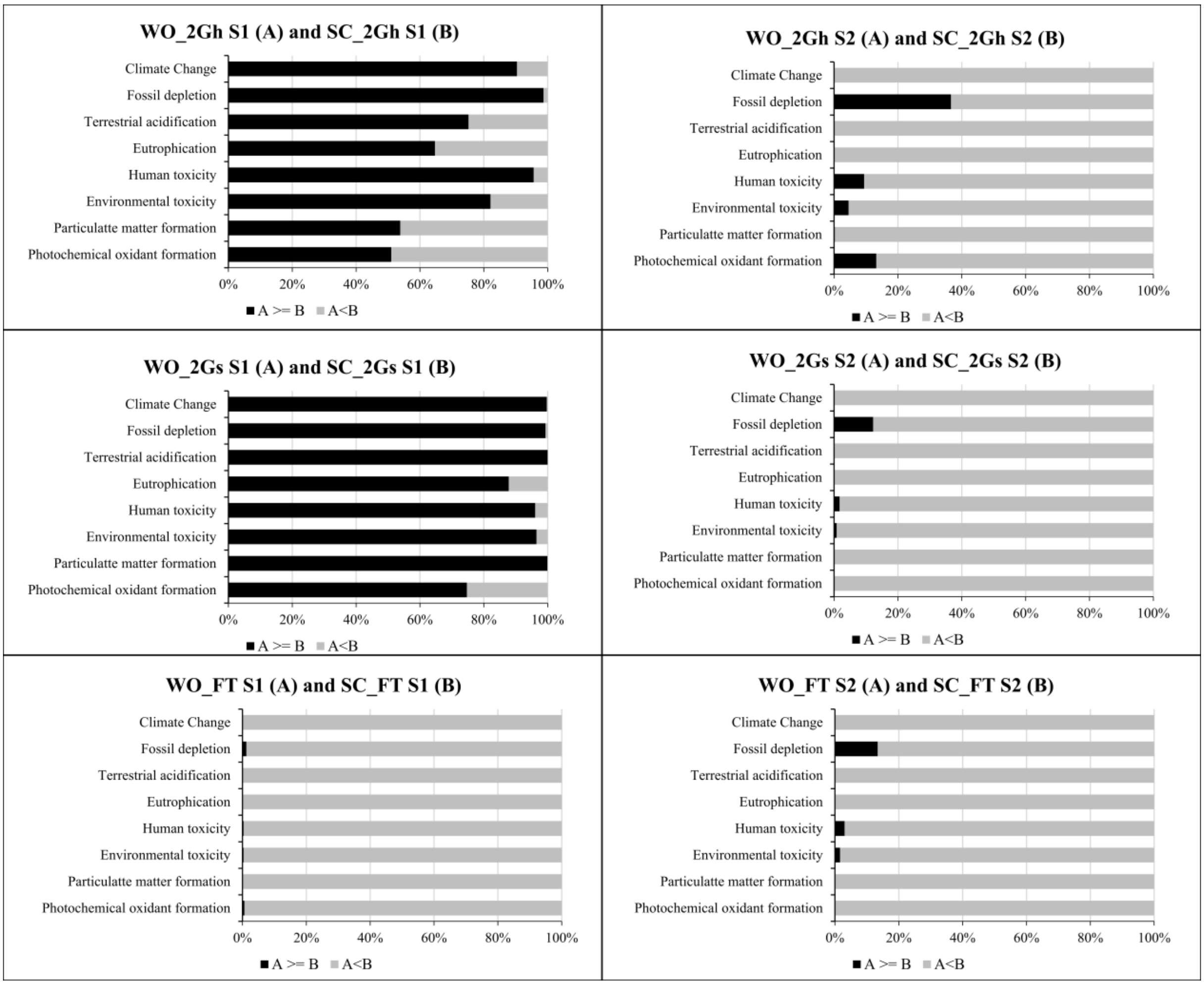
PARTIC. MAT. FORMATION (g PM_e/MJ)	Wood-residues based			Sugarcane-based pathways				Oil-based pathways		
	FT	2Gs/ ATJ	2Gh/ ATJ	1G/ ATJ	FT	2Gs/ ATJ	2Gh/ ATJ	Soy-oil/ HEFA	UCO/ HEFA	Tallow/ HEFA
Fertilizers (NPK)	6.13E-04	1.20E-03	1.26E-03	7.42E-03	1.67E-03	3.37E-03	3.01E-03	1.44E-02	n.a.	3.75E-03
Chemicals	1.25E-04	2.45E-04	2.57E-04	1.38E-03	6.32E-04	1.27E-03	1.14E-03	4.49E-03	n.a.	1.91E-02
Agric. operations	4.01E-03	7.84E-03	8.25E-03	1.57E-02	3.55E-03	7.15E-03	6.38E-03	6.84E-03	n.a.	n.a.
Other operations	n.a.	n.a.	n.a.	1.82E-03	1.45E-03	2.92E-03	2.60E-03	7.15E-03	n.a.	2.76E-04
Industrial utilities	n.a.	n.a.	n.a.	n.a.	2.06E-02	3.20E-02	2.85E-02	0.00E+00	n.a.	1.10E-04
Direct emissions	1.56E-03	3.05E-03	3.21E-03	9.14E-02	1.59E-02	4.15E-02	3.70E-02	3.29E-03	n.a.	2.20E-01
Upstream Total	**6.31E-03**	**1.23E-02**	**1.30E-02**	**1.18E-01**	**4.38E-02**	**8.82E-02**	**7.86E-02**	**3.62E-02**	**n.a.**	**2.44E-01**
Enzyme	n.a.	n.a.	1.84E-02	n.a.	n.a.	n.a.	1.94E-02	0.00E+00	n.a.	n.a.
Chemicals	n.a.	1.45E-03	7.16E-03	1.27E-03	n.a.	1.50E-03	7.08E-03	4.25E-04	n.a.	n.a.
Utilities	n.a.	n.a.	1.05E-01	1.69E-01	n.a.	n.a.	1.10E-01	1.04E-02	7.27E-04	n.a.
Other emissions	n.a.	3.34E-05	n.a.	n.a.	n.a.	3.58E-05	n.a.	0.00E+00	n.a.	n.a.
Midstream Total	**n.a.**	**1.49E-03**	**1.30E-01**	**1.70E-01**	**n.a.**	**1.53E-03**	**1.36E-01**	**1.08E-02**	**7.27E-04**	**n.a.**
Hydrogen	n.a.	2.39E-03	2.39E-03	2.39E-03	n.a.	2.39E-03	2.39E-03	4.60E-03	4.60E-03	3.85E-03
Utilities	n.a.	1.53E-03	1.53E-03	1.53E-03	n.a.	1.53E-03	1.53E-03	0.00E+00	n.a.	n.a.
Other emissions	3.04E-04	7.72E-03	7.72E-03	7.72E-03	3.09E-04	7.72E-03	7.72E-03	2.75E-03	2.75E-03	2.75E-03
Downst. Total	**3.04E-04**	**1.16E-02**	**1.16E-02**	**1.16E-02**	**3.09E-04**	**1.16E-02**	**1.16E-02**	**7.35E-03**	**7.35E-03**	**6.60E-03**
Transportation	**4.49E-03**	**8.61E-03**	**8.77E-03**	**1.02E-02**	**2.97E-03**	**5.64E-03**	**5.64E-03**	**8.13E-03**	**5.01E-03**	**3.33E-03**
Use	**6.64E-02**	**6.64E-02**	**6.64E-02**	**6.64E-02**	**6.64E-02**	**6.64E-02**	**6.64E-02**	**6.64E-02**	**6.64E-02**	**6.64E-02**
TOTAL	**7.75E-02**	**1.00E-01**	**2.30E-01**	**3.76E-01**	**1.13E-01**	**1.73E-01**	**2.99E-01**	**1.29E-01**	**7.95E-02**	**3.20E-01**

PHOT. OXID. FORMATION (g $NMVOC_e$/MJ)	Wood-residues based			Sugarcane-based pathways				Oil-based pathways		
	FT	2Gs/ ATJ	2Gh/ ATJ	1G/ ATJ	FT	2Gs/ ATJ	2Gh/ ATJ	Soy-oil/ HEFA	UCO/ HEFA	Tallow/ HEFA
Fertilizers (NPK)	4.92E-04	9.61E-04	1.01E-03	6.79E-03	1.53E-03	3.08E-03	2.75E-03	1.30E-02	n.a.	3.17E-03
Chemicals	1.30E-04	2.54E-04	2.68E-04	8.32E-04	5.53E-04	1.11E-03	9.94E-04	5.26E-03	n.a.	2.43E-02
Agric. operations	1.29E-02	2.51E-02	2.64E-02	4.99E-02	1.13E-02	2.27E-02	2.02E-02	2.15E-02	n.a.	n.a.
Other operations	n.a.	n.a.	n.a.	5.56E-03	4.17E-03	8.39E-03	7.48E-03	1.94E-02	n.a.	8.46E-04
Industrial utilities	n.a.	n.a.	n.a.	n.a.	1.05E-02	2.16E-02	1.92E-02	n.a.	n.a.	2.76E-04
Direct emissions	5.51E-05	1.08E-04	1.13E-04	4.82E-03	1.07E-02	2.11E-02	1.88E-02	6.35E-03	n.a.	4.75E-02
Upstream Total	**1.35E-02**	**2.64E-02**	**2.78E-02**	**6.79E-02**	**3.87E-02**	**7.79E-02**	**6.95E-02**	**6.55E-02**	**n.a.**	**7.60E-02**
Enzyme	n.a.	n.a.	1.90E-02	n.a.	n.a.	n.a.	1.99E-02	n.a.	n.a.	n.a.
Chemicals	n.a.	1.34E-03	8.15E-03	1.48E-03	n.a.	1.39E-03	8.05E-03	1.02E-03	n.a.	n.a.
Utilities	n.a.	n.a.	7.07E-02	1.14E-01	n.a.	n.a.	7.43E-02	1.61E-02	1.81E-03	n.a.
Other emissions	n.a.	6.83E-02	1.88E-01	1.36E-01	n.a.	7.83E-02	2.08E-01	n.a.	n.a.	n.a.
Midstream Total	**n.a.**	**6.96E-02**	**2.86E-01**	**2.51E-01**	**n.a.**	**7.96E-02**	**3.10E-01**	**1.71E-02**	**1.81E-03**	**n.a.**
Hydrogen	n.a.	4.63E-03	4.63E-03	4.63E-03	n.a.	4.63E-03	4.63E-03	8.91E-03	8.91E-03	7.46E-03
Utilities	n.a.	3.02E-03	3.02E-03	3.02E-03	n.a.	3.02E-03	3.02E-03	n.a.	n.a.	n.a.
Other emissions	9.88E-04	2.51E-02	2.51E-02	2.51E-02	1.00E-03	2.51E-02	2.51E-02	8.94E-03	8.94E-03	8.93E-03
Downst. Total	**9.88E-04**	**3.27E-02**	**3.27E-02**	**3.27E-02**	**1.00E-03**	**3.27E-02**	**3.27E-02**	**1.79E-02**	**1.79E-02**	**1.64E-02**
Transportation	**1.29E-02**	**2.47E-02**	**2.52E-02**	**2.85E-02**	**8.23E-03**	**1.56E-02**	**1.56E-02**	**2.25E-02**	**1.44E-02**	**9.22E-03**
Use	**3.25E-01**	**3.25E-01**	**3.25E-01**	**3.25E-01**	**3.25E-01**	**3.25E-01**	**3.25E-01**	**3.25E-01**	**3.25E-01**	**3.25E-01**
TOTAL	**3.52E-01**	**4.78E-01**	**6.97E-01**	**7.05E-01**	**3.73E-01**	**5.31E-01**	**7.52E-01**	**4.48E-01**	**3.59E-01**	**4.27E-01**

4. Uncertainty analysis

Figure SM.1: Uncertainty evaluation using Monte Carlo analysis with 95% confidence interval. Differences higher than 95% were considered significant.




WO_2Gh S1 (A) and SC_2Gh S1 (B)
WO_2Gh S2 (A) and SC_2Gh S2 (B)
WO_2Gs S1 (A) and SC_2Gs S1 (B)
WO_2Gs S2 (A) and SC_2Gs S2 (B)
WO_FT S1 (A) and SC_FT S1 (B)
WO_FT S2 (A) and SC_FT S2 (B)
Climate Change
Fossil depletion
Terrestrial acidification
Eutrophication
Human toxicity
Environmental toxicity
Particulatte matter formation
Photochemical oxidant formation
0% 20% 40% 60% 80% 100%
A >= B
A<B

5. Sensitivity analysis

The Sensitivity Analysis for residues-based pathways was presented from S2 results in order to capture the sensitivity to energy allocation and yields at the upstream. This discussion is the same, in qualitative terms, for S1 approach.

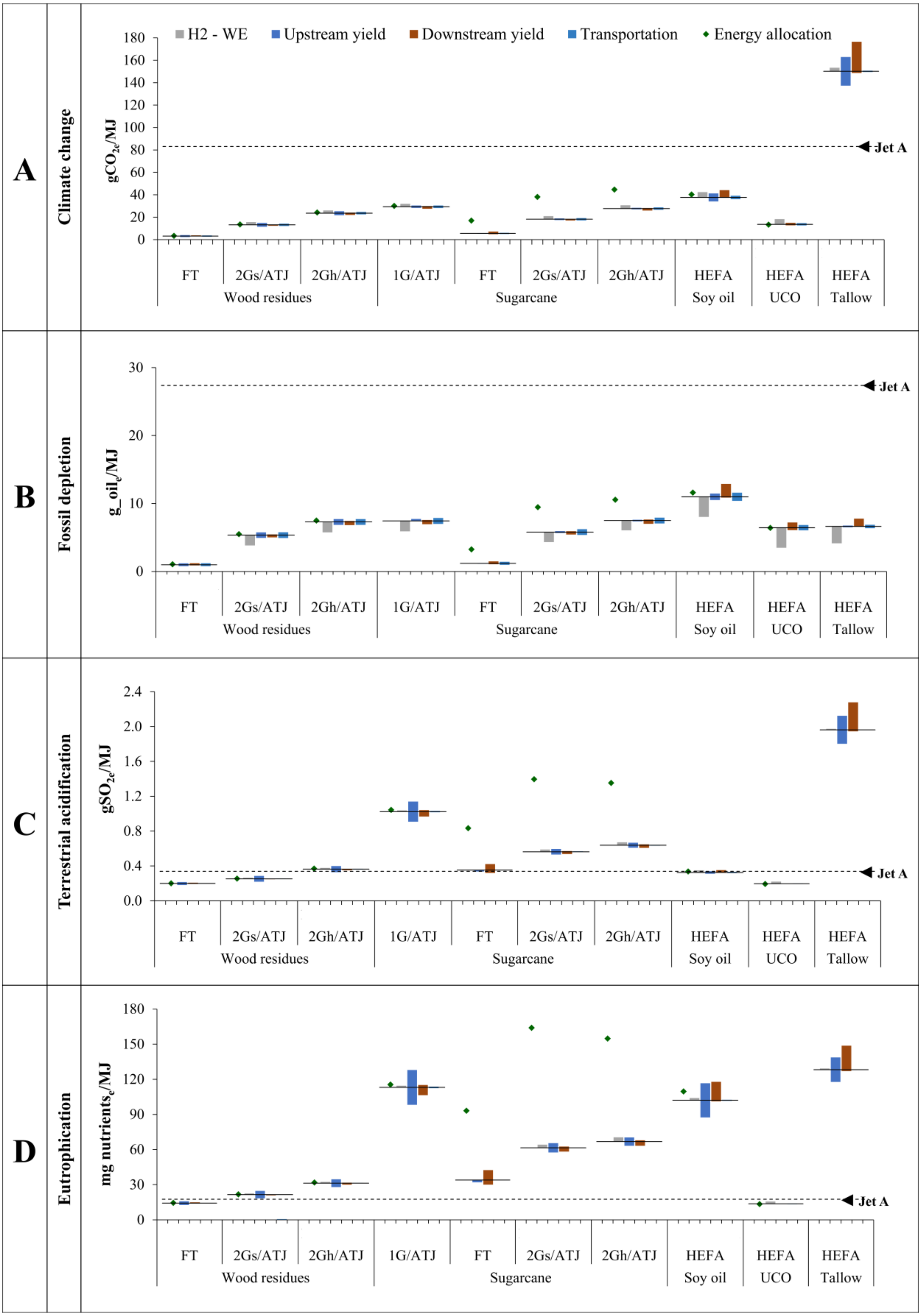
Regarding to inventory parameters, terrestrial acidification, eutrophication, and toxicity impacts are reasonably sensitive to upstream yields. Assuming ±20% on upstream yields, the original values in Soy oil/HEFA range by ±14% for eutrophication and human toxicity; or ±13% in SC_1G/ATJ for terrestrial acidification and eutrophication. Specifically for sugarcane residues at S2, the same impact categories reported to SC_1G/ATJ present similar variations relative to ±10% in upstream yields.

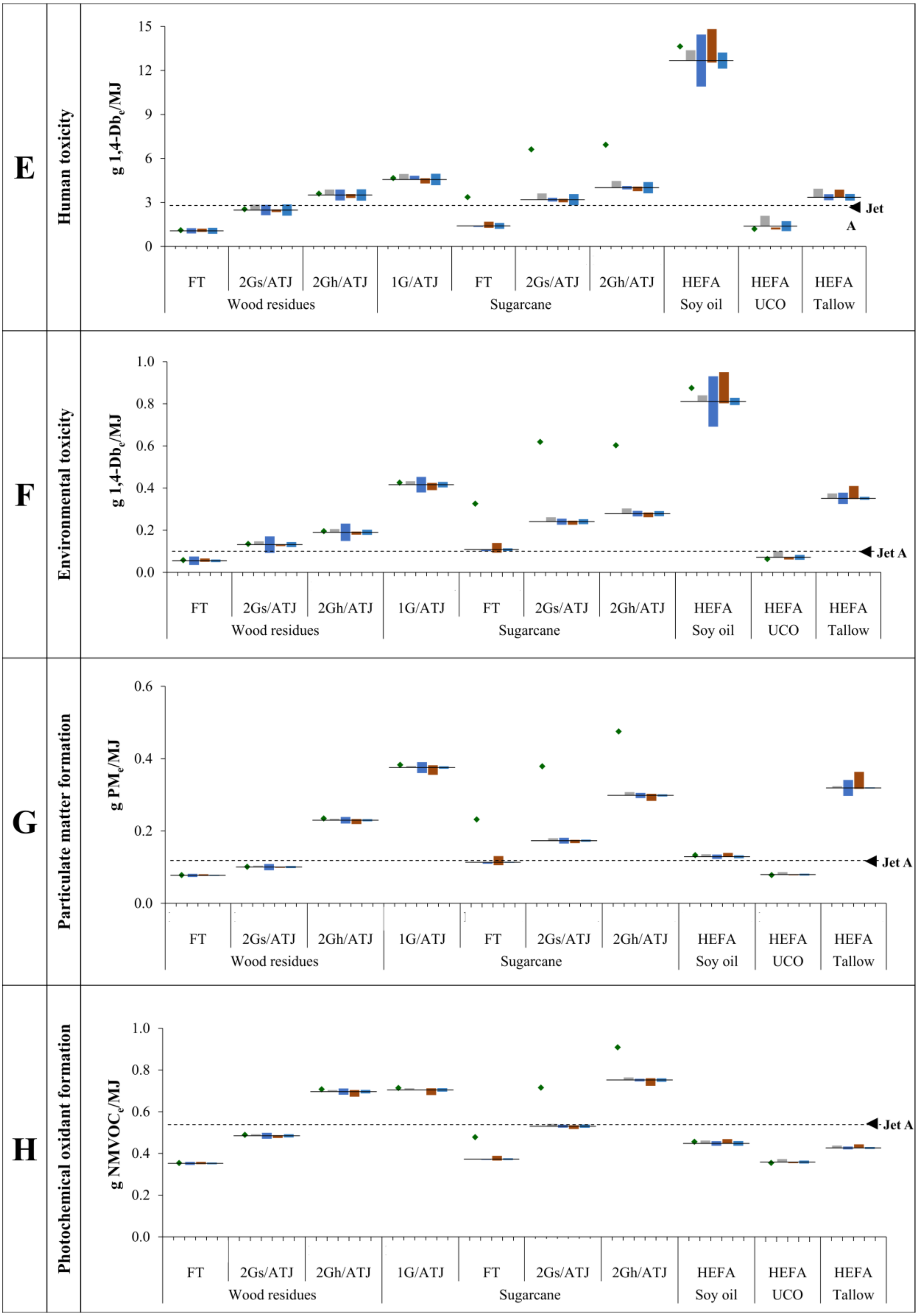
Considering the downstream yields, the sensitivity analysis was carried out using the typical ranges reported in the literature for RJF technologies. In general, climate change, fossil depletion, and toxicity impacts were the most sensitive categories. In HEFA pathways – assuming (-15% to +1%) on the process yield – the original values increase up to 20% and decrease by around 1%, respectively, for these impact categories. Soy oil/HEFA presents similar variations as the eutrophication results. In ATJ pathways, the results range similarly to the downstream yields (-2% to +7%), *i.e.,* the original values increase by around 2% and decrease by 7%, respectively. For FT pathways, the same is observed.

Hydrogen production via water electrolysis (WE) would increase GHG emissions in 1G pathways by 8% (2.5 gCO_{2e}/MJ at SC_1G/ATJ) and 13% (4.7 gCO_{2e}/MJ at Soy oil/HEFA). On the same way, for 2G pathways at S2, GHG emissions would be on average 15% higher in ATJ pathways and 2% or 35% in Tallow/HEFA or UCO/HEFA, respectively. Otherwise, the fossil depletion would decrease by around 20% for ATJ pathways (1.5 g_oil_e/MJ); 37% (2.5 g_oil_e/MJ) in Tallow/HEFA, or 30-45% (2.95 g_oil_e/MJ) in Soy oil/HEFA and UCO/HEFA, respectively. It's clearly observed that the relevant contribution of renewable energy sources in Brazilian grid (84%, according to EPE, 2018) provides a lower fossil depletion. Nevertheless, the high demand of electricity by the WE process associated to the hydrogen use in the RJF production explain the positive variations on climate change.

Fossil depletion and human toxicity present reasonable sensitivity to ±50% of the transportation distance than other categories for wood-based pathways. In these cases, the results would vary on average ±15%.

Figure SM.2: Sensitivity analysis of the environmental impacts of RJF pathways, at System 2 (S2).




E
Human toxicity
g 1,4-Db$_e$/MJ
15
12
9
6
3
0
Jet A
FT
2Gs/ATJ
2Gh/ATJ
1G/ATJ
FT
2Gs/ATJ
2Gh/ATJ
HEFA Soy oil
HEFA UCO
HEFA Tallow
Wood residues
Sugarcane
F
Environmental toxicity
g 1,4-Db$_e$/MJ
1.0
0.8
0.6
0.4
0.2
0.0
Jet A
FT
2Gs/ATJ
2Gh/ATJ
1G/ATJ
FT
2Gs/ATJ
2Gh/ATJ
HEFA Soy oil
HEFA UCO
HEFA Tallow
Wood residues
Sugarcane
G
Particulate matter formation
g PM$_e$/MJ
0.6
0.4
0.2
0.0
Jet A
FT
2Gs/ATJ
2Gh/ATJ
1G/ATJ
FT
2Gs/ATJ
2Gh/ATJ
HEFA Soy oil
HEFA UCO
HEFA Tallow
Wood residues
Sugarcane
H
Photochemical oxidant formation
g NMVOC$_e$/MJ
1.0
0.8
0.6
0.4
0.2
0.0
Jet A
FT
2Gs/ATJ
2Gh/ATJ
1G/ATJ
FT
2Gs/ATJ
2Gh/ATJ
HEFA Soy oil
HEFA UCO
HEFA Tallow
Wood residues
Sugarcane

References

1. ICAO. Assembly Resolutions in Force; A39-2: Consolidated statement of continuing ICAO policies and practices related to environmental protection — Climate change [Internet]. Montreal; 2016. Report No.: Doc 10075. Available from: https://www.icao.int/Meetings/a39/Documents/Resolutions/10075_en.pdf
2. ICAO. Sustainable Aviation Fuel Guide [Internet]. 2017. Available from: https://www.icao.int/environmental-protection/GFAAF/Pages/default.aspx
3. Cortez LAB, Nigro FEB, Nassar AM, Cantarella H, Nogueira LAH, Moraes MAFD de, et al. Roadmap for sustainable aviation biofuels for Brazil — A Flightpath to Aviation Biofuels in Brazil [Internet]. São Paulo: Edgard Blücher; 2014. 272 p. Available from: http://openaccess.blucher.com.br/article-list/roadmap-aviation-272/list
4. Pearlson MN. A Techno-economic and Environmental Assessment of Hydroprocessed Renewable Distillate Fuels [Internet]. *Department of Aeronautics and Astronautics*. Massachusetts Institute of Technology; 2011. Available from: http://dspace.mit.edu/bitstream/handle/1721.1/65508/746766700.pdf?sequence=1
5. Klerk A De. Fischer–Tropsch fuels refinery design. *Energy Environ Sci [Internet]*. 2011;4(4):1177. Available from: http://xlink.rsc.org/?DOI=c0ee00692k
6. Moreira M, Gurgel AC, Seabra JEA. Life Cycle Greenhouse Gas Emissions of Sugar Cane Renewable Jet Fuel. *Environ Sci Technol*. 2014;48:14756−14763.
7. Staples MD, Malina R, Olcay H, Pearlson MN, Hileman JI, Boies A, et al. Lifecycle greenhouse gas footprint and minimum selling price of renewable diesel and jet fuel from fermentation and advanced fermentation production technologies. *Energy Environ Sci [Internet]*. 2014;7(5):1545. Available from: http://xlink.rsc.org/?DOI=c3ee43655a
8. ASTM. ASTM D7566-20 Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons. West Conshohocken, Pennsylvania, USA; 2020.
9. Dodd H. Strategic Considerations [Internet]. *Sustainable Aviation Fuel Symposium - IATA*. Singapore; 2018 [cited 2019 Dec 6]. Available from: https://www.iata.org/events/Pages/alternative-fuels-symposium.aspx
10. Feuvre P Le. The Big Picture [Internet]. *Sustainable Aviation Fuel Symposium - IATA*. Singapore; 2018 [cited 2019 Nov 6]. Available from: https://www.iata.org/events/Pages/alternative-fuels-symposium.aspx
11. EPE. National Energy Balance [Internet]. Brasilia; 2020 [cited 2019 Oct 26]. Available from: https://ben.epe.gov.br/BENSeriesCompletas.aspx
12. U.S. EPA. Renewable Fuel Standard Program (RFS2) Regulatory Impact Analysis. *EPA-420-R-10-006*. 2010.
13. European Union. Renewable Energy Directive 2009/28/EC -Promotion of the use of energy from renewable sources [Internet]. 2009. Available from: https://ec.europa.eu/jrc/en/jec/renewable-energy-recast-2030-red-ii
14. IBA. Annual Report - Brazilian Tree Industry [Internet]. 2019 [cited 2020 Jul 14]. p. 80. Available from: http://iba.org/images/shared/Biblioteca/IBA_RelatorioAnual2017.pdf
15. Corbella C, Puigagut J, Garfí M. Life cycle assessment of constructed wetland systems for wastewater treatment coupled with microbial fuel cells. *Sci Total Environ [Internet]*. 2017 Apr;584–585:355–62. Available from:

https://linkinghub.elsevier.com/retrieve/pii/S0048969716328820
16. Zhang P, Huang G, An C, Fu H, Gao P, Yao Y, et al. An integrated gravity-driven ecological bed for wastewater treatment in subtropical regions: Process design, performance analysis, and greenhouse gas emissions assessment. *J Clean Prod [Internet]*. 2019 Mar;212:1143–53. Available from: https://doi.org/10.1016/j.jclepro.2018.12.027
17. Klein BC, Chagas MF, Junqueira TL, Rezende MCAF, Cardoso T de F, Cavalett O, et al. Techno-economic and environmental assessment of renewable jet fuel production in integrated Brazilian sugarcane biorefineries. *Appl Energy [Internet]*. 2018 Jan;209(August 2017):290–305. Available from: https://doi.org/10.1016/j.apenergy.2017.10.079
18. de Jong S, Antonissen K, Hoefnagels R, Lonza L, Wang M, Faaij A, et al. Life-cycle analysis of greenhouse gas emissions from renewable jet fuel production. *Biotechnol Biofuels [Internet]*. 2017 Dec 14;10(1):64. Available from: http://biotechnologyforbiofuels.biomedcentral.com/articles/10.1186/s13068-017-0739-7
19. Han J, Elgowainy A, Cai H, Wang MQ. Life-cycle analysis of bio-based aviation fuels. *Bioresour Technol [Internet]*. 2013;150:447–56. Available from: http://linkinghub.elsevier.com/retrieve/pii/S0960852413012297
20. Han J, Tao L, Wang M. Well-to-wake analysis of ethanol-to-jet and sugar-to-jet pathways. *Biotechnol Biofuels [Internet]*. 2017 Dec 24;10(1):21. Available from: http://biotechnologyforbiofuels.biomedcentral.com/articles/10.1186/s13068-017-0698-z
21. Cavalett O, Cherubini F. Contribution of jet fuel from forest residues to multiple Sustainable Development Goals. *Nat Sustain [Internet]*. 2018 Dec 19;1(12):799–807. Available from: http://www.nature.com/articles/s41893-018-0181-2
22. Seber G, Malina R, Pearlson MN, Olcay H, Hileman JI, Barrett SRH. Environmental and economic assessment of producing hydroprocessed jet and diesel fuel from waste oils and tallow. *Biomass and Bioenergy [Internet]*. 2014;67:108–18. Available from: http://linkinghub.elsevier.com/retrieve/pii/S0961953414002189
23. Staples MD, Olcay H, Malina R, Trivedi P, Pearlson MN, Strzepek K, et al. Water consumption footprint and land requirements of large-scale alternative diesel and jet fuel production. *Environ Sci Technol.* 2013;47(21):12557–65.
24. Cox K, Renouf M, Dargan A, Turner C, Klein-Marcuschamer D. Environmental life cycle assessment (LCA) of aviation biofuel from microalgae, Pongamia pinnata , and sugarcane molasses. *Biofuels, Bioprod Biorefining [Internet]*. 2014 Jul;8(4):579–93. Available from: http://doi.wiley.com/10.1002/bbb.1488
25. Li X, Mupondwa E. Life cycle assessment of camelina oil derived biodiesel and jet fuel in the Canadian Prairies. *Sci Total Environ [Internet]*. 2014;481(1):17–26. Available from: http://dx.doi.org/10.1016/j.scitotenv.2014.02.003
26. UN. Work of the Statistical Commission Pertaining to the 2030 Agenda for Sustainable Development: Resolution Adopted by the General Assembly on 6 July 2017 [Internet]. 2017. Available from: http://ggim.un.org/documents/A_RES_71_313.pdf
27. ISO. ISO 14040:2006 Environmental management -- Life cycle assessment -- Principles and framework [Internet]. *International Organization for Standardization, editor.* 2006 p. 20. Available from: https://www.iso.org/standard/37456.html
28. JCR. International Reference Life Cycle Data System (ILCD) Handbook: General

guide for Life Cycle Assessment - Detailed guidance. 1st ed. *Joint Research Centre - Institute for Environment and Sustainability, editor.* Luxembourg; 2010. 417 p.
29. ANP. Renovabio - National Policy of Biofuels [Internet]. *National Agency of Petroleum Natural Gas and Biofuels.* 2018 [cited 2018 Dec 16]. Available from: http://www.anp.gov.br/producao-de-biocombustiveis/renovabio
30. U.S. EPA. Renewable Fuel Standard (RFS2): Final Rule Additional Resources [Internet]. *Renewable Fuel Standard (RFS2):* 2010 [cited 2019 Feb 11]. Available from: https://www.epa.gov/renewable-fuel-standard-program/renewable-fuel-standard-rfs2-final-rule-additional-resources
31. Sousa VMZ, Luz SM, Caldeira-Pires A, Machado FS, Silveira CM. Life cycle assessment of biodiesel production from beef tallow in Brazil. *Int J Life Cycle Assess.* 2017;22(11):1837–50.
32. RSB. Standard for Advanced Fuels - RSB-STD-01-010. Geneva, Switzerland; 2017.
33. Bonomi A, Cavalett O, Pereira da Cunha M, Lima MAP, editors. Virtual Biorefinery [Internet]. 1st ed. Cham: Springer International Publishing; 2016. 285 p. (Green Energy and Technology). Available from: http://link.springer.com/10.1007/978-3-319-26045-7
34. UNEP-SETAP. Global Guidance Principles for Life Cycle Assessment Databases. *Sonnemann G, Guido B, editors.* 2011. 160 p.
35. Bailis RE, Baka JE. Greenhouse gas emissions and land use change from Jatropha curcas-based jet fuel in Brazil. *Environ Sci Technol.* 2010;44(22):8684–91.
36. BRAZIL. Law 12651, 25/05/2012 [Internet]. *Lei de Proteção da Vegetação Nativa.* 2012 [cited 2019 Mar 20]. Available from: http://www.planalto.gov.br/ccivil_03/_Ato2011-2014/2012/Lei/L12651.htm
37. ICAO. Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) [Internet]. *International Civil Aviation Organization.* 2020 [cited 2020 Apr 28]. Available from: https://www.icao.int/environmental-protection/Pages/market-based-measures.aspx
38. Huijbregts MAJ, Steinmann ZJN, Elshout PMF, Stam G, Verones F, Vieira MDM, et al. ReCiPe2016: A harmonized life cycle impact assessment method at midpoint and endpoint level [Internet]. Bilthoven; 2016. Available from: https://www.rivm.nl/en/life-cycle-assessment-lca/downloads
39. Ecoinvent. Ecoinvent database. Version 3.3 [Internet]. Zurich; 2016 [cited 2017 Jun 6]. Available from: http://www.ecoinvent.ch/
40. NREL NREL. U.S. Life Cycle Inventory Database [Internet]. 2018 [cited 2018 Jun 29]. Available from: https://uslci.lcacommons.gov/uslci/search
41. ANL. GREET [Internet]. *Greenhouse gases, regulated emissions, and energy use in transportation.* Argonne: Argonne National Laboratory; 2020 [cited 2020 Jan 11]. Available from: https://greet.es.anl.gov/
42. IBICT/SICV. National database of Life Cycle Inventories (SICV) [Internet]. 2019 [cited 2019 Feb 5]. Available from: http://sicv.acv.ibict.br/Node/
43. IBGE. Brazilian Institute of Geography and Statistics [Internet]. *Municipal Agricultural Production.* 2019 [cited 2019 Aug 22]. Available from: https://sidra.ibge.gov.br/pesquisa/pam/tabelas
44. LNBR. Virtual Sugarcane Biorefinery (VSB) [Internet]. Campinas: Brazilian Biorenewables National Laboratory; 2018. Available from: https://lnbr.cnpem.br/
45. Coelho M. Personal Communication of a Brazilian Company of paper and cellulose. 2018.

46. Sugawara ET. Comparação dos desempenhos ambientais do B5 etílico de soja e do óleo diesel, por meio da Avaliação do Ciclo de Vida (ACV). [Internet]. [São Paulo]: Universidade de São Paulo; 2012. Available from: http://www.teses.usp.br/teses/disponiveis/3/3137/tde-16072013-122953/en.php
47. Humbird D, Davis R, Tao L, Kinchin C, Hsu D, Aden A, et al. Process Design and Economics for Biochemical Conversion of Lignocellulosic Biomass to Ethanol: Dilute-Acid Pretreatment and Enzymatic Hydrolysis of Corn Stover [Internet]. *Technical Report NREL/TP-5100-47764*. Golden, CO (United States); 2011. Available from: http://www.nrel.gov/biomass/pdfs/47764.pdf
48. España-Gamboa E, Mijangos-Cortes J, Barahona-Perez L, Dominguez-Maldonado J, Hernández-Zarate G, Alzate-Gaviria L. Vinasses: characterization and treatments. *Waste Manag Res [Internet]*. 2011 Dec 16;29(12):1235–50. Available from: http://journals.sagepub.com/doi/10.1177/0734242X10387313
49. Wilkie AC, Riedesel KJ, Owens JM. Stillage characterization and anaerobic treatment of ethanol stillage from conventional and cellulosic feedstocks. *Biomass and Bioenergy*. 2000;19(2):63–102.
50. Da Silva CRU, Franco HCJ, Junqueira TL, Van Oers L, Van Der Voet E, Seabra JEA. Long-term prospects for the environmental profile of advanced sugar cane ethanol. *Environ Sci Technol*. 2014;48(20):12394–402.
51. de Medeiros EM, Posada JA, Noorman H, Osseweijer P, Filho RM. Hydrous bioethanol production from sugarcane bagasse via energy self-sufficient gasification-fermentation hybrid route: Simulation and financial analysis. *J Clean Prod [Internet]*. 2017 Dec;168:1625–35. Available from: https://doi.org/10.1016/j.jclepro.2017.01.165
52. Gaddy JL, Arora D k., Ko C-W, Phillips JR, Basu R, Wikstrom CV, et al. Methods for increasing the production of ethanol from microbial fermentation. United States; US7285402B2, 2007.
53. Klein B. Personal Communication of Brazilian Bioethanol Science and Technology Laboratory. 2019.
54. IBGE. Brazilian Institute of Geography and Statistics [Internet]. *SIDRA Database - Consumer Expenditure Survey - POF*. 2019 [cited 2019 Nov 7]. Available from: http://www.sidra.ibge.gov.br/
55. INRA. INRA-CIRAD-AFZ feed tables [Internet]. *Institut national de la recherche agronomique*. 2018 [cited 2018 Dec 3]. Available from: https://feedtables.com/content/tallow
56. Marin A. Personal Communication of Hytron Company. 2018.
57. Lino FAM, Bizzo WA, Da Silva EP, Ismail KAR. Energy impact of waste recyclable in a Brazilian metropolitan. *Resour Conserv Recycl [Internet]*. 2010;54(11):916–22. Available from: http://dx.doi.org/10.1016/j.resconrec.2010.01.010
58. ANP. Oil, Natural Gas and Biofuels Statistical Yearbook 2019 [Internet]. Rio de Janeiro; 2020. Available from: http://www.anp.gov.br/publicacoes/anuario-estatistico/anuario-estatistico-2020
59. Coelho JM. Projeções da Demanda de Óleo Diesel e de Ciclo Otto [Internet]. Empresa de Pesquisa Energética; 2017. Available from: http://www.epe.gov.br/sites-pt/publicacoes-dados-abertos/publicacoes/PublicacoesArquivos/publicacao-244/topico-260/EPE_WORKSHOP COMBUSTIVEL BRASIL_JOSE MAURO_2017_1311.pdf
60. U. S. EPA. A comprehensive analysis of Biodiesel Impacts on Exhaust Emissions.

United States Air and Radiation Environmental Protection Agency. 2002.
61. Moore RH, Thornhill KL, Weinzierl B, Sauer D, D'Ascoli E, Kim J, et al. Biofuel blending reduces particle emissions from aircraft engines at cruise conditions. *Nature [Internet]*. 2017 Mar 16;543(7645):411–5. Available from: http://www.nature.com/articles/nature21420
62. Stratton RW, Wolfe PJ, Hileman JI. Impact of Aviation Non-CO 2 Combustion Effects on the Environmental Feasibility of Alternative Jet Fuels. *Environ Sci Technol [Internet]*. 2011 Dec 15;45(24):10736–43. Available from: http://pubs.acs.org/doi/abs/10.1021/es2017522
63. Donohoo P. Scaling Air Quality Effects from Alternative Jet Fuel in Aircraft and Ground Support Equipment. Massachusetts Institute of Technology; 2010.
64. Weidema BP, Wesnæs MS. Data quality management for life cycle inventories—an example of using data quality indicators. *J Clean Prod [Internet]*. 1996 Jan;4(3–4):167–74. Available from: https://linkinghub.elsevier.com/retrieve/pii/S0959652696000431
65. Goedkoop M, Oele M, Leijting J, Ponsioen T, Meijer E. Introduction to LCA with SimaPro [Internet]. 2016. Available from: https://www.pre-sustainability.com/download/SimaPro8IntroductionToLCA.pdf
66. Handler RM, Shonnard DR, Griffing EM, Lai A, Palou-Rivera I. Life Cycle Assessments of Ethanol Production via Gas Fermentation: Anticipated Greenhouse Gas Emissions for Cellulosic and Waste Gas Feedstocks. *Ind Eng Chem Res [Internet]*. 2016 Mar 30;55(12):3253–61. Available from: http://pubs.acs.org/doi/10.1021/acs.iecr.5b03215
67. Nemecek T, Kagi T. Life cycle inventories of Agricultural Production Systems, ecoinvent report No. 15 [Internet]. *Final report of Ecoinvent V2.0*. 2007. Available from: http://www.upe.poli.br/~cardim/PEC/Ecoinvent LCA/ecoinventReports/15_Agriculture.pdf
68. Jungblut N, Dinkel F, Stettler C, Doka G, Chudacoff M, Dauriat A, et al. Life Cycle Inventories of Bioenergy. Ecoinvent report n.17. Dubendorf; 2007.
69. Tsiropoulos I, Faaij APC, Seabra JEA, Lundquist L, Schenker U, Briois J-F, et al. Life cycle assessment of sugarcane ethanol production in India in comparison to Brazil. *Int J Life Cycle Assess [Internet]*. 2014 May 25;19(5):1049–67. Available from: http://link.springer.com/10.1007/s11367-014-0714-5
70. Cavalett O, Chagas MF, Seabra JEA, Bonomi A. Comparative LCA of ethanol versus gasoline in Brazil using different LCIA methods. *Int J Life Cycle Assess [Internet]*. 2013 Mar 3;18(3):647–58. Available from: http://link.springer.com/10.1007/s11367-012-0465-0
71. Riskin SH, Porder S, Schipanski ME, Bennett EM, Neill C. Regional Differences in Phosphorus Budgets in Intensive Soybean Agriculture. *Bioscience [Internet]*. 2013 Jan;63(1):49–54. Available from: https://academic.oup.com/bioscience/article-lookup/doi/10.1525/bio.2013.63.1.10
72. Macedo I de C. Sugar cane's energy. Twelve studies on Brazilian sugarcane agribusiness and its sustainability. *União da Agroindústria canavieira do Estado de São Paulo, editor.* São Paulo: Belendis & Vertecchia; 2005. 230 p.
73. Berthoud A, Maupu P, Huet C, Poupart A. Assessing freshwater ecotoxicity of agricultural products in life cycle assessment (LCA): a case study of wheat using French agricultural practices databases and USEtox model. *Int J Life Cycle Assess [Internet]*. 2011 Sep 22;16(8):841–7. Available from:

http://link.springer.com/10.1007/s11367-011-0321-7
74. European Commission. Product Environmental Footprint Category Rules Guidance (PEFCR), v.6.3 [Internet]. 2018. Available from: http://ec.europa.eu/environment/eussd/smgp/pdf/PEFCR_guidance_v6.3.pdf
75. Schmidt Rivera XC, Bacenetti J, Fusi A, Niero M. The influence of fertiliser and pesticide emissions model on life cycle assessment of agricultural products: The case of Danish and Italian barley. *Sci Total Environ [Internet]*. 2017 Aug;592:745–57. Available from: http://dx.doi.org/10.1016/j.scitotenv.2016.11.183
76. Nordborg MK. Pesticide use and freshwater ecotoxic impacts in biofuel feedstock production: a comparison between maize, rapeseed, Salix, soybean, sugarcane and wheat. Chalmers University of Technology; 2013.
77. Benosa G, Zhu S, Kinnon M Mac, Dabdub D. Air quality impacts of implementing emission reduction strategies at southern California airports. *Atmos Environ [Internet]*. 2018;185(April):121–7. Available from: https://doi.org/10.1016/j.atmosenv.2018.04.048
78. IPCC. IPCC Guidelines for National Greenhouse Gas Inventories - Volume 4 - Agriculture, Forestry and other land use. *Eggleston H., Buendia L, Miwa K, Ngara T, Tanabe K, editors.* Kanagawa, Japan; 2006.
79. Oliveira LOF, Fernandes AHBM, Fernandes FA, Abreu UGP, Crispim SMA, Garcia JB. Comparison of methane emissions by cattle pastures in the Pantanal , between two seasons of the year . [Internet]. 2016. Available from: https://ainfo.cnptia.embrapa.br/digital/bitstream/item/150888/1/oliveira-comparison.pdf
80. Raucci GS, Moreira CS, Alves PA, Mello FFC, Frazão L de A, Cerri CEP, et al. Greenhouse gas assessment of Brazilian soybean production: A case study of Mato Grosso State. *J Clean Prod [Internet]*. 2015 Jun;96:418–25. Available from: http://dx.doi.org/10.1016/j.jclepro.2014.02.064
81. CEPEA C for AS on AE. Ethanol Index [Internet]. 2020 [cited 2020 Jan 10]. Available from: https://www.cepea.esalq.usp.br/en/indicator/ethanol.aspx
82. CCEE. Chamber of Electric Energy Commercialization [Internet]. *Preço de Liquidação das Diferenças - PLD, SE/CO regions.* 2018 [cited 2018 Nov 25]. Available from: https://www.ccee.org.br/portal/faces/pages_publico/o-que-fazemos/como_ccee_atua/precos/precos_medios
83. Seabra JEA, Tao L, Chum HL, Macedo IC. A techno-economic evaluation of the effects of centralized cellulosic ethanol and co-products refinery options with sugarcane mill clustering. *Biomass and Bioenergy [Internet]*. 2010;34(8):1065–78. Available from: http://dx.doi.org/10.1016/j.biombioe.2010.01.042
84. ECN. Database for biomass and waste [Internet]. 2018 [cited 2017 Jun 12]. Available from: https://phyllis.nl/
85. SEAB S of A and S. Forestry Prices [Internet]. 2018 [cited 2018 Dec 8]. Available from: http://www.agricultura.pr.gov.br/modules/conteudo/conteudo.php?conteudo=129
86. MDIC. COMEX-STAT Brazilian foreign trade statistics [Internet]. *Ministry of Industry, Foreign Trade and Services.* 2019 [cited 2019 Dec 8]. Available from: http://comexstat.mdic.gov.br/en/home
87. Scot Consultoria. Beef Tallow - Market price (Brazil Central region) [Internet]. 2018 [cited 2018 Nov 20]. Available from: https://www.scotconsultoria.com.br/
88. Elgowainy A, Dieffenthaler D, Sokolov V, Sabbisetti R, Cooney C, Anjum A. GREET

- Greenhouse gases, Regulated Emissions, and Energy use in Transportation [Internet]. Chicago: Argonne National Laboratory; 2013. Available from: https://greet.es.anl.gov/
89. ABIOVE. Database of Oil Brazilian Industry [Internet]. *Brazilian Association of Vegetable Oil Industries.* 2020 [cited 2020 Aug 2]. Available from: http://abiove.org.br/en/statistics/
90. Seabra JEA, Macedo IC, Chum HL, Faroni CE, Sarto CA. Life cycle assessment of Brazilian sugarcane products: GHG emissions and energy use. *Biofuels, Bioprod Biorefining [Internet].* 2011 Sep;5(5):519–32. Available from: http://doi.wiley.com/10.1002/bbb.289
91. Muñoz E, Navia R, Zaror C, Alfaro M. Ammonia emissions from livestock production in Chile : an inventory and uncertainty analysis. *J Soil Sci Plant Nutr.* 2016;16(1):60–75.
92. Garcilasso VP. Análise entre processos e matérias-primas para a produção de biodiesel. University of São Paulo; 2014.
93. EMBRAPA. Tecnologias de Produção de Soja: Região Central do Brasil 2014. Londrina; 2013.
94. Corrêa ES, Vieira A, Costa FP, Cezar IM. Sistema semi-intensivo de produção de carne de bovinos nelores no Centro-Oeste do Brasi. Campo Grande; 2000.
95. Ribeiro AC., Guimarães PTG., Alvarer VH. Recomendações para uso de corretivos e fertilizantes em Minas Gerais. Viçosa: Comissão de Fertilidade do Solo do Estado de Minas Gerais; 1999. 359 p.
96. ANDA. Brazilian national fertilizer association [Internet]. 2018 [cited 2018 Jun 1]. Available from: http://www.anda.org.br
97. Bragatto J. Avaliação do potencial da casca de Eucalyptus spp . para a produção de bioetanol. Universidade de São Paulo - Escola Superior de Agricultura “ Luiz de Queiroz ”; 2010.

5 Discussions

In 2010, the International Civil Aviation Organization (ICAO) set forth ambitious targets to decarbonize the aviation sector, aiming to reduce GHG emissions from international flights[1]. The use of alternative aviation fuels (AJF) is a crucial way to achieve these objectives.

Currently, seven pathways for producing AJF have been approved for use as drop-in fuels within blending limits with fossil kerosene[2]. These pathways are based on oleaginous biomass, sugar/starch-based feedstocks, and lignocellulosic materials. In the last decade, more than two thousand commercial flights have operated using AJF, which has been supplied regularly at six airports worldwide. It is expected that 2% of fossil kerosene demand in 2025 will be supplied by AJF[3].

Considering the Brazilian potential and its expertise in bioenergy production[4], a question arises: "***Can Brazil help a sustainable energy transition for the aviation sector?***"

The production and use of AJFs can lead the energy-intensive aviation sector – which has been exclusively dependent on fossil fuels – to an effective energy transition. However, it is reasonable to argue that, for a sustainable transition, the potential of each AJF pathway should be evaluated in a broader perspective.

This thesis aimed to contribute to this discussion addressing specific knowledge gaps, such as the different methodological approaches for carbon emissions accounting, the cost-effectiveness of carbon emissions reduction through AJF, and the environmental performance of AJF pathways regarding other environmental categories.

The main results, which are presented in the previous chapters (**Chapters 2-4**), are combined in **Figure 5.1**. The values were normalized according to the maximum values reported for each category.

The performance of fossil kerosene (Jet A) in all issues considered here (see grey areas in **Figure 5.1**) is essential for a comparative analysis with AJFs. Besides the results for Jet A already reported in the previous chapters, for the category "*Potential production of AJF*", it was considered 50% volume of the Jet A consumed in Brazil in 2018 (7.2 billion liters)[5], since it is the maximum approved blend of AJF with fossil kerosene, for certified pathways. For the category "*carbon mitigation*", the AJF performance was compared with the total carbon emission estimated for the aviation sector in Brazil (16.7 $MtCO_{2e}$ in 2018)[6]. In turn, for the category "*mitigation costs*", no value was assumed for Jet A, and the AJFs were compared among each other.

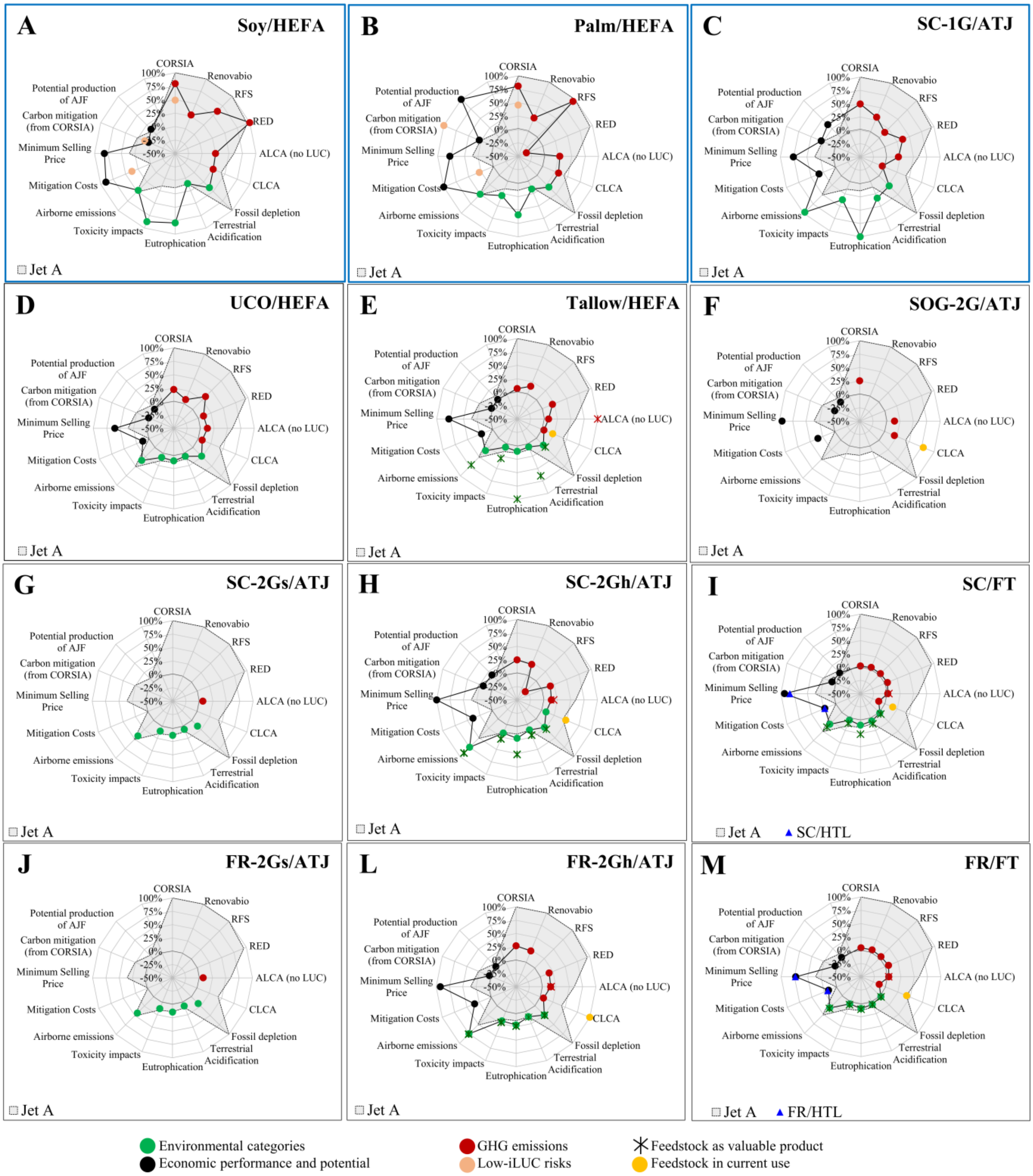


Figure 5.1: Multi-criteria evaluation for AJF produced in Brazil considering the parameters assessed in this thesis. Values were normalized according to the maximum values reported for each category. Food-based pathways (1G) are outlined with a blue line. 1G: first-generation ethanol mill; 2Gh: second-generation ethanol mill from enzymatic hydrolysis; 2Gs: second-generation ethanol mill from syngas fermentation; ALCA: attributional LCA; ATJ: Alcohol-to-Jet; CLCA: consequential LCA; FR: Forestry residues; FT: Fischer-Tropsch; HEFA: Hydroprocessed Esters and Fatty Acids; HTL: Hydrothermal Liquefaction; LUC: Land Use Change; SC: Sugarcane; SOG: Steel off-gases; UCO: Used Cooking Oil.

Chapter 2, whose main outcomes are shown in red dots, explored the carbon footprint of AJFs (gCO_{2e}/MJ) under six different approaches: the attributional LCA and the consequential LCA, and four regulatory schemes of Low-Carbon Policies (*RenovaBio*, CORSIA, RFS, and REDII). It is worth mentioning that, although the pathways based on syngas fermentation (see **Figure 5.1.G** and **5.1.J**) were evaluated only in **Chapter 4**, the results related to their potential impacts on climate change (in gCO2e/MJ) are expressed in red dots.

In turn, the results from **Chapter 3** (see black dots) expressed the potential AJF production and carbon mitigation (Mt CO_{2e}) considering the feedstock availability for each AJF pathway, as well as their economic performance – reported as the minimum selling price (MSP, USD/GJ) – and their mitigation costs (USD/tCO_{2e} reduced).

Finally, the green dots summarize the results presented in **Chapter 4**, where the environmental performance of AJFs pathways was analyzed for seven other relevant impact categories than climate change, *i.e.,* fossil depletion, terrestrial acidification, eutrophication, human toxicity, environmental toxicity, photochemical oxidant formation, and particulate matter formation. It is worth mentioning that, in **Figure 5.1**, human and environmental toxicity were combined in the "Toxicity impacts" label, while "Airborne emissions" comprise the average levelized impacts of particulate matter formation and photochemical oxidant formation. These arbitrary aggregations aim to provide better visualization of the results, and it was not intended to represent any particular environmental mechanism.

Considering the strategic potential of Palm/HEFA and the common concerns related to it, the environmental performance of this pathway, which was not analyzed in **Chapter 4**, was completed here (see green dots in **Figure 5.1.B**). For this, an LCA was carried out using similar assumptions and methods than Soy/HEFA and SC-1G/ATJ in **Chapter 4**, basing on the inventory reported in the Supplementary Material in **Chapter 2** (**Table SM.4**). On the other hand, the results related to the hydrothermal liquefaction of lignocellulosic residues (SC/HTL and FR/HTL) – which was evaluated only in **Chapter 2** – were combined with the results of AJF produced with Fischer-Tropsch technology (see **Figures 5.1.I** and **5.1.M**).

As mentioned in the introduction of this thesis (**Chapter 1**), each subsequent chapter was motivated by one specific research question, which is answered and discussed as follows (**sections 5.1** to **5.3**). Basing on these discussions, future studies are recommended in **section 5.4**.

5.1. Could AJF produced in Brazil reduce GHG emissions in comparison with fossil fuel?

As observed in **Figure 5.1** (red dots), the AJF produced in Brazil from pathways based on food crops (1G pathways) or residual feedstocks (2G pathways) can provide GHG reductions for all approaches. Soy/HEFA tends to provide the lowest GHG reduction (20-73%), and the SC-1G/ATJ is the best alternative for 1G pathways under most approaches (51-112%), mainly when power surplus is credited. The potential GHG reductions provided by 2G pathways (50 - 130%) tend to be higher than 1G-based pathways since the emissions from the upstream stage are commonly disregarded, and residues are typically assumed to be available. Thermochemical conversion of lignocellulosic residues through FT technology could provide 94% to 130% GHG reductions.

Two methodological issues led to great differences among the approaches: i) emissions related to land use change (LUC) in 1G pathways, and ii) consequential emissions related to by-products or residual feedstock procurement when it is not freely available.

The former is relevant for decision-making, especially under regulatory schemes. Taking the CORSIA scheme, SC-1G/ATJ would be still the best alternative of the 1G pathways (51% of GHG reduction), while Soy/HEFA and Palm/HEFA resulted in reductions of only 20%, mainly due to relevant LUC emissions, which correspond to more than 40% of the carbon footprint.

The default LUC values assumed for CORSIA[7] comprise induced land use change (iLUC) emissions[8], and they are currently available in Brazil only for soybean and sugarcane. There is no default value (until the publication of this work) for palm expansion in Brazil. Hence, the Palm/HEFA performance related to CORSIA and reported here was based on palm expansion in Malaysia/Indonesia, which probably led to overestimated values since most emissions in that region have been driven by palm expansion onto peatlands and native forests.

Despite these discrepancies, 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[9], 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 displacing other services, such as food, feed, and bioenergy[9].

According to Ramalho Filho *et al.*[10], 7.3 Mha of already deforested areas in the Amazon region would be highly suitable for palm expansion through tillage with modest technological levels. The potential areas could reach 29.6 Mha, also assuming lands with regular suitability. Although the authors considered deforested areas in 2006, these available lands would correspond to more than all global palm harvest areas in 2018[11], indicating a considerable potential for Brazilian palm expansion, as highlighted by some other authors[12,13].

Even so, risks for indirect deforestation from reallocating cattle activities[13,14], which already occupy some deforested areas, should be considered. Additionally, it is worth stressing the deforestation risks to provide a suitable infrastructure for transporting fresh fruit palm bunches[15]. Currently, some potential regions for palm expansion are accessed by roads in poor conditions, and the transportation of fresh fruit bunches from field to mill must happen quickly to guarantee the quality of the feedstock.

There are some ongoing research initiatives for expanding palm crops onto degraded pasturelands in Brazilian cerrado (tropical savannas). Despite the demand for irrigation, in this case, the agricultural yields have been higher than palm crops in Amazon regions[16,17].

Soybean could eventually fit low-risks iLUC requirements by CORSIA if its yield increases from adopting sequential cropping, *i.e.,* the combination of two or more crops that grow at different periods of the year, or intercropping, *i.e.*, the combination of two or more crops that grow simultaneously[9]. The eligible share of low-iLUC feedstocks corresponds to the net feedstock production attributable to adopting these management practices, relative to the historical practices from the preceding five years. The sequential cropping of soybean with maize, cotton, or millet has become common in Brazil over the last twenty years[18]. In 2011, half of the soybean crop in Mato Grosso State – the larger Brazilian soybean producer –is already developed in double-cropping systems, while only 3.5% of the global soybean production is cultivated through this practice[18]. Otherwise, relevant gains on soybean yield have not been observed through intercropping practices[19,20]. Likewise, other authors have reported productivity losses related to soybean-forestry systems[21,22].

Other oil-bearing plants with high agricultural yields – such as macaw (*Acronomia Aculeata*) [23] – have been frequently considered as sustainable alternatives for bioenergy production. Plath *et al.* (2016)[23] reported a high potential for macaw expansion of 6.2 Mha in the Southern Brazilian region with highly suitable environmental conditions. While the potential distribution area of macaw identified by those authors is mostly outside of tropical rainforests region, its expansion would decrease possible pressures related to Amazon deforestation, which were also related to soybean and palm expansion in the last decades[14,24]. Furthermore, macaw crops occur in pasturelands and, as palm crops, it can be used for recovering degraded areas. Additionally, since macaw products are not largely used for food, their use for bioenergy production would not directly compete with food[25].

On the other hand, several research gaps should be overcome before considering macaw expansion and its commercial production. It depends on the research efforts for addressing genetic relationships between different botanical species in the same area, quality seedlings, and sustainable plantation models[23,25]. Cortez *et al.*[4] estimated that, at least, for the next 20 years, the AJF industry should not be count on this feedstock.

As observed in **Figures 5.1.A**, **5.1.B,** and **5.1.C** (see red dots), according to the current Brazilian policy for supporting biofuels use (*RenovaBio*), 1G pathways had similar performance – *i.e.,* around 70% of GHG reduction in comparison with fossil kerosene – since LUC is considered only as eligibility criteria and it is not accounted for.

It is worth stressing that the eligible areas for biomass production in each regulatory scheme respect different timeframes and definitions. It can lead to some conflicts since the same biofuel can be eligible for one regulatory scheme and not for another. While *RenovaBio* allows biofuels from native vegetation converted before December 2018[26], CORSIA and REDII allow biofuels from specif land categories converted before January 2008[27,28]. Furthermore, the definitions of the "no-go" areas for biofuel production are not always convergent. For *RenovaBio*, "native vegetation" comprises primary and secondary forests, as well as primary and secondary grasslands[29]. On the other hand, according to the original CORSIA's criteria[27], "no-go" areas comprise explicitly only primary forest, wetlands, and peatlands. In turn, the REDII scheme added high biodiversity grasslands and areas protected by law to the "no-go" areas set by CORSIA.

To supply the European market (see red dots in **Figure 5.1** for *RED*) – which is responsible for one-third of all international aviation operations[30] – Palm/HEFA (**Figure 5.1.B**) and SC-1G/ATJ (**Figure 5.1.C**) could be feasible options, assuming biomass production from pasture lands. In this case, the minimum threshold defined by REDII (50-

65% GHG reduction)[28] is achieved, which does not happen with Soy/HEFA (**Figure 5.1.A**) mainly due to land use emissions.

However, the current version of the European Directive has limited food/feed-based biofuels and has proposed decreasing limits for those related to high-iLUC risks. According to REDII[31], high-iLUC risk biofuels are obtained from feedstocks with significant expansion into high-carbon lands[28]. For instance, 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[32]. On the other hand, low iLUC risk biofuels – *i.e.*, obtained from residues-based feedstocks or obtained from abandoned or severely degraded lands or smallholders – will play an important role in Europe in the coming years.

At first glance, the Brazilian palm obtained from degraded Amazon areas could fit the RED requirements for low-iLUC risk fuel. Over the last years (2010-2018), according to Benami *et al.*[14], palm expansion in Brazil, which is mostly concentrated in Pará State, has been associated with a decreasing rate of direct deforestation: while in 2006-2010, 4.0% of the new palm areas came from the direct conversion of primary forest, in 2010-2014, it decreased to 0.8%, while more than 90% of palm expansion came from the conversion of pasturelands conversion. It is worth mentioning that the current areas dedicated to palm crops in Brazil correspond to less than 1.0% of the potential degraded areas for palm expansion[10]. Nonetheless, some authors[13,14] have pointed out risks for increasing palm oil demand from Brazil, which may lead to expansion into native forests since the current palm plantations are very close to them and already have an infrastructure for transporting fruits.

From the few AJF pathways currently approved under RFS, none correspond to pathways evaluated here. The results reported in **Figure 5.1** (see red dots for *RFS*) were estimated from the models for AJF available in GREET and assuming the induced effects of co-products and land use changes already reported for biodiesel and ethanol[33]. SC-1G/ATJ was the best alternative for the 1G pathways, also due to the benefits of the credits related to power surplus. On the other hand, Soy/HEFA and Palm/HEFA were based on biomass expansion in the United States and Malaysia, respectively. Thus, different results could be expected if land use-related effects were assumed in Brazil.

Regarding the performance of 2G pathways, as above-mentioned, attributing a null environmental burden to residual feedstocks procurement results in a relevant potential for GHG reductions of at least 75%. Under RFS guidelines, which are exclusively based on consequential LCA, these pathways reached more than 65% GHG reductions, mostly because the feedstocks are assumed to be freely available for biofuel production. These typical assumptions, although appropriate in several cases, may benefit the performance of residues-based pathways indistinguishably.

The consolidated market for some residual feedstocks could lead to some competition between current use and AJF production. For instance, around 60% of beef tallow generated in Brazil is used for biodiesel production[5,34,35], while the remainder is destined for the cleaning industry and animal feed[36]. In turn, at least 60% of steel refining off-gases have been recovered to supply the internal energy demand[37] in Brazilian steel mills, which indicates that it has become a common practice in steelmaking processes.

Regarding lignocellulosic residues, most forestry residues – such as barks, branches, and leaves – generated during harvest operations are kept on field[38,39]. However, the recovery and use of forestry residues for energy generation – when debarking is made at the plant, for instance – is a common practice in some wood-based industries[39]. In addition, although small, 1% of the installed power capacity at Brazilian thermal plants is related to forestry residues[40].

Sugarcane residues are commonly used in CHP systems to supply the internal energy demand by ethanol distilleries, corresponding to 28% of the installed capacity in Brazilian thermal plants. In 2019, around 6% of the power generated in Brazil came from sugarcane residues. There is not a consolidated market for sugarcane residues yet[41], and alternative uses could compete with current power generation. Furthermore, sugarcane residues could be freely available in the current sugarcane mills at expenses of technical improvements in the process, comprising efficient gains, including the CHP system.

Considering the growing or consolidated market for residues, possible consequences from deviating residual feedstock from its current use to produce biofuel are not covered by any regulatory scheme. In this case, the performance of 2G pathways could vary substantially if these consequences were captured.

From a consequential LCA, the potential GHG reduction of Tallow/HEFA decreased from 91% to 50% (**Figure 5.1.E**), mostly led by the replacement of beef tallow from its current use to soybean oil. In turn, AJF via SOG-2G/ATJ (**Figure 5.1.F**) could provide GHG emissions 82% higher than fossil kerosene, assuming that the currently recovered steel off-gases are replaced by natural gas. Alternatively, the deviation of sugarcane and forestry residues from their current use to produce AJF could imply marginal power and heat demands. In these cases, the carbon footprint of SC-2Gh/ATJ (**Figure 5.1.H**) and FR-2Gh/ATJ (**Figure 5.1.L**) would become 12% and 132% higher than fossil kerosene, respectively; or only 1% lower for FR/FT (**Figure 5.1.M**).

5.2. How much would cost the carbon mitigated by each AJF pathway?

The total Brazilian annual demand for fossil kerosene reached roughly 7.0 million m³ in 2018 [6]. However, considering the blend limits for approved AJF pathways – *i.e.*, 50% (v/v) for the technologies assumed here – the maximum possible demand for AJF would be 3.5 million m³, which could be supplied exclusively by residues-based pathways, with a special highlight for the potential production of AJF from 2G ethanol obtained from sugarcane residues (5.9 million m³, see **Figure 5.1.H**). The potential production of AJF from waste-greases and steel off-gases corresponds to what was demanded by international flights originating in Brazil (1.5 million m³) in 2018, assuming the maximum approved blend.

On the other hand, the potential AJF production from 1G pathways exceeds the maximum demand for aviation fuel by 1.4 times (Soy/HEFA, **Figure 5.1.A**), 3.6 times (SC-1G/ATJ, **Figure 5.1.C**) to 10.8 times (Palm/HEFA, **Figure 5.1.B**), considering the available areas estimated by Cervi *et al.*[42]. It is worth mentioning that, for the estimation of these available areas (19.1. Mha for soybean, 3.9 Mha for sugarcane, and 23.5 Mha for palm), it was considered simultaneous competition with other biomass to produce AJF and no competition with the current land use, such as for food and feed.

Even considering the areas with high suitability for palm expansion[10] (7.4 Mha), it still would provide 11.8 million m³ of AJF, *i.e.,* 3-fold higher than maximum Brazilian demand.

According to the agro-zoning of sugarcane[43] and the recent expansion of the crop into pasturelands[44,45], around 10 Mha would be highly suitable for crop expansion, which could provide 32.0 million m³ of AJF. In addition, to supply the fuel demand of light vehicles in 2030-scenarios[46], ethanol production could double at the expense of sugarcane expansion in 1.9 Mha, suggesting that there is still a considerable potential for sugarcane expansion dedicated for supplying AJF. Considering the dynamics of different land use in the last years could provide a more accurate estimation for available areas for sugarcane expansion.

The total fossil kerosene demand in Brazil was forecasted at 9.0 to 10 million m³ in 2030 with an increasing share of imports (2.5 million m³)[47], which highlights the strategic importance of a supply-chain AJF. It is worth mentioning that, according to the Brazilian plans for energy expansion[47], the use of AJF is expected to be 1% of the national kerosene demand from 2027.

Despite this huge potential, none of the pathways were economically competitive with fossil kerosene (Jet A), according to the analysis carried out here and already pointed out in previous studies[48–51]. The minimum selling price (MSP) of AJFs was estimated at 69% (see black dot in UCO/HEFA, **Figure 5.1.D)** to 182% (SC-2Gh/ATJ, **Figure 5.1.H**) higher than fossil kerosene in Brazil, which presented an average of 15.9 USD/GJ in 2017-2019.

The values for 1G pathways remained within a narrow range of 33.7 USD/GJ (SC-1G/ATJ, **Figure 5.1.C**) to 36.4 USD/GJ (Soy/HEFA, **Figure 5.1.A**). On the other hand, the conversion of used cooking oil had the lowest value (26.4 USD/GJ), followed by the thermochemical conversion of forest residues (32.4 - 32.7 USD/GJ). ATJ-based pathways via 2G ethanol had the highest MSP (42.3 - 44.6 USD/GJ).

One option to decrease the overall production costs is to tackle the major cost-contributor aspects. Feedstock costs are relevant for HEFA-based pathways and AJF produced from 1G-ethanol (SC-1G/ATJ). In these cases, oleaginous feedstocks and 1G-ethanol corresponded to 50% and 80% of the overall values, respectively. In turn, gains on the production scale are more strategic for thermochemical processes, such as FT and HTL, where capital expenses corresponded to more than 40% of the overall costs. Finally, 2G ethanol production led to 85% of the overall costs in ATJ pathways, where the inputs, including utilities, were the main contributors.

None of the parameters evaluated in the sensitivity analysis – such as transportation distance, feedstock price, production scale, and interest rate (see **section 3.3.3**, **Chapter 3**) – led to MSPs lower than the highest Jet A prices (20.9 USD/GJ in the top ten percentile) observed in Brazil in 2004-2019. In general, variations on feedstock prices (±20%) were more influential on the MSP of HEFA-based pathways (±14%), while the production scale (±20%) and the interest rate (±30%) were relevant for ATJ-based pathways (±21%) and thermochemical process (±17%), respectively. HEFA-based pathways, SC-1G/ATJ, and the thermochemical conversion of forest residues could be competitive only with cumulative variations on these parameters.

Regarding the mitigation costs, in general, 2G pathways present lower values than 1G ones since the high carbon mitigation provided by residues-based pathways is combined with the relative production costs mostly led by the low acquisition costs of the feedstocks. Then, UCO/HEFA presented the lowest value (185 USD/tCO_{2e}), followed by the thermochemical conversion of forestry residues – *i.e.*, FR/FT (234 USD/tCO_{2e}) and FR/HTL (263 USD/tCO_{2e}) – and Tallow/HEFA (326 USD/tCO_{2e}). However, in some cases, the high costs for AJF production surpass the carbon mitigation, as observed in pathways based on 2G ethanol (507 - 575 USD/tCO_{2e}, see **Figures 5.1.F, 5.1.H,** and **5.1.L**) compared with AJF from 1G ethanol (495 USD/tCO_{2e}). Oil-based pathways had the highest results – *i.e.*, 1320-1470 USD/tCO_{2e} for Soy/HEFA and Palm/HEFA, respectively – especially due to land use emissions.

AJFs produced using Palm/HEFA and Soy/HEFA could be strategic options under CORSIA guidelines if they were obtained from certified areas with low-risks for land use changes, as previously mentioned. In this case, their related mitigation costs could decrease substantially by 58% and 72%, respectively, achieving 550 USD/tCO_{2e} (Soy/HEFA) and 420 USD/tCO_{2e} (Palm/HEFA).

According to potential on carbon mitigation (see **Chapter 3, Figure 3.4** for more details), waste grease-based pathways (UCO/HEFA and Tallow/HEFA) and thermochemical conversion of sugarcane and forestry residues could provide carbon mitigation equivalent to emissions from international flights originating in Brazil (around 7.6 MtCO_{2e} in 2018) with moderate costs (185 - 371 USD/tCO_{2e}). Considering the total potential, the pathways evaluated here could provide a reduction of 48.5 MtCO_{2e}, which is 8% of the carbon emissions related to international flights around the world – or 29% for international flights originating in Europe, or even 41% of the international flights originating in the American continent[52] – especially led by Palm/HEFA (**Figure 5.1.B**) and SC-1G/ATJ (**Figure 5.1.C**). In the case of Soy/HEFA (see pink dots in **Figure 5.1.A**) and Palm/HEFA obtained from low-iLUC risk areas, AJF produced in Brazil could mitigate 18% of the carbon emissions related to international aviation operations (98 MtCO_{2e}) at expenses of 185-575 USD/tCO_{2e}.

As discussed in **Chapter 3**, most mitigation costs of AJF are much higher than the current prices of the emission units (1.02 - 3.13 USD/tCO_{2e}) or even future ones (5.90 - 55.2 USD/tCO_{2e}), which indicates a preferably way in the short-term for airlines operators for achieving their GHG reduction targets for CORSIA. Some competitiveness is observed in UCO/HEFA or thermochemical conversion of forest residues assuming higher production scale and lower feedstock prices, according to the sensitivity analysis presented in **Chapter**

3 (**Figure 3.5**). Of the 1G pathways, SC-1G/ATJ seems to be a promising pathway presenting a minimum mitigation cost close to the maximum carbon price reported for future scenarios (see **Chapter 3** for more details).

On the other hand, several concerns about the credibility of the emissions units and their effective mitigation[53,54] indicate the great importance of AJF for the aviation sector goals. Indeed, only AJF, in the current circumstances and considering conditions of production, could lead the aviation sector to an effective energy transition associated with GHG reductions.

However, a new sector of fuels with all technology obstacles and current financial limits does not appear overnight and should be supported by robust policies. It is supposed that in the case of the current CORSIA guidelines[55], which treat carbon offset and carbon reduction equally, any effort to support initiatives for AJF production is discouraged or postponed since the carbon reduction targets can be achieved by airlines in the short-term by purchasing emission units that are much cheaper than carbon reduced through AJF.

In general, the current Low-Carbon policies (LCPs) do not still address AJFs[56] in a consistent way, like the biofuels for road transportation. Some LCPs – such as *RenovaBio* in Brazil and RFS in the United States – have already addressed some AJF pathways in their platforms. HEFA-based pathways are available in the *RenovaBio* tool[57] for evaluation, while four pathways based on HEFA and FT technologies are currently approved and categorized by RFS as advanced or cellulosic biofuels[58]. For the Low Carbon Fuel Standard (LCFS) in California, three AJF pathways based on Tallow/HEFA are already approved.

Furthermore, in the current LCPs, AJFs are still an "opt-in" provision, based on voluntary contribution, without specific targets or mandates, which lead to some concerns regarding the effectiveness of such policies to boost *de facto* AJF market. Additional issues should be considered in future policy efforts for promoting AJF: i) the still-high costs of AJF compared to fossil kerosene; ii) the substantial sensitivity of aviation operations to fuel prices that correspond to around 30% of the operations costs, on average[59]; and iii) the possible competition between AJF and other refining products, especially alternative diesel since the most conversion processes can be designed to favor the slate of one product over the other. In the latter issue, the producer's choice is highly influenced by the opportunity costs of each product.

Regarding the current incentives for aviation biofuels, in RED policy[28], the energy use from non-food-based AJFs can be counted 1.2 times for complying with the minimum renewable energy mandate. However, Pavlenko *et al.*[60] pointed out minimum impacts and unintended effects from applying the "1.2 multiplier", since maximizing AJF slate lead to higher costs and lower overall yield for liquid biofuels, as already estimated by Pearlson *et al.*[61], which would result in higher costs for the overall carbon reduction. Ambel[62] also stressed that the "1.2 multiplier" does not compensate the gap between the production costs of AJF and fossil kerosene. Furthermore, the author mentioned that higher multipliers could undermine an energy transition to renewable energy or even encourage the transfer of the high costs to preferentially produce AJF for road drivers since the fuel suppliers probable would avoid passing the full high costs exclusively to airlines.

Currently, *ReFuelEU*[63] is a new initiative aiming to make AJF take off in Europe. The original proposal for regulation – which is open for public consultation – comprises AJF blending mandate, funding mechanisms for developing AJF supply-chain, prioritization of AJF production compared with other biofuels, and the increase of RED multiplier. In a recent report, Murphy[64] suggests a blending AJF mandate of 1% to 2% of fossil kerosene demand in the European context, prioritizing AJF from residues.

According to Ghatala[56], RFS in the United States or LFSC (California) have also not favored AJF's competitiveness with alternative diesel, *i.e.*, AJF production is not attractive to be started or expanded from the producer's standpoint.

In RFS, while the production of AJF production is more expensive than alternative diesel, AJF would be related to a lower Renewable Identification Number (RIN) (1.6) than the alternative diesel (1.7) due to the lower volumetric energy content of the former than the latter. It is worth mentioning that RIN's generation is based on ethanol energy content, which corresponds to 1.0 RIN. Furthermore, RFS does not necessarily benefit biofuels pathways that provide the greatest GHG reduction. Regardless of the GHG performance of a biofuel, each one is categorized according to a minimum threshold emission, which does not motivate GHG reduction beyond this minimum value[65], discouraging more environmentally efficient processes.

In LFSC, which is also based on the GHG performance of fuels, the average carbon intensity (CI) assumed for renewable fuels and their fossil counterparts can lead to more credits to alternative diesel. While the CI of fossil diesel and the average CI for certified alternative diesel are 92.9 and 32.0, respectively, the CI for fossil kerosene and alternative jet fuel are reported as 89.4 and 35.0. It means that alternative diesel production can generate more credits than AJF.

Recent manifestations proposing policy adjustments to support an AJF market were summarized by Baines[65] and Ghatala[56] and comprised: i) explicit inclusion of AJF in the policy targets and blending mandates; ii) tax credits to decrease production costs and supporting investments, similarly what successfully happened with ethanol and biodiesel; iii) loan programs for expanding AJF industry; iv) setting RIN multiplier for AJF production similarly to RED; v) monetize other environmental benefits provided by AJF, such as air quality; and vi) value GHG reduction performance of each biofuels pathways motivating more efficient process designs.

The mitigation costs evaluated in **Chapter 3** would be a strategic indicator in the policy context since they price the efforts for GHG reductions directly, and help to provide a ranking for cost-effective pathways. Although LCPs are based on GHG reduction performance of the pathways, few of them explicitly incorporate the carbon price into policy mechanisms[60]. Nevertheless, none of the current LCP that price the carbon reduced, such as *RenovaBio* and LCFS, pays the mitigations costs estimated here for AJF production.

In *RenovaBio* (Brazil), the reduced carbon emissions (on life cycle basis) provided by a specific biofuel producer is traded in stock exchanges through Decarbonization Credits (called as *CBios*), according to pre-established decarbonization goals for fuel distributors and importers. Each CBIO corresponds to 1.0 tCO_{2e} reduced, and it was traded in 10.0 USD/tCO_{2e} at the first negotiations held in June 2020[66]. Although this value is far from the mitigation costs estimated here, the price projections for CBIOs are still uncertain due to doubts about taxation and commercial barriers[67]. For comparison purposes, LCFs prices in California – based on a more consolidated Low Carbon Policy (CARB) – ranged in 89-196 USD/tCO_{2e} in 2017-2019 and have stayed around 200 USD/tCO_{2e} in 2020[68].

It is worth emphasizing some concerns of the aviation sector regarding the role of *RenovaBio* for AJF promotion since the Brazilian market for biofuels comprises only ethanol and biodiesel. The current law of decarbonization goals for fuel distributors[69] does not consider fossil kerosene, although the HEFA-pathway is available on the *RenovaBio* tool for possible evaluation, and the inclusion of other pathways can be requested. Including fossil kerosene in the decarbonization goals, without a minimum consolidated supply-chain of AJF, could further harm the aviation sector since CBIOs would benefit the producers of biodiesel and ethanol instead of those that produce AJF. Several airlines and associations have suggested that fossil kerosene should be considered in decarbonization goals only when AJF corresponds to 1% of the total kerosene demand[70].

5.3. Could AJF bring other environmental benefits beyond GHG emissions mitigation?

As shown in **Figure 5.1** (see red dots), all pathways featured possible GHG reduction compared to fossil kerosene (Jet A), but trade-offs arose for local impact categories, primarily related to agricultural stages.

In these cases, although Soy/HEFA (**Figure 5.1.A**), Palm/HEFA (**Figure 5.1.B**), and SC-1G/ATJ (**Figure 5.1.C**) led to possible GHG reductions of more than 50%, they presented significant values for local impacts (see green dots on these figures). Trade-offs could be observed regarding the toxicity category, which is mostly related to agrochemicals use. Soybean crop presented much higher values (96.6$mg_{agrochemicals}/MJ_{AJF}$) than palm (13.6 mg/MJ_{AJF}) and sugarcane (8.8 mg/MJ_{AJF}), which led the former to environmental and human toxicity impacts three times higher than those for Palm/HEFA and SC-1G/ATJ, and about five times higher than those for Jet A. Episodes of water pollution with direct impact on riverside populations have already been reported for soybean[71,72] and palm[73] crops due to the use of pesticides.

Trade-offs comprising terrestrial acidification and eutrophication, which are related to fertilizer application, are more prominent in SC-1G/ATJ than Soy/HEFA and Palm/HEFA. Compared with Jet A, SC-1G/ATJ presented values three and seven times higher for both categories, respectively.

For airborne impacts – which comprise photochemical oxidant formation and particulate matter formation – the main differences between the pathways were mostly related to dinitrogen monoxide emissions in the agricultural stage and direct process emissions at industrial plants, including biomass use for energy purposes. While Palm/HEFA would release 45.5 gN_2O/MJ_{AJF} to the atmosphere – mainly due to crop residues kept on the field, and empty fruit bunches returned to it – Soy/HEFA and SC-1G/ATJ presented 35.5 and 24.2 gN_2O/MJ_{AJF}, respectively. In turn, the use of crop residues in industrial plants – such as shells and husks (16.8 $kg_{biomass}/ MJ_{AJF}$) that supplied the energy demand of palm mill – is lower than the use of sugarcane residues in ethanol mills (136.9 $kg_{biomass}$/ MJ_{AJF}). All these aspects led SC-1G/ATJ to two-fold higher impacts for these categories, even compared to Jet A.

Regarding fossil depletion, no trade-offs are observed. While fossil energy consumption is mainly related to hydrogen input, 1G pathways presented values 27% (SC-1G/ATJ) to 40% (Soy/HEFA) lower than Jet A.

When residual feedstock is treated as waste (see green dots in **Figures 5.1.D** to **5.1M**) – *i.e.*, assuming null burden for the feedstock procurement stage – some trade-offs were observed only in SC-2Gh/ATJ (**Figure 5.1.H**) and FR-2Gh/ATJ (**Figure 5.1.L**), which are related to process emissions in ethanol distilleries.

On the other hand, if the residual feedstock is treated as a by-product relevant trade-offs were encountered. See the green asterisks in **Figures 5.1.D** to **5.1M.** The most considerable discrepancy was observed for Tallow/HEFA (**Figure 5.1.F**), which confirms the high impacts related to pasture activities. For climate change, the values become 80% higher than Jet A, and even when compared to 1G pathways, the results for terrestrial acidification and eutrophication were 90% and 12% higher than SC-1G/ATJ, respectively. For pathways based on sugarcane residues (**Figure 5.1.G** to **5.1.I**), terrestrial acidification and eutrophication become, on average, 77% and four times higher than Jet A, respectively. No relevant variation was observed for wood residue-based pathways.

In general, FT pathways in both approaches, followed by UCO/HEFA, represented the highest potential reduction in GHG emissions (over 85%) with no relevant environmental trade-offs. In turn, the low dependence of external chemical inputs and utilities also led AJF from ethanol obtained via syngas fermentation to show good environmental performance (see **Figure 5.1.G** and **5.1.J**). The novel syngas technology has already reached commercial scale[74,75] and, despite its still weak competitiveness with conventional ethanol production, it has been shown as a promising alternative production of energy and chemicals from lignocellulosic material[76–78].

The current CORSIA criteria[27] for Sustainable Aviation Fuels (SAF) is exclusively based on GHG reduction performance. However, as discussed above, trade-offs between GHG performance and other environmental categories may occur on the local site, especially when the agricultural stage is considered. This can be extended to other legal and social issues. Themes related to conservation, human and labor rights, land and water use rights, local and social development, and food security are ongoing evaluations to be implemented on CORSIA by the end of the pilot phase[27].

Some voluntary SCSs, which comprise several issues mentioned above, have already addressed alternative aviation fuels in their platforms, such as the Roundtable On Sustainable Biomaterials (RSB)[79] and the International Carbon and Sustainability Certification (ISCC)[80].

5.4. Recommendations for future research

During the development of this thesis, some challenges remain and can be explored in future researches. Some of them are listed as follows.

- **Environmental effects from a large production of AJF through residues-based pathways**

In general, residue-based pathways present a good environmental performance on life cycle basis, mainly because feedstock procurement is typically related to low or null environmental burdens. However, some residues, such as beef tallow, sugarcane bagasse or steel off-gases are currently used for other purposes, *e.g.,* biodiesel production, power generation, and internal heat supply, respectively. Then, it is reasonable to expect that a widespread use of these feedstocks could result in competition with its current use, leading to possible environmental effects. This relevant aspect arose during the thesis (see **Chapter 2**), and no regulatory scheme has addressed such issue. Even the Renewable Fuel Standard (RFS), which is based on consequential life cycle assessment (CLCA), has assumed that residues would be freely available, with environmental burdens mostly related to procurement and transportation.

Although the CLCA is suggested for evaluating effects from a decision, it focuses on marginal effects. Furthermore, as default assumption, it is typically assumed that the demand of the product would be smaller 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[81,82].

In this context, the market effects – and the environmental ones – of the large-scale production of AJF from residues could be better explored by Computable General Equilibrium (CGE) models, where the market conditions and price elasticities are included.

- **Socio-economic impacts of AJF**

Despite the considerable bioenergy potential, Brazil is expected to remain a net kerosene importer in the coming decade[47]. On the other hand, a new demand for AJF could be supplied by a new sector in the Brazilian economy, which would lead to socio-economic benefits from repurposing the uses of the current feedstocks and from alterations in the fossil kerosene demand.

Recently, Wang *et al.*[83] addressed some of these impacts using input-output modeling, based on the Leontief assessment. They evaluated the hydrotreating of macaw oil (HEFA), gasification and Fisher-Tropsch of eucalyptus, and dehydration and hydrotreating of sugarcane ethanol (ATJ) to supply 3 to 15% of the Brazilian kerosene demand in 2050.

However, AJF from soybean oil – likely the most relevant pathway in the short-term[59,84] – or from residue-based pathways, such as sugarcane residues and beef tallow, have not been explored from a socio-economic perspective yet. Also, the impacts of different supply-chains, which are located in different regions, are not expected to be equally distributed throughout the country and across the economic sectors or income classes[85].

In this context, an interregional input-output analysis could contribute to filling this gap. Assuming an additional increment of AJF production, macro-economic impacts could be estimated by addressing some "*what if questions*", such as: the decrease of fossil kerosene imports, the increase of AJF exports, the expansion of food crops to supply a new demand o AJF, or the deviation of residual feedstock from its current use to produce AJF. Furthermore, it is possible to discuss the benefits of placing industrial plants in a specific region or where AJF is consumed.

- **AJF production from palm oil in Brazil**

The use of palm oil for producing biofuels has been directly associated with deforestation and high carbon emissions, considering the known practices of the major producers. It could be different in Brazil, which holds available and suitable areas, with no need for deforestation, and a consolidated supply-chain for palm oil.

Although the palm expansion in Brazil has occurred mostly in pasturelands, there are risks for crop expansion onto native forests since the current crops are close to Amazon forest, and some available areas would demand suitable infrastructure to be used for palm fruits transportation.

Therefore, the evaluation of the current opportunities and risks could motivate future works, as already pointed out by some researchers and companies of palm oil in Brazil, who were contacted during this Ph.D. The assessment of the indirect land use changes from palm expansion in Brazil through the guidelines of CORSIA[8] is highly recommended. The potential of other palm trees with high oil yields could be further included in future investigations.

- **Policies to promote the production AJF and their impacts**

As discussed in this thesis, the production and use of AJF face its low competitiveness with fossil kerosene, even in future scenarios with high oil prices. This aspect is crucial to promote an effective energy transition in the highly competitive aviation sector.

Several actions have been proposed to make the AJF industry take off, such as blending mandates, specific taxes and loan programs, and other policy subsidies. Considering the Brazilian expertise in promoting biofuels, with positive and negative experiences (see the historical aspects of ethanol and biodiesel programs), it is recommended an extended and comparative analysis of possible policy alternatives to promote AJF.

- **Other feedstocks/technologies for AJF**

Regarding the several pathways to produce AJF, it is worth deepening the discussions about the techno-economic and the environmental performance of other feedstocks for AJF production, such as municipal solid waste (MSP) and algae, as well as alternative technologies based on hydrogen[86] and power[87].

6 Conclusions

But, after all, **can Brazil help a sustainable energy transition for the aviation sector?** Positively, the huge Brazilian potential for biomass production allied to its recognized expertise in bioenergy could place the country as an important global supplier of AJF. According to **Chapters 2-4** and the additional discussion in **Chapter 5**, it was possible to present the following conclusions.

Statement 1: 1G ethanol from sugarcane is the best option for AJF production in Brazil in the short-term.

In the short-term, ethanol from sugarcane is a strategic feedstock to supply a Brazilian (and foreign) new demand for AJF. This pathway could reduce at least 50% of GHG emissions in comparison with its fossil counterpart under all regulatory schemes evaluated here. It is also related to lower LUC impacts and mitigation costs than oil-based pathways. However, local impacts related to agrochemicals use and nitrogen input, such as toxicity and eutrophication, should be carefully considered, as well as impacts related to airborne emissions during ethanol production.

According to sugarcane agro-zoning[43] and considering the sugarcane expansion over the last years[44,45], around 10.0 Mha would be highly suitable for sugarcane expansion. From this potential area, around 30 million m^3 of AJF could be produced, taking typical agro-industrial yields. Other projections indicate that 13.9 million m^3 of AJF could be obtained from 3.9 Mha of abandoned agricultural land, shrublands, and grasslands, assuming simultaneous competition with other biomass to produce AJF[42]. Regardless of the scenarios, all of them substantially overcame the current annual demand for fossil kerosene in Brazil (7.0 million m^3)[6] or even the estimations for 2030 (10. 0 million m^3)[47]. It is worth mentioning that the maximum allowed blend (v/v) between the AJF obtained from the Alcohol-to-Jet (ATJ) process and Jet A is 50%[2], which highlights the great potential for export AJF obtained from this pathway. Initiatives to integrate sugarcane with other crops or livestock can also be applied[88,89], without land expansion.

As mentioned above, the economic feasibility is the main obstacle for this pathway to take off. The minimum selling price of AJF was estimated two-fold higher than the average price of fossil kerosene in Brazil, assuming an integrated supply-chain with sugarcane as primary feedstock. AJF from sugarcane ethanol could mitigate similar values for GHG emissions related to aviation operations in Brazil (16.7 $MtCO_{2e}$ in 2018), comprising domestic and international flights, at the cost of 495 USD/tCO_{2e}, and considering the 3.9 Mha of available areas for sugarcane expansion. The mitigation costs could decrease to 96 USD/tCO_{2e} assuming possible optimal conditions, such as large production scale, and low feedstock prices in a context of high prices for fossil kerosene. This value would be closer to the carbon offset price in future trading scenarios than other pathways, highlighting the strategic position of this pathway in the Brazilian context.

In general, ATJ technology does not struggle with technical issues[4,75], as it is composed of well-known processes typically used in the petrochemical industry, such as dehydration of ethanol, oligomerization of alkenes, and hydrogenation[90]. However, the alcohol input – ethanol in this case – contributes roughly 80% of the final costs of the whole pathway, which confirms its large influence on the economic feasibility of the ATJ process. The AJF production from isobutanol, which is an already approved pathway, has been reported with lower costs than ethanol-based pathways, although the industrial processes for ethanol production are much more mature than those for isobutanol[90].

Currently, the tool of the Brazilian Program for biofuels (*RenovaBio*) does not address this pathway in its current version. Then, incentives for AJF production from sugarcane ethanol cannot be accounted for. Even though it is possible to request the inclusion of this pathway in the regulatory scheme.

Statement 2: Brazilian palm-based AJF may not be associated with deforestation and high carbon emissions.

Hydrotreating palm oil (Palm/HEFA) could be a strategic alternative for AJF production in Brazil if palm crops were expanded into degraded areas, and palm oil was obtained from well-controlled processes, especially related to wastewater effluents such as Palm Oil Mill Effluent (POME). Under these conditions, Palm/HEFA could provide GHG reduction by more than 60% according to CORSIA guidelines, with mitigation costs (419 USD/tCO_{2e}) lower those of sugarcane (495 USD/tCO_{2e}) and soybean (1,319 USD/tCO_{2e}), and lower trade-offs regarding other environmental categories compared to soybean, such as terrestrial acidification, eutrophication, human and environmental toxicity.

Based on a detailed agro-zoning for palm in the Brazilian Amazon region[10], up to 7.3 Mha of degraded areas would be highly suitable for palm cultivation, which could provide 3-fold the current Brazilian demand for fossil kerosene – assuming a maximum 50% (v/v) blending – or 2-fold the 2030-demand. Considering the available areas for palm expansion (around 20 Mha) estimated by Cervi *et al.*[42], the potential AJF production is even higher. This large potential could even supply the European market as a low-iLUC risk biofuel, although the consolidated image of palm-based biofuels – which is still directly linked to crop conditions in South-Asian countries[12,32,91] – is an obstacle to be overcome.

Currently, palm crop has occupied around 236 thousand hectares in Brazil, mostly in the North region. Even small, less than 1.0% of the crop expansion since 2010 was related to the conversion of native forests[14]. Furthermore, the domestic industry already sees market advantages of sustainable production and of not being associated with deforestation of tropical forests. Currently, Brazil has presented one of the highest proportion (around 30%) of palm oil production certified by the Roundtable on Sustainable Palm Oil (RSPO)[13,92].

On the other hand, risks of deforestation from the increasing demand for palm oil in Brazil should be considered since the current palm crops are mostly close to the Amazon forest and the potential areas for palm expansion request a suitable infrastructure to be accessed. Thus, robust support and monitoring policies for palm expansion can enable this potential and eventually overcome past problems[93], including policy ones, that prevented the sector from taking off.

Statement 3: The oasis of the waste-based pathways for AJF can be a mirage.

Several Low-Carbon Policies have motivated the use of residual feedstocks for biofuel production, like the recent initiatives of RED to limit the contribution of food-based biofuels for the European goals. The reasons for it are clear since residues are typically not related to food competition and the apparent low costs for feedstock procurement.

The AJF pathways based on residual-feedstocks presented better GHG reduction performance than food-based pathways, with a minimum GHG reduction of 70%. It is especially so because the environmental burden related to the upstream stage is not considered, which also did not result in relevant trade-offs with other environmental categories.

Similar to the 1G pathways evaluated here, the minimum selling price of AJF from residues feedstocks ranged from 1.7 to 2.8 times higher than the average price of fossil kerosene in the last years in Brazil (15.8 USD/GJ). The hydrotreating of UCO presented the lowest values, while the AJF via 2G-ethanol presented the highest ones. It was the same for mitigation costs, which varied from 185 to 575 USD/tCO_{2e} for the same pathways.

Residues-based pathways could produce together 3.4 to 8.1 million m³, mainly led by the considerable potential of lignocellulosic residues. According to the industrial designs assumed here, the Fischer-Tropsch of lignocellulosic residues could provide 2.5 million m³ of AJF, while the ATJ pathway through 2G ethanol could provide 7.2 million m³. Even so, hydrotreating of waste greases and Fischer-Tropsch of forestry and sugarcane residues could provide a similar amount of fossil kerosene demanded by international flights originating in Brazil in 2018 – *i.e.*, roughly 3.0 million m³ – and reduce half of the GHG emissions (8.5 MtCO_{2e}) than what was estimated for Brazilian aviation sector[6], at expenses of 185 to 371 USD/tCO_{2e}.

However, the use of residues for producing AJF would face some obstacles that limit the potential of 2G pathways, regarding their effective availability of these residues and the technical feasibility of the conversion technologies.

As previously mentioned, the economic performance of AJF through Alcohol-to-Jet technology is mostly influenced by ethanol costs. In this context, 2G-ethanol production is not economically competitive, and the entire process has faced some technical problems, which have also been observed in two Brazilian plants of 2G ethanol[94]. According to the investment plans, the production of 1.0 million m³ of 2G-ethanol is estimated for 2030 in Brazil. It corresponds to only 2% of the total forecasted ethanol production[46].

In turn, although ethanol production from gas fermentation – including the possible use of off-gases – has reached commercial scale[95], the production costs are still high. The considerable power demand by these plants can be supplied through integrated designs with power surplus generation, such as efficient steel mills.

On the other hand, while residual feedstocks are often assumed to be freely available with null environmental burden related to the feedstock procurement, no regulatory scheme considers possible environmental consequences if they diverge from their current use.

Beef tallow is mostly consumed for biodiesel production and cleaning industry, while the energy recovery from the off-gases streams in the steel mills has become a common practice. In turn, sugarcane residues are commonly used for sugarcane mills for energy self-supply and generation of power surplus. They would be available in large amounts, as estimated here, only in case of industrial plants are retrofitted with energy-efficient processes, providing lignocellulosic surplus generation.

From a consequential LCA perspective, the potential GHG reduction provided by hydrotreating of beef tallow would decrease from 90% to 50%, assuming that an additional soybean oil would compensate the use of beef tallow for AJF production. In turn, if forestry and sugarcane residues were not freely available, the mitigation benefits related to AJF production through Fischer-Tropsch technology – *i.e.*, 130% of GHG reduction compared to fossil kerosene – could decrease to 0.4% and 63%, respectively, assuming the additional demand for natural gas, power and heat generation. Furthermore, the GHG emissions for lignocellulose-based pathways via 2G-ethanol could reach 12% to 132% higher than fossil kerosene, assuming marginal power and heat demand, respectively. In turn, AJF obtained from steel off-gases in current use could lead to GHG emissions 82% higher, assuming new demand for natural gas.

These significant discrepancies related to residue-based pathways should be investigated, at least, in periodic assessments of Low Carbon Policies in order to support decision-making and adverse induced effects.

Statement 4: The vast interest in AJF has faced a lack of proper incentives.

While all AJFs assessed here are far from being economically competitive with respect to fossil kerosene, an effective energy transition of the aviation sector will only be possible through well-supported and robust policies, which also value the environmental and strategic benefits of AJFs, such as the independence of fossil fuels and regional development.

Furthermore, specificities of the aviation sector should also be considered for policymaking, such as the substantial sensitivity of aviation operations to fuel price, few alternatives for providing GHG reduction, and the absence of a commercial supply-chain for AJF.

According to the current scheme of international aviation for carbon reduction goals (CORSIA), carbon offset from purchasing emission unite and carbon reduction from AJF use is treated equally. It discourages any private efforts to move forward in the commercial production of AJF and its use since the mitigation costs related to AJF are much higher than the emission units in the actual and future scenarios.

On the other hand, the current Low-Carbon Policies (LCPs) – such as *RenovaBio*, RED, RFS, and LCFS – have addressed AJF as an "opt-in" provision, without specific targets or suitable subsidies. One important issue to be considered is the possible competition between AJF slate with other refining products at the refining stage, which is highly influenced by the opportunity costs of the possible products. From HEFA technology, for instance, maximizing AJF production is possible at expenses of lowering overall yields of liquid biofuels and increasing operational costs. If the producer does not count on any specific incentive worth this choice, AJF production will never benefit.

Blending mandates, special investment conditions, and tax credits could support the ramping-up of this new supply-chain. Also, considering the ICAO goals, incentives for AJF production should directly incorporate the carbon pricing into the policy mechanisms, as well as other environmental benefits provided by AJF. The mitigation cost would be a strategic indicator in the policy context if it could price the efforts for GHG reductions directly, ranking cost-effective pathways.

References for Discussion and Conclusions

1. ICAO. Resolutions 37th Assembly [Internet]. 2010. Available from: http://www.icao.int/Meetings/AMC/Assembly37/Documents/ProvisionalEdition/a37_res_prov_en.pdf
2. ASTM. ASTM D7566-20 Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons. West Conshohocken, Pennsylvania, USA; 2020.
3. Aviantionbenefits. Aviation Benefits Beyond Borders [Internet]. *Sustainable aviation fuel.* 2020 [cited 2020 Feb 12]. Available from: https://aviationbenefits.org/
4. Cortez LAB. Roadmap for sustainable aviation biofuels for Brazil. *Blucher, editor.* São Paulo; 2014. 272 p.
5. ANP. Oil, Natural Gas and Biofuels Statistical Yearbook 2019 [Internet]. Rio de Janeiro; 2020. Available from: http://www.anp.gov.br/publicacoes/anuario-estatistico/anuario-estatistico-2020
6. ANAC. National Inventory of the atmospheric emissions of civil aviation - Base 2018. Brasilia; 2019.
7. ICAO. CORSIA Default Life Cycle Emissions Values for CORSIA Eligible Fuels [Internet]. Montreal; 2019. Available from: https://www.icao.int/environmental-protection/CORSIA/Pages/CORSIA-Eligible-Fuels.aspx
8. ICAO. CORSIA Supporting Document: Eligible Fuels – Life Cycle Assessment Methodology [Internet]. Montreal; 2019. Available from: https://www.icao.int/environmental-protection/CORSIA/Documents/CORSIA Supporting Document_CORSIA Eligible Fuels_LCA Methodology.pdf
9. ICAO. CORSIA - Methodology for Calculating Actual Life Cycle Emissions Values. Montreal; 2019.
10. Ramalho Filho A, Motta PEF. Zoneamento Agroecológico, Produção e Manejo para a Cultura da Palma de Óleo na Amazônia. Rio de Janeiro; 2010.
11. FAO. FAOSTAT [Internet]. *Food and Agriculture Organization.* 2018 [cited 2018 Jan 10]. Available from: http://faostat.fao.org/site/339/default.aspx
12. Pirker J, Mosnier A, Kraxner F, Havlík P, Obersteiner M. What are the limits to oil palm expansion? *Glob Environ Chang [Internet].* 2016 Sep;40:73–81. Available from: http://dx.doi.org/10.1016/j.gloenvcha.2016.06.007
13. Branford S, Torres M. Brazilian Amazon oil palm deforestation under control, for now [Internet]. *Mongabay Series: Amazon Agribusiness.* 2018 [cited 2020 Sep 7]. Available from: https://news.mongabay.com/2018/05/brazilian-amazon-oil-palm-deforestation-under-control-for-now/
14. Benami E, Curran LM, Cochrane M, Venturieri A, Franco R, Kneipp J, et al. Oil palm land conversion in Pará, Brazil, from 2006-2014: Evaluating the 2010 Brazilian Sustainable Palm Oil Production Program. *Environ Res Lett.* 2018;13(3).
15. Barber CP, Cochrane MA, Souza CM, Laurance WF. Roads, deforestation, and the mitigating effect of protected areas in the Amazon. *Biol Conserv [Internet].* 2014 Sep;177(2014):203–9. Available from: http://dx.doi.org/10.1016/j.biocon.2014.07.004
16. Embrapa Cerrados. Pesquisa define manejo da irrigação do dendezeiro no Cerrado [Internet]. *Embrapa Pesquisa.* 2020 [cited 2020 Oct 15]. Available from: https://www.embrapa.br/en/cerrados/-

/asset_publisher/JY3381IKCcOA/content/id/51192237
17. Antonini JC dos A, Malaquias JV. Estabelecimento do Momento de Irrigação da Palma de Óleo, Cultivada sob Condições de Clima Tropical de Savana. Planaltina; 2019.
18. Waha K, Dietrich JP, Portmann FT, Siebert S, Thornton PK, Bondeau A, et al. Multiple cropping systems of the world and the potential for increasing cropping intensity. *Glob Environ Chang [Internet]*. 2020 Sep;64(May):102131. Available from: https://doi.org/10.1016/j.gloenvcha.2020.102131
19. Batista VV, Adami PF, Moraes PVD de, Oligini KF, Giacomel CL, Link L. Row Arrangements of Maize and Soybean Intercrop on Silage Quality and Grain Yield. *J Agric Sci [Internet]*. 2019 Jan 15;11(2):286. Available from: http://www.ccsenet.org/journal/index.php/jas/article/view/0/38103
20. Xu Z, Li C, Zhang C, Yu Y, van der Werf W, Zhang F. Intercropping maize and soybean increases efficiency of land and fertilizer nitrogen use; A meta-analysis. *F Crop Res [Internet]*. 2020 Feb;246(2):107661. Available from: https://doi.org/10.1016/j.fcr.2019.107661
21. Balbinot Junior AA, Franchini JC, Debiasi H, Mandarino JMG, Sichieri F. Desempenho da soja em sistemas agroflorestais com eucalipto em solo arenoso e clima tropical. *Rev Ciências Agroveterinárias [Internet]*. 2018 Nov 21;17(4):556–63. Available from: http://revistas.udesc.br/index.php/agroveterinaria/article/view/10069
22. Werner F, Balbinot Junior AA, Franchini JC, Ferreira AS, Silva MA de A e. Agronomic performance of soybean cultivars in an agroforestry system1. *Pesqui Agropecuária Trop [Internet]*. 2017 Sep;47(3):279–85. Available from: http://www.scielo.br/scielo.php?script=sci_arttext&pid=S1983-40632017000300279&lng=en&tlng=en
23. Plath M, Moser C, Bailis R, Brandt P, Hirsch H, Klein A, et al. A novel bioenergy feedstock in Latin America? Cultivation potential of Acrocomia aculeata under current and future climate conditions. *Biomass and Bioenergy [Internet]*. 2016 Aug;91:186–95. Available from: http://dx.doi.org/10.1016/j.biombioe.2016.04.009
24. ABIOVE. Soy Moratorium -Twelth Year. São Paulo; 2020.
25. Cardoso A, Laviola BG, Santos GS, de Sousa HU, de Oliveira HB, Veras LC, et al. Opportunities and challenges for sustainable production of A. aculeata through agroforestry systems. *Ind Crops Prod [Internet]*. 2017 Nov;107(January):573–80. Available from: http://dx.doi.org/10.1016/j.indcrop.2017.04.023
26. ANP. Resolution ANP Nº 758, 23.11.2018 [Internet]. *Production certification or efficient imports of biofuels.* 2018 [cited 2020 Sep 2]. Available from: http://legislacao.anp.gov.br/?path=legislacao-anp/resol-anp/2018/novembro&item=ranp-758-2018
27. ICAO. CORSIA - Sustainability Criteria for CORSIA Eligible Fuels. Montreal; 2019.
28. European Union. Renewable Energy Directive (EU) 2018/2001 - Promotion of the use of energy from renewable sources [Internet]. 2018. Available from: https://eur-lex.europa.eu/eli/dir/2018/2001/oj
29. ANP. Informe Técnico nº 02/SBQ v.3. Orientações Gerais: Procedimentos para Certificação da Produção ou Importação Eficiente de Biocombustíveis [Internet]. Brasília; 2019. Available from: https://www.gov.br/anp/pt-br/assuntos/producao-e-fornecimento-de-biocombustiveis/renovabio/renovabio/orientacoes-para-certificacao-do-renovabio
30. ICAO. Annual Report of the Council - 2018 [Internet]. *Annual Reports of the Council.*

Montreal; 2019 [cited 2020 Aug 7]. Available from: https://www.icao.int/publications/pages/annual-reports.aspx

31. European Union. Commission Delegated Regulation (EU) 2019/807 of 13 March 2019 [Internet]. 2019. Available from: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32019R0807&from=EN
32. European Commission. Report from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the regions on the status of production expansion of relevant food and feed crops worldwide. Brussels; 2019.
33. U. S. EPA. Lifecycle Greenhouse Gas Results [Internet]. *Fuels Registration, Reporting, and Compliance Help.* 2020 [cited 2020 Jan 16]. Available from: https://www.epa.gov/fuels-registration-reporting-and-compliance-help/lifecycle-greenhouse-gas-results
34. IBGE. Brazilian Institute of Geoghaphy and Statistics [Internet]. *SIDRA Database - Quarterly Survey of Animal Slaughter.* 2020 [cited 2020 Aug 21]. Available from: https://www.ibge.gov.br/en/statistics/economic/agriculture-forestry-and-fishing/21163-first-results-1abate-2.html?=&t=o-que-e
35. Garcilasso VP. Análise entre processos e matérias-primas para a produção de biodiesel. University of São Paulo; 2014.
36. ABRA. Anuário ABRA - Setor de Reciclagem Animal [Internet]. Brasilia; 2019. Available from: https://abra.ind.br/
37. ABM. Seminário de Balanço Energético Global e Utilidades [Internet]. *Seminar on Global Energy Balances and Utiliities.* Belo Horizonte, Brazil: Brazilian Mettalurgy, Materials and Mining Association; 2017 [cited 2019 Oct 20]. Available from: https://www.abmbrasil.com.br/
38. IBA. Annual Report - Brazilian Tree Industry [Internet]. 2019 [cited 2020 Jul 14]. p. 80. Available from: http://iba.org/images/shared/Biblioteca/IBA_RelatorioAnual2017.pdf
39. Coelho M. Personal Communication of a Brazilian Company of paper and cellulose. 2018.
40. EPE. National Energy Balance [Internet]. Brasilia; 2020 [cited 2019 Oct 26]. Available from: https://ben.epe.gov.br/BENSeriesCompletas.aspx
41. Bonomi A, Cavalett O, Pereira da Cunha M, Lima MAP, editors. Virtual Biorefinery [Internet]. 1st ed. Cham: Springer International Publishing; 2016. 285 p. (Green Energy and Technology). Available from: http://link.springer.com/10.1007/978-3-319-26045-7
42. Cervi WR, Lamparelli RAC, Seabra JEA, Junginger M, de Jong S, van der Hilst F. Spatial modeling of techno-economic potential of biojet fuel production in Brazil. *GCB Bioenergy [Internet].* 2020 Feb 14;12(2):136–57. Available from: https://onlinelibrary.wiley.com/doi/abs/10.1111/gcbb.12659
43. Manzatto CV, Assad ED, Bacca JFM, Zaroni MJ, Pereira SEM. Zoneamento Agroecológico da Cana-de Açúcar. *Documentos 110.* Rio de Janeiro; 2009.
44. Novaes RML, Pazianotto RAA, Brandão M, Alves BJR, May A, Folegatti-Matsuura MIS. Estimating 20-year land-use change and derived CO2 emissions associated with crops, pasture and forestry in Brazil and each of its 27 states. *Glob Chang Biol [Internet].* 2017 Sep 9;23(9):3716–28. Available from: https://onlinelibrary.wiley.com/doi/abs/10.1111/gcb.13708
45. UNICAData. Statistics of Sugarcane Industry Union [Internet]. 2020 [cited 2020 Jul

14]. Available from: http://www.unicadata.com.br/
46. EPE. Ethanol supply scenarios and Otto cycle demand [Internet]. Rio de Janeiro; 2019. Available from: https://www.epe.gov.br/en/publications/publications/ethanol-supply-scenarios-and-otto-cycle-demand
47. EPE. PDE 2030 – The Ten-Year Energy Expansion Plan 2030 [Internet]. Brasilia; 2020. Available from: http://www.epe.gov.br/pt/publicacoes-dados-abertos/publicacoes/plano-decenal-de-expansao-de-energia-pde
48. de Jong S, Hoefnagels R, Faaij A, Slade R, Mawhood R, Junginger M. The feasibility of short-term production strategies for renewable jet fuels - a comprehensive techno-economic comparison. *Biofuels, Bioprod Biorefining [Internet]*. 2015 Nov;9(6):778–800. Available from: http://doi.wiley.com/10.1002/bbb.1613
49. Bann SJ, Malina R, Staples MD, Suresh P, Pearlson M, Tyner WE, et al. The costs of production of alternative jet fuel: A harmonized stochastic assessment. *Bioresour Technol [Internet]*. 2017 Mar;227:179–87. Available from: https://linkinghub.elsevier.com/retrieve/pii/S0960852416316911
50. Santos CI, Silva CC, Mussatto SI, Osseweijer P, van der Wielen LAM, Posada JA. Integrated 1st and 2nd generation sugarcane bio-refinery for jet fuel production in Brazil: Techno-economic and greenhouse gas emissions assessment. *Renew Energy [Internet]*. 2018 Dec;129:733–47. Available from: http://dx.doi.org/10.1016/j.renene.2017.05.011
51. Diederichs GW, Ali Mandegari M, Farzad S, Görgens JF. Techno-economic comparison of biojet fuel production from lignocellulose, vegetable oil and sugar cane juice. *Bioresour Technol [Internet]*. 2016 Sep;216:331–9. Available from: http://dx.doi.org/10.1016/j.biortech.2016.05.090
52. IEA. CO2 Emissions from Fuel Combustion: Overview [Internet]. Paris; 2020 [cited 2020 Aug 27]. Available from: https://www.iea.org/reports/co2-emissions-from-fuel-combustion-overview
53. Cames M, Harthan RO, Füssler J, Lazarus M, Lee CM, Erickson P, et al. How additional is the Clean Development Mechanism? [Internet]. Berlin; 2016. Available from: https://ec.europa.eu/clima/sites/clima/files/ets/docs/clean_dev_mechanism_en.pdf
54. Fearnehough H, Warnecke C, Schneider L, Broekhoff D, La Hoz Theuer S. Offset credit supply potential for CORSIA [Internet]. Berlin; 2019. Available from: https://newclimate.org/2019/11/05/offset-credit-supply-potential-for-corsia/
55. ICAO. Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) [Internet]. *International Civil Aviation Organization.* 2020 [cited 2020 Apr 28]. Available from: https://www.icao.int/environmental-protection/Pages/market-based-measures.aspx
56. Ghatala F. Sustainable Aviation Fuel Policy in the United States : A Pragmatic Way Forward. Washington; 2020.
57. ANP. Renovacalc - v.6.1 [Internet]. *National Agency of Petroleum Natural Gas and Biofuels - Renovabio.* 2020 [cited 2020 Feb 16]. Available from: http://www.anp.gov.br/producao-de-biocombustiveis/renovabio/renovacalc
58. U.S. EPA. Approved Pathways for Renewable Fuel. *Renewable Fuel Standard Program.* 2020.
59. Cortez LAB, Nigro FEB, Nassar AM, Cantarella H, Nogueira LAH, Moraes MAFD de, et al. Roadmap for sustainable aviation biofuels for Brazil — A Flightpath to Aviation Biofuels in Brazil [Internet]. São Paulo: Edgard Blücher; 2014. 272 p.

Available from: http://openaccess.blucher.com.br/article-list/roadmap-aviation-272/list

60. Pavlenko AN, Searle S, Christensen A. The cost of supporting a lternative jet fuels in the European Union. 2019. (2019-5).
61. Pearlson M, Wollersheim C, Hileman J. A techno-economic review of hydroprocessed renewable esters and fatty acids for jet fuel production. *Biofuels, Bioprod Biorefining [Internet]*. 2013 Jan;7(1):89–96. Available from: http://doi.wiley.com/10.1002/bbb.1378
62. Ambel CC. How to incentivize renewable aviation fuel through the RED [Internet]. 2017. Available from: https://www.transportenvironment.org/
63. European Commission. Sustainable aviation fuels – ReFuelEU Aviation [Internet]. *Published Initiatives.* 2020 [cited 2020 Oct 16]. Available from: https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/12303-ReFuelEU-Aviation-Sustainable-Aviation-Fuels
64. Murphy A. Legislating for aviation alternative fuels [Internet]. 2020. Available from: https://www.transportenvironment.org/sites/te/files/publications/T%26E ReFuelEU position paper %281%29.pdf
65. Baines J. Statement of Jeremy Baines President, Neste US House Energy and Commerce Committee, Subcommittee on the Environment and Climate Change Hearing on “Building a 100 Percent Clean Economy: Solutions for Planes, Trains and Everything Beyond Automobiles” [Internet]. [cited 2020 Oct 16]. Available from: https://docs.house.gov/meetings/IF/IF18/20191023/110124/HHRG-116-IF18-Wstate-BainesJ-20191023.pdf
66. Chiappini G. Preços dos créditos de carbono do RenovaBio ainda são incertos [Internet]. *EPBR.* 2019 [cited 2020 Jul 15]. Available from: https://epbr.com.br/precos-do-creditos-de-carbono-do-renovabio-ainda-sao-incertos/
67. UDOP. Preços dos créditos de carbono do RenovaBio ainda são incertos [Internet]. 2020 [cited 2020 Oct 15]. Available from: https://www.udop.com.br/noticia/2020/06/18/precos-dos-creditos-de-carbono-do-renovabio-ainda-sao-incertos.html
68. CARB. Monthly LCFS Credit Transfer Activity Reports [Internet]. *Credit trading activity reports.* 2020 [cited 2020 Aug 20]. Available from: https://ww3.arb.ca.gov/fuels/lcfs/credit/lrtmonthlycreditreports.htm
69. ANP. Resolution ANP nº 791/2019, de 12.06.2019 [Internet]. *Annual mandatory goals for GHG emission reduction.* 2019 [cited 2020 Oct 16]. Available from: http://legislacao.anp.gov.br/?path=legislacao-anp/resol-anp/2019/junho&item=ranp-791-2019
70. ANP. Consultas e Audiências Públicas - Resoluções do RenovaBio [Internet]. 2020 [cited 2020 Oct 16]. Available from: http://www.anp.gov.br/producao-de-biocombustiveis/renovabio/consultas-publicas-resolucoes-renovabio
71. Belo MS da SP, Pignati W, Dores EFG de C, Moreira JC, Peres F. Uso de agrotóxicos na produção de soja do estado do Mato Grosso: um estudo preliminar de riscos ocupacionais e ambientais. *Rev Bras Saúde Ocup [Internet]*. 2012 Jun;37(125):78–88. Available from: http://www.scielo.br/scielo.php?script=sci_arttext&pid=S0303-76572012000100011&lng=pt&tlng=pt
72. Bernieri T, Rodrigues D, Barbosa IR, Ardenghi PG, Basso da Silva L. Occupational exposure to pesticides and thyroid function in Brazilian soybean farmers. *Chemosphere [Internet]*. 2019 Mar;218:425–9. Available from:

https://linkinghub.elsevier.com/retrieve/pii/S004565351832232X

73. Sakamoto L. Expansão do dendê na Amazônia Brasileira. São Paulo; 2013.
74. Handler RM, Shonnard DR, Griffing EM, Lai A, Palou-Rivera I. Life Cycle Assessments of Ethanol Production via Gas Fermentation: Anticipated Greenhouse Gas Emissions for Cellulosic and Waste Gas Feedstocks. *Ind Eng Chem Res [Internet]*. 2016 Mar 30;55(12):3253–61. Available from: http://pubs.acs.org/doi/10.1021/acs.iecr.5b03215
75. Brooks KP, Snowden-Swan LJ, Jones SB, Butcher MG, Lee G-SJ, Anderson DM, et al. Low-Carbon Aviation Fuel Through the Alcohol to Jet Pathway. *In: Biofuels for aviation: feedstocks, technology and implementation.* London: Elsevier Inc.; 2016. p. 109–50.
76. de Medeiros EM, Noorman H, Maciel Filho R, Posada JA. Production of ethanol fuel via syngas fermentation: Optimization of economic performance and energy efficiency. *Chem Eng Sci X [Internet]*. 2020 Jan;5:100056. Available from: https://linkinghub.elsevier.com/retrieve/pii/S2590140020300022
77. de Medeiros EM, Posada JA, Noorman H, Osseweijer P, Filho RM. Hydrous bioethanol production from sugarcane bagasse via energy self-sufficient gasification-fermentation hybrid route: Simulation and financial analysis. *J Clean Prod [Internet]*. 2017 Dec;168:1625–35. Available from: https://doi.org/10.1016/j.jclepro.2017.01.165
78. Almeida Benalcázar EF, Gevers-Deynoot B, Noorman H, Osseweijer P, Posada JA. Production of bulk chemicals from lignocellulosic biomass via thermochemical conversion and syngas fermentation: a comparative techno-economic and environmental assessment of different site-specific supply chain configurations. *Biofuels, Bioprod Biorefining [Internet]*. 2017 Sep;11(5):861–86. Available from: http://www.ncbi.nlm.nih.gov/pubmed/2571
79. RSB. Sustainable Aviation Fuels [Internet]. [cited 2020 Oct 17]. Available from: https://rsb.org/aviation/
80. ISCC. Sustainable Aviation Fuels Certification with ISCC [Internet]. [cited 2020 Oct 17]. Available from: https://www.iscc-system.org/about/sustainable-aviation-fuels/
81. Weidema BP, Ekvall T, Heijungs R. Guidelines for application of deepened and broadened LCA. *Final report Co-ordination Action for innovation in Life- Cycle Analysis for Sustainability – Calcas. Project no.037075.* 2009.
82. Weidema BP. Market information in life cycle assessment [Internet]. *Vol. 863, Danish Ministry of the Environment.* Denmark: Danish Environmental Protection Agency, Danish Ministry of the Environment; 2003. Report No.: Environmental Project No. 863. Available from: http://www.norlca.org/resources/780.pdf
83. Wang Z, Pashaei Kamali F, Osseweijer P, Posada JA. Socioeconomic effects of aviation biofuel production in Brazil: A scenarios-based Input-Output analysis. *J Clean Prod [Internet]*. 2019 May 16 [cited 2019 May 22];230:1036–50. Available from: https://www.sciencedirect.com/science/article/pii/S0959652619316713?via%3Dihub#appsec1
84. Cantarella H, Nassar AM, Cortez LAB, Baldassin R. Potential feedstock for renewable aviation fuel in Brazil. *Environ Dev [Internet]*. 2015;15:52–63. Available from: http://dx.doi.org/10.1016/j.envdev.2015.05.004
85. Brinkman MLJ, da Cunha MP, Heijnen S, Wicke B, Guilhoto JJM, Walter A, et al. Interregional assessment of socio-economic effects of sugarcane ethanol production

in Brazil. *Renew Sustain Energy Rev [Internet]*. 2018;88(February):347–62. Available from: https://doi.org/10.1016/j.rser.2018.02.014
86. AIRBUS. Airbus reveals new zero-emission concept aircraft [Internet]. 2020 [cited 2020 Dec 17]. Available from: https://www.airbus.com/newsroom/press-releases/en/2020/09/airbus-reveals-new-zeroemission-concept-aircraft.html
87. Aviation Benefits Beyond Borders. When will commercial electric aircraft become a reality? [Internet]. 2020 [cited 2020 Dec 17]. Available from: https://aviationbenefits.org/faqs/electric-aircraft/
88. Souza SP, de Ávila MT, Pacca S. Life cycle assessment of sugarcane ethanol and palm oil biodiesel joint production. *Biomass and Bioenergy [Internet]*. 2012 Sep;44:70–9. Available from: https://linkinghub.elsevier.com/retrieve/pii/S0961953412001894
89. de Souza NRD, Fracarolli JA, Junqueira TL, Chagas MF, Cardoso TF, Watanabe MDB, et al. Sugarcane ethanol and beef cattle integration in Brazil. *Biomass and Bioenergy [Internet]*. 2019 Jan;120:448–57. Available from: https://linkinghub.elsevier.com/retrieve/pii/S0961953418303465
90. Geleynse S, Brandt K, Garcia-Perez M, Wolcott M, Zhang X. The Alcohol-to-Jet Conversion Pathway for Drop-In Biofuels: Techno-Economic Evaluation. *ChemSusChem [Internet]*. 2018 Nov 9;11(21):3728–41. Available from: http://doi.wiley.com/10.1002/cssc.201801690
91. Swain F. How do we go palm oil free? [Internet]. *BBC - Future*. 2020 [cited 2020 Dec 16]. Available from: https://www.bbc.com/future/article/20200109-what-are-the-alternatives-to-palm-oil
92. RSPO. Reflecting on a decade of growth - Impact Report 2019 [Internet]. 2019 [cited 2020 Sep 18]. Available from: https://rspo.org/resources/rspo-reports/impact-reports
93. Abreu A de. Prejuízo em cacho - Petrobras enterra centenas de milhões de reais em projeto de biocombustível a partir do dendê, que não produziu nem um litro de óleo. *Revista Piauí [Internet]*. 2020; Available from: https://piaui.folha.uol.com.br/prejuizo-em-cacho/
94. NovaCana Website. Unpublished survey details production of cellulosic ethanol from Raízen and GranBio [Internet]. 2020 [cited 2020 Dec 16]. Available from: https://www.novacana.com/n/etanol/2-geracao-celulose/levantamento-inedito-detalhes-producao-etanol-celulosico-raizen-granbio-270820
95. LanzaTech. World’s First Commercial Waste Gas to Ethanol Plant Starts Up [Internet]. 2018 [cited 2019 Jul 31]. Available from: https://www.lanzatech.com/2018/06/08/worlds-first-commercial-waste-gas-ethanol-plant-starts/

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Run
Live to fly
Fly to live
Do or die

Face up, make your stand
Realize you're living in the golden years.

Campinas, December 2020.

Curriculum Vitae

Rafael Silva Capaz was born on the 14th of May, 1985, in Itajubá/Brazil. In 2007 he received the Bachelor's Degree in Environmental Engineering from the Federal University of Itajubá (UNIFEI), campus Itajubá. In the same year, he awarned the Prize of the Engineering Society of Minas Gerais with the project "*Methanolysis of soybean oil under heterogeneous catalysis*", being supervised by Prof. Dr. Álvaro de Queiroz.

From the UNIFEI, he also received the Master's Degree in Energy Engineering in 2009 with the dissertation "*Analysis of the energy performance of biofuels production: methodological issues and case studies*", being supervised by Prof. Dr. Luiz Horta Nogueira.

During his Master's course, he worked as a researcher in elaborating guide plans for river basins in Brazil and as technical consultant in environmental impacts assessments for the installation and operation of small hydropower plants. Furthermore, he assisted courses *in company* related to bioenergy, life cycle assessment, and environmental impacts assessment.

Since 2010, he has worked as a lecturer at UNIFEI, teaching for Bachelor's courses and supervising students on the following themes: renewable energies, biofuels, life cycle assessment, environmental impacts assessment, environmental management systems, and management of river basins. Besides scientific papers and technical reports, in 2014, he organized with Prof. Dr. Luiz Horta Nogueira the book "Environmental Sciences for Engineering" (in Portuguese, published by Elsevier) to be used in Bachelor's courses.

Regarding administrative positions, in 2010, he implemented and coordinated the Bachelor course of Environmental Engineering at UNIFEI, campus Itabira/Brazil. In 2013-2014 he served as director of the Student Assistance Directorate, managing financial and human resources to support needy bachelor's students of UNIFEI.

In 2015, he started his Ph.D. Degree on the Planing of Energy Systems at the University of Campinas (UNICAMP), Campinas/Brazil, being supervised by Prof. Dr. Joaquim Seabra. His original project was about the techno-economic and socio-environmental performance of alternative aviation fuels. In 2016, he was approved with the same project for the Dual Degree agreement between UNICAMP and Technology University of Delft (TUDelft), Delft/Netherlands. In 2017, as part of the agreement, he lived in Delft and developed his thesis with the BTS (Biotechnology and Society) Group, coordinated by Prof. Dr. Patricia Osseweijer and supervised by Prof. Dr. John Posada. The results of his Dual Degree are published in this thesis.

Nowadays, he works as Assistant professor at UNIFEI and technical consultant on bioenergy of international agencies and Brazilian research companies.

Publications during Ph.D.

1. Nogueira, L.A.H.; **Capaz, R.S.**; Souza, S.P.; Seabra, J.E.A. ***Biodiesel program in Brazil: learning curve over ten years (2005-2015).*** Biofuels, Bioproducts and Biorefining, 10, 728-737, 2016.

2. **Capaz, R.S.**; Seabra, J.E.A. ***Life Cycle Assessment of Biojet Fuels*** In: Christopher Chuck. (Org.). Biofuels for Aviation: an overview of the sector. 1ª ed.: Elsevier, 2016, p. 281-297.

3. Nogueira, L.A.H.; Seabra, J.E.A.; **Capaz, R.S.** ***ICAO Guidance Aviation Biofuels***, 2017.

4. **Capaz, R.S.**; Seabra, J.E.A.; Osseweijer, P.; Posada, J.A. ***Carbon footprint of ethanol-to-jet from residues: Attributional and Consequential approaches***. 26th European Biomass Conference & Exhibition (EUCBE), 14-18 May 2018, Copenhagen (Denmark).

5. **Capaz, R.S.**; de Medeiros, E.M.; Falco, D.G.; Seabra, J.E.A.; Osseweijer, P.; Posada, J.A. ***Environmental trade-offs of renewable jet fuels in Brazil: Beyond the carbon footprint***. Science of the Total Environment. (Available online 15 January 2020, v. 714). https://doi.org/10.1016/j.scitotenv.2020.136696.

6. **Capaz, R.S.**; Posada, J.A.; Osseweijer, P.; Seabra, J.E.A. The carbon footprint of alternative jet fuels produced in Brazil: exploring different approaches. Resources, Conservation and Recycling. (Available online 12 November 2020, 105260). https://doi.org/10.1016/j.resconrec.2020.105260

7. **Capaz, R.S.**; Guida, E.; Seabra, J.E.A.; Osseweijer, P.; Posada, J.A. ***Mitigating carbon emissions through sustainable aviation fuels: costs and potential.*** Biofuels, Bioproducts, and Biorefining. (Available online 16 November 2020). https://doi.org/10.1002/bbb.2168

8. **Capaz, R.S.**; Seabra, J.E.A.; Osseweijer, P.; Posada, J.A. ***Production of aviation Fuels:*** *Aviation biofuels and sustainability – The decarbonization challenge*. Book chapter (with editor). 2020.