

The Broader Sustainability Aspects of Biobased Aviation Fuels: An Investigation into Socioeconomic and Environmental Impacts

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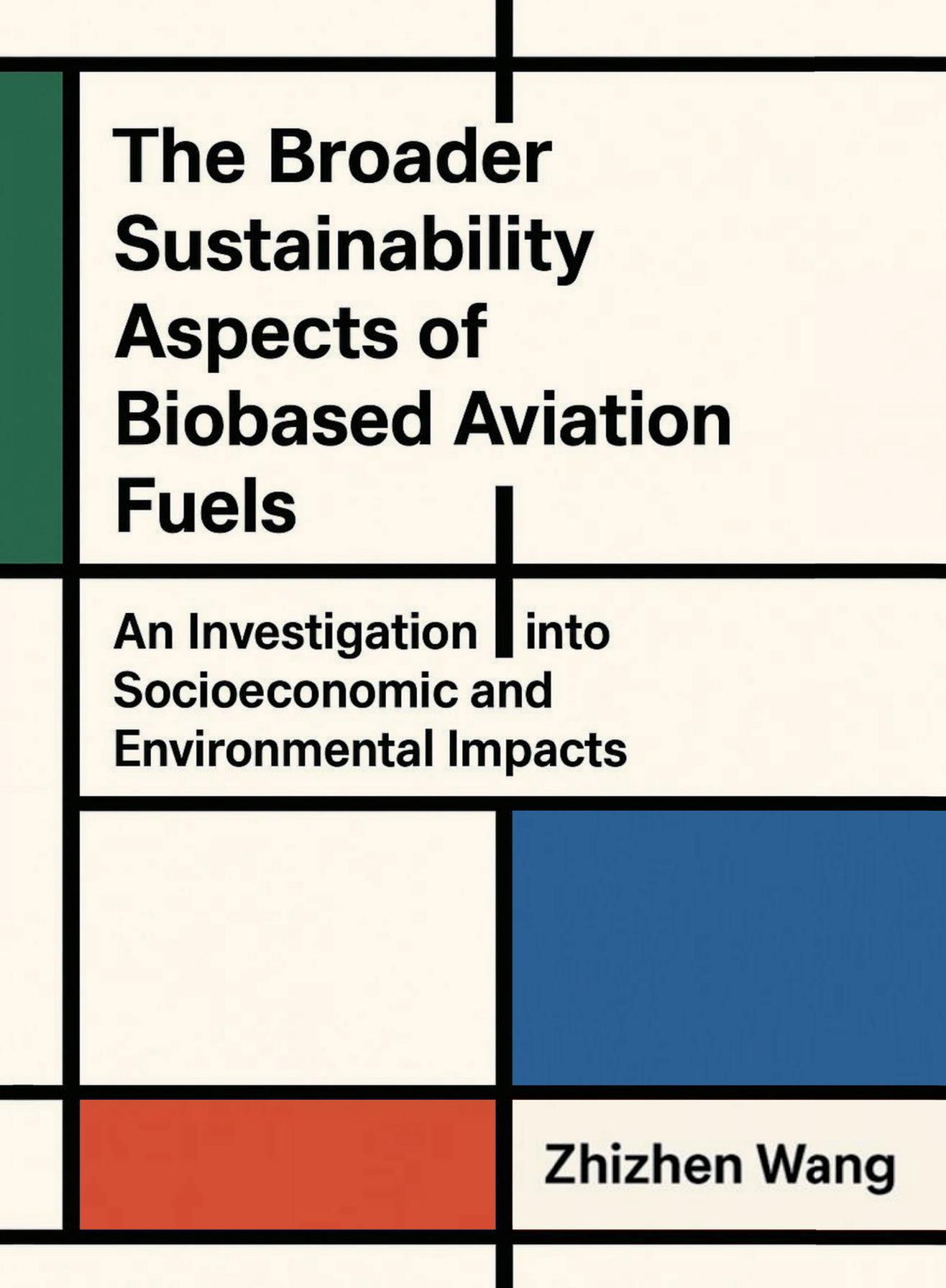
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The Broader Sustainability Aspects of Biobased Aviation Fuels

**An Investigation into
Socioeconomic and
Environmental Impacts**

Zhizhen Wang

The Broader Sustainability Aspects of Biobased Aviation Fuels: An Investigation into Socioeconomic and Environmental Impacts

Dissertation

for the purpose of obtaining the degree of doctor
at Delft University of Technology
by the authority of the Rector Magnificus prof. dr. ir. T.H.J.J. van der Hagen
Chair of the Board of Doctorates
to be defended publicly on
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Summary

In the current era of climate anxiety coexisting with climate change optimism, the scientific consensus lands on the urgency and necessity of combating climate change. Among other solutions, renewable energy is perceived as one of the most important levers to drive the transition toward a low-carbon or even zero-carbon economy. The transportation sector emits more than 20% of today's global greenhouse (GHG) gas emissions and the aviation sector accounts for 2-3% of global emissions. Unlike the road transportation sector where sustainable hydrogen and electric vehicles have been adopted on a large scale, the aviation industry still relies heavily on biobased sustainable aviation fuel (SAF) as the best “drop-in” fuel alternative in the short- to medium-term transition, due to technological and economic constraints. Over the past decade, multiple SAF production pathways have been approved by the American Society for Testing and Materials (ASTM) technical certification of commercial jet fuel and a wide variety of biomass feedstock have been tested for producing SAF. While biobased SAFs have demonstrated their promising potential as a technical solution to replacing conventional jet fuels, their integral sustainability performance is still to be validated, given that the value chain of biobased aviation fuel involves a wide range of economic sectors and interacts with various stakeholders in society.

Several sustainability aspects around the production and supply of biobased SAF have been discussed and evaluated by researchers from multiple disciplines. A large number of studies have been focusing on the environmental front and specifically the life cycle impacts of biobased SAF, considering a wide range of technologies and biomass feedstock. However, the resulting GHG emissions reduction potential (along with other environmental impacts) is highly context-dependent and can vary significantly. On the other hand, biofuel production could stimulate socioeconomic development at the national and local levels, while most existing studies have only analyzed the socioeconomic impact in a generic and conceptual manner, and therefore lack an empirical perspective. In addition to emissions reduction and socioeconomic effects, recent studies have pointed out that biofuel production could result in negative impacts on human health. Nonetheless, few studies have been dedicated to the in-depth analysis of the human health impacts attributed to biobased SAF with an empirical approach, in part due to the absence of consensus in the life cycle impact modeling of human health impacts. Moreover, as the demand for biobased SAF is expected to increase rapidly due to climate goals and emerging policy mandates, competition for land and biobased resources will intensify between various biobased industries such as biofuels, biochemicals, and biomaterials. This, in turn, limits the biomass availability for biobased SAF production and renders the supply-demand balance unclear.

From a value chain perspective, the production and supply chain of biobased SAF can result in impacts on numerous sustainability aspects. Decarbonizing the aviation sector in a sustainable manner requires a thorough understanding of the integral sustainability performance of biobased SAF. It is key to not only have a holistic sustainability assessment of biobased SAF production and supply chain, but also to identify potential positive and negative impacts at an early development stage of these novel technologies and supply chains for the biobased SAF roadmap.

Chapter 1 provides a general introduction to the development of biobased SAF and the essential role it plays in decarbonizing the global aviation sector. The knowledge gaps in terms of sustainability performance are elaborated and research needs to understand those under-studies sustainability impacts are addressed. The main goal of this thesis is to provide in-depth insights into the integral sustainability performance of biobased SAF production and supply chains, considering the socioeconomic effects, human health impacts, supply-demand balance, and the resulting GHG emissions reduction potential, in order to facilitate the strategic decision-making around biobased SAF. To achieve this goal, Chapters 2 to 4 are structured accordingly.

Chapter 2 addresses the first under-studied sustainability aspect of biobased SAF – socioeconomic effects in terms of employment, gross domestic product (GDP), and trade balance, aiming to identify the economy sectors that could be positively or negatively affected and the degree of such impacts resulting from the establishment of biobased SAF supply chains in a certain context. A scenario-based Input-Output (IO) analysis was used to perform a systematic evaluation of the socioeconomic effects of biobased SAF production, considering specific regions, feedstocks, technologies, and future scenarios. The uncertainty of the IO model was addressed with a stochastic simulation. The assessment showed promising positive socioeconomic benefits of creating employment opportunities and boosting GDP while recognizing potential negative impacts on trade balance as well as job displacement in other sectors. It is therefore recommended to have a balanced view of the socioeconomic effects, and it is key to understand potential unintended tradeoffs in the decision-making process.

Chapter 3 addresses the second under-studied sustainability aspect of biobased SAF – human health. Life Cycle Impact Assessment (LCIA) of human health impacts related to biobased SAF production and supply chain was performed. As there is a lack of consensus on the LCIA methods for assessing human health, a comparative analysis of six most commonly used LCA methods was used and compared in a systematic manner. As a result, the hotspots in the biobased SAF life cycle were identified, namely SAF conversion, followed by feedstock production. In response to these findings, research directions and measures to mitigate the negative impacts were proposed. Due to the high levels of uncertainty of the LCIA methods for quantifying human health impacts, distinct results were observed in the comparative analysis, making it challenging to draw the conclusion of which SAF conversion technology performs

the best from the perspective of human health impacts. Nevertheless, the differences in results were predominantly attributed to factors such as study scope, geographical location, and value preference. To improve the understanding of the life cycle human health impact, a self-checklist and a decision tree based on the goal and scope were proposed for selecting the most appropriate method for future LCA studies.

In **Chapter 4**, additional under-studied sustainability aspects of biobased SAF – supply-demand balance and the resulting GHG emissions reduction were addressed. The starting point of this chapter is the fact that multiple SAF production pathways have been approved by the ASTM standards due to the accelerated development of SAF technologies in the recent decade. This triggers the inquiry about which technological pathway and which biomass feedstock is the most sustainable, and whether the supply of biobased SAF will be sufficient to meet the demand in line with the aviation sector’s climate-neutral goal by 2050. Accordingly, a refreshed and critical literature review of biobased SAF production pathways was performed based on their sustainability performance, namely technical maturity level, economic performance, and environmental impacts (mainly GHG emissions reduction potential). Through this comprehensive literature review, a shortlist of the most sustainable biobased SAF production pathways was proposed, together with the suitable second-generation biomass that does not pose a threat to food security. To provide further empirical insights into the supply-demand balance of biobased SAF towards 2050, several scenarios based on various levels of SAF demand, blending mandate, and biomass availability within Europe were used as the case study. The resulting GHG emissions reduction was also calculated to facilitate decision-making and strategic planning of the biobased SAF future development. The analysis suggested that theoretically, a high level of biomass availability could be sufficient to fulfill the SAF supply in Europe towards 2050. However, that level of biomass availability would be challenging to achieve due to the fact that other biobased economy sectors would compete for biomass. Additionally, a few tradeoffs were revealed from the empirical case study that were worth highlighting. The challenges and limitations at the continental and national levels are not always aligned. The SAF conversion pathway resulting in the highest yield and the SAF conversion pathway resulting in the highest emissions reduction potential are not necessarily the same.

Chapter 5 concludes the main research findings, summarizes the key contributions of this thesis, and provides recommendations for future research activities in the space of sustainability performance and decision-making around biobased SAF.

Samenvatting

In het huidige tijdperk van klimaatangst en optimisme over klimaatverandering, is er wetenschappelijke consensus over de urgentie en noodzaak om klimaatverandering te bestrijden. Onder andere oplossingen wordt hernieuwbare energie beschouwd als een van de belangrijkste hefboomen om de overgang naar een koolstofarme of zelfs koolstofvrije economie te stimuleren. De transportsector is verantwoordelijk voor meer dan 20% van de huidige wereldwijde uitstoot van broeikasgassen (GHG) en de luchtvaartsector draagt bij aan 2-3% van de wereldwijde emissies. In tegenstelling tot de wegtransportsector, waar duurzame waterstof- en elektrische voertuigen op grote schaal zijn aangepast, blijft de luchtvaartindustrie nog steeds sterk afhankelijk van biobased duurzame vliegtuigbrandstof (SAF) als het beste alternatief voor "drop-in" brandstof op korte tot middellange termijn, vanwege technologische en economische beperkingen.

In de afgelopen tien jaar zijn meerdere SAF-productieroutes goedgekeurd door de American Society for Testing and Materials (ASTM) voor technische certificering van commerciële vliegtuigbrandstof en is een breed scala aan biomassa-feedstocks getest voor de productie van SAF. Hoewel biobased SAF's hun veelbelovende potentieel als technische oplossing hebben aangetoond om conventionele vliegtuigbrandstoffen te vervangen, moet hun integrale duurzaamheidsprestatie nog worden gevalideerd, gezien de waardeketen van biobased vliegtuigbrandstof die een breed scala van economische sectoren omvat en verschillende belanghebbenden in de samenleving. Verschillende duurzaamheidsaspecten rond de productie en levering van biobased SAF zijn besproken en geëvalueerd door onderzoekers uit verschillende disciplines. Een groot aantal studies heeft zich gericht op de milieuvriendelijke kant en met name de levenscyclusimpact van biobased SAF, waarbij rekening werd gehouden met een breed scala aan technologieën en biomassa-feedstocks. De resulterende vermindering van de uitstoot van broeikasgassen (samen met andere milieueffecten) is echter sterk afhankelijk van de context en kan aanzienlijk variëren. Aan de andere kant kan de productie van biobrandstoffen de sociaaleconomische ontwikkeling op nationaal en lokaal niveau stimuleren, terwijl de meeste bestaande studies alleen de sociaaleconomische impact op een algemene en conceptuele manier hebben geanalyseerd en daarom een empirisch perspectief missen. Naast de vermindering van de uitstoot en sociaaleconomische effecten, hebben recente studies erop gewezen dat biobrandstofproductie negatieve effecten op de menselijke gezondheid kan hebben. Niettemin zijn er weinig studies gewijd aan de diepgaande analyse van de menselijke gezondheidseffecten die worden toegeschreven aan biobased SAF met een empirische benadering, mede door het ontbreken van consensus in de levenscyclusimpact.

Vanuit een waardeketenperspectief kan de productie- en toeleveringsketen van biobased SAF gevolgen hebben voor tal van duurzaamheidsaspecten. Het decarboniseren van de luchtvaartsector op een duurzame manier vereist een grondig begrip van de integrale duurzaamheidsprestatie van biobased SAF. Het is essentieel om niet alleen een holistische duurzaamheidsbeoordeling van biobased SAF-productie en toeleveringsketen te hebben, maar ook om potentiële positieve en negatieve effecten te identificeren in een vroeg ontwikkelingsstadium van deze nieuwe technologieën en toeleveringsketens voor de biobased SAF-routekaart.

Hoofdstuk 1 biedt een algemene introductie van de ontwikkeling van biobased SAF en de essentiële rol die het speelt bij het decarboniseren van de wereldwijde luchtvaartsector. De kenniskloven op het gebied van duurzaamheidsprestaties worden uitgebreid besproken en onderzoek naar het begrijpen van deze onderbelichte duurzaamheidseffecten wordt aangekaart. Het belangrijkste doel van dit proefschrift is om diepgaande inzichten te bieden in de integrale duurzaamheidsprestatie van biobased SAF-productie en toeleveringsketens, rekening houdend met de sociaaleconomische effecten, gezondheidseffecten, de vraag- en aanbodbalans en het resulterende potentieel voor vermindering van broeikasgasemissies, om strategische besluitvorming rond biobased SAF te faciliteren. Om dit doel te bereiken, zijn **Hoofdstuk 2** tot en met 4 dienovereenkomstig gestructureerd.

Hoofdstuk 2 richt zich op het eerste onderbelichte duurzaamheidsaspect van biobased SAF - de sociaaleconomische effecten in termen van werkgelegenheid, bruto binnenlands product (BBP) en handelsbalans - met als doel de economische sectoren te identificeren die positief of negatief kunnen worden beïnvloed en de mate van dergelijke effecten als gevolg van de oprichting van biobased SAF-toeleveringsketens in bepaalde contexten. Een scenario-gebaseerde Input-Output (IO) analyse werd gebruikt om een systematische evaluatie uit te voeren van de sociaaleconomische effecten van biobased SAF-productie, rekening houdend met specifieke regio's, feedstocks, technologieën en toekomstscenario's. De onzekerheid van het IO-model werd aangepakt met een stochastische simulatie. De beoordeling toonde veelbelovende positieve sociaaleconomische voordelen van het creëren van werkgelegenheidskansen en het stimuleren van het BBP, terwijl potentiële negatieve impact op de handelsbalans en baanverdringing in andere sectoren werden erkend. Het is daarom aanbevolen om een gebalanceerd beeld te hebben van de sociaaleconomische effecten en om potentiële onbedoelde trade-offs te begrijpen in het besluitvormingsproces.

Hoofdstuk 3 richt zich op het tweede onderbelichte duurzaamheidsaspect van biobased SAF - de menselijke gezondheid. Er werd een Life Cycle Impact Assessment (LCIA) van de menselijke gezondheidseffecten die verband houden met de productie en toeleveringsketen van biobased SAF uitgevoerd. Aangezien er geen consensus bestaat over de LCIA-methoden voor het beoordelen van de menselijke gezondheid, werden zes meest gebruikte LCA-methoden vergeleken en systematisch

geanalyseerd. Als gevolg hiervan werden de hotspots in de levenscyclus van biobased SAF geïdentificeerd, namelijk SAF-conversie, gevolgd door de productie van feedstocks. Als reactie op deze bevindingen werden onderzoeksrichtingen en maatregelen voorgesteld om de negatieve effecten te verminderen. Vanwege de hoge mate van onzekerheid van de LCIA-methoden voor het kwantificeren van menselijke gezondheidseffecten werden verschillende resultaten waargenomen in de vergelijkende analyse, waardoor het uitdagend was om de conclusie te trekken welke SAF-conversietechnologie het beste presteert vanuit het perspectief van menselijke gezondheidseffecten. Niettemin werden de verschillen in resultaten voornamelijk toegeschreven aan factoren zoals de reikwijdte van het onderzoek, geografische locatie en de waardevoorkeur. Om het begrip van de levenscyclus van menselijke gezondheidseffecten te verbeteren, werden een self-checklist en een beslissingsboom op basis van doel en reikwijdte voorgesteld voor het selecteren van de meest geschikte methode voor toekomstige LCA-studies.

In **Hoofdstuk 4** werden aanvullende onderbelichte duurzaamheidsaspecten van biobased SAF behandeld - de vraag- en aanbodbalans en het resulterende potentieel voor vermindering van broeikasgasemissies. Het vertrekpunt van dit hoofdstuk is het feit dat meerdere SAF-productieroutes zijn goedgekeurd volgens de ASTM-normen als gevolg van de versnelde ontwikkeling van SAF-technologieën in het afgelopen decennium. Dit roept de vraag op welke technologische route en welke biomassa-feedstock het meest duurzaam zijn en of de levering van biobased SAF voldoende zal zijn om te voldoen aan de vraag in lijn met het klimaatneutrale doel van de luchtvaartsector tegen 2050. Dienovereenkomstig werd een kritische literatuurstudie van biobased SAF-productieroutes uitgevoerd op basis van hun duurzaamheidsprestatie, namelijk technisch rijpheidsniveau, economische prestaties en milieueffecten (voornamelijk potentieel voor vermindering van broeikasgasemissies). Door deze uitgebreide literatuurstudie werd een shortlist voorgesteld van de meest duurzame biobased SAF-productieroutes, samen met geschikte biomassa van de tweede generatie die geen bedreiging vormen voor de voedselzekerheid. Om verdere empirische inzichten te bieden in de vraag- en aanbodbalans van biobased SAF richting 2050, werden enkele scenario's gebruikt op basis van verschillende niveaus van SAF-vraag, mengverplichting en beschikbaarheid van biomassa binnen Europa als casestudy. De resulterende vermindering van broeikasgasemissies werd ook berekend om besluitvorming en strategische planning van de toekomstige ontwikkeling van biobased SAF te vergemakkelijken. De analyse suggereerde dat theoretisch gezien een hoog niveau van biomassa-beschikbaarheid voldoende zou zijn om de SAF-levering in Europa richting 2050 te vervullen. Echter, dat niveau van biomassa-beschikbaarheid zou uitdagend zijn om te bereiken aangezien andere biobased economie sectoren zouden concurreren om biomassa. Bovendien werden enkele trade-offs onthuld uit de empirische casestudy die het vermelden waard waren. De uitdagingen en beperkingen op continentale en nationale niveaus zijn niet altijd op één lijn. De SAF-conversieroute met de hoogste opbrengst en de SAF-

conversieroute met het hoogste potentieel voor vermindering van broeikasgasemissies zijn niet noodzakelijk dezelfde.

Hoofdstuk 5 concludeert de belangrijkste onderzoeksresultaten, vat de belangrijkste bijdragen van dit proefschrift samen en geeft aanbevelingen voor toekomstige onderzoeksactiviteiten op het gebied van duurzaamheidsprestaties en besluitvorming rond biobased SAF.

Chapter 1

General Introduction

1.1 Introduction and motivation

We live in an era of climate change anxiety intertwined with climate change action optimism. Ideas and beliefs aside, the fact is that the global economic growth has been relying primarily on fossil energy. Throughout the life cycle of fossil energy, from extraction, refining, transportation, to processing and combustion, a significant amount of carbon dioxide emissions are released. Typically, the natural process of mineralization and sequestration of the equivalent amount of CO₂ emissions from burning fossil fuels would take millions of years. As a result, the equilibrium of carbon emissions and sequestration has been broken by human activities, leading to an accelerating accumulation of greenhouse gas (GHG) emissions in the atmosphere since industrialization and in consequence, global temperature rises.

In 2023, the Intergovernmental Panel on Climate Change (IPCC) published its latest report Sixth Assessment Report, underlining the urgency and significance of mitigating climate change (Lee et al., 2023). To pursue sustainable development across the globe, the scientific consensus has addressed the necessity of limiting global warming to well-below 2 degrees Celsius and preferable below 1.5 degrees compared to the pre-industrial level (Lee et al., 2023). In response, 196 Parties signed the Paris Agreement back in 2015 committing to the well-below 2 degrees scenario, substantially reducing the impact of climate change (Agreement Paris, 2015; Horowitz, 2016). Recent years has witnessed multiple encouraging government commitments addressing climate change such as European Green Deal (European Commission, 2021), US Inflation Reduction Act (H.R. 812, 2023), China's Dual Carbon policy (Jia et al., 2022).

In the context of combating climate change, renewable energy is perceived as one of the most impactful levers to drive the transition toward sustainable development and a zero-carbon economy. The transportation sector emits 22% of global GHG emissions and the aviation sector accounts for 2-3% of global emissions (Crippa et al., 2022; IEA, 2022). In order to decarbonize the transportation industry, road transportation has been replacing fossil fuels by sustainable hydrogen or electric vehicles including heavy duty trucks and long-distance transportation whereas for the aviation sector, "drop-in" sustainable aviation fuels (SAFs), namely biobased SAF and e-fuels are still the best alternative for the short- and mid-term due to technological and economic constraints (Quante et al., 2023; Afonso et al., 2023; Verma and Goel, 2023; Cabrera-Jimenez et al., 2023; IEA, 2022; Kargbo et al., 2021; Ng et al., 2021; O'Connell et al., 2019; Change and Hwang, 2017). Thanks to the accelerated technological advancement, specific policy mandates on SAF blending have started to emerge. An important example is the ReFuelEU Aviation rules, as part of the "Fit for 55 package", has been approved by EU to ensure the SAF blending will reach 70% by 2050 (ReFuelEU, 2023). Major organizations such as the International Air Transport Association (IATA) and the International Civil Aviation Organization (ICAO, a United Nations agency)

have committed to significantly reducing emissions and achieving net-zero carbon emissions by 2050 for the global aviation industry (IATA, 2021; ICAO, 2022). SAF plays a vital role in the decarbonization roadmap of the aviation sector while addressing such meaningful challenges as socioeconomic development and energy security at the present time. Since “drop-in” e-fuels have not reached the commercialization stage due to constraints of the existing aircraft engine design and battery capacity, this thesis, therefore, excludes the analysis of e-fuels and focuses only on assessing biobased SAF’s sustainability performance because of data unavailability.

To date, various studies have been dedicated to the techno-economic feasibility of biobased SAF (Undavalli et al., 2023; Rojas-Michaga et al., 2023; Mussatto et al., 2022; Tanzil et al., 2021; Holladay et al., 2020; Tzanetis et al., 2017; Santos et al., 2017). Eight production pathways have past the American Society for Testing and Materials (ASTM) technical certification for commercial jet fuel and a wide variety of biomass feedstock have been tested for producing SAF, ranging from carbohydrates and cellulose to fats and oils. When concentrating on various sustainability aspects, the production and consequences of biobased SAF have been evaluated by researchers from multiple disciplines. From the economic perspective, the Minimum Fuel Selling Price (MFSP) of biobased SAF can be 2–8 times of the price of petroleum-based jet fuel (Pavlenko et al. 2019; Santos et al., 2017), determined by various factors ranging from feedstock cost, production cost, biofuel yield, and policy instruments. On the environmental front, a number of studies have evaluated the life cycle impacts of biobased SAF (Kossarev et al., 2023; Puschnigg et al., 2023; Rojas-Michaga et al., 2023; Gonzelez-Garay et al., 2022; Mussatto et al., 2022; Capaz et al., 2021 (a); Capaz et al., 2021 (b); Siddiqui and Dincer, 2021; Capaz et al., 2020; De Jong et al., 2017) considering various technologies and biomass feedstock. The expected GHG emissions reduction potential (along with other environmental impacts) is highly context-dependent and can vary largely from one to another. The calculated life cycle GHG emissions reduction of biobased SAF ranges from around 25% to 100%. Additionally, producing biofuels could also boost socioeconomic development at the local and national levels (Kumar et al., 2023; Mvelase et al., 2022; Arun et al., 2020; van Eijck et al., 2014;). More specifically, promoting biobased SAF could improve income and employment opportunities, thereby stimulating economic growth. Nevertheless, most existing studies have only analyzed the socioeconomic impact in a generic and conceptual manner without a systematic methodology for empirical assessment. Hence, while biobased SAFs have demonstrated their potential as a technical solution to replace conventional jet fuels, their potential to realize significant GHG emissions reduction as well as positive socioeconomic impact is still to be validated.

In addition to the capability of reducing GHG emissions and socioeconomic effect, another understudied sustainability aspect of biobased SAF is its impact on human health (Siddiqui and Dincer, 2021; Vasquez et al., 2019). Fuel production and combustion are associated with human health related issues,

such as generating particulate matters (PM), a main indicator of air pollution. Recent studies have pointed out that biofuel production could result in more negative impacts on human health compared to the production of the fossil counterpart (De Jong et al., 2015; Tsang et al., 2015; Yang, 2013). However, few studies have been dedicated to the in-depth analysis of the human health impacts attributed to biobased aviation fuel in particular. An important reason for this is the high level of uncertainty and low level of consensus in the life cycle impact modelling of human health impacts (Bulle et al., 2019; Arvidsson et al., 2018; Galdos et al., 2013; Pizzol et al., 2011). Moreover, an overarching guideline is lacking when it comes to selecting the appropriate life cycle impact analysis (LCIA) methods for quantifying human health impacts. Because the results of LCIA studies heavily depend on methodological choices, timeframe, and data inputs, failing to recognize this strong dependence makes the comparison among various studies not only challenging, but contradicting at times (Bulle et al., 2019; Arvidsson et al., 2018; Galdos et al., 2013; Pizzol et al., 2011). This is why an up-to-date comparison of different LCIA methods for quantifying the impacts on human health in the context of biobased SAF is desired to shed light on how results can be affected by the choice of methods, thereby addressing contradictory results from literature, and understanding the potential impacts of biobased SAF production on human health.

Furthermore, as the demand for biobased SAF rises, competition for land and biobased resources will intensify between the production of food/feed, biomaterials, and other biofuel final products (Meijaard et al., 2020; Muscat et al., 2020; Naylor et al., 2018; Santeramo and Searle, 2019). Regions like the EU have taken measures to phase out food-based biofuels produced by feedstock associated with high indirect land use change (LUC) risk after 2020 (Fortuna, 2019). As a key activity in the agricultural and forestry industry, biomass production should follow stringent land management rules to avoid deforestation, land degradation and biodiversity loss (Hinkes et al., 2020; Tyson and Meganingtyas, 2022; Carlson and Garrett, 2018). This, however, further limits biomass availability including the biomass in general and biomass for biobased SAF production in particular. Thus, a focused analysis is needed to investigate the interconnections between SAF demand, biomass availability, SAF supply potential, and the resulting emission reduction in line with future policy planning. Such knowledge is a necessity for strategic decision- and policy-making in order to mitigate the impact of the aviation industry on climate change.

From a life cycle perspective, the value chain of biobased SAF involves a wide range of sectors and can have impacts on numerous sustainability aspects. To decarbonize the aviation sector in a sustainable manner, there is a need to understand the overall sustainability performance concerning technoeconomic, socioeconomic, and environmental dimensions of SAF production and supply chain.

It is vital to not only have a holistic sustainability assessment of biobased SAF production and supply chain, but also to identify potential negative impacts, revealing hotspots and specifying improvement opportunities early-on in the development of novel technologies and supply chains (Parada et al., 2017; Darda et al., 2019). This holds particularly true in the case of biobased SAF as an emerging new sector where new feedstocks are still being investigated, new conversion technologies are being tested, and new supply chains are being established. Providing novel insights into the sustainability performance of SAF that contributes to reducing GHG emissions, improving socioeconomic development, and enhancing energy security has been the motivating challenges for this thesis.

1.2 Research objectives and thesis structure

The main goal of this thesis is to provide in-depth insights into the integral sustainability performance of biobased SAF production and supply chains, considering the socioeconomic effects, human health impacts, supply-demand balance, and the resulting GHG emissions reduction potential, which contributes to the strategic decision-making around biobased SAF. Furthermore, we aim to investigate the potential positive and negative impacts of the large-scale implementation of biobased SAF production at an early-design stage while addressing the methodological challenges and limitations related to making such integral sustainability analysis operational. It is worth mentioning that we do not intend to provide a definitive answer to the question that “which biobased SAF technology is the most sustainable”, because it heavily depends on the context and scenarios determined by a wide range of parameters such as but not limited to geographic location, type of feedstock, and policy instruments. On the other hand, as context is key in answering research questions related to biobased SAF, this thesis aims to demonstrate an operational approach to establish specificities, present results, and analyze trade-offs in such a way that can lead to a meaningful decision-making process focusing on biobased SAF technology and supply chain, by providing empirical and conceptual approaches to quantitatively assess three sustainability aspects of the biobased SAF production that have been overlooked in scientific literature and technical reports: (1) socioeconomic effects, (2) human health impacts, and (3) supply-demand balance.

Related to the research goals, the main research question of this thesis is: What is the integral sustainability performance of biobased SAF production and supply chain, focusing on the under-studied aspects of socioeconomic effects, human health impacts and supply-demand balance? And how to quantitatively assess these aspects? To answer this question, a few sub research questions are addressed respectively in Chapters 2 to 5 as follows.

As biobased SAF is the latest member of the biofuel family, its social or socioeconomic impacts have only been analyzed in a generic and conceptual manner without a systematic methodology and an

empirical perspective. Therefore, **Chapter 2** addresses the first sub-research question: What are the socioeconomic sustainability effects of biobased SAF production and supply chain, and how to quantitatively assess these impacts? Accordingly, three primary socioeconomic effects related to biobased SAF in terms of employment, gross domestic product (GDP), and trade balance were analyzed, in order to identify the economic sectors that could be positively or negatively affected and the degree of such impacts resulting from the establishment of biobased SAF supply chains in a given geographical and social context. With a scenarios-based Input-Output (IO) analysis, a systematic assessment of socioeconomic effects of biobased SAF production was performed, considering specific regions, feedstocks, technologies, and future scenarios in the context of Brazil towards 2050. Moreover, to capture the uncertainty associated with employment, GDP, and trade balance resulting from IO analysis, a stochastic simulation using parameters calculated from historical IO data was applied. As a result, new insights into the socioeconomic effects of three potential biobased SAF supply chains for four demand scenarios were presented; and the associated levels of uncertainty were compared.

Chapter 3 addresses the second sub-research question: What are the human health impacts of biobased SAF production and supply chain and what is the most appropriate methodology for assessing such impact? To do so, this chapter investigates the life cycle human health impacts related to biobased SAF production by conducting an up-to-date systematic comparative analysis of six commonly used Life Cycle Impact Assessment (LCIA) methods. The three biobased SAF supply chains evaluated in Chapter 2 were used for empirically quantifying life cycle human health impacts and revealing how assessment results can be affected by the choice of methods. As a result, potential human health impact hotspots were identified, and improvement opportunities were proposed in terms of SAF production processes, waste management as well as fertilizer and pesticide management.

Moreover, LCIA methods for assessing human health are often associated with a high level of uncertainty and a low level of consensus. No published studies have fully specified how decisions were made regarding the selection and implementation of LCIA methods for quantifying human health impacts. However, the results of LCIA studies heavily depend on the methodological choices, timeframe, and data inputs (Parada et al., 2017). Contradicting conclusions could be drawn when different LCIA methods are used. Hence, the strong dependence between LCIA methods and resulting impacts needs to be taken into account when making comparisons among different systems and studies. Recognizing that there is no single one-size-fits-all LCIA method, **Chapter 3** also provides a guideline for LCA practitioners, consisting of a self-check question list and a decision tree for determining an appropriate method for assessing life cycle human health impacts.

The last decade has witnessed the accelerated development of biobased SAF thanks to its potential of delivering immediate net emissions reduction. To date, eight biobased drop-in SAFs production

pathways have been approved by the American Society for Testing and Materials (ASTM)'s standards (CAAFI, 2023). There is, therefore, a need to provide a refreshed literature review of all approved biobased SAF production pathways and explore the role they can play in decarbonizing the aviation sector. **Chapter 4** addresses the third sub-research question: What are the most promising SAF production pathways using lignocellulosic and waste biomass; and will the supply of biobased SAF be sufficient to meet the demand in line with the aviation sector's climate neutral goal by 2050. Hence, Chapter 4 aims to provide a critical, and comprehensive literature review of the biobased SAF production pathways based on their sustainability performance, namely technical maturity level, economic performance, and environmental impacts (predominantly potential GHG emissions reduction compared to their fossil counterpart). By doing so, a shortlist of the most sustainable production pathways for biobased SAF using lignocellulosic and waste biomass was proposed for further evaluation and policy making.

To combat climate crisis, the European Commission has published several regulations during the recent years including the European Green Deal (European Commission, 2019) and the "Fit for 55 package" (ReFuelEU, 2023). European aviation sector has committed to the reduction of net CO₂ emissions by 55% (compared to 1990 levels) by 2030 and reaching net zero CO₂ emissions by 2050. SAF has an urgent and vital role to play in the decarbonization roadmap of the aviation sector. Hence, **Chapter 4** also aims to explore the supply-demand scenarios within Europe towards the 2050 horizon, by deep diving into the shortlisted SAF production pathways in four different demand scenarios, while exploring the implications of various levels of SAF blending and biomass availability. This eventually generated new insights into the potential biomass availability and potential supply of SAF for the European aviation sector, which in turn can be used in policy recommendations and the strategic planning of future SAF outlook.

Chapter 5 concludes with the main research findings throughout this thesis. It also summarizes the key contributions of this thesis and provides recommendations for future research activities in the space of integral sustainability performance assessment of biobased SAF technologies and supply chains.

Chapter 2

Socioeconomic effects of aviation biofuel production in Brazil: A scenarios-based Input-Output analysis

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2.1 Introduction

Driven by climate change and the price volatility of fossil fuels, the importance of renewable energy sources has been widely recognized. In particular, biofuels are considered as key contributors to greenhouse gas (GHG) emissions reduction in the transport sector (Chum et al., 2011; IEA 2019). However, sustainability concerns have been raised around biofuel production, in such aspects as land use change, food insecurity, and biodiversity loss (Fritsche et al., 2010; Goldemberg et al., 2008; Janssen and Rutz, 2011). On the other hand, producing biofuels shows positive impacts on social development by providing employment and stimulating local economic growth (Phalan, 2009; van Eijck et al., 2014; Walter et al., 2011). Therefore, the overall impacts of biofuel production call for a full investigation into various aspects of its sustainability (Parada et al., 2017; Darda et al., 2019). This holds particularly true in the case of aviation biofuel, where new feedstocks are being studied, new conversion technologies are being developed, and new supply chains are being established.

As a relatively new member of the biofuel family, aviation biofuel has entered early commercialization stage. So far, commercial production of aviation biofuel has been achieved only via the hydro-processed esters and fatty acids pathway (ICAO, 2019). According to the International Air Transport Association (IATA, 2018), more than 150,000 commercial flights using aviation biofuel have been performed. Based on the announced International Civil Aviation Organization's offtake agreements (ICAO, 2019), the annual production volume of aviation biofuel for 2020 is expected to be about 0.45 Mt.

Derived from renewable feedstocks, aviation biofuel is generally perceived as sustainable (Agusdinata et al., 2011; Li and Mupondwa, 2014), due to its potential in emissions reduction and energy security enhancement (Hileman and Stratton, 2014; IATA, 2013). However, only a limited number of studies have analyzed the sustainability effects (i.e., environmental, economic, and social dimensions) of aviation biofuel production. In particular, social or socioeconomic impacts have only been analyzed in a generic and conceptual manner without a systematic methodology for empirical assessment. As a result, most of studies in literature have focused on evaluating environmental impacts (Cox et al., 2014; de Jong et al., 2017; Han et al., 2013), technical feasibility (Tongpun et al., 2019; Tzanetis et al., 2017; Vyhmeister et al., 2018), and economic competitiveness (Lu, 2018; Rutten et al., 2017; Vyhmeister et al., 2018) of aviation biofuel, while none has addressed its social or socioeconomic aspects in depth, as noticed by Kamali et al. (2018).

Nonetheless, the social pillar of sustainability plays an important role for aviation biofuel's future development (Cremonez et al., 2015b; Hari et al., 2015; Moraes et al., 2014). In order to ensure a sustainable aviation biofuel production, it is imperative to first understand its potential socioeconomic effects in details (Parada et al., 2018). This requires an assessment that takes into account the specifics

of context, production volume, conversion technology, and potential feedstock. Differences in these specifics between aviation biofuel and other biofuels (i.e., bioethanol and biodiesel) can have large effects on the resulting socioeconomic impacts. This is why a focused analysis of aviation biofuel is necessary. Such an in-depth assessment of socioeconomic effects can provide deepened insights into the prospective socioeconomic benefits or concerns associated with aviation biofuel. The generated context-specific knowledge can facilitate communication and decision-making around sustainable aviation biofuel production.

Hence, the objective of this study is to assess key socioeconomic effects related to aviation biofuel production on employment, GDP, and trade balance. Brazil was selected as case study in this analysis as it has been a front-runner in biofuel development since the 1970s, when the government introduced a scheme to promote sugarcane ethanol production. Apart from its successful experiences with bioethanol, the availability of land and benign climatic conditions can also potentially contribute to the establishment of aviation biofuel production. Locally produced aviation biofuel offers Brazil the opportunity to facilitate its fast growing aviation sector in a more sustainable way (AGROPOLO, 2016). Using a scenarios-based Input-Output (IO) analysis, we assessed the socioeconomic effects of aviation biofuel production in Brazil for 2050 under different scenarios. Additionally, a stochastic simulation was carried out to understand the uncertainties associated with the IO model and shed light on the robustness of assessment results. Although stochastic simulation has been applied in other IO studies (Wiedmann et al., 2007; Wiedmann, 2009), this approach is scarce in empirical case studies (Lenzen et al., 2010). To the best of the authors' knowledge, there has been no case study in the field of socioeconomic assessment of biofuel supply chains that applied stochastic simulation to capture uncertainty in the resulting socioeconomic effects.

The contributions of this study are two-fold. We present the first systematic, in-depth, and empirical assessment of socioeconomic effects of aviation biofuel production, considering specific regions, feedstocks, technologies, and future scenarios. Furthermore, in the field of *ex-ante* socioeconomic sustainability assessment of biofuels, we are also the first to apply stochastic simulation (and the first to use parameters calculated from historical IO data rather than assumed ones) to capture the uncertainty associated with employment, GDP, and trade balance resulting from IO analysis. Overall, this study complements the current sustainability assessments of aviation biofuel (which are dominated by GHG emission and techno-economic feasibility analysis), and contributes not only towards a well-informed decision-making for aviation biofuel production but also to the development of systematic methods for empirical assessment of sustainability.

The remainder of this paper is organized as follows. Section 2 describes the methodology, including scenarios, IO analysis, and stochastic simulation. Section 3 represents the results and discussion of the socioeconomic effects. Section 4 discusses the limitations of this study. And lastly, Section 5 concludes.

2.2 Methodology

2.2.1 Methodological choices

The scope of this study covered the main phases of the aviation biofuel supply chain, including feedstock production, pretreatment (if needed), biofuel conversion, and transportation. The supply chains studied were expected to produce aviation biofuel for two major local airports, Guarulhos in São Paulo and Galeão in Rio de Janeiro. These are both located in the Southeast of Brazil and together account for around 45% of national jet fuel consumption (Cortez, 2014).

We applied a scenarios-based IO analysis to evaluate the socioeconomic effects of aviation biofuel production. Given the current stage of aviation biofuel development, the uncertainty associated with its production is relatively high in various respects: from demand for fuel to the selection of feedstock and conversion technology (Moncada et al., 2019). In this regard, scenario analysis was helpful to integrate uncertainties about different aspects and to amalgamate them into plausible futures (Kishita et al., 2017). To explore how possible futures of aviation biofuel in Brazil may unfold, we applied the exploratory scenario approach. This provides implicit and descriptive representations of alternative futures (Kowalski et al., 2009). The time horizon of our scenarios was set at 2050, which is the reference year for the targets laid down in many international policies concerning climate change and renewable energy.

IO analysis has been commonly used to measure socioeconomic effects on employment, GDP, and trade balance associated with biofuel production from a macroeconomic perspective (Martínez et al., 2013; Silalertruksa et al., 2012; Souza et al., 2018). Despite some inherent shortcomings of this method (see Section 2.4), IO analysis is able to isolate the effects on an economy caused by a particular economic activity.

2.2.2 Scenarios

2.2.2.1 Identify driving forces

The construction of scenarios is influenced by many factors, particularly in the case of aviation biofuel where available knowledge and data are limited. These are the driving forces of the diverging futures. In the Brazilian context, three key drivers were identified through a review of the drivers of aviation biofuel development and bioenergy/biofuel scenarios defined by existing studies, namely the growth of the aviation industry, aviation and general biofuel policies, and technological advancement.

- Growth of the aviation industry

As a key driver, “growth of aviation industry” was relatively predictable across the scenarios’ timeline. There is a shared consensus in a number of studies that the global aviation industry will continue to grow rapidly in the next few decades, due to economic and demographic growth (AGROPOLO, 2016; Cortez et al., 2014; Rosillo-Calle et al., 2012). We thus considered this driver as a predetermined factor, regardless of the scenario being investigated.

For the Brazilian aviation sector, an annual growth rate of 4.5% was forecasted (AGROPOLO, 2016). The efficiency improvement of aircraft was estimated at 1.5% annually (ICAO, 2016). Together these percentages resulted in a 3% net increase in national demand for aviation fuel, reaching about 17.7 million tons by 2050 based on a demand of 5.6 million tons in 2011 (AGROPOLO, 2016; Cortez et al., 2014). The two airports in our case study together consume 45% of Brazil’s aviation fuel (Cortez, 2014), equivalent to 8 million tons a year. This total demand for aviation fuel remained constant in all the scenarios developed below.

- Biofuel policies

Policies and regulations regarding bioenergy in general and aviation biofuel in particular are bound to play a key role in shaping the market and introducing aviation biofuel application on a large scale (Hagemann et al., 2016). Effective policy incentives (e.g., subsidies and tax deductions) could attract investment to the aviation biofuel industry, while at the same time spreading confidence in the transition from fossil to biobased fuels (Mulholland et al., 2017; Peters and Thielmann, 2008). In many cases, schemes targeting climate change mitigation and sustainable development are effective incentives for the development of biofuels (Dias et al., 2016; Hagemann et al., 2016). For instance, the National Alcohol Program in Brazil has played a positive role in promoting ethanol production and country-wide consumption. On the other hand, in the absence of specific measures energy policies might exert little influence on aviation biofuel development.

As well as environmental advantages, social benefits of biofuels such as job creation, social inclusion, and rural development have also been acknowledged by Brazilian policy makers (Cremonez et al., 2015c). Similarly, blend mandates for aviation biofuel, as an extension of Brazilian biofuel policies, could potentially be an instrument favored politically. So far, however, and regardless of its potential benefits, no blend mandate has been enforced for aviation fuel in Brazil.

- Technological advancement

While a number of conversion technologies are currently being researched, most have not been put into full-scale production. In fact, only four main conversion pathways have been ASTM certified: *hydro-processed esters and fatty acids (HEFA)*, *Fischer-Tropsch (FT)*, *direct sugars to hydrocarbon (DSHC)*, and *alcohol to jet (ATJ)* (Alves et al., 2017; de Jong et al., 2015; Mawhood et al., 2016). Understanding

how advanced these technologies are offers an insight into the feasibility of each in future scenarios. The technological bottleneck not only constrains the upscaling of aviation biofuel production, it also results in uncompetitive pricing compared with fossil aviation fuel (Hagemann et al., 2016; Hari et al., 2015). Large-scale production of aviation biofuel still has a long way to go. A technological breakthrough is highly desirable in order to open up the market for aviation biofuel, as this would allow the utilization of a wider range of feedstocks while lowering production costs.

2.2.2.2 Develop scenarios

Based on expected aviation industry growth and the diverging trends in the other two driving forces—(i) biofuel policies (proactive or conservative), and (ii) technological advancement (gradual or breakthrough)—four scenarios were compiled, as shown in **Fig. 2.1**. The narrative of each alternative future was depicted using four variables, namely market share of aviation biofuel, conversion technology, selection of feedstock, and competition for biomass (as summarized in **Table 2.1**). Elaborated rationales for the scenarios developed can be found in Appendix I.

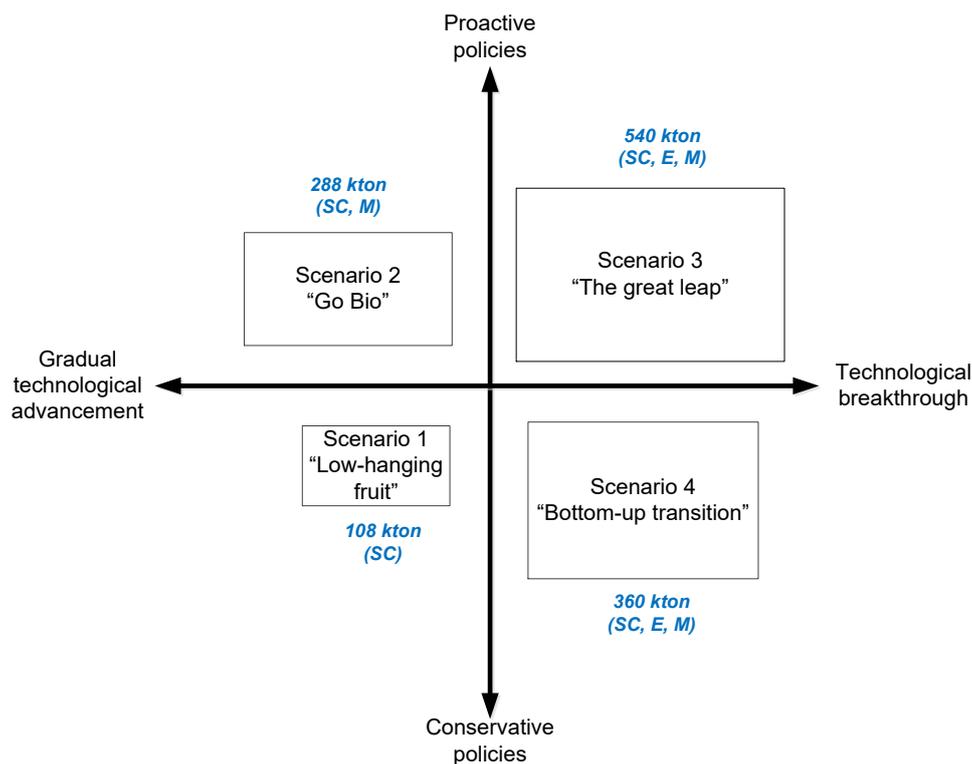


Fig. 2.1 Schematic presentation of scenarios for aviation biofuel development (SC: sugarcane, E: eucalyptus, M: macauba)

Scenario 1: "Low-Emission Flightpath". Biofuel policies remain conservative for aviation, while conversion technologies see little innovation, rendering aviation biofuel commercially unappealing. This narrative results in low interest in producing aviation biofuel. Nevertheless, driven by strong commitment of the private sector to control emissions, aviation biofuel is expected to have a small share

of the market by 2050. In line with the expected 3% net annual growth rate in demand for aviation fuel, it is assumed that 3% of that demand is supplied by biofuel. This amounts to 108 kt (based on the estimated total demand for aviation biofuel in Section 2.2.1.1). The aviation industry can thus expect to mitigate emissions growth by absorbing the net increase in the demand for fuel by means of biofuel. Due to technological constraints, the conversion of lignocellulosic biomass remains challenging. Only a mature supply chain is considered suitable for production. Since knowledge of macauba cultivation and processing in Brazil is not as established as knowledge of sugarcane, the sugarcane-ATJ chain is the only viable option in this scenario. Moreover, it is possible that aviation biofuel would need to compete for biomass resources with other biobased industries, potentially driving up the price of feedstock. Here, a 20% price increase for feedstock was assumed since detailed information on how biomass competition affects feedstock prices is not available.

Scenario 2: “Go Bio”. The government recognizes the urgent necessity of emissions control for the fast-growing aviation industry. A biofuel blend mandate is in place and relevant policy incentives are provided. With technological development stagnated, however, it is still difficult to produce second-generation aviation biofuel on large scale. Regarding first-generation feedstocks, sugarcane is the primary crop facilitating Brazilian ethanol and sugar production. Producing aviation biofuel from sugarcane may therefore lead to competition for biomass with these industries. Nevertheless, the pressure of increasing sugarcane prices is likely to be eased by policy interventions such as subsidies on feedstocks or regulated expansion of sugarcane cultivation. Similarly, the government’s proactive role promotes the cultivation of macauba, which is designated for producing aviation biofuel. In this case, competition for biomass can be considered negligible. As a result, the sugarcane-ATJ and the macauba-HEFA chains are both considered suitable for producing aviation biofuel.

In order to estimate the potential demand for aviation biofuel in this storyline, we turned to the World Energy Council’s world energy scenarios analysis (WEC, 2016), in which three distinct scenarios are developed, complete with explicit projections for transportation fuel and the fractions taken up by biofuels. Given that literature on future demand for aviation biofuel under different technological or policy scenarios is limited, we consider the estimations in the WEC scenarios as the best available for our analysis. It is reasonable to assume that aviation biofuel in particular would follow a development trajectory similar to that for transportation biofuel in general. Scenario 2.2 in our study is comparable with the “Hard Rock” scenario proposed by the WEC, in which the main drivers are energy policies based on the local context in respect of energy security and sustainability issues, while technological advancement contributes very little. Consequently, aviation biofuel is assumed to substitute 8% (i.e., 288 kt; WEC, 2016) of conventional aviation fuel.

Scenario 3: “The Grand Leap”. Proactive biofuel policies and technological breakthroughs go hand in hand, paving a promising pathway towards a sustainable aviation sector. Locality-specific policy plans are introduced, with executive measures to support biofuel production and local sustainability. An aviation biofuel blend mandate is backed by advanced technologies, including second-generation biofuel conversion. This contributes towards increasing the competitiveness of aviation biofuel, thereby fostering its smooth commercialization and rapid adoption. Hence, the sugarcane-ATJ, the eucalyptus-FT, and the macauba-HEFA chains are all considered viable for aviation biofuel production. No competition for biomass is anticipated in this case, regardless of the feedstocks concerned. Since the objective of its policies is to achieve quick adoption of aviation biofuel while improving local sustainability, the government is motivated to ensure the sustainable expansion of feedstock production. This is expected to stabilize feedstock prices. The market share of aviation biofuel in this scenario is comparable with that in the WEC’s “Unfinished Symphony” scenario (WEC, 2016), in which governments take effective climate-change policy action while large-scale (renewable) energy integration is led by technological innovation, resulting in aviation biofuel accounting for 15% of demand (i.e., 540 kt).

Scenario 4: “Bottom-Up Transition”. Policy support is limited as conservative policies reveal a reluctance to take risks and to promote aviation biofuel more ambitiously. On the other hand, research and development make significant progresses, enabling multiple conversion pathways and feedstocks for biofuel production. The private sector (biofuel companies and airlines) takes the lead in establishing a sustainable aviation biofuel supply chain. This has a positive impact on the market position of aviation biofuel. The sugarcane-ATJ, the eucalyptus-FT, and the macauba-HEFA chains are all candidate supply chains, regardless of the possible competition for biomass resources. Here, a 10% price increase for the feedstocks is assumed due to biomass competition. Nonetheless, because of the positive market situation and the proactive private sector, the price increase in this case is lower than in Scenario 1. This scenario is comparable with the WEC’s “Modern Jazz” scenario, which features market mechanisms and an energy landscape shaped by rapid technological innovation (WEC, 2016). Accordingly, aviation biofuel is expected to account for 10% of demand, equivalent to 360 kt.

Table 2.1 Summary of drivers and key variables in each scenario

Scenarios		Narratives described with key features	
Scenario 1: “Low-emissions flightpath”	Drivers	- Biofuel and climate policies remain conservative; - Technological advancement is gradual.	
	Variable	- Market share of aviation biofuel is around 3%, i.e. 108 kton; - Candidate feedstock is sugarcane; - Aviation biofuel is produced via ATJ pathway; - Competition for biomass is expected and feedstock prices are driven up by 20%.	
Scenario 2: “Go Bio”	Drivers	- Biofuel and climate policies are proactive and supportive; - Technological innovation is stagnated.	
	Variable	- Market share of aviation biofuel is estimated to be 8%, i.e. 288 kton; - Candidate feedstocks are sugarcane and macauba; - Aviation biofuel is produced via ATJ and HEFA pathways, respectively; - Competition for biomass is expected and feedstock prices stay stable due to supportive schemes.	
Scenario 3: “The grand leap”	Drivers	- Biofuel and climate policies are proactive and enabling; - Technological advancement sees a breakthrough;	
	Variable	- Market share of aviation biofuel reaches 15%, i.e. 540 kton; - Candidate feedstocks are sugarcane, macauba and eucalyptus; - Aviation biofuel is produced via ATJ, HEFA and FT pathways, respectively; - Competition for biomass is not expected and feedstock prices remain stable.	
Scenario 4: “Bottom-up transition”	Drivers	- Biofuel and climate policies appear conservative; - Technological breakthrough is expected;	
	Variable	- Market share of aviation biofuel is assumed to be 10%, i.e. 360 kton; - Candidate feedstocks are sugarcane, macauba and eucalyptus; - Aviation biofuel is produced via ATJ, HEFA and FT pathways, respectively; - Competition for biomass is foreseeable and feedstock prices increase by 10%.	

Additionally, it is worth noting that producing aviation biofuel as a substitute for its fossil counterpart will likely induce a *displacement effect* (Lehr et al., 2008; Mukhopadhyay and Thomassin, 2011). This means, in simple terms, that the increase in demand for biofuel leads to less production of fossil fuels, thereby affecting the socioeconomic indicators of the sectors involved. Some of the socioeconomic effects related to fossil aviation fuel production might be displaced by the production of aviation biofuel. For example, whilst aviation biofuel production may create a large number of “green jobs”, those originally producing the same amount of fossil aviation fuel could be lost. To shed light on this factor, we have investigated the *net* socioeconomic effects (using IO analysis) to account for the displacement effect.

2.2.3 Input-Output Analysis

IO analysis is a technique commonly applied to evaluate macroeconomic effects resulting from a given (final demand) shock to the economic structure of a country (Miller and Blair, 2009). IO tables contain annual flows of products and services (in monetary terms) and represent the interdependence of different sectors in the economy. IO analysis can provide *ex-ante* estimations of macroeconomic effects related to new economic activities (producing aviation biofuel, in this case) on the national scale, which can

then be translated into socioeconomic effects, namely employment, GDP, and trade balance (represented by imports, which inform us of the dependence of local aviation biofuel production on commodities produced outside the country), with the aid of the corresponding coefficients.

IO analysis was used in this study for two particular reasons: (i) because, due to the lack of data on actual aviation biofuel production, capturing the socioeconomic effects in a very precise way is challenging; and (ii) because IO analysis allows the evaluation of both direct and indirect effects indifferent economic sectors, thus enabling a relatively complete assessment of socioeconomic effects on both national and sectoral scales, directly and indirectly (Miller and Blair, 2009). The direct effects reflect the direct input requirements needed to produce the final demand for aviation biofuel, while the indirect effects reflect the intermediate inputs needed to fulfill intermediate production activities (Miller and Blair, 2009; Silalertruksa et al., 2012; Wicke et al., 2009).

The most recent version of the Brazilian IO tables, for the year 2010, include 67 industries and 110 commodities (IBGE, 2017). Since aviation biofuel is not specified in the IO tables, we consider its production as a new sector called “biojet”, which can be added into the original IO model to help determine the macroeconomic effects of producing aviation biofuel, as described below.

The core of an IO model is the interindustry flows of products from each sector to each of all sectors (Miller and Blair, 2009). In monetary terms, the fundamental structure of an IO model is shown in Eq. (1):

$$\mathbf{X} = \mathbf{Z} + \mathbf{F}, \quad (1)$$

where \mathbf{X} represents total output of the economy, \mathbf{Z} represents total interindustry transactions, and \mathbf{F} represents total final demand. From here on, we use bold capital letters for matrices (e.g., \mathbf{Z} in Eq. (1)), bold lower-case letters for column vectors (e.g., \mathbf{z} in Eq. (6)), bold and italic lower-case letters for row vectors (e.g., $\mathbf{a}(n+1)$ in Eq. (6)), *italic* lower-case letters for elements in corresponding matrices (e.g., z_{ij} in Eq. (2)), and Roman lower-case letters for values (e.g., j_i in Eq. (8)). Also, henceforth “input”, “output”, and “(final) demand” are all expressed in monetary terms.

Total output is the sum of total interindustry transactions and total final demand. One basic assumption of an IO model is that interindustry transactions are constant within a given timeframe, usually a year, and dependent on the total output within the same period (Allan, 2015; Miller and Blair, 2009). Thus, the interindustry transaction or intermediate transaction from sector i to sector j , denoted by a_{ij} , can be expressed in Eq. (2) as:

$$\mathbf{a}_{ij} = \frac{z_{ij}}{x_j}, \quad (2)$$

where z_{ij} is the monetary value of products and services that sector j purchases from sector i in order to produce the total output x_j in of sector j . Here, a_{ij} is called a technical coefficient in IO models. For an economy with n sectors, the $n \times n$ matrix \mathbf{A} consisting of all technical coefficients a_{ij} is called a technical coefficient matrix or technology matrix. The IO model can then be expressed by Eq. (3) as:

$$\mathbf{X} = \mathbf{A}\mathbf{X} + \mathbf{F}. \quad (3)$$

Let \mathbf{I} be the $n \times n$ identity matrix, meaning that the IO model can now be expressed by Eq. (4) as:

$$(\mathbf{I} - \mathbf{A})\mathbf{X} = \mathbf{F}. \quad (4)$$

It is clear now that IO models are demand driven, which is why the assessment of macroeconomic effects is determined by introducing a final demand change (or shock) to the model. To address the change in final demand, Eq. (4) can further be expressed by Eq. (5):

$$\Delta\mathbf{X} = (\mathbf{I} - \mathbf{A})^{-1} \Delta\mathbf{F}, \quad (5)$$

where $(\mathbf{I} - \mathbf{A})^{-1}$ is also known as the ‘‘Leontief inverse matrix’’, $\Delta\mathbf{F}$ represents the change in final demand, and $\Delta\mathbf{X}$ represents the change in total (including direct and indirect) output in line with the change in final demand. The total output change can then be translated into socioeconomic effects on employment, GDP and imports with corresponding coefficients (Miller and Blair, 2009).

To analyze the macroeconomic effects attributed to aviation biofuel production, the new sector ‘‘biojet’’ is added into the original technology matrix \mathbf{A} (Miller and Blair, 2009; Wicke et al., 2009), which then becomes \mathbf{A}_{new} in Eq. (6):

$$\mathbf{A}_{new} = \begin{bmatrix} \mathbf{A}^* & \mathbf{a}_{new} \\ \mathbf{a}_{(n+1)} & a_{(n+1)new} \end{bmatrix}, \quad (6)$$

where $\mathbf{a}_{(n+1)}$ is a row vector representing the inputs needed from the new sector to produce a unit of output by the original sectors. Here we assume that: (i) no input is required from the new sector to produce outputs by original sectors; and (ii) the addition of the new sector does not change the structure of the intermediate inputs to the original sectors. Matrix \mathbf{A}^* is the new technology matrix of the original sectors. Further, \mathbf{a}_{new} is a column vector of the newly added technical coefficients of the ‘‘biojet’’ sector. And $a_{(n+1)new}$ is the input from the new sector required to produce one unit of output of the new sector

itself. In this case it is assumed that there is only one product in the “biojet” sector (i.e., aviation biofuel), and that no input is needed from the “biojet” sector to produce itself.

In short, the new technology matrix A_{new} was constructed by adding a new sector “biojet” to the original technology matrix A . This new sector was included as an additional column of its technical coefficients that represent the production of aviation biofuel. The new sector’s technical coefficients were calculated with the inputs needed from the original sectors to produce one unit of output of the new sector. To distinguish different feedstock-based supply chains, different sets of the new technical coefficients of the “biojet” sector were added to construct different A_{new} .

Eq. (5) is now expressed as Eq. (7):

$$\Delta \mathbf{X}_{\text{new}} = (\mathbf{I} - \mathbf{A}_{\text{new}})^{-1} \Delta \mathbf{F}_{\text{new}}, \quad (7)$$

where $\Delta \mathbf{X}_{\text{new}}$ is the change in total output and $\Delta \mathbf{F}_{\text{new}}$ is the change in final demand, which is in line with the estimated demands for aviation biofuel in the scenarios. Eq. (7) is now solvable, meaning that the change in total output $\Delta \mathbf{X}_{\text{new}}$ can be calculated. Here, $\Delta \mathbf{X}_{\text{new}}$ represents the total macroeconomic effects due to the new production activities in the “biojet” sector. Each element in $\Delta \mathbf{X}_{\text{new}}$ represents the total macroeconomic effects in each corresponding sector.

The direct macroeconomic effects are direct input requirements in sectors directly involved in producing aviation biofuel. These direct effects were determined by breaking down the production costs of aviation biofuel and then allocating them to the corresponding sectors. Next, the indirect macroeconomic effect in each sector was calculated by subtracting the sectoral direct effect from the sectoral total effect.

2.2.4 Link scenarios with socioeconomic effects

As a result of the scenarios, a demand for aviation biofuel production was projected for each scenario and also used to shock the IO model in the subsequent IO analysis¹. In response to the final demand shock, the IO analysis simulated the change of total outputs in each sector, that is, the macroeconomic effects in each sector caused by aviation biofuel production with each supply chain. Subsequently, these sectoral macroeconomic effects were translated into the socioeconomic effects on employment, GDP, and imports, with the help of employment coefficients (number of jobs per million USD), GDP coefficients (million USD GDP per million USD output), and import coefficients (million USD imports

¹ Note that for scenarios with multiple biofuel supply chains, demand was fulfilled by each supply chain individually. No mix or combination of multiple supply chains was considered. In other words, the model considers only one supply chain at a time. For example, in Scenario 3 the demand for 540 kt of aviation biofuel was expected to be met solely by either the sugarcane-ATJ chain, the eucalyptus-FT chain, or the macauba-HEFA chain.

per million USD output), respectively. For each sector, these employment, GDP, and import coefficients were calculated with the number of jobs, value of GDP, and value of imports in the concerned sector divided by the total output of this sector, using official data (Souza et al., 2018).

To provide an insight into the displacement effects caused by aviation biofuel production on the fossil jet fuel production market, the *net* socioeconomic effects of each supply chain under each scenario were calculated. This was achieved by shocking the IO model with a net final demand, which was the difference between two demands: (i) the fraction of total demand for aviation fuel covered by biofuel (as projected under each scenario in Section 2.2.2), with fossil fuel accounting for the remainder; and (ii) total demand for aviation fuel fulfilled entirely by fossil fuel.

2.2.5 Uncertainty analysis

Although IO analysis is useful for estimating socioeconomic effects, the method has certain inherent drawbacks as elaborated and discussed in several notable studies (Allan, 2015; Miller and Blair, 2009; Wicke et al., 2009). One of the main drawbacks is the assumed constant return to scale (Allan, 2015; Miller and Blair, 2009). Since IO models are linear, the calculated economic effects are proportional to the demand shock regardless of the scale of that shock. This means that IO models do not consider price fluctuations and market mechanisms. Another drawback lies in the time-lag between the year of assessment and the year of the latest available IO table. The underlying assumption here is that the economic structure and the interdependence of different sectors stay constant over time. However, it is unclear how suitable the “old” IO table is to assess the “new” economic activities. These shortcomings of IO models are reflected in the fixed technical coefficients, which are important sources of uncertainties in the model outcomes. Ignoring these uncertainties may lead to inaccurate estimation, and hence to ill-informed decision-making. In order to understand how robust and reliable our results are, we therefore examined the uncertainty of our IO analysis by means of stochastic simulation. Specifically, a Monte Carlo (MC) simulation was performed for all technical coefficients (a_{ij}) in the IO matrix. The MC approach allows stochastic analysis of variables based on their distributions, and provides probability distribution for the model outcomes (Lenzen et al., 2010; Wilting, 2012; Yamakawa and Peters, 2009).

The uncertainty analysis started with a reorganization of the IO tables for different years. Time-series data regarding technical coefficients was obtained from Brazilian IO tables for previous years (i.e., 2010, 2005, 2000, 1996, 1995, 1994, 1993, 1992, 1991, and 1990). However, the sectoral structure in the different IO tables varies. Specifically, the 2010 tables contain 67 sectors; the 2005 and 2000 tables contain 55 sectors; and the 1996, 1995, 1994, 1993, 1992, 1991, and 1990 tables contain 43 sectors. Bearing in mind that the sectors were structured and aggregated differently throughout the years, we prepared the data as follows. Based on the IO table summarizing the intermediate transactions on the

“product-to-sector” level, it was clear how much of each product in sector i was needed to produce the total output of sector j . We reorganized the sectors (by aggregating/disaggregating them) according to the product-sector compositions referred to in the 2010 table (the latest version containing such information). The interindustry transactions were reorganized, and then the corresponding technical coefficients were recalculated based on Eq. (2). Ideally, this would lead to a 67×67 technology matrix containing 4489 technical coefficients, each of which would have a data-input set consisting of ten historical coefficients from different years. Due to technological and economic developments over time, however, some relatively new sectors were not represented in IO tables before 2010. In these cases, the technical coefficients had less than ten historical coefficients. As a result, 3011 technical coefficients in the reorganized technology matrix did have ten historical coefficients, whilst 776 had three and 702 had one. Due to the limited amount of data available for each technical coefficient, testing for distribution was not feasible. Nevertheless, normal distribution was assumed for the technical coefficients with ten or three historical coefficients. We calculated the mean value and the standard deviation as the input parameters for MC simulation. For the technical coefficients with one historical coefficient, no distribution type was assumed. These technical coefficients stayed unchanged during the MC simulation. The calculated parameters were then used as inputs to run an MC simulation with 5000 iterations. The stochastic simulation was implemented in the software MATLAB[®] R2017b. The calculation time of the simulation was about 105 seconds for 5000 iterations. The distributions of all simulated outcomes were thus obtained, which offered us insights into the uncertainty associated with technical coefficients and the robustness of the outcomes. Specifically, the mean values and the standard deviations around the outcomes of the simulation were calculated. In addition, the 95% confidence intervals were calculated with Student’s t distribution (with t value of 1.96) and the standard deviation (of stochastic outcomes).

2.2.6 Data inputs and basic assumptions

Initially, three potential supply chains for aviation biofuel production were selected for the Brazilian context, namely the sugarcane-ATJ chain, the eucalyptus-FT chain, and the macauba-HEFA chain. The sugarcane fields were assumed to be located in São Paulo, while for eucalyptus and macauba the fields were expected to be located in Minas Gerais. The biorefineries were assumed to be located at the feedstock cultivation sites, for economic and environmental reasons. Each supply chain started with feedstock production, followed by transport to the biorefinery where pretreatment (if needed) and conversion took place. The produced aviation biofuel was then transported to the two airports. Average distances of 10 km, 150 km, and 570 km were assumed for the transportation of feedstock to biorefinery, aviation biofuel to Guarulhos Airport, and aviation biofuel to Galeao Airport, respectively (Santos et al., 2017). The production costs in each supply chain were derived from the studies by Alves et al. (2017) and Santos et al. (2017), which contain comprehensive techno-economic analyses of aviation biofuel production in Brazil. The breakdown of production costs (in monetary values) were converted to

USD2010. The inventory production costs for different supply chains are presented in **Table S1** and **Table S2** in Appendix I. Various versions of IO tables were obtained from the Brazilian Institute of Geography and Statistics IBGE (2017). Sectoral data on employment, GDP, and imports were derived from IBGE (2017) and the Ministry of Labour and Employment (MTE, 2017).

2.3 Results and discussion

2.3.1 Socioeconomic effects

2.3.1.1 Total effects on employment, GDP, and imports

The calculated socioeconomic effects increase with the estimated demand for aviation biofuel under the different scenarios. **Table 2.2** shows that the largest number of jobs is generated in Scenario 3 – 55,840-65,037 in all, taking all the different supply chains into consideration, followed by Scenario 4 (38,363-44,740 jobs) and Scenario 2 (29,781-34,686 jobs). Relatively low levels of employment are created in Scenario 1, with 11,850 jobs contributed by the sugarcane-ATJ chain alone (the number here is a single value rather a range, as only one supply chain is considered viable in this scenario). Similarly, in respect of GDP Scenario 3 contributes US\$1,044-1,087 million to national GDP. This is 47-48%, 46-47%, and 382% higher than those in Scenario 4, Scenario 2, and Scenario 1, respectively. The import requirements in Scenario 3 equal to US\$280-374 million, higher than those in Scenario 4, Scenario 2, and Scenario 1 by 32-33%, 46-47%, and 389%, respectively.

Scenario 3 therefore has the greatest effects in terms of increasing employment, GDP, and imports, suggesting that proactive biofuel policies and advanced technologies lead to the most pronounced socioeconomic effects. The results also indicate that when policies shift from conservative towards proactive and technological advancement moves from gradual towards a breakthrough, not only do the socioeconomic effects increase but more feedstocks and technologies become available for producing aviation biofuel.

2.3.1.2 Direct and indirect effects

Breaking down the socioeconomic effects by type (direct and indirect) shows that indirect effects make a larger contribution towards total employment and total GDP in all scenarios. This suggests that the production of aviation biofuel could positively stimulate economic activities in its supporting sectors, especially trade, as shown in **Fig. 2.2** and **Fig. 2.3**. These stimulated supporting sectors are important, as their outputs are the intermediate inputs required by the direct sectors. On the other hand, the direct employment and GDP effects are concentrated predominately in the feedstock sectors. This is due to (i) the large amount of biomass needed as raw material for aviation biofuel production, and (ii) the labor-intensive nature of these sectors. By comparison, the majority of import effects are associated with the

chemicals sector, directly and indirectly, meaning that producing aviation biofuel would be highly dependent on chemicals produced outside the country.

2.3.1.3 Supply chains

Regardless of scenarios, the macauba-HEFA chain leads to the highest level of employment creation—greater than both the eucalyptus-FT chain (by 15-16%) and the sugarcane-ATJ chain (by 16-17%). Similar patterns are observed for GDP, where the macauba-HEFA chain results in larger effects than either the eucalyptus-FT chain and the sugarcane-ATJ chain by 1-2% and 3-4%, respectively. By contrast, the largest import effects are found in the sugarcane-ATJ chain: 31-32% higher than those in the eucalyptus-FT chain and 33-34% higher than those in the macauba-HEFA chain. The disparities between these effects can be explained by the different configurations of the supply chains (including type of feedstock involved, conversion technology used, and location of biorefineries), different sectoral socioeconomic (i.e., employment, GDP, and imports) coefficients, and different technical coefficients of the “biojet” sector. In the macauba-HEFA chain, for instance, the high costs of biomass and the labor-intensive nature of the feedstock sector are two main factors responsible for its large employment and GDP effects. Meanwhile, the large import effects in the sugarcane-ATJ chain are due to the high demand for inputs from the chemicals sector, which are associated with a relatively high imports coefficient.

Higher proportions of indirect jobs are estimated for the sugarcane-ATJ chain (61-63%) and for the eucalyptus-FT chain (62-63%) than for the macauba-HEFA chain (53-54%). This may indicate that the sugarcane-ATJ and the eucalyptus-FT chains rely more on intermediate inputs from supporting sectors to produce aviation biofuel. Note that in all the supply chains, the transportation sector is associated with relatively large effects on direct employment and direct GDP. This could be due to two factors: (i) the transportation of biofuel from the biorefinery to the airport was also considered in this study, revealing a high input requirement in this sector, and (ii) labor intensity is relatively high in this sector.

2.3.1.4 Net effects

When taking displacement into account, the net socioeconomic effects decrease by 19-24% for employment, 38-42% for GDP, and 32-49% for imports. Moreover, disaggregating net effects by sector reveals negative effects in certain sectors. The main sectors showing large displacement effects include extraction of oil and gas, and also oil refining (as shown in **Table S3** in Appendix I). This confirms the assumption that a fraction of the socioeconomic benefits (employment and GDP) will be reallocated from the fossil sectors to the new “biojet” sector. GDP is more negatively affected than employment, due to the relatively high GDP coefficients in the affected sectors.

At the national level, all the scenarios lead to positive net socioeconomic effects, as shown in **Fig. 2.4**. The positive net effects on employment and GDP suggest that, overall, no net jobs and added value will

be lost due to the development of aviation biofuel. The positive net import effects, however, suggest that producing aviation biofuel requires more imported goods than fossil aviation fuel, which reveals a negative impact on trade balance. At the sector level, although the scales of the negative effects are considerably low compared with the overall net effects (less than 0.1% in the case of employment and less than 2% for GDP), these potential negative socioeconomic effects of aviation biofuel production should not be overlooked.

2.3.2 Uncertainty analysis

To analyze the uncertainty related to IO analysis, we compared the results calculated for the deterministic case (based on the latest IO table) and for the stochastic simulation (in **Fig. 2.5**). The descriptive statistics are presented in **Tables S3-S6** in Appendix I. For total effects on employment, GDP, and imports, the confidence intervals are about 10-15%, 10-13%, and 12-14% around the mean values, respectively. Similar ranges of uncertainty are observed for the net effect on employment, GDP, and imports, with confidence intervals of 10-16%, 12-16%, and 16-18% around the mean values, respectively. Based on the values of the relative standard deviation, the sugarcane-ATJ chain appears to be associated with a higher level of uncertainty than both the macauba-HEFA chain (by 32-45% for total employment, 30-32% for total GDP, and 13-17% for total import effects) and the eucalyptus-FT chain (by 16-38% for employment, 25-26% for total GDP, and 13-17% for total import effects).

At the sector level, the confidence intervals were also calculated for each supply chain under each scenario. The relative standard deviation values disaggregated to each sector range from 2% to 50% for total employment effects, from 2% to 55% for total GDP effects, and from 1% to 50% for total import effects (as shown in **Table S4** in Appendix I). Sectors associated with high uncertainties include feedstock and mining (e.g., extraction of oil and gas, coal extraction, and metal extraction). One possible explanation for these high uncertainties could be that these sectors are associated with notable changes in the national economy throughout the past two decades. For those sectors, therefore, it is recommended that the data and the results to be handled with discretion. More accurate and detailed data can help lower the level of uncertainty in the analysis.

The socioeconomic effects calculated in the deterministic case are generally higher than the stochastically simulated mean values. Specifically, in terms of total effects on employment, GDP, and imports, the variances between the deterministic results and the stochastically simulated mean values are 15-22%, 21-25%, and 13-21%, respectively. Furthermore, the deterministic results of employment, GDP, and import effects are generally close to the maximum value resulting from the stochastic simulation. The differences between the outcomes calculated for the deterministic case and the stochastic simulation are caused mainly by such factors as technological learning and economic development over time, since the stochastic results are decided by historical data while the deterministic

results represent the most recent data available for each sector. From a retrospective point of view, this implies the current economy has grown to a relatively high level but might have experienced some kind of setback such as an economic crisis (such that the deterministic results do not exceed the maximum values of the stochastic results). Additionally, different levels of variations were found in the uncertainty analyses of employment, GDP, and import effects, which could be attributable to other parameters such as employment, GDP, and import coefficients, whose uncertainties were not included in the stochastic simulation.

2.3.3 Understanding the results in the Brazilian context

In this study, the sugarcane-ATJ chain is located in São Paulo due to the siting of the airports concerned. Nevertheless, other areas such as the Northeast of Brazil have also become potential locations for sugarcane expansion (Guilhoto et al., 2002; Macedo, 2005; Martínez et al., 2013). Aviation biofuel could thus become a product of an expanded sugarcane industry in the Northeast, providing fuel for nearby airports. Meanwhile, the eucalyptus and macauba chains will likely be located in the Minas Gerais area. Locating aviation biofuel production out of the traditional feedstock-growing regions could have positive consequences. First, it would ease pressure on the already intensive production in traditional biofuel areas, and thereby avoid competition for agricultural land with other biobased production. Second, establishing aviation biofuel supply chains can lead to positive socioeconomic effects at the regional level, including rural development and job creation. This is in line with the local development goals, which include improving social development by establishing sustainable biofuel production (AGROPOLO, 2016). In our case, considering the direct effects in feedstock sectors alone, the sugarcane-ATJ, the eucalyptus-FT, and the macauba-HEFA chains would contribute to regional development by creating 2,976-12,398, 2,337-9,736, and 4,563-19,011 jobs, respectively, and by adding US\$24-102 million, 19-80 million, and 37-156 million to GDP, respectively (as shown in **Fig. 2.2**). Furthermore, it is not only the location of the biomass fields which matters, regional economic structures and characteristics also play a part (Brinkman et al., 2018; Martínez et al., 2013). All three supply chains we studied result in more indirect than direct effects on employment and GDP. So if sectors providing intermediate inputs for aviation biofuel are mostly located outside the actual region of biofuel production, interregional economic activities will be stimulated. On the other hand, if the aim is to retain as many of the socioeconomic benefits as possible within the region of production, policy incentives will be required to expand local sectors in order to increase regional economic independence.

In the scenarios we studied, the macauba-HEFA chain is associated with relatively high employment and GDP effects, and with low import effects. The underlying assumption here is that the macauba-based supply chain will have the same production capacity as the relatively more established sugarcane and eucalyptus supply chains in Brazil. This assumption is based on the favorable position of macauba as a promising feedstock for biofuel production. Despite its great potential, it remains uncertain whether

a sustainable and mature macauba supply chain will be in place by 2050. The cultivation of macauba is currently being promoted by supportive programs in the Minas Gerais region (AGROPOLO, 2016; Evaristo et al., 2016). The continuity of such programs will play an essential role in the development of macauba-based biofuel supply chains.

To mitigate the negative impact of replacing fossil aviation fuel with biofuel on trade balance, one solution worth considering is the integration of bio-chemicals production within the biorefinery. This would help reduce dependency on imported chemical products, and potentially generate additional value. Current demand for aviation fuel in Brazil is not entirely met by domestic production. In fact, about 25% of the aviation fuel consumed in Brazil is imported (ANP, 2018). Hence, establishing domestic aviation biofuel production could have a positive effect on energy security. Furthermore, if the Brazilian aviation biofuel industry manages to grow in a sustainable way, it has the potential to make the country a vital player in the international market by exporting “cleaner” fuel to nations with stringent emissions regulations and scarce biomass resources.

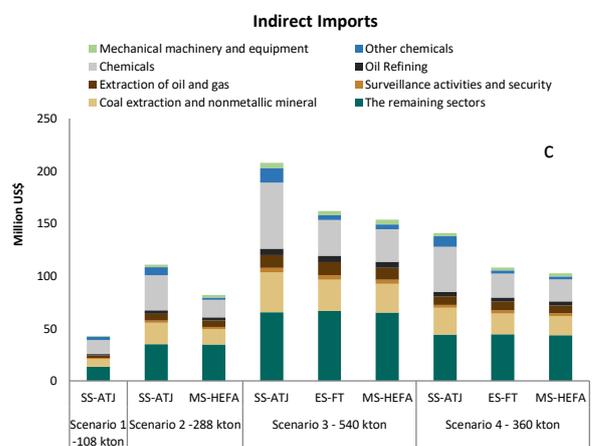
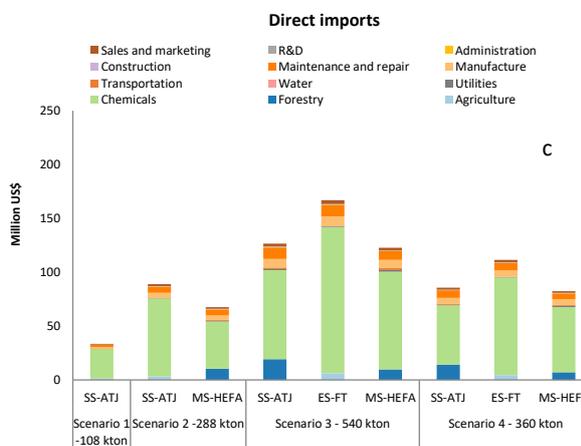
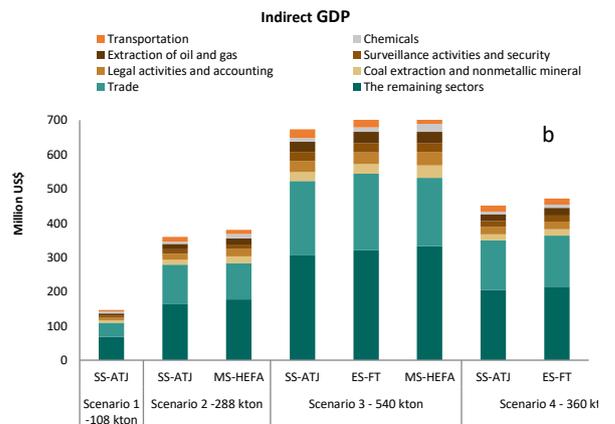
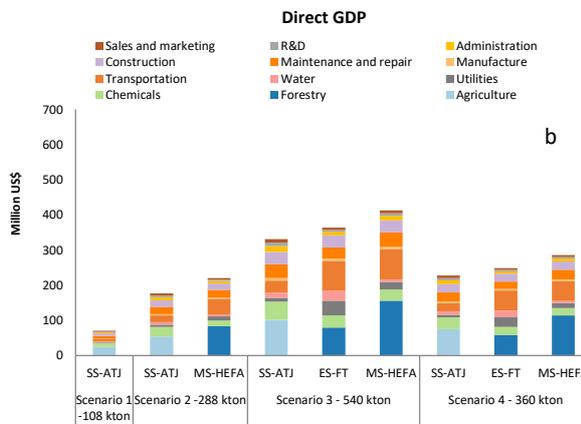
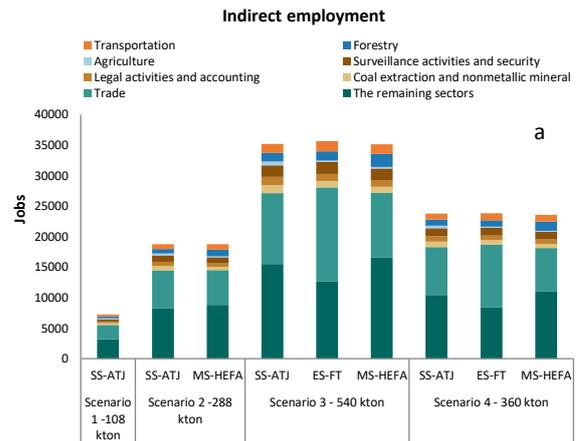
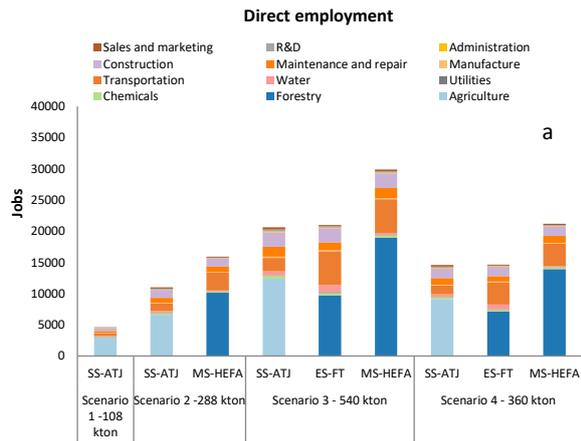


Fig. 2.2 Composition of direct effects on (a) employment, (b) GDP and (c) imports by sector

Fig. 2.3 Composition of indirect effects on (a) employment, (b) GDP and (c) imports by sector, demonstrated with top 5 sectors

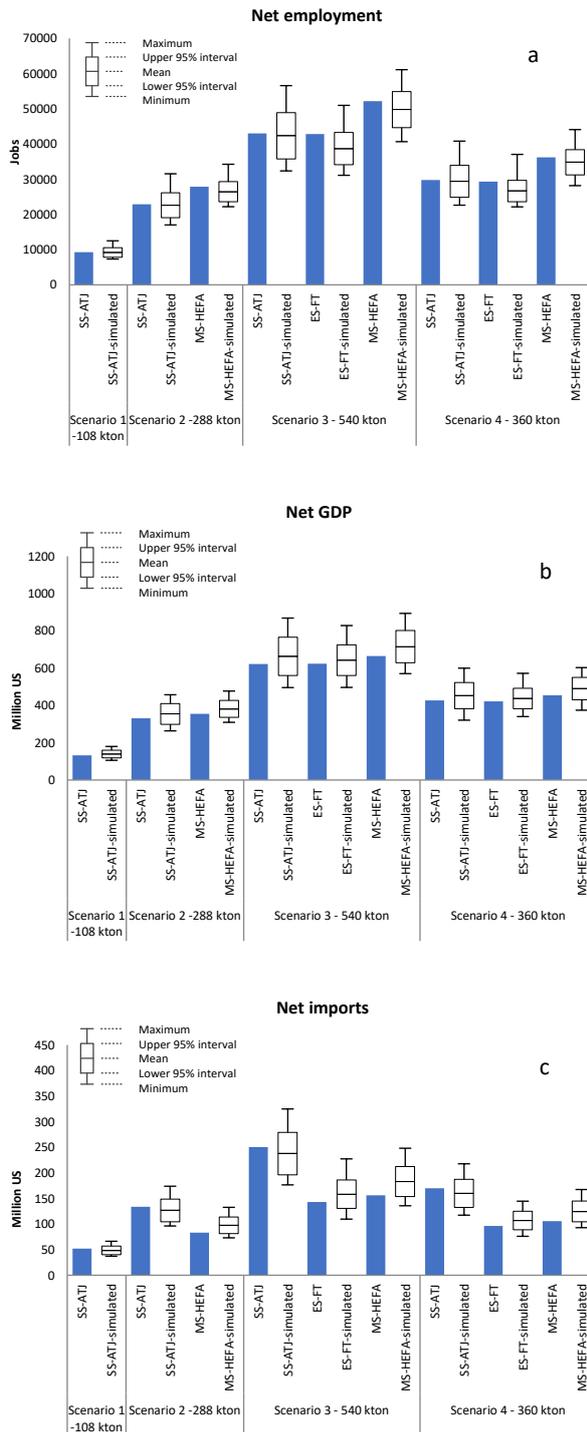


Fig. 2.4 Comparison between the deterministic outcomes and the simulated outcomes of net effects on (a) employment, (b) GDP and (c) imports. (SS-sugarcane, MS-macaba, and ES-eucalyptus.)

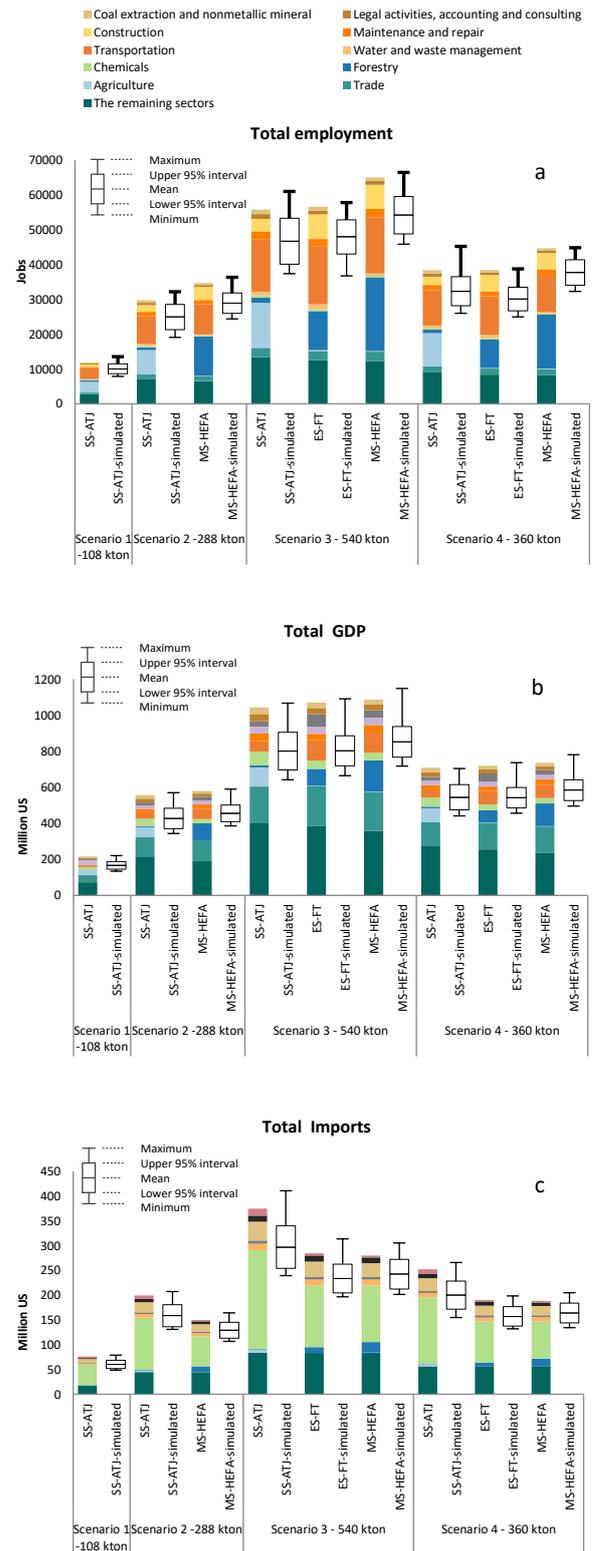


Fig. 2.5 Comparison between the deterministic outcomes and the stochastic outcomes of total effects on (a) employment, (b) GDP and (c) imports. (SS-sugarcane, MS-macaba, and ES-eucalyptus.)

Table 2.2 Summary of total effects of aviation biofuel production on employment, GDP and imports

Socioeconomic effects	Employment (Number of jobs)				GDP (Million US\$)				Imports (Million US\$)			
	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Sugarcane-ATJ chain												
Total	11850	29781	55840	38363	216.52	556.72	1043.86	708.81	76.59	199.75	374.54	252.49
Direct	4626	11014	20652	14594	70.23	176.40	330.75	227.29	33.61	88.97	166.83	111.62
Indirect	7224	18767	35188	23769	146.29	380.32	713.10	481.82	42.98	110.78	207.71	140.87
Macauba-HEFA chain												
Total	N.A.	34686	65037	44740	N.A.	579.57	1086.69	736.06	N.A.	149.51	280.32	188.34
Direct	N.A.	15946	29898	21199	N.A.	220.12	412.73	285.56	N.A.	67.59	126.74	85.78
Indirect	N.A.	18741	35139	23540	N.A.	359.45	673.96	450.50	N.A.	81.92	153.58	102.56
Eucalyptus-FT chain												
Total	N.A.	N.A.	56634	38464	N.A.	N.A.	1069.70	719.07	N.A.	N.A.	284.58	190.47
Direct	N.A.	N.A.	21000	14649	N.A.	N.A.	364.03	248.02	N.A.	N.A.	122.63	82.42
Indirect	N.A.	N.A.	35634	23815	N.A.	N.A.	705.67	471.06	N.A.	N.A.	161.95	108.05

2.4 Limitations

2.4.1 Scenarios

Scenario analysis has been used in this study to depict the possible futures of aviation biofuel development in Brazil. These constructed scenarios were useful in providing a plausible basis for the quantification of socioeconomic effects. However, they do not rule out the possibility of other alternative futures for aviation biofuel with different production volumes or feedstocks. For example, used cooking oil and municipal wastes are also seen as promising feedstocks, which opens up the possibility of a scenario involving waste-based aviation biofuel production. The challenge in this case, however, is the limited availability of the feedstocks for large-scale production, not to mention the competition for feedstock with biodiesel production (Hileman and Stratton, 2014). On the other hand, aviation biofuel produced from oil crops via the HEFA pathway might be less advantageous than other options when life cycle GHG emissions are borne in mind (de Jong et al., 2017). Since the macauba-HEFA chain seems to be associated with the greatest socioeconomic benefits, a trade-off becomes apparent once more aspects are taken into consideration.

Secondly, due to the lack of published data on future demand for aviation biofuel in particular, the projected demand shock for each scenario was based on the trajectory formulated by the WEC (2016). These projections are, however, rather conservative when compared with the ambitious emission-related targets set for the aviation sector. Even in “The Grand Leap” scenario, where the projected demand for aviation biofuel is the highest, only 15% of the fuel needs are covered by biofuel. But taking into account the current state of technological development, the political environment, and sustainability concerns associated with biofuel expansion, we have estimated the demands for aviation biofuel based on scientific literature rather than wild guesses.

Thirdly, to account for the potential competition for biomass resources attributed to aviation biofuel production, we included feedstock price fluctuations. It was assumed that feedstock prices were driven up when aviation biofuel industry competes for biomass with other biobased industries. However, this is rather a simplified assumption. The actual effects of biomass competition and further land competition effects require more in-depth analysis in order to reveal the actual mechanisms involved.

2.4.2 IO analysis

For each feedstock, the availability of information and data differs. Specifically, there is a lack of data on actual current production of macauba. Consequently, data regarding the macauba-HEFA chain was derived from recent techno-economic evaluations reported in literature on aviation biofuel production using macauba feedstock. Hence, the calculations provided for the macauba-HEFA chain should not be considered as absolute results. Rather, they should be seen as a proxy for the way macauba-based

aviation biofuel might develop in the foreseeable futures. Further studies with field data would contribute to a more accurate analysis of this chain.

As described in Section 2.5, a stochastic simulation was performed to address the uncertainties of IO analysis. The historical trend could shed light on the structural changes to the macro-economy over time. However, it remains unclear whether such trends are representative for the emerging “biojet” sector, which features radical and advanced technologies. Nevertheless, the stochastic simulation approach has been helpful in providing a deeper understanding of the robustness of IO analysis. In this study, the stochastic simulation was performed around the uncertainties of the technical coefficients, excluding other variables (e.g., employment, GDP, and imports coefficients) which might further affect the robustness and the overall uncertainty of the results. To better understand uncertainty and improve IO analysis, uncertainties stemming from all variables should be further investigated in future studies.

2.5 Conclusions

The objective of this study was to assess the socioeconomic effects of aviation biofuel development on employment, GDP, and trade balance. This was achieved by applying a scenarios-based IO analysis, taking Brazil as an example. All the scenarios presented result in significant socioeconomic effects on employment and GDP. In terms of employment, depending on the scenario concerned either about 11,850, 29,800-34,500, 55,800-65,000, or 38,400-44,700 jobs are created to cover, respectively, 3%, 8%, 15%, or 10% of the demand for aviation fuel in Brazil. Under each scenario, the macauba-HEFA chain has the greatest positive effects on employment, creating 16-17% more jobs than the sugarcane-ATJ chain and 15-16% more than the eucalyptus-FT chain. The production of aviation biofuel contributes about US\$220 million, US\$560-580 million, US\$1,040-1,090 million, or US\$710-740 million to Brazil’s GDP annually, in Scenario 1, 2, 3, or 4, respectively. In this regard, the macauba-HEFA chain also outperforms the other two by 3-4% (sugarcane-ATJ) and 1-2% (eucalyptus-FT). The effects on trade balance, on the other hand, reveal different trends. To fulfill demands for aviation biofuel, imports worth approximately US\$80 million, US\$150-200 million, US\$280-370 million, or US\$190~250 million are needed in Scenarios 1, 2, 3, or 4, respectively. The sugarcane-ATJ chain results in the largest import effects, 31-32% higher than those for the eucalyptus-FT chain and 33-34% higher than those for the macauba-HEFA chain.

Aviation biofuel production shows large positive net socioeconomic effects on employment and GDP, whereas some of the fossil sectors are negatively affected. Despite the relatively modest scales of these negative effects, efforts such as professional training for new jobs or reaching agreements to re-allocate labor to aviation biofuel-related sectors are desirable, in order to rebalance the displaced socioeconomic benefits in those sectors.

Overall, the macauba-HEFA chain (with the greatest effects on employment and GDP, and the least effects on imports) seems to be the most favorable option considering the scenarios studied, despite the uncertainty associated with its establishment. In this regard, regional policies to stimulate economic activities related to the “biojet” sector, especially the production of macauba feedstock, could be helpful to lower the risks and eventually to achieve the desired level of socioeconomic benefits.

Chapter 3

Human Health Impacts of Aviation Biofuel Production: Exploring the Application of Different Life Cycle Impact Assessment (LCIA) Methods for Biofuel Supply Chains

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3.1 Introduction

Biofuels play a significant role in sustainable development worldwide. As one of the most important and highly demanded alternative fuels, biofuels enable a more flexible energy mix and transition from a fossil-based economy to a biobased one. Among others, biofuel for aviation has gained growing interest in the recent decade. Major organizations in the aviation industry, the International Air Transport Association (IATA) and the International Civil Aviation Organization (ICAO), have committed to largely reduce emissions and achieve carbon neutral growth (IATA, 2014; ICAO 2016). Previous studies have examined the greenhouse gas (GHG) emissions of aviation biofuel produced via different technological pathways (Bailis, et al., 2010; Cox et al., 2014; de Jong et al., 2017; Elgowainy et al., 2012; Han et al., 2013; Santos et al., 2017; Shonnard et al., 2010; Staples et al., 2014; Prussi et al., 2019; Chuck, 2016; Crossin, 2014). These studies show that considerable reduction of GHG emissions can be achieved by substituting fossil aviation fuel with biofuel, although the reduction percentage varies largely in the range of 41-104 % due to differences in assessment scope, methodologies, and data inputs. However, it remains uncertain how aviation biofuel performs in terms of other sustainability-related impacts. A number of life cycle assessment (LCA) studies have pointed out biofuels could result in larger effects in acidification, eutrophication, and ecotoxicity than fossil fuels (Kim and Dale, 2008; Tsang et al., 2015; de Jong et al., 2015; Yang, 2013; Yang et al., 2012).

In comparison, the life cycle human health impacts related to biofuels are addressed and understood in a limited way. An important reason for this is the high level of uncertainty and low level of consensus in the modelling of human health impacts (Pizzol et al., 2011; Rosenbaum et al., 2008; Parada et al., 2017). Several recent studies have focused on life cycle assessment of human health impacts related to biofuel production. For instance, Weldu et al. (2017) analysed the human health impacts of electricity production from wood biomass in Alberta, Canada, and concluded that bioenergy pathways showed better performance in human health, but not in respiratory effects. Yang (2013). investigated the life cycle human cancer, and non-cancer effects of corn ethanol production in the U.S. The author showed that corn ethanol had higher potential non-cancer impacts than gasoline, however, both fuels led to similar potential cancer impacts. Galdos et al. (2013) evaluated the human health impacts associated with Brazilian sugarcane ethanol production considering the phasing out of pre-harvesting burning. The results showed a clear improvement in human health related to the gradual termination of pre-harvesting burning. Other studies (Kim and Dale, 2018; Tsang et al., 2015; de Jong et al., 2015; Yang 2013) included human health impacts in their LCA without further in-depth analysis, as most LCA studies underline GHG emission and energy related impacts (Parada et al., 2017).

So far, few studies have assessed the life cycle human health impacts related to aviation biofuel production. Furthermore, none of these studies specified how decisions were made regarding the

selection of life cycle impact analysis (LCIA) method for quantifying human health impacts. As recognized by several authors (Pizzol et al., 2011; Rosenbaum et al., 2008; Parada et al., 2017), the results of LCIA studies heavily depend on methodological choices, timeframe, and data inputs. Ignoring this strong dependence makes comparison among different studies challenging. Moreover, assessment results may contradict each other when different LCIA methods are used. Therefore, it is imperative to understand how the selection of an LCIA method affects the results of assessment, especially the effects on human health. In this regard, Pizzol et al. (2011) conducted a comparative analysis of nine different LCIA methods for assessing effects of metals on human health in an “imaginary” process. Significant differences were reported for the model structure, characterization factors (CFs), and assessment results. However, this comparison of LCIA methods was performed for a simple “imaginary” process, which (1) did not reflect the complexity of real-life case studies, and (2) did not resemble the features of a biofuel production supply chain. Additionally, almost all the LCIA methods analysed in that study have experienced updates in terms of data sources or/and model structure.

The objective of this study is to provide an up-to-date comparison of different LCIA methods for quantifying the impacts on human health in the context of biofuel supply chains, taking aviation biofuel as an example in order to understand how results can be affected by the choice of method. Further, we aim to understand the potential impacts of aviation biofuel production on human health, identify hotspots, and specify improvement opportunities. Hence, this study contributes to the overall understanding of sustainability impacts assessment of aviation biofuel, especially the human health related aspects. First, the comparative analysis of LCIA methods demonstrates empirically their differences in assessing human health impacts as well as the consistency among various methods. Second, the analysis of human health impacts provides new insights into the life cycle impacts of aviation biofuel, broadening the discussion of biofuel’s sustainability. As a result, a general guideline for selecting a LCIA method for assessing biofuels’ impacts on human health is proposed.

3.2 Materials and Methods

3.2.1 Overview of LCIA methods compared in this study

As described by Pizzol et al. (2011), a number of LCIA methods have been developed to assess the impacts on human health, based on life cycle emissions. Most of the existing LCIA methods calculate impacts not only on human health, but also on other impact categories such as climate change and resource depletion. Unlike these methods, the USEtox 2 model, a relatively newly developed “scientific consensus” model (Rosenbaum et al., 2008; Hauschild et al., 2008), only characterizes human toxicity and freshwater toxicity.

Here we considered six commonly used LCIA methods for the comparative study based on three criteria: (i) the method contains a characterization model for impacts on human health, regardless of midpoint or endpoint level, (ii) the method has been used for LCA in peer-reviewed scientific articles, and (iii) the characterization model is transparent (i.e., at least the characterization factors (CFs) are published). Note that only the most recent version of each method is compared in this study. These six selected LCIA methods are: ReCiPe 2016 [25], USEtox 2 (Rosenbaum et al., 2008; Hauschild et al., 2008), IMPACT 2002+ (Jolliet et al., 2003), EDIP 2003 (Hauchild et al., 2006; Hauchild et al., 2005), CML-IA (Guinée, 2002), and TRACI (Bare et al., 2012)². These methods are compared based on their fundamental features (later in this section) and their results (in Section 3.3) for different impact categories. Consensus and disagreement on the impacts on human health among these methods were analyzed. The comparison was conducted in an empirical case study of Brazilian aviation biofuel production.

The considered LCIA methods are different from each other in many aspects, such as the impact categories, the number of toxic chemicals included in the calculation, and the values of each characterization factor. As the focus of this study was not on model development, we concentrated on comparing the key differences in model basics: model structure (multimedia or single media, exposure pathways, and environmental compartments), impact categories, characterization factors, temporal, and spatial scales, and how uncertainty is dealt with in each method.

In general, an LCIA model represents different environmental compartments that are taken into account and how substances move around, transport, and transform within and between them. The impacts on human health are modelled as shown in Eq. (1):

$$HH = \sum (CF_i \times M_i) = \sum (IF_i \times EF_i \times M_i) \quad (1),$$

where HH represents human health impact expressed at midpoint level or endpoint level, CF is the characterization factor that determines the potential impacts on human health of a substance released to a certain compartment (e.g., air, water, or soil), and M is the amount of a substance emitted to a certain compartment. CF can further be determined by the intake factor (denoted by IF) and effect factor (denoted by EF). IF reflects the fate and exposure pathway of a certain substance, meaning how the emitted substance disperses among compartments and the quantity of this substance reaching the human population (by inhalation, ingestion, or dermal exposure). EF quantifies the impacts on human health on the basis of per unit of intake of a certain substance. The fate, human exposure, and toxicity effect are

² Note that the ILCD (International Reference Life Cycle Data System) method [28] proposed by the European Commission-Joint Research Centre is excluded from this comparative study. This is because ILCD only provides recommendations on the best practices in existing LCIA models and characterization factor, rather than developing a new model that is different from any other methods

generally modelled with matrix algebra-based calculations. Different LCIA methods use different approaches to determine their intake (fate and exposure) factor and effect factor, resulting in different sets of CFs. These factors are essentially where the major differences between different LCIA methods originate. The main differences concerning different human health LCIA models are summarized in Table 3.1. Here and hereinafter, the term “human health impacts” or “impacts on human health” refers to all impact pathways relevant to human health at midpoint and endpoint levels, while “human health” refers to the endpoint impact category: human health.

Table 3.1. Main features of different LCIA methods (\checkmark : the method considers the feature described; \times : the method does not consider the feature described)

Method		USEtox2	ReCiPe2016	IMPACT2002+	EDIP2003	CML-IA	TRACI
Reference		(de Jong et al., 2015; Weldu et al., 2017; Guinée et al., 2002)	(Galdos et al., 2013; Bare et al., 2012)	(Parada et al., 2017; Hauschild et al., 2011)	(Hauschild et al., 2008; Huijbregts et al., 2016)	(Jolliet et al., 2003)	(Hauschild et al., 2006; Fantke, 2017)
Model structure	Multimedia	\checkmark	\checkmark	\checkmark	\times	\checkmark	\checkmark
	HCT ^a (cases)	\checkmark	\times	\times	\times	\times	\checkmark
	HNCT ^b (cases)	\checkmark	\times	\times	\times	\times	\checkmark
	HCT ^a (kg 1,4DCB-eq)	\times	\checkmark	\times	\times	\times	\times
	HNCT ^b (kg 1,4DCB-eq)	\times	\checkmark	\times	\times	\times	\times
	HCT ^a (kg C ₂ H ₃ Cl-eq)	\times	\times	\checkmark	\times	\times	\times
	HNCT ^b (kg C ₂ H ₃ Cl-eq)	\times	\times	\checkmark	\times	\times	\times
	HT ^c (kg 1,4DCB-eq)	\times	\times	\times	\times	\checkmark	\times
	FPM ^d (kg PM _{2.5} -eq)	\times	\checkmark	\times	\times	\times	\times
	RI ^e (kg PM _{2.5} -eq)	\times	\times	\checkmark	\times	\times	\times
	HHP ^f (kg PM _{2.5} -eq)	\times	\times	\times	\times	\times	\checkmark
Impact	Midpoint						
	FPM ^d (kg PM _{2.5} -eq)	\times	\checkmark	\times	\times	\times	\times
	POF ^g (kg NO _x -eq)	\times	\checkmark	\times	\times	\times	\times
	PO ^h (kg Ethylene-eq)	\times	\times	\checkmark	\times	\times	\times
	PSF ⁱ (kg O ₃ -eq)	\times	\times	\times	\times	\times	\checkmark
	OLD ^j (kg CFC-11-eq)	\times	\checkmark	\checkmark	\times	\times	\times
	IR ^k (Bq Carbon-14-eq)	\times	\times	\checkmark	\times	\times	\times
	IR ^k (Bq Co-60-eq)	\times	\checkmark	\times	\times	\times	\times
	GW ^l (kg CO ₂ -eq)	\times	\checkmark	\times	\times	\times	\times
	HTP ^m -air (person·yr)	\times	\times	\times	\checkmark	\times	\times
	HTP ^m -water (person·yr)	\times	\times	\times	\checkmark	\times	\times
	HTP ^m -soil (person·yr)	\times	\times	\times	\checkmark	\times	\times
	Endpoint						
	HH ⁿ (DALY)	\checkmark	\checkmark	\checkmark	\times	\times	\times
	CTU _h ^o (cases/kg)	\checkmark	\times	\times	\times	\times	\checkmark
	HTP ^m (kg 1,4DCB-eq/kg)	\times	\checkmark	\times	\times	\checkmark	\times
	HTP ^m (kg chloroethylene-eq/kg)	\times	\times	\checkmark	\times	\times	\times
	RIP ^p (kg PM _{2.5} -eq/kg)	\times	\times	\checkmark	\times	\times	\times
	PMFP ^q (kg PM _{2.5} into air-eq/kg)	\times	\checkmark	\times	\times	\times	\checkmark
	POP ^r (kg Ethylene into air-eq/kg)	\times	\times	\checkmark	\times	\times	\checkmark
	HOFP ^s (kg NO _x into air-eq/kg)	\times	\checkmark	\times	\times	\times	\times
	Midpoint						
	SFP ^t (kg O ₃ into air-eq/kg)	\times	\times	\times	\times	\times	\checkmark
	ODP ^u (kg CFC-11 into air-eq/kg)	\times	\checkmark	\checkmark	\times	\times	\times
CF	IRP ^v (kBqCarbon-14-eq/kBq)	\times	\times	\checkmark	\times	\times	\times
	IRP ^v (kBq Co-60 into air eq/kBq)	\times	\checkmark	\times	\times	\times	\times
	GWP ^w (kg CO ₂ -eq/kg)	\times	\checkmark	\checkmark	\times	\times	\times
	HTCF ^x (m ³ /g)	\times	\times	\times	\checkmark	\times	\times

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	CDU _h ^y (DALY/kg)	√	×	×	×	×	×
Endpoint	ECF _{hum} ^z (DALY/kg)	×	√	√	×	×	×
	ECF _{hum} ^z (DALY/m ³)	×	√	×	×	×	×
Scale	Long term/infinite	√	√	√	√	√	×
	Temporal 20 years	×	√	×	×	×	×
	100 years	×	√	×	×	×	×
Spatial	Global	√	√	×	×	√	√
	Europe	√	×	√	√	×	×
	North America	√	×	×	×	×	√
Enviro. Comp. ^{aa}	Air	√, detailed	√, detailed	√, general	√, general	√, general	√, detailed
	Water	√, detailed	√, detailed	√, general	√, general	√, detailed	√, detailed
	Soil	√, detailed	√, detailed	√, detailed	√, general	√, detailed	√, detailed
Exposure pathway	Inhalation	√, general					
	Ingestion	√, detailed	√, detailed	√, general	√, detailed	√, detailed	√, detailed
	Dermal exposure	×	×	√, general	√, general	×	×
Databases	USEtox 2	√	√	×	×	√	√
	USES-LCA 2.0	×	√	×	×	√	×
	CalTox	×	×	×	×	×	√
	IMPACT 2002	×	×	√	×	×	×
	Eco-indicator 99	×	×	√	×	×	×
	EDIP 97	×	×	×	√	×	×
	Secondary data from literature or other data bases	√	√	√	√	√	√

a: HCT – human carcinogenic toxicity

b: HNCT – human non-carcinogenic toxicity

c: HT – human toxicity

d: FPM – fine particulate matter

e: RI – respiratory inorganics

f: HHP – human health particulate

g: POF – photochemical ozone formation

h: PO – photochemical oxidation (also named “respiratory effects from organics”)

i: PSF – photochemical smog formation

j: OLD – ozone layer depletion

k: IR – ionizing radiations

l: GW – global warming

m: HTP – human toxicity potential

n: HH – human health

o: CTU – comparative toxic units

p: RIP – respiratory inorganics potential

q: PMFP – particulate matter formation potentials

r: POP – photochemical oxidation potential

s: HOF – human health ozone formation potentials

t: SFP – smog formation potentials

u: ODP – ozone depleting potential

v: IRP – ionizing radiation potential

w: GWP – global warming potential

x: CDU_h – comparative damage units (human health characterization factor)

y: DCF_{hum} – endpoint characterization factor for human health

z: HCTCF – human toxicity characterization factor

aa: Environmental compartment

3.2.1.1 Impact category

USEtox 2, ReCiPe 2016, and IMPACT 2002+ express human health impacts at both midpoint level and endpoint level, although different impact categories and units are used in different methods. At endpoint

level, disability adjusted life years (DALY) is the commonly used unit by these methods to measure the impacts on human health (HH). The categories of midpoint level impacts, on the other hand, are more diverse and vary from method to method. The midpoint impact categories of human carcinogenic toxicity (HCT) and human non-carcinogenic toxicity (HNCT) are covered by USEtox 2, ReCiPe 2016, IMPACT 2002+, and TRACI. Apart from that, ReCiPe 2016 and IMPACT 2002+ assess several additional midpoint impacts (as shown in Table 3.1), resulting in impacts on human health at the endpoint level through a damage pathway. Specifically, ReCiPe 2016 assesses fine particulate matter formation, photochemical ozone formation, ionizing radiation, and stratospheric ozone depletion, global warming, and water use, whereas IMPACT 2002+ evaluates respiratory inorganics, photochemical oxidation (equivalent to respiratory organics), ionizing radiations, ozone layer depletion, water withdrawal, and water consumption. TRACI is a midpoint assessment method, which expresses impacts on human health as human health particulate and photochemical smog formation, in addition to human carcinogenic and non-carcinogenic toxicity. CML-IA only provides the quantification of impacts on human health at midpoint level, expressed as Human Toxicity Potential (HTP). In addition, EDIP 2003 offers solely the midpoint characterization of human health impacts, expressed as Person Equivalents (PE).

It is worth noting that ReCiPe 2016, IMPACT 2002+ and TRACI all evaluate respiratory health impacts but expressed as differently named impact categories. However, taking a closer look at the definitions of these impacts, the “respiratory inorganics” in IMPACT 2002+, “fine particulate matter formation” in ReCiPe 2016, and “human health particulate” in TRACI are in fact similar to or equivalent, referring to the respiratory effects caused by fine particulate matter. Similarly, “respiratory organic” in IMPACT 2002+, “photochemical ozone formation” in ReCiPe 2016, and “photochemical smog formation” in TRACI all refer to the impact of photochemical reaction on human health.

3.2.1.2 Model structure and inputs

Most LCIA methods compared in this study use the multimedia model structure for capturing the fate of emissions. USEtox 2 (Fantke et al., 2017) uses a multimedia box model at four spatial scales (i.e. indoor, urban, continental, and global) for calculating fate factors and exposure factors. The effect modelling is based on aggregated statistics for cancer and non-cancer effects. All model inputs are obtained from existing databases and peer reviewed literature. All input data used in USEtox 2 have been evaluated for consistency and reliability (Fantke et al., 2017). ReCiPe 2016 (Huijbregts et al., 2016) calculates the fate, exposure, and effect factors with the USES-LCA 2.0 multimedia fate, exposure, and effects model (van Zelm et al., 2009). The determination of CFs is based on toxicity data on lab animals and human beings, the USEtox 2 organic and inorganic database (Fantke et al., 2017), and the USES-LCA 2.0 substance database (van Zelm et al., 2009). IMPACT 2002+ (Jolliet et al., 2003) uses a multimedia fate & multi-pathway exposure model. The effect factors are then determined with a dose-response slope. CFs are calculated based on other models including IMPACT 2002 (Humbert et al., 2012) and Eco-indicator 99

(Goedkoop, 1999). CML-IA also uses the USES-LCA 2.0 multimedia model for calculating fate, exposure, and effect factors. The CFs are determined with substance databases of USES-LCA 2.0 [35] and USEtox 2 (Fantke et al., 2017). The midpoint method, TRACI, applies different models for characterizing different impacts on human health. TRACI (Bare et al., 2012; van Zelm et al., 2009) has replaced its previous CalTox model (McKone, 1993) with the USEtox model for characterizing human carcinogenic and non-carcinogenic toxicity. Additionally, human health particulate matter in TRACI is calculated based on the modelling of fate and exposure into intake fractions, which represent the ratio of the emitted substance expected to be inhaled, considering the U.S. locality. For calculating photochemical smog formation, the Maximum Incremental Reactivity (MIR) method (Carter, 2010; Hauschild and Wenzel, 1998) developed specifically for the U.S. context, is used in TRACI. In EDIP 2003 (Hauschild, 2006; Hauschild and Potting, 2005), a different modelling approach, “some-fate modelling” according to EDIP, is used to account for the properties that are vital for substances’ potential for human toxicity. This approach aims to incorporate these properties in the expression of CFs in a transparency way. The human toxicity impacts are modelled based on a fate-corrected human reference dose or concentration. The calculation of CFs is based on values provided in the previous version of the method, EDIP 97 (Hauschild and Wenzel, 1998; Wenzel et al., 1997) in addition to newly added spatial differentiated “exposure factors” for Europe concerning emissions to air via inhalation (Hauschild, 2006; Hauschild and Potting, 2005). These site-dependent exposure factors offer the possibility to assess spatially differentiated variations in case of an increase in accumulated exposure (Hauschild, 2006; Hauschild and Potting, 2005).

3.2.1.3 Temporal and spatial scales

In terms of the temporal scale of different methods, almost all methods consider only the default long-term or infinite time frame, except for ReCiPe 2016, which considers three different time spans: 20 years, 100 years, or infinite. With regard to the spatial scale, IMPACT 2002+ is Western Europe based. EDIP 2003 allows three different modes of evaluation: site-generic, site-dependent, and site-specific, where the latter two modes are only suitable for Europe, whereas the site-generic mode is global. USEtox 2 and CML-IA are global methods without detailed spatial resolution. TRACI used to be completely based on North American data. But since it has adopted the USEtox model and substance database, the effect modelling of human carcinogenic and non-carcinogenic toxicity is now based on global data (van Zelm et al., 2009) while the assessment of human health particulate matter and photochemical smog formation remains American.

3.2.1.4 Uncertainties

Uncertainties are also handled differently by different methods. USEtox 2 addresses uncertainty by distinguishing two categories of CFs for human toxicity: “recommended” and “indicative”. The “indicative” CFs are suggested with a higher level of uncertainty than the “recommended” CFs. LCA practitioners are advised to use the “indicative” CFs together with the “recommended” ones, as otherwise,

the impacts of the substances with “indicative” CFs will be zero (Fantke, 2017). Accordingly, USEtox (r) represents the effects modelling using only “recommended” CFs whereas USEtox (r + i) represents the effects modelling considering both “recommended” and “indicative” CFs. The ReCiPe 2016 method groups uncertainties stemming from different sources and different value choices into three different perspectives (i.e. individualist, hierarchist, and egalitarian) (Huijbregts et al., 2016; Huijbregts et al., 2017), based on the “Cultural Theory” proposed by Thompson et al (1990). LCA practitioners are encouraged to consider all three perspectives for a sensitivity analysis on the outcomes (Huijbregts et al., 2016). The “individualist” perspective, denoted by ReCiPe 2016(I), is short-term interest oriented. It focuses on undisputed impact categories, and believes human adaptation is based on technological optimism. The “hierarchist” perspective, denoted by ReCiPe 2016(H), is based on scientific consensus in respect to the assessment time frame and the plausibility of impact mechanisms. The “egalitarian” perspective, denoted by ReCiPe 2016(E), considers the longest time frame and accounts for all impacts with available data (Huijbregts et al., 2016). IMPACT 2002+ provides a rough estimation of uncertainty on three scales (high, medium, and low) for fate, exposure, and effect modelling for each impact category. Human toxicity (at midpoint level) and human health (endpoint level) are marked as “high” in uncertainty (Jolliet et al., 2003) in IMPACT 2002+. EDIP 2003 suggests using a site-dependent CF for those processes with the largest contribution to site-generic impacts, aiming to reduce the spatially determined uncertainty (Hauschild and Potting, 2005). CML-IA points out several uncertainties related to embodying value choices and model structure; thus, sensitivity analysis is suggested by the method on different time horizons and spatial scales (Guinée, 2002). TRACI points out that it is important to understand the uncertainties in results associated with the underlying method, which can be achieved by consulting the original sources of the CFs (Hauschild et al., 2011; van Zelm et al., 2009).

3.2.2 Methodology

3.2.2.1 Goal and scope definition

This study follows the LCA methodological framework, which contains four main steps: goal and scope definition, life cycle inventory analysis, impact assessment, and interpretation. The goal of this study is to compare and examine different methods for assessing the life cycle impacts on human health in the context of biofuel supply chains, in order to empirically understand the effects of method selection on the assessment results, identify the level of consensus among various LCIA methods, and further provide insights into the potential impacts of biofuel production on human health.

The comparative analysis was conducted for the life cycle impacts of aviation biofuel on human health in the case of Brazil, a key player in global biofuel production. Based on recent literature on aviation biofuel, three feedstocks stand out in respects of techno-economic feasibility (Prussi et al., 2019; Wenzel et al., 1997), environmental impacts (mainly GHG emissions reduction) (Wenzel et al., 1997), and socioeconomic impacts (Saraiva et al., 2017) for the Brazilian context. Therefore, we focused on three

aviation biofuel alternatives produced from these feedstocks with corresponding conversion technologies that are suitable for each feedstock: (i) sugarcane via alcohol to jet (ATJ) pathway, (ii) eucalyptus via fast pyrolysis (FP) pathway, and (iii) macauba via hydro-processed esters and fatty acids (HEFA) pathway. The LCA was performed on the basis of a functional unit of 1MJ aviation fuel, assuming the lower heating value (LHV) for fossil aviation fuel and aviation biofuel are 44.1 MJ/kg and 43.3 MJ/kg, respectively (Elgowainy et al., 2012; Santos et al., 2018).

Figure 3.1 depicts the system boundaries, which cover feedstock production, biomass transport (to biorefinery), aviation biofuel production technology, biofuel distribution (from biorefinery to airports), and end use (i.e., combustion). The fields of sugarcane, eucalyptus, and macauba were assumed to be located in São Paulo, Minas Gerais, and Minas Gerais, respectively. The produced aviation biofuel was expected to be used in two major Brazilian airports: Guarulhos airport (in São Paulo) and Galeão airport (in Rio de Janeiro State). Fossil jet fuel production is considered as the reference system. Its inventories were analyzed for crude oil refining, transport and distribution, and combustion.

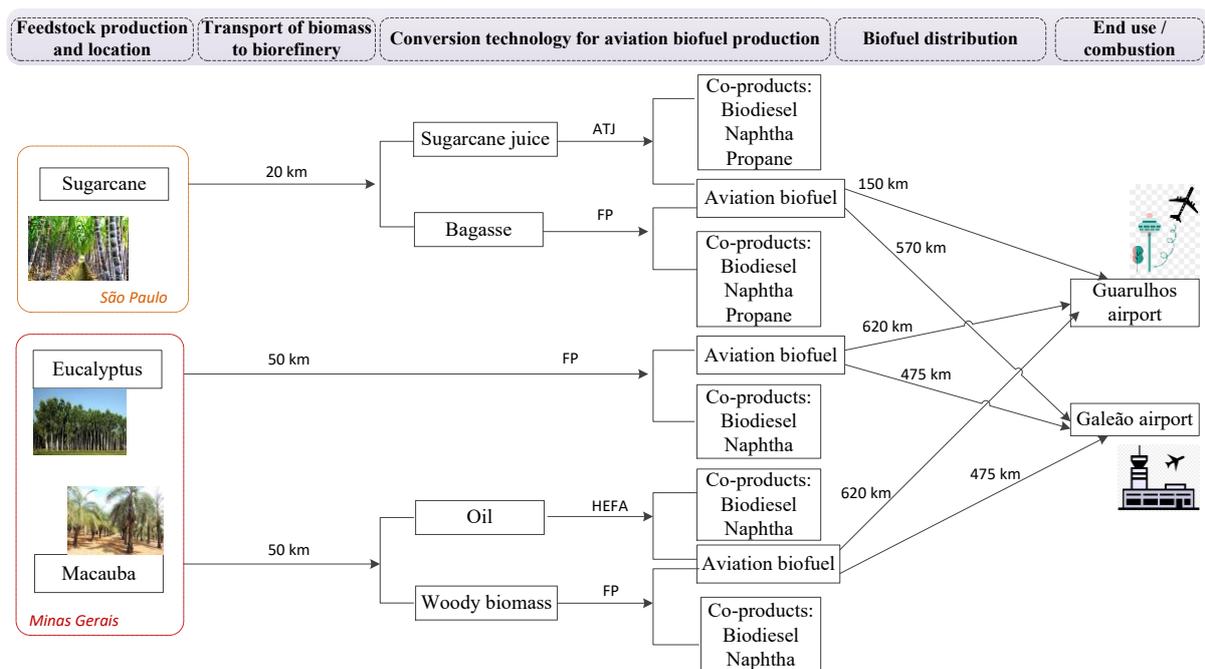


Figure 3.1 Scope of aviation biofuel supply chains for comparative analysis of LCIA methods on human health-related impacts.

3.2.2.2 Life cycle inventory

Inventories of aviation fuel production

This study focuses on the construction of foreground processes inputs and outputs. Detailed inventory of foreground data can be found in Tables S1 and S2 in Appendix II. The background inventories were compiled with Simapro software using the Ecoinvent 3 database.

The practices of feedstock (i.e., sugarcane, eucalyptus, and macauba) cultivation and their related emissions are highly dependent on the locations and technologies available. Thus, data on emissions for feedstocks production were obtained from the most recent context specific LCA/LCI studies of sugarcane production in Sao Paulo (Maga et al., 2019), average eucalyptus production (forest production subsystem) in Brazil (Saraiva et al., 2017; Silva et al., 2015), and macauba cultivation in Minas Gerais (Fernández-Coppel et al., 2018).

Aviation biofuel was considered to be obtained via different technologies in biorefineries. The Sugarcane-ATJ route mainly involves six processes: sugarcane milling, sugarcane juice fermentation, and ethanol upgrade to jet fuel (and co-products) via dehydration, oligomerization, and hydrogenation (Astonios et al., 2015; Wang and Tao, 2016). Furthermore, bagasse produced in the sugarcane milling process was also considered to be converted to aviation biofuel via the thermochemical process FP (Xu et al., 2013). The eucalyptus-FP route contains two subsequent processes: (1) dried lignocellulosic feedstocks are converted at high temperatures (around 500 °C) into bio-oil (Jones et al. 2013), and (2) bio-oil is subsequently converted into aviation biofuel (and co-products) via hydrogenation (Xu et al., 2013). The macauba-HEFA route requires (1) oil extraction from seeds, (2) oil hydro-treatment for deoxygenation, and (3) isomerization and hydrocracking (Pearlson et al., 2013). The rest of the macauba feedstock (woody biomass residue) was also considered to be converted to aviation biofuel via the FP process. Each of these three aviation biofuel routes generates co-products, namely biodiesel, naphtha, and propane. In addition, several auxiliary units producing heat/electricity (i.e., co-generation of steam and power (co-gen)), and hydrogen (via steam methane reforming (SMR)) were integrated in the biorefineries. A wastewater treatment plant (WWT) was also integrated for water reuse purpose.

Input data on biomass transport and biofuel distribution are adopted from the configuration design of aviation biofuel supply chains in Brazil by (Santos et al., 2018; Alves et al., 2016). An average of 20 km, 50 km, and 50 km was considered for transporting feedstocks from the fields to the biorefineries by heavy-duty trucks for the sugarcane-ATJ biofuel, eucalyptus-FP biofuel, and macauba-HEFA biofuel, respectively. The considered distribution distance of each biofuel to Guarulhos airport was 150 km, 620 km, and 620 km, respectively, and to Galeão airport was 570 km, 475 km, and 475 km, respectively.

So far, emissions data of aviation biofuel combustion have only been reported for HEFA and gasification Fischer-Tropsch (GFT) biofuels (Elgowainy et al., 2012; Bhagwan et al., 2014; Corporan et al., 2011; Stratton et al., 2011). Here we drew on the same inventories of HEFA aviation biofuel combustion in the Regulated Emissions and Energy use in Transportation (GREET) tool (Elgowainy et al., 2012) for all three aviation biofuels considered in our study, as the properties of aviation biofuels are similar by design and the majority of current commercial aviation biofuel is produced via HEFA. The inventories of fossil

aviation fuel were derived from the GREET database (Elgowainy et al., 2012), which enables the calculation of well-to-wake emissions of both fossil and biofuels.

Allocation method

Allocation is commonly applied in LCA studies to empirically deal with co-products as they are produced along the processes. However, the way of handling co-products can have large effects on the results. Essentially, either system expansion or partitioning method is used to handle the allocation issue of multiple inputs and outputs of processes (Suh et al., 2010). According to the International Standards Organization (ISO) 14044 standard (ISO, 2006), the system expansion approach is preferable as it recognizes the mitigated emissions attributed to co-products. Nonetheless, system expansion requires defining production systems of the co-products (e.g., biodiesel), which, in reality, can be produced by different pathways. This adds to the overall uncertainty and complexity of the study. Therefore, the partitioning method seems to better fit the objective of this study. Allocation based on mass, energy, or economic values has been used in LCA studies of biofuel or bioenergy systems. Each allocation method has its own advantages and disadvantages. Mass allocation is based on the weight of main product and co-products, thus not applicable for co-products that cannot be measured by mass (such as electricity). Energy allocation is based on the energy content of product and co-products, which means that it is less suitable for non-energy co-products. Although economic allocation is suggested as the last resort by ISO standard, it is able to capture the competitiveness of products' market value (Silva et al., 2015). For comparison purposes, this study applies mass, energy, and economic allocations, respectively, to distribute the emissions burden among all products of the aviation biofuel production process. The allocation factors used are presented in Table 3.2. In Section 3.3, the results and discussion presented are based on energy allocation as the main product and co-products are all energy products. Mass and economic allocations were used for sensitivity analysis.

Table 3.2 Allocation factors used for aviation biofuel and co-products (SC: sugarcane, EC: eucalyptus, and MC: macauba).

Supply chain	Conversion pathway	Product fraction	Allocation method		
			Mass	Energy	Economic
SC-ATJ ^a	Juice-ATJ	Jet fuel	0.81	0.80	0.89
		Diesel	0.11	0.12	0.08
		Naphtha	0.03	0.03	0.02
		Propane	0.05	0.05	0.01
	Bagasse-FP	Jet fuel	0.42	0.42	0.54
		Diesel	0.33	0.32	0.28
		Naphtha	0.19	0.20	0.16
		Propane	0.06	0.06	0.02
EC-FP	Jet fuel	0.41	0.40	0.52	
	Diesel	0.37	0.37	0.30	
	Naphtha	0.22	0.23	0.18	
MC-HEFA ^b	Oil-HEFA	Jet fuel	0.55	0.54	0.69
		Diesel	0.26	0.26	0.21
		Naphtha	0.08	0.08	0.07
		Propane	0.11	0.12	0.03
	Woody biomass-FP	Jet fuel	0.41	0.42	0.52
		Diesel	0.37	0.37	0.30
		Naphtha	0.22	0.21	0.18

a. After milling, sugarcane juice was converted to aviation biofuel via ATJ, while bagasse is also converted to aviation biofuel via FP.

b. After oil extraction, macauba oil was converted aviation biofuel via HEFA while the rest parts of macauba feedstock (EFB, fronds, and trunks) were also converted to aviation biofuel via FP.

3.2.2.3 Impact assessment: comparison among different methods

It is challenging to compare the results in absolute values, as these LCIA methods vary in multiple aspects (Yang et al., 2012; Dreyer et al., 2003; Gloria et al., 2006). Thus, we performed a contribution analysis for the results calculated with different methods. This means comparing (1) the relative ranking of human health impacts of different aviation biofuel alternatives, and (2) the percentages of impacts that different life cycle stages, processes, and substances account for. The life cycle human health impacts of aviation biofuels were analysed and compared using the LCA software tool Simapro[®], which integrates all the above discussed methods and allows a comparative contribution analysis at the life cycle, process, and substance levels.

First, an overview is given for all relevant impact categories at midpoint and endpoint levels calculated with all methods. This step reveals the relative ranking (in %) of the aviation biofuel alternatives based on each human health LCIA method: the impacts of the worst alternative would be marked as 100%, whereas the impacts of other alternatives would be less than 100%.

Secondly, a qualitative comparison was conducted between fossil jet fuel and each of the aviation biofuel alternatives in respect to each impact on human health that are comparable. Here we intended to determine whether the biofuels outperform fossil fuel. Specifically, two loose tolerance ranges (rule of thumb) were considered for the qualitative comparison, namely $\pm 15\%$ and $\pm 20\%$. The rationale here is that given the

potentially large and implicit uncertainty (while can be caused by model performance, data, and variability) in the calculated impacts on human health, the comparison between fossil fuel and aviation biofuel based on deterministic calculation can be indecisive. That is, it is not strictly clear which one performs better, especially when the differences in the deterministically calculated results are relatively small and might not be able to differentiate whether the alternative actually performs better. Thus, we drew on these two tolerance ranges ($\pm 15\%$ and $\pm 20\%$) and considered biofuels perform “equally” well as the fossil-based fuel (reference system) when the differences in the concern impact categories are within $\pm 15\%$ or $\pm 20\%$.

Thirdly, we performed a contribution analysis for each impact category resulting from the comparable LCIA methods. This analysis compared how the individual life cycle stage and the process of each aviation biofuel supply chain contribute to each impact on human health. We aimed to identify similarities as well as differences among these three aviation biofuel alternatives based on these LCIA methods.

In order to be considered comparable, LCIA methods should include the same or equivalent impact category and have the same or similar definition for the impact category concerned. As described in Section 2, some impact categories are expressed in different names by different methods. Thus, for the sake of unity and simplicity, we use the terms “fine particulate matter (FPM)” and “photochemical smog (PS)” to represent the two impact categories named differently in ReCiPe 2016, IMPACT 2002+, and TRACI. Based on the comparison provided in Table 3.1, the following LCIA methods are considered comparable and their results are compared in Sections 3.3.2 and 3.3.3:

- For midpoint human carcinogenic toxicity (HCT): USEtox 2(r+i)³, ReCiPe 2016(E)⁴, ReCiPe 2016(H)³, IMPACT 2002+, and TRACI;
- For midpoint human non-carcinogenic toxicity (HNCT): USEtox 2(r+i)¹, ReCiPe 2016(E)³, ReCiPe 2016(H)³, IMPACT 2002+, and TRACI;
- For midpoint fine particulate matter (FPM): ReCiPe 2016(E)³, ReCiPe 2016(H)³, IMPACT 2002+, and TRACI;
- For midpoint photochemical smog (PS): ReCiPe 2016(E)³, ReCiPe 2016(H)³, IMPACT 2002+, and TRACI;
- For endpoint human health (HH): ReCiPe 2016(E)³, ReCiPe 2016 (H)³, and IMPACT 2002+.

³ Only USEtox 2(r+i) is included in the comparative analysis, as according to the developers of this method, practitioners should always use indicative CFs together with recommended CFs to calculate toxicity in empirical studies. Thus, USEtox 2(r) is excluded.

⁴ ReCiPe 2016(I) is excluded from the comparative analysis as its timeframe is 20 years, which is significantly shorter than the remaining methods.

3.3 Results and discussion

3.3.1 Relative ranking of aviation biofuel alternatives

Figure 3.2 gives an overview of all relevant impacts of the three aviation biofuel alternatives and fossil jet fuel on human health. Results are shown at both midpoint and endpoint levels. The majority of LCIA methods suggest that in respect to midpoint impacts, macauba-HEFA biofuel is associated with the lowest impacts while eucalyptus-FP is associated with the highest. In most cases, fossil jet fuel is associated with neither the highest nor the lowest midpoint impacts on human health. At midpoint level, there seems to be a high level of consensus between USEtox 2 (r+i), ReCiPe 2016 (E), ReCiPe 2016 (H), TRACI, and CML-IA regarding human toxicity, despite some fluctuations. USEtox 2 (r) leads to different results than these four methods because it only considers “recommended” CFs for calculating human toxicity. Consequently, the effects caused by toxic substances with “indicative” CFs are left out, which means toxicity is essentially underestimated. Further, ReCiPe 2016 (I) results in a different relative ranking as it reflects the value perspective of an “individualist”, in which case a timeframe of 20 years is considered for effect modelling. This is considerably shorter than that of the remaining methods (i.e., 100 years or infinite). Additionally, IMPACT 2002+ is a European method whereas the rest of the methods are global (regarding the default CFs). The spatial-temporal differences can be responsible for the large differences in the resulting relative ranking. Moreover, different methods lead to different FPM and ozone layer depletion (OLD) impacts due to geographic differences, whereas the resulting impacts on PS, ionizing radiations (IR), and global warming (GW) are highly consistent regardless of methods.

At endpoint level, the results are more scattered in terms of the relative ranking of these four fuels. This is mainly due to the differences in the definition and scope of the endpoint human health impact, including different geographical and temporal scales, different coverage of substances, difference input data, as well as different damage pathways in each method. For example, IMPACT 2002+ takes into account carcinogenic and non-carcinogenic toxicity, fine particulate matter, photochemical smog, ozone depletion, and ionizing radiation, when quantifying the damage to human health at the endpoint. In addition to all impact pathways considered in IMPACT 2002+, ReCiPe 2016 also considers global warming as a potential cause of damage to human health.

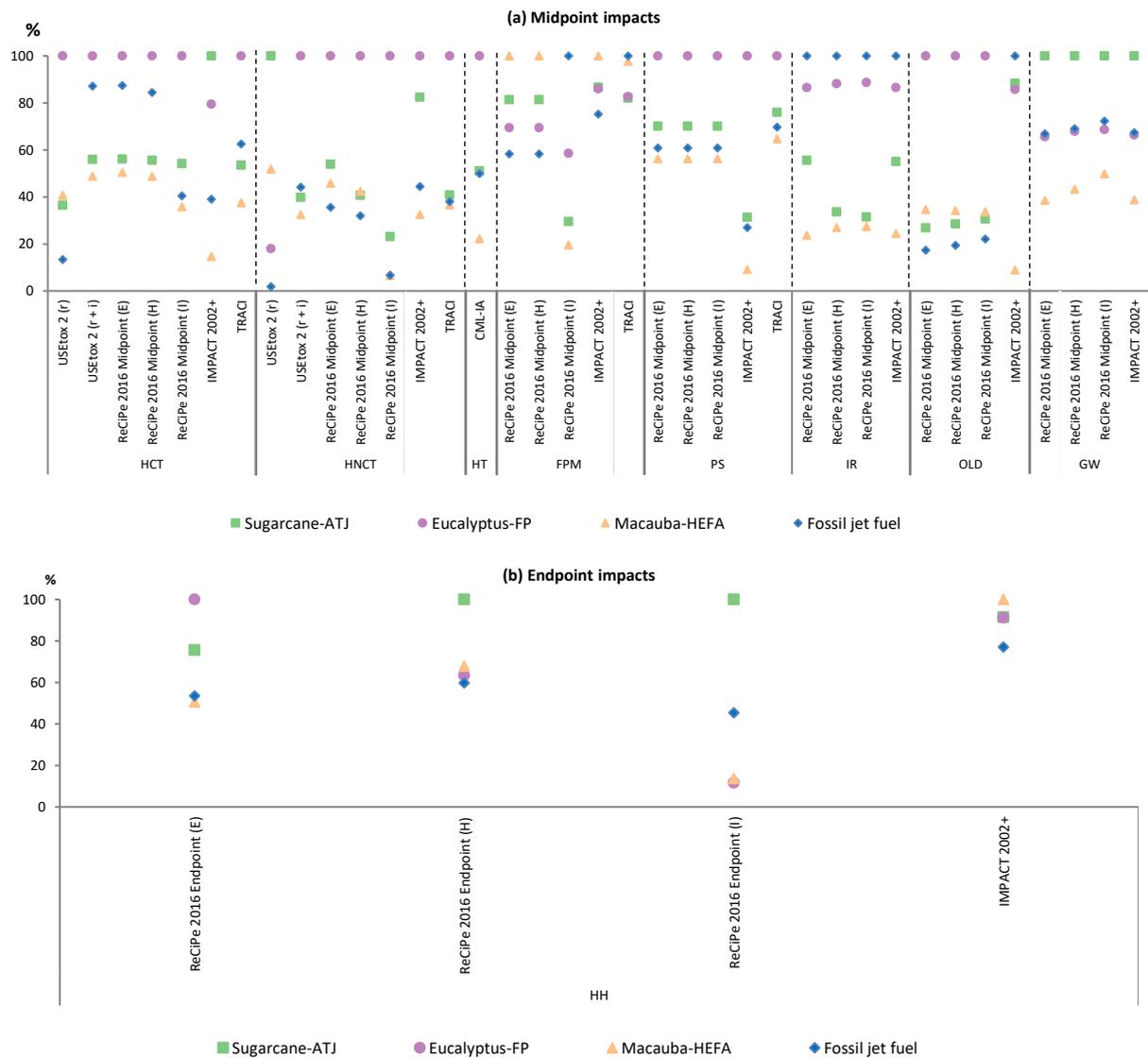


Figure 3.2. Life cycle midpoint (a) and endpoint (b) impacts of 1 L jet fuel, resulted from different LCIA methods (HCT: human carcinogenic toxicity, HNCT: human non-carcinogenic toxicity, FPM: fine particular matter, PS: Photochemical smog, IR: ionizing radiations, OLD: ozone layer depletion, GW: global warming, HT: human toxicity, HH: human health, HTP: human toxicity potential).

3.3.2. How do aviation biofuel alternatives perform compared to fossil jet fuel?

Section 3.3.1 has demonstrated general trends of the relative ranking of the four jet fuels calculated with different LCIA methods from a helicopter view. This section takes a closer look at the results, focusing on the LCIA methods that are comparable, intending to answer the question “do these methods agree with each other on whether biofuels outperform fossil fuel and (if yes) what do they agree on?”

As shown in Figure 3.3, the qualitative comparison shows that aviation biofuels do not always lead to lower impacts on human health. In terms of HCT, all methods suggest that macauba-HEFA biofuel always performs better than fossil jet fuel while the eucalyptus-FP biofuel performs no better than fossil

fuel, regardless of the tolerance range. With respect to HNCT, all methods agree that sugarcane-ATJ biofuel performs no better than fossil fuel whereas eucalyptus-FP biofuel always performs worse than fossil fuel, despite the tolerance range. Regarding FPM, all methods agree that macauba-HEFA biofuel performs no better than its fossil counterpart despite the tolerance range. With a $\pm 20\%$ tolerance range, all methods show that eucalyptus-FP biofuel performs equivalently to fossil fuel in respect to FPM. Furthermore, PS receives the highest level of consensus among different methods. In this regard, the sugarcane-ATJ and the macauba-HEFA biofuels perform no worse than fossil fuel while the eucalyptus-FP biofuel always performs worse than fossil fuel, in spite of the tolerance range. On the other hand, all methods agree that all three biofuel alternatives perform no better than fossil fuel in respect of HH at endpoint, regardless of the tolerance range.

It is worth noting that with a $\pm 15\%$ tolerance range, sugarcane-ATJ biofuel performs worse than fossil fuel in terms of PS, with the exception of TRACI. However, when expanding the tolerance range to $\pm 20\%$, all methods show that sugarcane-ATJ biofuel always performs as well as fossil fuel. This indicates that uncertainties in the calculated results play an important part and can essentially affect interpretation.

On the other hand, LCIA methods do not agree on how well aviation biofuels perform in respects to HCT and FPM of sugarcane-ATJ biofuel, HNCT of macauba-HEFA biofuel, and FPM ($\pm 15\%$) of eucalyptus-FP biofuel. This can be explained by the differences in geographic scope, substance coverage, toxicity data, and modelling choices, in addition to uncertainties in effect modelling between IMPACT 2002+, TRACI, ReCiPe 2016, and USEtox 2.

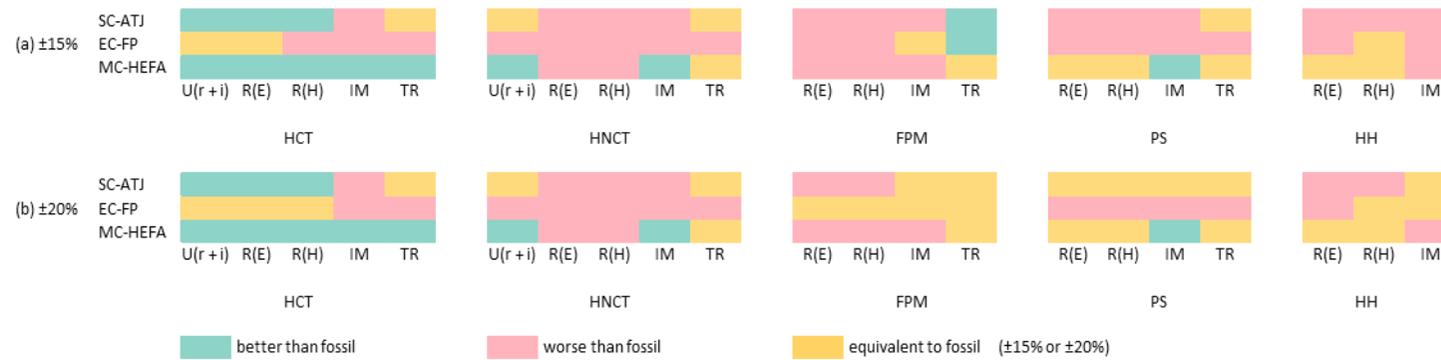


Figure 3.3 Color matrices illustrating the qualitative comparison between aviation biofuels and fossil jet fuel with regard to each impact category (HCT: human carcinogenic toxicity, HNCT: human non-carcinogenic toxicity, FPM: fine particular matter, PS: Photochemical smog, HH: human health; U(r+i): USEtox 2(r+i), R(E): ReCiPe(E), R(H): ReCiPe(H), IM: IMPACT2002+, TR: TRACI), considering tolerance ranges of (a) ±15% and (b) ±20%.

3.3.3 Contribution analysis

3.3.3.1 Human carcinogenic and non-carcinogenic toxicity

As shown in Figure 3.4, USEtox 2(r+i), ReCiPe 2016(E), ReCiPe 2016(H), and TRACI result in similar process contributions in respects to HCT and HNCT for all fuels. This is because these are all global methods and (partially or entirely) rely on the USEtox 2 substance database, which is also why IMPACT 2002+ does not share the consensus among the other four methods.

Despite this disagreement, all methods suggest that biofuel conversion and the production of H₂ are the main contributors to HCT and HNCT of all three aviation biofuels. This means that industrial processing accounts for 41-95% HCT and 34-92% HNCT of aviation biofuel production.

3.3.3.2 Fine particulate matter

A general agreement is seen in FPM resulting from different methods, with the exception of some fluctuations in the results calculated for the end use stage of aviation biofuels. According to all methods, FPM is predominantly caused by biofuel conversion and feedstock production, which are responsible for 27-45% and 20-58% of this impact, respectively. The contributions of biofuels' end use calculated with IMPACT 2002+ is the largest, followed by ReCiPe 2016(E) and ReCiPe 2016(H), while TRACI allocates the smallest impacts to end use. The minor differences in results here can again be attributed to the differences in geographic specification, database, and model specification among these LCIA methods.

3.3.3.3 Photochemical smog

PS resulting from ReCiPe 2016 (E), ReCiPe 2016 (H), and TRACI leads to highly similar results: the end use stage of aviation biofuels is the predominant contributor, which accounts for 35-62% of this effect. In comparison, IMPACT 2002+ results in significantly lower effects for the end use of biofuels, which is responsible for only 4-40% of the life cycle PS impact. The large differences here can be explained by the differences in the definition and scope of this impacts⁵. Specifically, IMPACT 2002+ considers this impact as the respiratory effects from organics (Humbert et al., 2012); ReCiPe 2016 considers effects caused by ozone formed as a result of photochemical reactions of NO_x and non-methane volatile organic compounds (NMVOCs) (Huijbregts et al., 2019); and TRACI considers effects caused by ground level ozone created by chemical reactions, which occur between NO_x and volatile organic compounds (VOCs) in sunlight (Bare et al., 2012).

⁵ IMPACT 2002+ considers this impact as the respiratory effects from organics (Humbert et al., 2012); ReCiPe 2016 considers effects caused by ozone formed as a result of photochemical reactions of NO_x and non-methane volatile organic compounds (NMVOCs) (Huijbregts et al., 2016); and TRACI considers effects caused by ground level ozone created by chemical reactions, which occur between NO_x and volatile organic compounds (VOCs) in sunlight (Bare et al., 2012).

3.3.3.4 Human health

At the endpoint level, LCIA methods agree that biofuel conversion is an important contributor (25-57%) to HH. It is worth noting that although ReCiPe 2016(E) and ReCiPe 2016(H) lead to very similar results in respects to HCT, HNCT, FMP, and PS, they show different results in HH. This is because the ReCiPe 2016 method also models damage to human health caused by additional impacts, such as ionizing radiation, ozone layer depletion, and global warming (Huijbregts et al., 2019). Despite the similarities shared by the “egalitarian” and the “hierarchist” perspectives in HCT, HNCT, FMP, and PS, differences do exist regarding other impacts, leading to different human health impacts at the endpoint level.

In addition to the above discussed similarities shared among the three aviation biofuels, feedstock production in the eucalyptus-FP supply chain is another key contributor, accounting for 54-58% of HCT, 50-65% HNCT, 51-58% FPM, 39-66% PS, and 51-60% HH of this supply chain. As reported in literature (Silva et al., 2015), fertilizers used in eucalyptus cultivation are highly relevant to human toxicity and ecotoxicity.

3.3.3.5 Fossil jet fuel

The life cycle contribution analysis for fossil jet fuel seems highly consistent among all methods. All methods show the combustion of fossil jet fuel is the single predominant contributor (more than 80%) to life cycle HCT, HNCT, FPM, PS, and HH, followed by a significantly lower share of fuel refining whereas the contribution of transport and distribution is insignificant. The production system of fossil jet fuel is considerably more mature and standardized than that of the burgeoning aviation biofuel. Therefore, the life cycle impacts, including life cycle human health impacts of the fossil supply chain, are better captured and more consistently represented in different LCIA methods (Tsang et al., 2015).

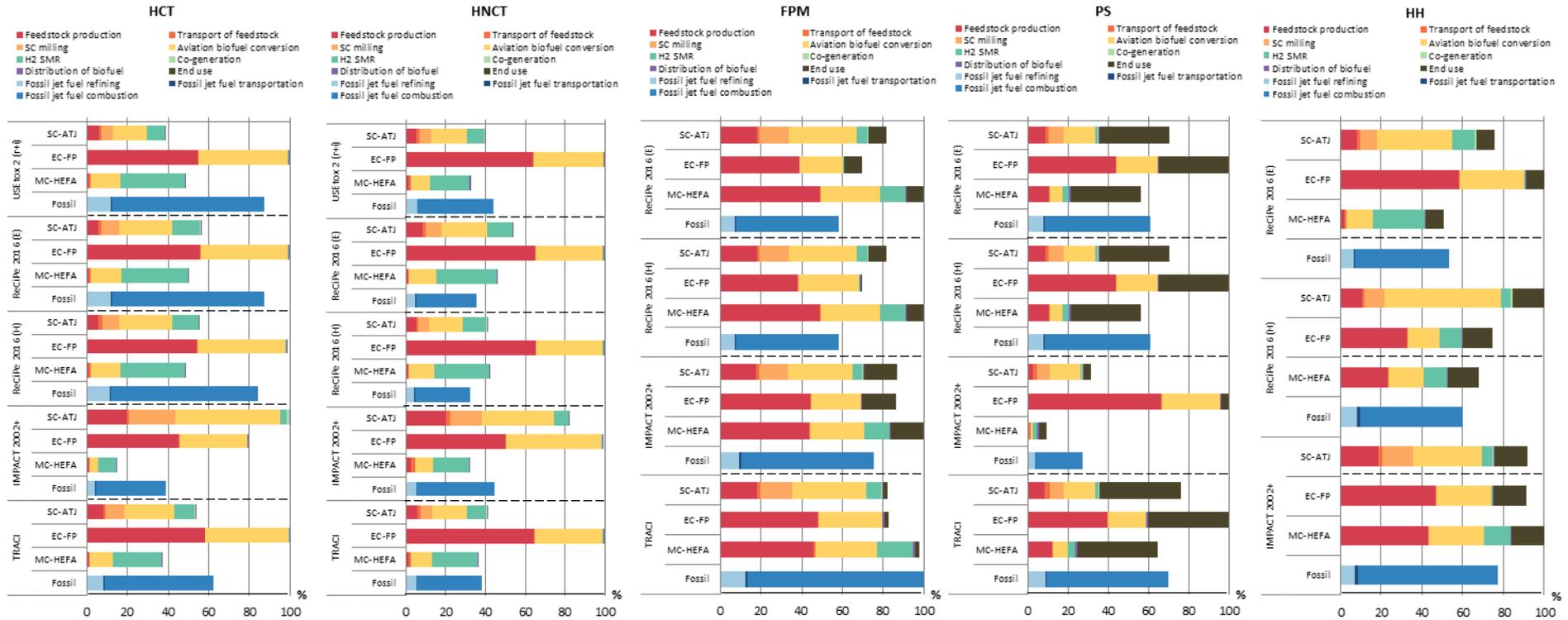


Figure 3.4 Contribution analysis for each impact category (HCT: human carcinogenic toxicity, HNCT: human non-carcinogenic toxicity, FPM: fine particular matter, PS: Photochemical smog, HH: human health).

3.3.4. Sensitivity analysis

As indicated in Section 3.2 that the allocation of emissions to main product and co-products can have large effects on results, and in Section 3.3.2 that biofuel conversion is the key contributor to all human health impacts, we conducted a sensitivity analysis on the allocation method and biofuel conversion yield. In comparison to energy allocation, we calculated each impact based on economic allocation and mass allocation, using the allocation factors shown in Section 3.2.2. To explore the effect of biofuel conversion yield on the resulting human health impacts, we considered a pessimistic yield and an optimistic yield for each aviation biofuel alternative, based on energy allocation. The values of these two yields were derived from literature, as shown in Table 3.3.

Table 3.3 Sensitivity analysis ranges of biofuel conversion yields.

Supply chain	Unit	Yield			Reference
		Pessimistic	Base	Optimistic	
SC-ATJ	kg biofuel/kg sugarcane,	0.81	0.80	0.89	[8]
EC-FP	kg biofuel/kg woody biomass	0.41	0.40	0.52	[16, 42]
MC-HEFA	kg biofuel/kg pulp oil	0.55	0.54	0.69	[16, 42]

Both economic and mass allocations assign larger effects to aviation biofuels for each impact category (Figure 3.5). Specifically, economic allocation results in a variation of 1.66-8.54%, 5.75-14.38 %, and 2.99-8.08% in all impact categories for sugarcane-ATJ, eucalyptus-FP, and macauba-HEFA biofuels, respectively. Mass allocation, in comparison, leads to considerably lower variation (< 2%) in all aviation biofuel alternatives, due to similar allocation factors in energy allocation. With the pessimistic conversion yield, these human health impacts in sugarcane-ATJ, eucalyptus-FP, and macauba-HEFA biofuels would increase by 0.96-2.64%, 1.20-2.03%, and 0.08-2.12%, respectively. On the other hand, the optimistic conversion yield would lower these impacts by 0.86-6.75%, 5.70-9.59%, and 0.23-8.27%, for sugarcane-ATJ, eucalyptus-FP, and macauba-HEFA biofuels, respectively.

Overall, the variations due to different allocation methods or biofuel conversion yields are moderate (< ±15%), whereas the eucalyptus-FP aviation biofuel supply chain is the most sensitive to the changes of variables for all impact categories.

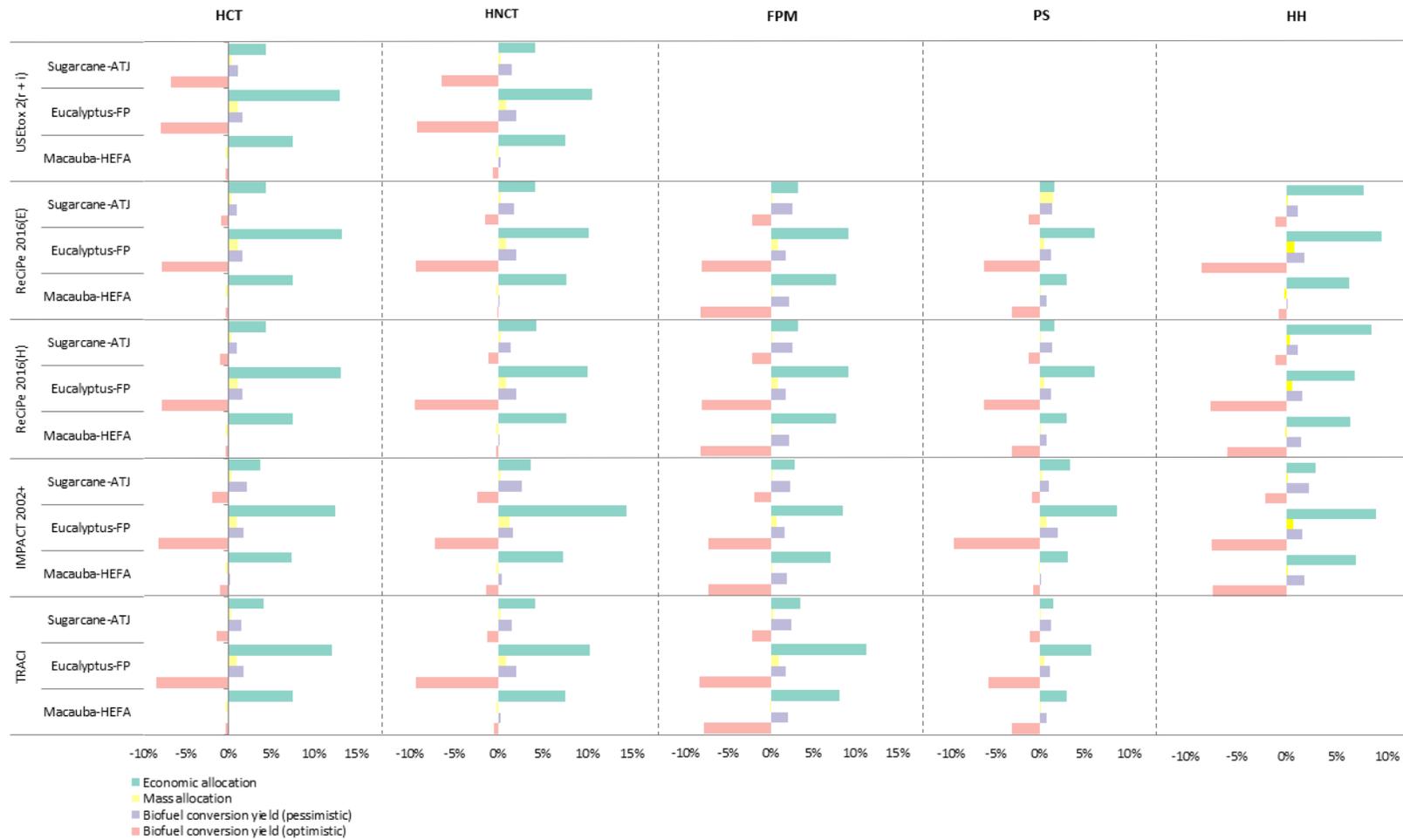


Figure 3.5. Sensitivity analysis on the allocation method (i.e., economic allocation and mass allocation) and biofuel conversion yield (i.e., pessimistic and optimistic), expressed in change in %, using energy allocation as the base case.

3.3.5. Improvement opportunities for aviation biofuel alternatives

Despite the discrepancy among the human health impacts resulting from different LCIA methods, conversion of biofuel is the common hotspot for all three aviation biofuels (as shown in Sections 3.3.3), which is primarily a result of the use of toxic chemicals, the use of primary energy, and the disposal of wastes (the substance contribution analysis for each aviation biofuel alternative can be found in Appendix II). It is, therefore, recommended to focus on the research and development of more efficient and cleaner aviation biofuel pathways that require fewer toxic chemicals or replace them entirely. H₂ is an indispensable input for all aviation biofuel conversion pathways. But H₂ SMR using natural gas is a major source of human health impacts. Other alternative processes such as gasification of biomass or electrolysis (Elgowainy et al., 2012; Parada et al., 2017) are alternatives to avoid the use of primary energy. In addition, the introduction of more stringent waste management practices to deal with waste disposal would also contribute to reducing life cycle impacts on human health. For instance, ash from the thermochemical degradation of biomass can be used as fertilizer in agriculture, which can potentially reduce the fertilizer needs in fields (Saraiva et al., 2017; Khan et al., 2009; James et al., 2012; Robertson and Vitousek, 2009). Nevertheless, the feasibility of this option depends on the content of minerals and heavy metals in the ash, as well as local regulations on the use of biomass ash in agriculture (Pizzol et al., 2011).

Another key contributor to the life cycle human health impacts is feedstock production, which is mainly caused by using fertilizers and pesticides. This calls for attention to cultivation practice improvement, especially in fertilizer and pesticide management. On the one hand, technological advancement in species selection would potentially increase yield, thereby reducing the total demand of agrichemicals. On the other hand, development of more efficient fertilizer and pesticide application techniques (e.g., optimizing the timing and placement of fertilizers, and improving the accuracy of nutrient needs prediction) would potentially improve the efficacy of the application of agrichemicals (Yang, 2013; Robertson and Vitousek, 2009). Additionally, given the combustion of aviation biofuel has large effects on the respiratory effects (FPM and PS), improvements in aircraft engines to increase efficiency is required in order to help reduce related effects.

3.3.6. Lessons learned for selecting LCIA methods for human health assessment

Although different LCIA methods lead to distinct results of life cycle impacts on human health, we were able to identify some general trends and consensus among these methods. While it may still remain challenging to draw a consensual conclusion on which method is the best, lessons can be learned with regard to the choice and application of LCIA methods for assessing human health in the context of biofuel supply chains.

Apparently, there is no single one-size-fits-all method here. In an LCA study, the first step of goal and scope definition determines the features of the study on a macro level. If the geographical specification plays an important role, then IMPACT 2002+, TRACI, USEtox 2, and EDIP 2003 might be favoured as they feature specific regions. Further, if the LCA study addresses certain value perspectives in particular, ReCiPe 2016 can shape the assessment in accordance with a specific value preference.

Focusing on the aviation biofuel supply chains in our case study, biofuel conversion is the primary contributor to all impacts. Thus, it is necessary to choose a method that includes the characterization of all inputs in industrial processes. Feedstock production is another significant contributor of aviation biofuel supply chains, especially eucalyptus-FP biofuel. The health effects related to the heavy metals in fertilizers are associated with high uncertainty [16, 18]. Hence, the differences in the characterization modelling of metals are important sources of discrepancy. Further, it is also important to consider the impact categories of interest. As the combustion of aviation biofuels results in considerable respiratory effects, it seems evident that the impacts on human health would be underestimated if only USEtox 2 were chosen. Hence, many factors need to be considered when making decisions on which method is the most appropriate.

Given that the USEtox 2 method was developed based on scientific consensus, it is intuitive to use this method as the reference method for assessing life cycle human health impacts. In fact, there has been a trend that a number of LCIA methods (e.g., ReCiPe 2016, TRACI, and CML-IA) have started to adopt the USEtox 2 substance database for calculating human health effects. However, the characterization of human health effects among these methods still differs, due to embedded differences in their own characterization models. This is why the results calculated with these methods still vary largely in some cases.

In line with the above discussed factors, the ReCiPe 2016 model appears to be a well-rounded method for assessing life cycle human health impacts of aviation biofuel supply chains, as it (i) includes assessment of both human toxicity and respiratory effects, (ii) provides CFs for a large number of substances, and (iii) is (partially) based on the consensus model USEtox 2.

Nevertheless, the choice of methods for assessing health effects should be made case by case, depending on each specific context. Therefore, we provide a self-check list below for LCA practitioners to choose the method that best suits their LCA study.

1. What are the spatial, temporal, and value choice specifications of the LCA study?
2. What is the preferred level of impact assessment (midpoint or endpoint)?
3. Which human health impact categories are of interest?

4. Which method(s) include as many CFs as possible for assessing all input substances?
5. Are there any environmental compartments and exposure pathways of particular interest?
6. What can be the potential “hotspots” of the LCA study?
7. Which method(s) include as many CFs as possible for assessing potential “hotspots”?
8. If multiple methods appear suitable, do they lead to consistent results? If not, a sensitivity analysis is recommended to provide insights into the differences.

A decision tree is shown in Figure 3.6, which exemplifies how to use these self-check questions to determine the most appropriate LCIA method(s) for assessing human health impacts. This example demonstrates various options based on the first three questions. These are the fundamental questions for a life cycle human health assessment study to start with. At this point, a preliminary screening of suitable LCIA methods should be achieved. Further, the LCA practitioner is recommended to continue with decision making based on the remaining questions and possible additional questions related to goal definition. It is also recommended to first compare results from different potentially suitable methods (based on the preliminary screening) to identify potential “hotspots”, and subsequently decide on the most appropriate method based on how these “hotspots” are assessed in each individual method, as listed in Questions 6-8.

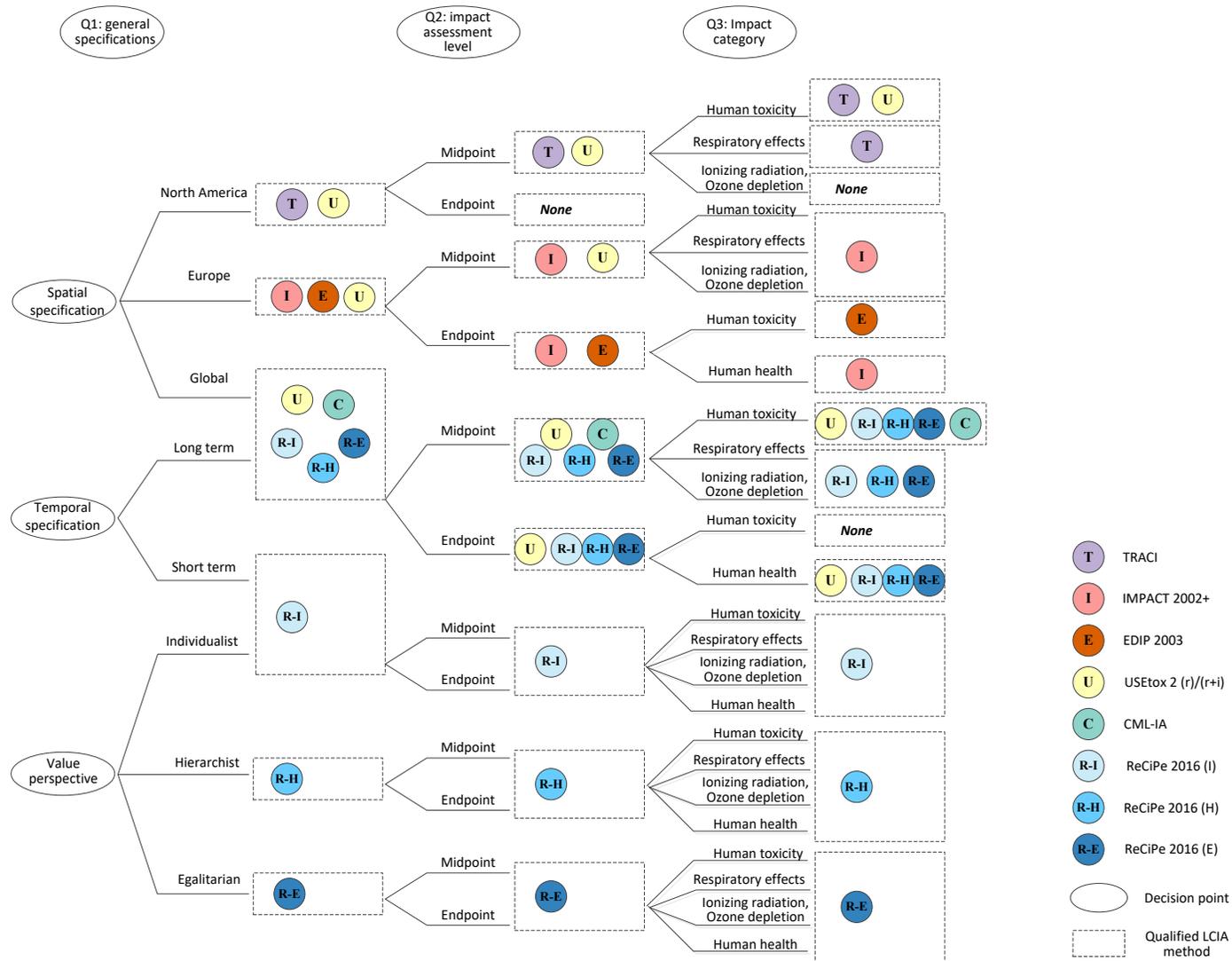


Figure 3.6 Schematic presentation of an example of the decision tree to identify the appropriate LCIA method(s).

3.4 Conclusions

This study aimed to provide a systematic comparison among six common LCIA methods for quantifying human health impacts, namely USEtox 2, ReCiPe 2016, IMPACT 2002+, EDIP 2003, CML-AI, and TRACI, in the context of biofuel supply chains. The comparative analysis was performed for the production of three distinct aviation biofuels in Brazil: sugarcane-ATJ, eucalyptus-FP, and macauba-HEFA biofuels; and the potential human health impacts were assessed for five life cycle impact indicators: HCT, HNCT, FPM, PS, and HH. Although these LCIA methods differ from each other in multiple aspects, the majority of them reveal that macauba-HEFA biofuel is associated with the lowest impacts and eucalyptus-FP biofuel with the highest, in respects to HCT, HNCT, FPM, and PS. That is, aviation biofuels do not always lead to better life cycle human health impacts than fossil jet fuel. In particular, aviation biofuels tend to outperform their fossil counterpart with regard to HCT, while performing equivalently or worse with regards to remaining human health impacts.

Overall, biomass conversion into aviation biofuel is a major contributor to all impact categories, namely HCT (by 28-52%), HNCT (by 19-45%), FPM (by 27-45%), PS (by 12-48%), and HH (by 25-57%) resulting from the three aviation biofuels, regardless of LCIA methods. Feedstock production also accounts for large effects in respect to FPM (20-56%), whereas the end use of aviation biofuel leads to a significant PS impact (4-62%). To reduce the impact of aviation biofuels on human health, it is worth considering the development of cleaner biofuel conversion technologies that require fewer toxic chemicals or avoid them altogether, that use sustainably produced H₂, and that encourage more stringent waste management practices. Additionally, improvements in feedstock cultivation practices, biofuel conversion yield, and aircraft engine efficiency can also contribute towards mitigating the impacts on human health.

There is no one-size-fits-all LCIA method for assessing human health impacts, and the choice of methods should be made case-by-case, depending on the specific context. In this regard, we have provided some general guidelines consisting of a list of self-check questions for LCA practitioners to determine an appropriate method for the assessment of human health impacts.

Chapter 4

Net Zero Flight Path Towards 2050 – Europe’s Sustainable Aviation Fuel Supply and GHG Emissions Reduction Potential

4.1 Introduction

According to the latest Sixth Assessment Report published by the Intergovernmental Panel on Climate Change (IPCC, 2023), the urgency and significance of mitigating climate change have been brought to an alarmingly new level. The world needs to cut greenhouse gas (GHG) emissions by 45% by 2030 and reach net zero GHG emissions by 2050 (IPCC, 2023) in order to limit global warming to well-below 2 degrees Celsius and preferably 1.5°C compared to the pre-industrial levels. The European Commission has published the European Green Deal for the EU's green transition and to ultimately achieve climate neutrality by 2050 (EC, 2021). The aviation sector accounts for about 2-3% of the global and 4% of Europe's GHG emissions (Adler et al., 2023). The European aviation sector has committed to reduce net CO₂ emissions by 55% (compared to 1990 levels) by 2030 and reach net zero CO₂ emissions by 2050. Sustainable Aviation Fuel (SAF) plays a key role in the decarbonization roadmap of this sector, as 34% emissions reduction is expected to be achieved by switching to SAF (Adler et al., 2023). Additionally, the ReFuelEU Aviation rules, as part of the "Fit for 55 package" has been approved by the EU to ensure the SAF blending will reach 70% by 2050 (6% in 2030, 20% in 2035, 34% in 2040, 42% in 2045 and 70% in 2050) (EC, 2023), contributing to not only reducing emissions but also strengthening energy security for Europe.

SAFs are alternative fuels that meet sustainability criteria including but not limited to lifecycle GHG emissions reduction compared to conventional fossil jet fuels (ICAO, 2017). Two main categories of SAFs have been under development to lower the environmental impact of the aviation sector. "Drop-in" SAFs are a novel type of aviation fuel that can be blended with conventional fossil fuel (Jet-A/Jet-A1) and used directly in the present aircraft infrastructure, while the "non-drop-in" SAFs require changes or new development in the aircraft structure before their application (ICAO, 2017), therefore still at their infancy. Drop-in SAFs can be further categorized into biobased SAFs and non-biobased SAFs (e-fuels). This study focuses on biobased drop-in SAFs only, as e-fuels are still under early stage of technological development (Peacock et al., 2024; Detsios et al., 2023).

The last two decades have witnessed the accelerated development of drop-in SAFs thanks to their potential of delivering immediate net emissions reduction (Kossarev et al., 2023; Peters et al., 2023; Puschnigg et al., 2023; Rojas-Michaga et al., 2023; Gonzelez-Garay et al., 2022; Mussatto et al., 2022; Capaz et al., 2021 (a); Capaz et al., 2021 (b); Siddiqui & Dincer, 2021; Capaz et al., 2020). For large-scale commercial applications, these alternative drop-in SAFs need to fulfill the technical requirements of the American Society for Testing and Materials (ASTM) standards (CAAFI, 2023). To date, 11 biobased drop-in SAFs production pathways have been approved by the ASTM, namely (1) Fischer-Tropsch Synthetic Paraffinic Kerosene (FT-SPK), (2) Hydroprocessed Esters and Fatty Acids Synthetic Paraffinic Kerosene (HEFA-SPK), (3) Hydroprocessed Fermented Sugars to Synthetic Isoparaffins

(HFS-SIP), (4) Fischer-Tropsch Synthetic Paraffinic Kerosene with Aromatics (FT-SPK/A), (5) Alcohol to Jet Synthetic Paraffinic Kerosene (ATJ-SPK), (6) Catalytic Hydrothermolysis Synthesized Kerosene (CH-SK, or CHJ), (7) Hydroprocessed Hydrocarbons, Esters and Fatty Acids Synthetic Paraffinic Kerosene (HHC-SPK or HC-HEFA-SPK), and (8) Alcohol to Jet Synthetic Kerosene with Aromatics (ATJ-SKA) (CAAFI, 2023), whereas the remaining 3 are co-processing conversion in a conventional petroleum refinery or HEFA process. The most commonly studied biobased feedstocks include sugars, lignocellulosic biomass, energy crops, agricultural residues, forestry residues, used cooking oil, and other recycled biobased waste (EASA, 2019).

The production of biofuels has been associated with discussions around various sustainability aspects, concerning economic, environmental, and social dimensions. The economic performance of SAF is most commonly evaluated by Minimum Fuel Selling Price (MFSP) (Brandt et al. 2022; Tanzi et al., 2021; Ng et al., 2021; Santos et al., 2018), which indicates the minimum selling price point of the fuel to break even. The MFSP of biobased SAF can vary largely and is driven by the combination of multiple factors ranging from feedstock cost, production cost, biofuel yield, and policy instruments (Brandt et al. 2022; Tanzi et al., 2021; Ng et al., 2021). The International Council on Clean Transportation (ICCT) estimated the total cost of SAF production can be 2–8 times the price of petroleum-based jet fuel (Pavlenko et al. 2019). Furthermore, as a key activity in the agricultural and forestry industry, biomass production in Europe is regulated by stringent land management rules to avoid deforestation, land degradation, and loss of biodiversity (WEC, 2010; Ramirez-Contreras and Faaij, 2018). These strict rules, on the other hand, limit the overall biomass availability within Europe (Strengers, 2020; Ecofys, 2019).

Moreover, biofuel production could lead to direct and indirect land use change (LUC) (Barati et al., 2023; Das & Gundimeda, 2022; Maia & Bozelli, 2022; Gerssen-Gondelach, 2017), which can significantly affect the EU's overall GHG emissions (EU, 2018). It is worth noting that social aspects are also important pieces of the sustainability puzzle. Wang et al. (Wang et al., 2019; Wang et al., 2020) pointed out that the choice of aviation biofuel could lead to significantly different levels of impact on local employment and human health. Furthermore, as the demand for biofuels increases, competition for land will likely arise between the production of food, fuel, and other biobased final products (Das & Gundimeda, 2022; Muscat et al., 2020; Naylor, R. L., & Higgins, 2018; Herrmann et al., 2018; Cobuloglu & Büyüktaktın, 2015). In response, the EU's Renewable Energy Directive set targets to phase out food-based biofuels produced by feedstock associated with high indirect LUC risk after 2020 (Fortuna, 2019; Gardner, 2019).

Therefore, it is imperative to understand the overall sustainability performance of SAF and how Europe can decarbonize its aviation sector in a sustainable manner. Existing studies have predominantly concentrated on analyzing the technological development of SAF and the techno-economic and environmental performance of SAF compared to its fossil counterpart (Watson et al., 2024; Detsios et al., 2024; Afonso et al., 2023; Shahriar & Khanal, 2022; Gonzalez-Garay et al., 2022; Bauen et al., 2020; Wang et al., 2021; Tanzil et al., 2021; Zhang et al., 2020; Holladay et al., 2020; Chiaramonti, 2019; Wei et al., 2019; Gutierrez-Antonio et al., 2017; Wang & Tao, 2016; Hari et al., 2015). Several recent publications reviewed SAF production technologies by investigating their techno-economic and environmental performances in relation to global policies and incentives for promoting SAF (Watson et al., 2024; Lau et al., 2024; Braun et al., 2024; Shahriar & Khanal, 2022; Ng et al., 2021). To date, few studies have investigated SAF production potential and the related emissions reduction in line with Europe's decarbonization roadmap. O'mally et al. (2021) evaluated the feedstock availability in the EU for supporting SAF production from 2025 to 2035, focusing on sustainably available feedstocks. Abrantes et al. (2021) evaluated the future reduction of CO₂ emissions by 2050 in the global aviation sector related to improving aircraft technology and deploying sustainable low-carbon fuels, however, an in-depth analysis of feedstock availability is missing. Therefore, a comprehensive exploration of potential SAF demand and supply in the context of Europe's decarbonization pathway towards climate neutrality by 2050 is lacking. Such knowledge is in need for strategic decision- and policy-making in order to abate emissions from the aviation industry.

The objective of this study is to assess the potential demand for and supply of SAF within Europe towards the 2050 horizon and quantify the resulting GHG emissions reduction based on an up-to-date comparative analysis of SAF production pathways while exploring the implications of various levels of SAF blending and biomass availability. By doing so, this study generates new insights into the European SAF sector and provides recommendations for the strategic planning of future SAF development. The novelty of this study lies in the comprehensive empirical analysis of future SAF development in Europe in the context of EU's 2050 climate neutrality ambition, as this study is the first to integrate supply-demand balance, future scenarios, techno-economic feasibility, GHG emissions reduction as well as the latest EU biofuel policies into such an analysis. As a result, this study compliments the existing sustainability evaluation of SAF by providing an up-to-date and systematic perspective on the future SAF deployment in Europe. The remainder of this paper is structured as follows: Section 4.2 describes the methodology, including literature review, expert workshop, and the setup of SAF demand and supply scenarios; Section 4.3 presents the results and discussion of the European SAF demand and supply scenarios and the related GHG emissions reduction. Section 4.4 provides conclusions and recommendations.

4.2 Methodology

Figure 4.1 depicts a schematic overview of the methodology used in this study. First, a comprehensive literature review was performed to understand the state-of-the-art overview of biobased drop-in SAFs in terms of the technical, economic, and environmental aspects. As a result of the literature review, the most promising biobased drop-in SAF production pathways for the European aviation sector as well as their sustainability considerations were identified. A subsequent expert workshop was held to discuss and align on these sustainability aspects of SAF production, followed by an online survey to validate the findings resulting from the workshop and eventually arrive at a shortlist of SAF production pathways. Next, an evaluation of Europe's biobased SAF demand and supply for the timeframe of 2030 – 2050 was performed, aiming to examine whether there will be sufficient biomass available to match the SAF demand in Europe and provide a comparative analysis of GHG emissions reduction attributed to different production pathways and under different scenarios.

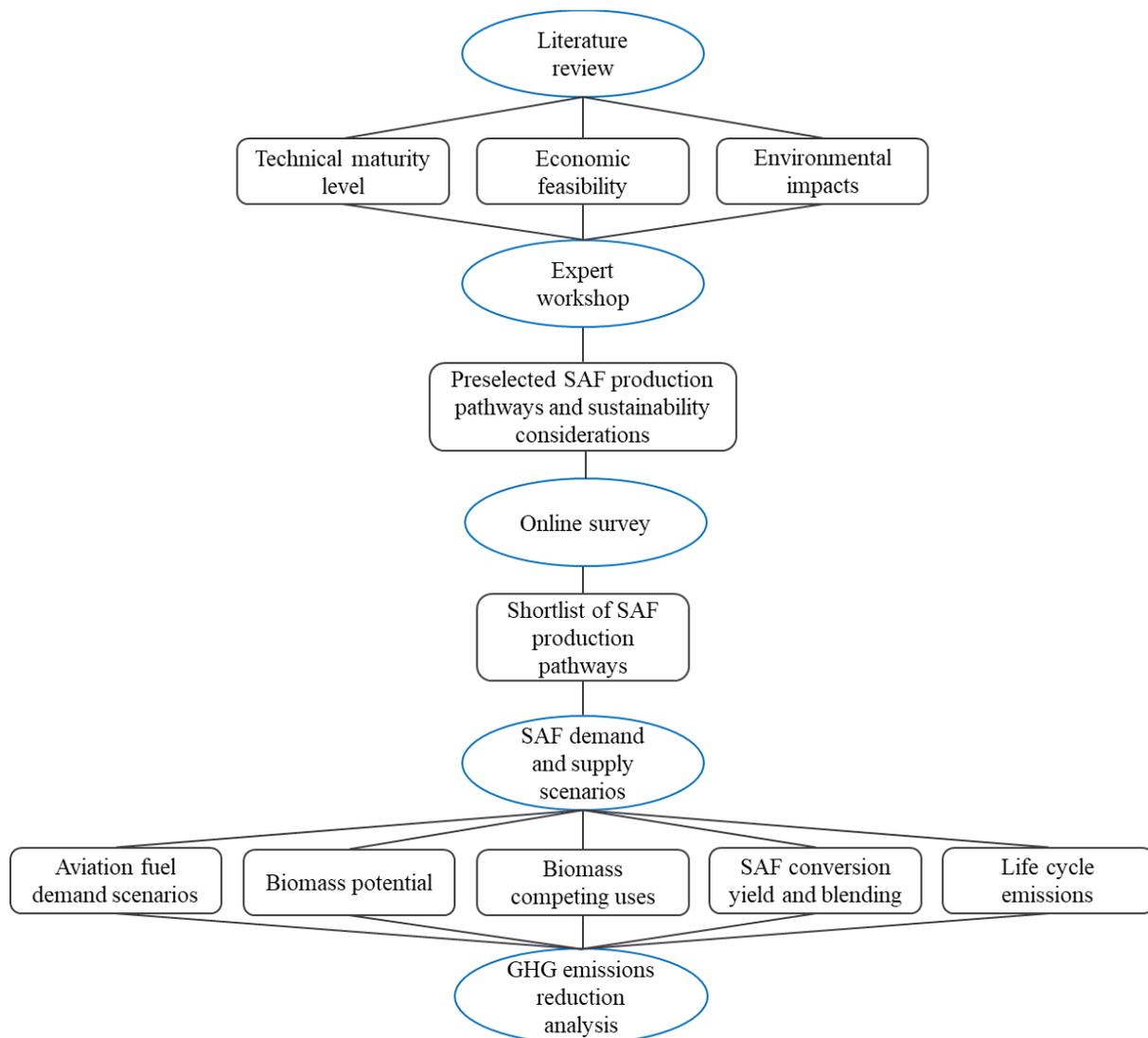


Figure 4.1 Schematic of methodology.

4.2.1 Literature review

An in-depth literature review was conducted to provide a state-of-the-art overview of biobased drop-in SAFs in terms of their technical maturity level, techno-economic feasibility, and potential environmental impacts (represented by GHG emissions reduction potential). Based on these criteria, the objective of the literature review was to select the most sustainable biobased drop-in SAF production pathways for Europe's 2050 Net Zero flight path. The scope of the literature research focuses on peer-reviewed publications such as scientific articles, conference proceedings, technical reports, policy documents, and research databases between 2000 and 2023. Web of Science, Scopus, and Google Scholar were used for the literature search. Specifically, the literature research was performed based on structured keywords, such as technical readiness level, feedstock readiness level, minimum selling price, production cost, life cycle assessment, life cycle analysis, life cycle GHG emissions, and GHG emissions reduction. A subsequent desk study was performed to compare the reviewed production pathways based on their technical, techno-economic, and environmental performance, resulting in a pre-selected shortlist of the most sustainable biobased drop-in SAFs alternatives, which was validated by a subsequent expert workshop (see Section 4.2.2)

4.2.1.1 Technical readiness

The ASTM's International Committee D02.J0.06 (Emerging Turbine Fuels) carries out the certification process that determines the technical qualification of SAFs production pathways, meaning whether SAFs can be used in aviation in the same way as conventional jet fuels or not. In order to be approved by ASTM, alternative SAFs must pass the certification procedure consisting of three phases (initial screening, follow-on testing, and balloting and approval) and four tiers (specification properties, fit-for-purpose properties, component/rig testing, and engine/APU testing). However, ASTM does not provide further insights into the level of commercial maturity of these alternative drop-in SAFs. Therefore, additional indicators such as Technology Readiness Level (TRL) have been considered to evaluate the technological development of the drop-in SAFs production pathways (Bhattacharya et al., 2022; CAAFI, 2023).

The TRL framework consists of 9 levels, from TRL 1 – Basic principles observed to TRL 9 – Actual system proven in operational environment. The TRL indicates the level of maturity of a technology toward commercialization, it therefore is commonly used to assess technological progress (Morone et al., 2023; Bhattacharya et al., 2022; Di Gruttola & Borello, 2021).

4.2.1.2 Economic performance

Among the reviewed literature, the economic feasibility of SAF production pathways has been assessed with different indicators. Minimum Jet Fuel Selling Price (MJFSP) is commonly used to evaluate the profitability of biobased SAFs (Braun et al., 2024; Detsios et al., 2024; Watson et al., 2024; Shahriar &

Khanal, 2022; Ng et al., 2021; Santos et al., 2017). MJFSP refers to the minimum price of the fuel to cover production expenses at a given internal rate of return. Moreover, Production Cost (PC) directly measures the costs incurred throughout the process of SAF production, including feedstock cost, plant operational cost, and installed capital cost (Braun et al., 2024; Detsios et al., 2024; Watson et al., 2024; Shahriar & Khanal, 2022; Ng et al., 2021; Santos et al., 2017). The present study reviews the economic indicators reported in literature and converts them into unit cost of energy (USD/MJ) to enable comparison among various production pathways while acknowledging that comparative analysis can be limited as the system boundaries and composition of PC may vary for different studies.

4.2.1.3 Environmental performance

The understanding of biobased SAFs' environmental performance requires a deep and balanced analysis of a wide range of impacts (Wang et al, 2019; Wang et al, 2020; Shahriar & Khanal, 2022). Nevertheless, life cycle GHG emissions reduction (in CO₂ equivalent) is predominantly recognized by many studies as a key indicator of environmental benefit. This is because GHG emissions reduction resulting from SAF plays a vital role in the decarbonization roadmap of the aviation sector, especially for the short- and mid-term when engine efficiency improvement can only bring limited emissions reduction. Therefore, this study focuses on reviewing the GHG emissions reduction potential over the full life cycle of SAF production in comparison to their fossil counterpart. Additionally, main elements such as system boundaries (well-to-wake or WtWa), functional unit (1 MJ of SAF), and co-production allocation (predominantly energy allocation) were considered for data collection and subsequent analysis.

4.2.2 Expert workshop and online survey

On 15 October 2022, a virtual workshop was organized by the Delft University of Technology (TU Delft) in collaboration with The Netherlands Aerospace Centre (NLR) to validate the shortlisted biobased SAF production pathways resulting from the literature review. 30 SAF experts with expertise in various fields participated in the workshop in the form of guided discussion to validate technical readiness, economic performance, potential environmental impacts as well as biomass availability for different SAF production pathways in the context of their contribution to the net zero aviation sector toward 2050.

These experts were from a wide range of sectors including academia, aircraft and engine manufacturers, airport groups, governmental bodies, international policy organizations, SAF technology R&D experts, SAF producers and distributors, and sustainability standards and certification experts; and from 8 different countries, namely, Belgium, Canada, Germany, France, Ireland, Spain, Switzerland, The Netherlands, and the United States.

During the workshop, the methodology and results of the literature review (as described in Section 4.2.1) were presented to the experts, who then provided feedback and recommendations to finalize the discussion on the role sustainability criteria play for future research directions. These key insights were further organized into an online survey that was distributed back to the same group of experts for validation. Consequently, a shortlist of the most promising biobased SAF production pathways for the European aviation sector was selected and validated.

4.2.3 Evaluation of SAF demand and supply scenarios for EU toward 2050

Based on the shortlisted biobased SAF production pathways concluded from the expert workshop, an analysis of Europe's biobased SAF demand and supply toward 2050 was performed, aiming to examine the biomass availability, the cost of SAF, and the GHG emissions reduction under different scenarios. 33 European countries are considered in this study (EU27 + 6 non-EU countries listed in footnote⁶).

On the demand side, the starting point is various national (total) aviation fuel demand described in the Clean Sky 2 (CS2) flight scenarios that were developed by the German Aerospace Center (DLR) (Gelhausen et al. 2022), considering differences aviation demand development scenarios in terms of number of flights and aircraft sizes from 2020 to 2050 for Europe. Gelhausen et al. (2022) developed a single forecast scenario for 2020 – 2035, whereas for the period from 2035 to 2050, two distinct scenarios were depicted: a “High” demand scenario and a “Low” demand scenario based on air traffic growth. The number of flights was projected to grow from 38 million in 2020 to 50 million in 2035, after which continued to reach 56 million in the “Low” scenario and 62 million in the “High” scenario by 2050. Accordingly, the compound annual growth rate of the aviation fuel demand is 1.5% from 2020 to 2035 for both scenarios and the demand trajectory of aviation fuel demand starts diverging from 2035 onward. The compound annual growth rates of aviation fuel demand in the “Low” and “High” scenarios between 2035 and 2050 are 0.4% and 1.6%, respectively.

Following the national aviation fuel demand, specific demand for SAF was explored by incorporating 2 theoretical and 1 practical biobased SAF blending ratio roadmaps. Theoretically, SAF blend could increase from 10% in 2030 to 40% in 2050 in a “LOW” blending roadmap while increasing from 10% in 2030 to 80% in 2050 in a “HIGH” blending roadmap, based on several published aviation decarbonization roadmaps (van der Sman, et al., 2021; IATA, 2021; ATAG, 2021). In practice, the European Union's ReFuelEU Aviation regulation, as the first binding EU-wide SAF mandate, requires

⁶ The 33 European countries (EU27 + 5 non-EU) and their two-digit ISO codes analyzed in study are as follows: EU27: Austria – AT, Belgium – BE, Bulgaria – BG, Czech Republic – CZ, Germany – DE, Denmark – DK, Estonia – EE, Greece – EL, Spain – ES, Finland – FI, France – FR, Croatia – HR, Hungary – HU, Ireland – IE, Italy – IT, Lithuania – LT, Luxembourg – LU, Latvia – LV, Netherlands – NL, Poland – PL, Portugal – PT, Romania – RO, Serbia – RS, Sweden – SE, Slovenia – SI, Slovakia – SK, and Ukraine – UA; non-EU: Albania – AL, Bosnia – BA, Moldova – MD, Montenegro – ME, Macedonia – MK, and United Kingdom – UK.

an upward blend trajectory, namely 6% in 2030, 20% in 2035, 34% in 2040, 42% in 2045, and 70% in 2050 (EC, 2023).

On the supply side, the production potential of biobased SAF was determined by analyzing a range of conversion pathways, meaning the combination of feedstock and conversion technology, in line with the preselected technologies (as described in Section 4.2.2). To facilitate the quantification of SAF supply, four factors were considered: biomass potential availability, biomass competing uses, total SAF production, and SAF blending ratio. The biomass potential availability by type and country is obtained using the S2Biom toolsets and datasets (S2Biom, 2023; Lammens et al. 2016), which provides the technical potential of biomass availability for a specific country and by a specific type (in kilo tonne dry mass) for 2012, 2020, and 2030. According to the S2BIOM database, the technical potential of biomass availability represents the maximum lignocellulosic biomass volume available, without considering competing uses and sustainability constraints (S2Biom, 2023; Lammens et al. 2016). The biomass potential availability for 2035, 2040, 2045, and 2050 was estimated using the 2030 S2Biom datasets and by applying a linear annual growth rate between 2030 and 2050. The biomass growth rates were calculated based on the biomass potential for 2050 reported by Panoutsou and Maniatis (2021) in their report.

However, it is unrealistic to expect 100% technical availability of biomass will be used for SAF production due to the competition for resources stemming from other biomass-based sectors such as biodiesel, biochemical, and biomaterials (Davis et al., 2024; Almena et al., 2024). Hence, this study considers that 40% of the total biomass technical availability will be left on the ground for sustainable agricultural practices and to preserve the soil quality, while the remaining 60% of the technical biomass potential is considered to be available for all biomass-based sectors, i.e., “usable biomass”. Furthermore, three different levels of biomass competing uses (CU) were considered here: 50%, 75%, and 90%. That is, 50%, 25%, and 10% of the 60% of total usable biomass will be allocated for SAF production, meaning that only 30%, 15%, and 6% of total biomass technical availability in Europe is considered to be allocated for SAF production, for these three CU levels, respectively. The total biomass technical availability combined with the three levels of CU determines the expected biomass availability for each scenario. Lastly, the yield of biobased SAF depends on the combination of feedstock type and the used conversion technology, in other words, the production pathway.

Overall, four SAF demand scenarios were analyzed in this study, considering diverging national aviation fuel demand and biobased SAF blend trajectory. Details are elaborated in Section 4.3.3.1.

4.2.4 Evaluation of SAF's contribution to GHG emissions reduction

Taking into account both demand scenarios and supply constraints, this study further investigates biobased SAF's contribution to the decarbonization of the European aviation sector towards 2050. To quantify the potential GHG emissions reduction, two indicators were analyzed per country: *i)* the relative GHG emissions reduction in percentage and *ii)* the net GHG emissions reduction as an absolute value (in tonne CO₂ equivalent). This study focuses on the Well-to-Wake (WtWa) GHG emissions, which include feedstock production and pre-treatment, upstream logistics, SAF conversion, downstream distribution, and end-use. It is worth noting that the CO₂ emissions from SAF combustion are considered part of the biogenic carbon cycle and are, therefore, assumed as zero (Sedjo et al. 2013). The net GHG emissions reduction refers to the WtWa GHG emissions difference between SAF and fossil jet fuel. The average WtWa emissions intensity of fossil jet fuel is around 90 gCO₂-eq/MJ (Wei et al., 2019; de Jong, 2017), which is considered as the fossil jet fuel emissions baseline in this study for assessing the net GHG emission reduction of SAF. The GHG emissions of each SAF production pathway are obtained from the GREET model (GREET, 2023) and the reviewed literature. Co-products allocation was included in the GHG emissions analysis based primarily on energy allocation.

4.3 Results and Discussion

4.3.1 Literature review

4.3.1.1 Biomass feedstock for SAF production

According to the Commercial Aviation Alternative Fuels Initiative (CAAFI, 2023), biomass feedstocks for SAF production can be categorized into four main groups: fats, oils, and greases (FOGs), carbohydrates/sugar, lignocellulose, and industrial wastes, as shown in Table 4.1.

Table 4.1 Biobased feedstock categories (Adapted from CAAFI, 2023).

Category	Example	Pros	Cons
Fats, oils, and greases (FOGs)	Oil Seeds (e.g., camelina, rapeseed)	<ul style="list-style-type: none"> - High adaptability under various climate and ecological conditions - Non-land competing - High productivity of algae 	<ul style="list-style-type: none"> - High cost of algae harvesting - UCO availability is limited for large-scale production
	Wastes/Industrial (e.g., tallow/lard)		
	Algae/Aquatic Species (cyanobacteria)		
	Used cooking oil (UCO)		
Lignocellulose	Woody biomass (e.g., sawdust)	<ul style="list-style-type: none"> - Widely available - High technical potential - Non-food competing 	<ul style="list-style-type: none"> - Still at the early stage of development - Pre-treatment is required
	Grasses (e.g., switchgrass)		
	Residues (e.g., corn stover, grain hulls)		
	Other (e.g., Brassicaceae, fungi)		
Carbohydrates/sugars	Crop Sugars (e.g., sugar beet, sugar cane)	High SAF yield	First-generation feedstocks could compete with food production
	Industrial (e.g., food processing, whey)		
Industrial wastes	Municipal solid wastes (MSW)	Improved waste management and contributing to the circular economy	Pre-treatment and separation are required
	Food wastes		
	Animal wastes		

So far, FOGs are the most widely used feedstock for biobased SAF production due to their adaptability under various climate and ecological conditions (Strengers, 2020; Ecofys, 2019). Used cooking oil (UCO) is a municipal waste stream that has been recognized as an affordable and non-land competing feedstock for SAF production in recent years, especially in Europe. However, as an estimated 90% of UCO collected in the EU is currently used for biofuel or biodiesel production (Strengers, 2020; Ecofys, 2019), only a limited amount of UCO is expected to be available for (large-scale) SAF production. Lignocellulose feedstocks cover a wide range of biomass from agroforestry residues to energy crops and woody biomass (Ng et al., 2021; Wei et al., 2019). Unlike UCO, the availability of lignocellulose is relatively high because of less competition (ATAG, 2023; Searle et al., 2019). Not competing with food production is another advantage of lignocellulose biomass that is worth noting (E4tech, 2017). However, preprocessing is required to convert lignocellulose biomass into SAF, and the technological development is still in its infancy. Carbohydrates or sugars are typically derived from a variety of crops with high sugar concentrations such as sugarcane and maize or similar. Multiple studies have reported a high yield of SAF from sugarcane (Santos et al., 2018; Hoang et al., 2015), nonetheless, first-generation feedstocks like sugarcane are unlikely to be a key crop for the large-scale commercial production of SAF in Europe due to sustainability concerns. Typically, industrial wastes refer to municipal solid wastes (MSW), food wastes, animal wastes, and household wastes. Using municipal or industrial waste streams for SAF production contributes to sustainable waste management and circular economy by avoiding hundreds of millions of tonnes of wastes ending up in landfill sites (Shahabuddin et al., 2020; Staph et al., 2019; Hari et al., 2015). Preprocessing before being used in SAF conversion is also required for MSW feedstocks as waste streams are usually contaminated.

4.3.1.2 Biobased SAF production pathways

In general, the production of biobased SAF starts with obtaining biomass, followed by biomass processing to reduce its oxygen content and subsequent conversion pathways leading to the final step of hydrocracking/fractionation and distillation, as illustrated in Figure 4.2. As a result, drop-in SAF is produced as a sustainable alternative to conventional jet fuel. FT and HEFA are considered the most promising SAF production pathways in the short term by the aviation industry due to their high level of technological maturity as well as their GHG emissions reduction potential (Shahriar & Khanal, 2022; Ng et al., 2021; Wei et al., 2019; Hari et al., 2015). This section provides a high-level overview of ASTM D7566-approved SAF production pathways (excluding co-processing), and the detailed technical description of each pathway can be found in other published studies (ICAO, 2024; Shahriar & Khanal, 2022; Ng et al., 2021; Wei et al., 2019; Hari et al., 2015).

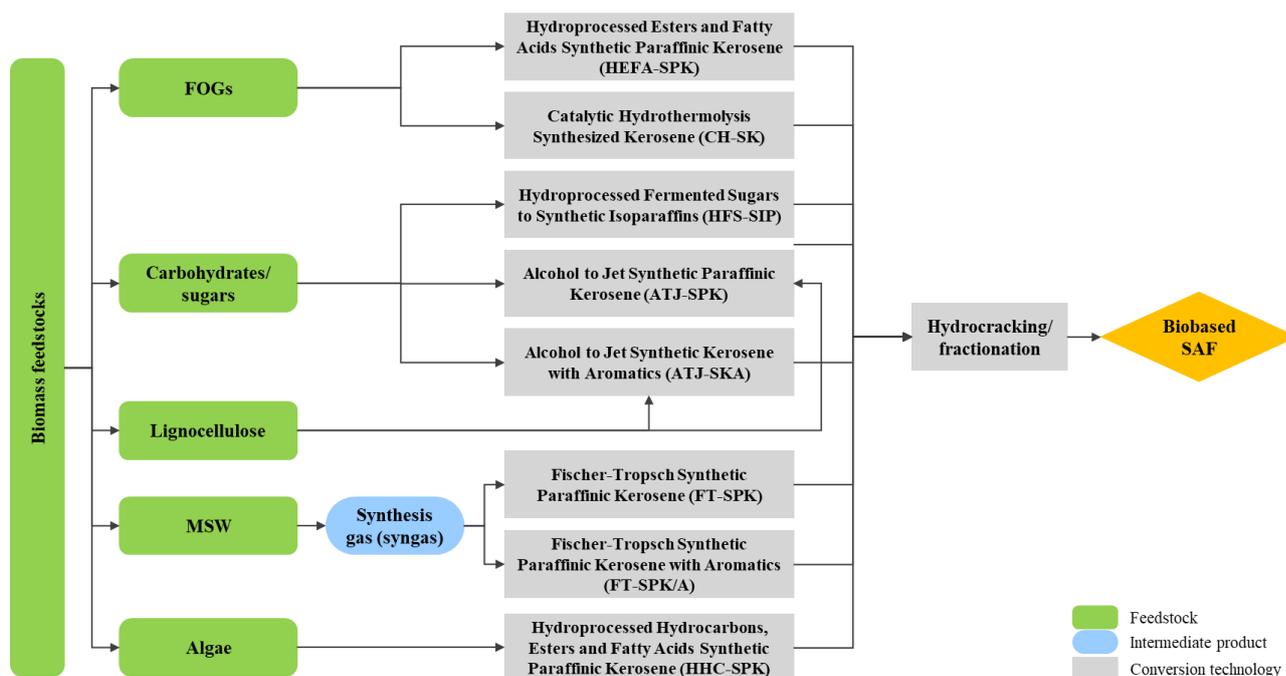


Figure 4.2 Biobased drop-in SAF production pathways proved by ASTM D7566.

To date, eight biobased drop-in SAF production pathways have been approved under the ASTM D7566 standard, with up to 50% blending with conventional jet fuel, (EASA, 2019; CAAFI, 2023). The blending potential of biobased SAF is expected to increase up to 100% by tackling the level of aromatics in the fuel (Undavalli et al., 2023). Table 4.2 presents an overview of these key biobased SAF production pathways and their corresponding blending volume as well as technology readiness level (TRL).

Fischer-Tropsch (FT) Synthesis

FT-SPK is the first ASTM-approved biobased SAF production pathway. It starts with the gasification of biomass to produce synthesis gas or syngas, a mixture mainly containing carbon monoxide and hydrogen, and the process is followed by the conversion of syngas and hydrocracking into clean and refined FT synthesis liquid fuel (Ail & Dasappa, 2016). FT synthesis can utilize various biomass feedstocks to produce SAF, such as municipal solid wastes and lignocellulosic (Wang et al., 2022; Searle et al., 2019; Jürgens et al., 2019). Similarly, the FT-SPK/A pathway couples biomass gasification and FT synthesis while also producing synthetic aromatics together with paraffin to mimic the composition of conventional jet fuel (CAAFI, 2023).

Hydroprocessed Fermented Sugars (HFS)

HFS-SIP is also known as direct-sugar-to-hydrocarbon (DSHC) jet fuel. The process utilizes genetically modified microorganisms to convert sugar directly into hydrocarbons or lipids via fermentation

(Shahriar & Khanal, 2022; Ng et al., 2021). HFS is different from the Alcohol to Jet (ATJ) production pathway as the latter requires the conversion of alcohol as an intermediate for jet fuel production. HFS can make use of sugars, starch, as well as lignocellulosic biomass coupled with pretreatments to obtain sugars (Shahriar & Khanal, 2022; Ng et al., 2021).

Table 4.2 Key biobased SAF production pathways (Adapted from ASTM, 2022 and CAAFI, 2023).

Production pathway	Year of ASTM certification	Biomass feedstock	Maximum blending volume	TRL
Fischer-Tropsch Synthetic Paraffinic Kerosene (FT-SPK)	2009	Syngas from municipal solid waste (MSW), agricultural and forest wastes, and wood and energy crops	50%	7-8
Hydroprocessed Esters and Fatty Acids Synthetic Paraffinic Kerosene (HEFA-SPK)	2011	Plant and animal fats, oils, and greases (FOGs)	50%	8-9
Hydroprocessed Fermented Sugars to Synthetic Isoparaffins (HFS-SIP)	2014	Carbohydrates/sugars	10%	6-8
Fischer-Tropsch Synthetic Paraffinic Kerosene with Aromatics (FT-SPK/A)	2015	Municipal solid waste (MSW), agricultural and forest wastes, and wood and energy crops.	50%	6-7
Alcohol to Jet Synthetic Paraffinic Kerosene (ATJ-SPK)	2016	Starches, sugars, and cellulosic biomass	50%	6-7
Catalytic Hydrothermolysis Synthesized Kerosene (CH-SK, or CHJ)	2020	Plant and animal fats, oils, and greases (FOGs)	50%	5-6
Hydroprocessed Hydrocarbons, Esters and Fatty Acids Synthetic Paraffinic Kerosene (HHC-SPK or HC-HEFA-SPK)	2020	Hydrocarbon-rich algae oil (the tri-terpenes produced by the <i>Botryococcus braunii</i> species of algae)	10%	5-6
Alcohol to Jet Synthetic Kerosene with Aromatics (ATJ-SKA)	2023	Fermentation of starches/sugars, coming from starch/sugar producing feedstocks or derived from cellulosic biomass	50%	5-6
Fast Pyrolysis + upgrading	N.A.	Woody biomass, corn stover	N.A.	4-6

Alcohol to Jet (ATJ)

ATJ process converts shorter-chain alcohols such as methanol, ethanol, and butanol into longer-chain hydrocarbon jet fuel (Shahriar & Khanal, 2022; Ng et al., 2021). Ethanol and butanol are the two predominant alcohols used in the ATJ process and are typically obtained from the fermentation of sugars, starch, and lignocellulosic biomass. The subsequent processing typically involves alcohol dehydration, oligomerization, and hydrogenation to produce jet fuel (Shahriar & Khanal, 2022; Ng et al., 2021).

Catalytic Hydrothermolysis (CH)

CH is one of the recent ASTM-approved pathways for producing SAF. The process utilizes oils, fats, and lipids in the catalytic hydrothermal conversion, via a series of hydrotreating, hydrocracking, and fractionation during refining (Shahriar & Khanal, 2022; Ng et al., 2021). The blending level with petroleum-based jet fuel is set to up to 50% (CAAFI, 2023).

Hydroprocessed Hydrocarbons, Esters and Fatty Acids (HHC or HC-HEFA)

HHC or HC-HEFA was approved by ASTM in 2020, and it utilizes specifically bio-derived hydrocarbons, fatty acid esters, and free fatty acids in the conversion process by treating the feedstock with hydrogen to remove oxygen, followed by cracking and isomerization to produce jet fuel (Shahriar & Khanal, 2022; Monterio et al., 2022; Ng et al., 2021). So far, the only recognized source of biobased feedstock is tri-terpenes produced by the *Botryococcus braunii* species of algae (CAAFI, 2023).

Fast Pyrolysis (FP)

In addition to the above-described certified SAF conversion technologies, the FP process converts organic materials such as woody biomass into bio-oil, organic vapors, pyrolysis gases, and charcoal at high temperatures (450 – 600 °C), followed by bio-oil upgrading (Liu et al., 2020; Perkins et al., 2018; Uddin et al., 2018; Venderbosch & Prins, 2010). It is worth noting that FP has not yet passed the ASTM certification due to the complexity of bio-oil upgrading, but it is expected to reach maturity in the midterm horizon (Shahriar & Khanal, 2022; Wei et al. 2019). Therefore, this technology is considered for further analysis in this study.

4.3.1.3 Technology Readiness Level (TRL)

As described in Section 4.1.2, nearly all the SAF production pathways can convert multiple biobased feedstocks into jet fuel and vice versa. Therefore, comparing the Technology Readiness Level (TRL) assists in identifying the most promising combinations of conversion pathways and biomass sources. As shown in Table 4.2, conversion pathways based on HEFA, FT, and HFS are most attractive with high levels of TRL, while CH appears to be least developed with very few explicit feedstock sources published in scientific or technical studies to date. The HEFA-SPK technology shows the highest level of TRL of 8-9. This is followed by the FT and HFS groups with TRL of 6-8. It is worth noting that HEFA, FT, and HFS have been applied in the commercial production of SAF (Ng et al., 2021).

4.3.1.4 Economic performance of biobased SAF production pathways

The cost of SAF production plays a significant role in large-scale commercialization. The aviation sector faces challenges in two key aspects to scale up SAF deployment. First, it will have to compete for biomass utilization with the already established biofuel and biodiesel industry for road transportation (ATAG, 2020; Searle et al. 2019). Moreover, unlike biofuel for road transportation, there are only limited supporting policy instruments such as subsidies, tax benefits, and mandates in the EU for biobased SAF (EC, 2023). The International Council on Clean Transportation (ICCT) estimated the total cost of SAF production can be 2–8 times the price of petroleum-based jet fuel (Pavlenko et al. 2019).

This section provides an overview of the economic performance of biobased SAF by comparing the Minimum Fuel Selling Price (MFSP), which is used to indicate the minimum selling price point of the fuel in order to break even. As shown in Figure 4.3, the overall MFSP of SAF produced from various pathways ranges from 0.8 to 7.8 USD/L. Most conversion pathways of the FT, HEFA, and ATJ groups are within the range of 0.8 to 3.1 USD/L, whereas the HFS group's MFSP appears to be on the higher end (2.2 – 7.3 USD/L). The FP group turns out to have the lowest MFSP in the range of 0.5 – 1.2 USD/L.

The MFSP of biobased SAF is determined by a wide range of elements including feedstock cost, location, facility scale, biofuel yield, capital expenditures (CAPEX), and operating expenditures (OPEX). Specifically, the MFSP of the FT group is predominantly driven by the CAPEX while the cost of feedstock is the most significant factor that determines the MFSP of the HEFA group. The MFSP of the HFS and ATJ groups is highly dependent on CAPEX as well as yield. However, there is a high level of uncertainty in the comparative analysis of MFSP and its future development. For example, technological learning and economic upscaling are likely to bring the production cost of SAF down in the future, however, this is hard to capture in the current analysis. Furthermore, the introduction of policy schemes such as mandates, subsidies, and carbon taxes will also influence the overall cost-benefit analysis of SAF compared to its fossil counterpart. Most of the reviewed publications did not take into account the policy lever.

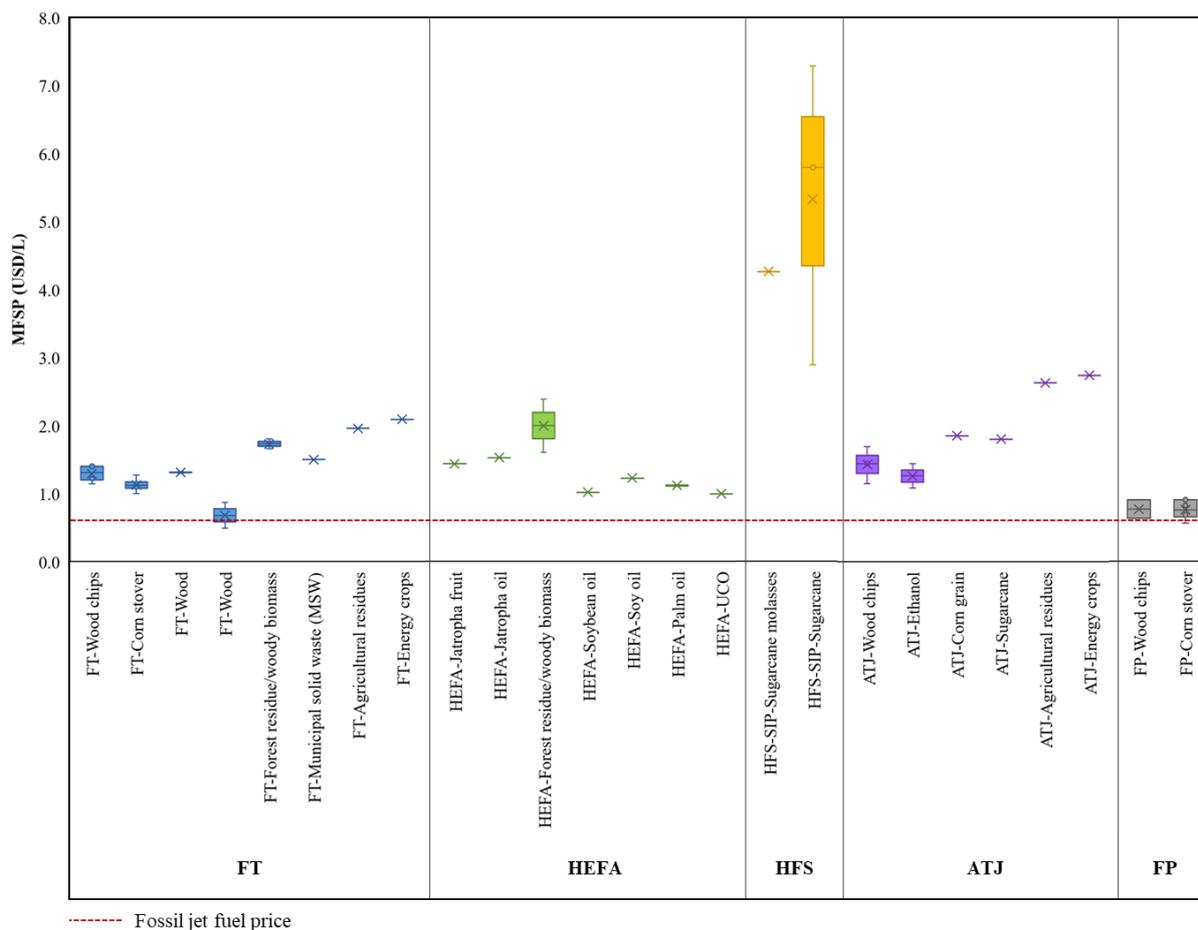


Figure 4.3 Comparison of biobased SAFs production pathways in terms of their economic performance (MFSP). (Source: Capaz et al., 2021 (a); Capaz et al., 2021 (b); Siddiqui and Dincer, 2021; De Jong et al., 2017; De Jong, 2018; Gonzalez-Garay et al., 2022; IATA, 2023; Kossarev et al., 2023; Mussatto et al., 2022; O'Connell et al., 2019; O'malley et al., 2019; Pavlenko et al., 2019; Puschnigg et al., 2023; Rojas-Michaga et al., 2023; Wei et al., 2019; Wang et al., 2023; Zemanek et al., 2020; fossil jet fuel price 0.65 USD/L, source: IATA, accessed in December 2023.)

4.3.1.5 Environmental performance of biobased SAF production pathways

The life cycle GHG emissions of SAF can vary drastically depending on the selected feedstock and conversion technology. A wide range of studies have performed life cycle analyses of different biobased SAF production pathways. Furthermore, the life cycle GHG emissions reduction of SAF is also affected by the LCA approach used to address multifunctionality, for example, the allocation for co-products, and the modeling of land use change (LUC). Through co-product allocation, SAF can receive higher environmental benefits, leading to relatively low or even negative GHG emissions. LUC is caused by converting existing or new cropland for the agroforestry activities required for biomass cultivation. Allocation and LUC impact calculation relies typically on scenario-based modeling, therefore, direct comparison of absolute GHG emissions should be dealt with caution.

As shown in Figure 4.4, most SAF pathways lead to lower GHG emissions than the petroleum-based jet fuel, resulting in a 20-95% reduction of GHG emissions, considering the GHG emission of

conventional jet fuel is 90 kg CO₂-eq/GJ (Wei et al. 2019). Notably, only certain feedstocks within the HEFA group, namely palm oil, beef tallow, and soybean oil result in higher GHG emissions than the conventional jet fuel. The HEFA group shows the widest range of GHG emissions, from 1 – 268 kg CO₂-eq/GJ. This is attributed to the assumptions of allocation and LUC as well as the wide range of feedstocks presented in the reviewed studies. The ATJ group results in -27 – 118 kg CO₂-eq/GJ depending on the feedstock type and the approach used for multifunctionality. The life cycle GHG emissions of the HFS group are concentrated between 15 and 80 kg CO₂-eq/GJ. The FT group is associated with low GHG emissions despite feedstock type, consistently lower than 40 kg CO₂-eq/GJ.

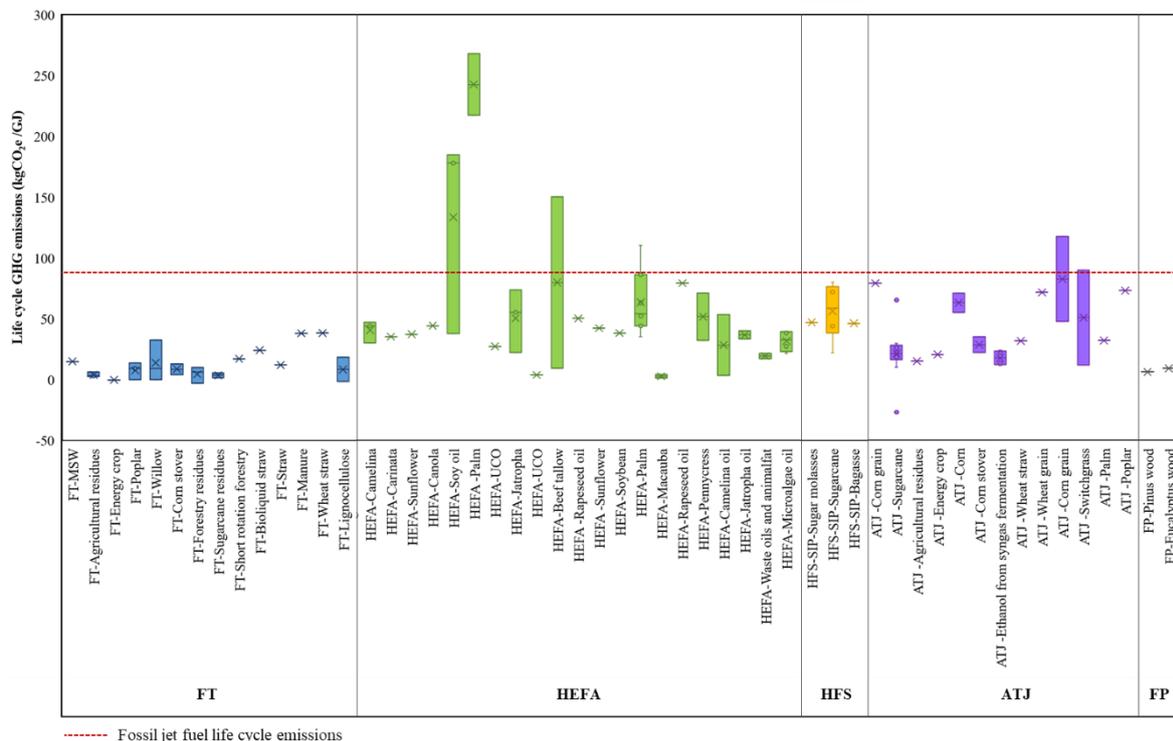


Figure 4.4 Comparison of biobased SAFs production pathways in terms of their life cycle GHG emissions. (Source: Capaz et al., 2021 (a); Capaz et al., 2021 (b); Siddiqui and Dincer, 2021; De Jong et al., 2017; De Jong, 2018; Gonzelez-Garay et al., 2022; IATA, 2023; Kossarev et al., 2023; Mussatto et al., 2022; O’Connell et al., 2019; Pavlenko et al., 2019; Puschnigg et al., 2023; Rojas-Michaga et al., 2023; Wei et al., 2019; Wang et al., 2023; Zemanek et al., 2020.)

4.3.2 Shortlist of biobased SAF production pathways for EU

Figure 4.5 illustrates the economic and environmental performance of the literature review (as indicated in Section 4.2.1). Three potential SAF production pathways are identified as the most sustainable, namely HEFA, FT, and FP. HEFA is the most mature SAF production technology and has been commercially deployed. It also leads to relatively attractive economic and environmental performance. FT stands out in terms of the lowest levels of GHG emissions. It is the second most mature conversion technology and shows relatively competitive economic performance. FP, in comparison, is technically less mature and less studied, nevertheless, it has demonstrated high potential for GHG emissions reduction and low costs.

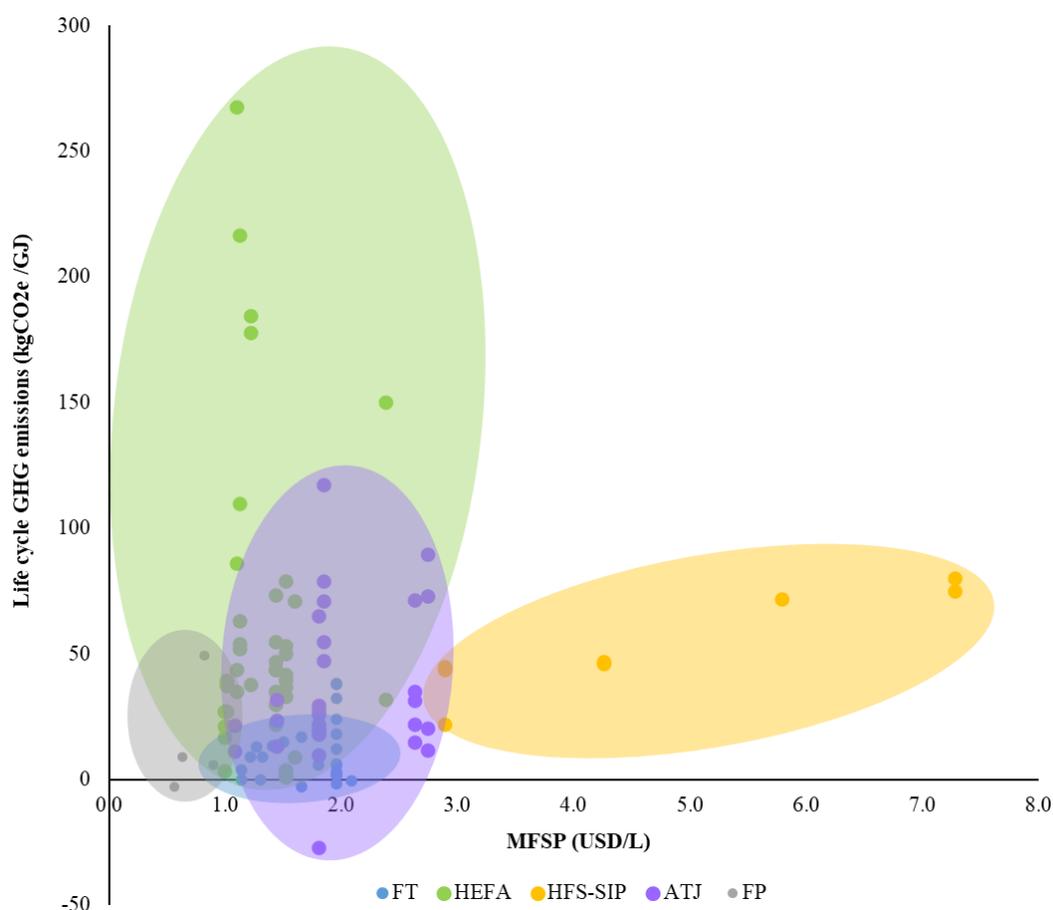


Figure 4.5 Two-dimensional comparison of biobased SAFs production pathways reported in literature in terms of their combined economic performance and life cycle GHG emissions (based on Figure 4.3 in Section 4.3.1.4 and Figure 4.4 in Section 4.3.1.5).

During the experts' workshop (as indicated in Section 4.2.2), additional insights and recommendations were collected. As pointed out by the experts, the ATJ pathway performs relatively well in terms of technological, economic, and environmental aspects. The ATJ pathway with lignocellulosic biomass was added to the shortlist despite higher GHG emissions when using sugar-rich first-generation feedstocks, as this study focuses on second-generation feedstock for a future-proof SAF production,

As a result, HEFA, FT, FP, and ATJ are shortlisted as the most sustainable technologies for biobased SAF production using lignocellulosic and waste biomass. Table 4.3 summarizes the yield factor of each SAF production pathway derived from literature as well as their life cycle GHG emissions and GHG emissions reduction compared to fossil jet fuel.

Table 4.3 Biobased SAF yields, life cycle GHG emissions, and GHG emissions reduction compared to fossil jet fuel. (Source: Capaz et al., 2021 (a); Capaz et al., 2021 (b); Siddiqui and Dincer, 2021; De Jong et al., 2017; De Jong, 2018; Gonzelez-Garay et al., 2022; IATA, 2023; Kossarev et al., 2023; Mussatto et al., 2022; O'Connell et al., 2019; O'malley et al., 2019; Pavlenko et al., 2019; Puschnigg et al., 2023; Rojas-Michaga et al., 2023; Wei et al., 2019; Wang et al., 2023; Zemanek et al., 2020.)

Conversion pathway	Feedstock cultivation (g CO ₂ -eq/MJ SAF)	Pre-processing & upstream transport (g CO ₂ -eq/MJ SAF)	Conversion (g CO ₂ -eq/MJ SAF)	Downstream distribution (g CO ₂ -eq/MJ SAF)	Net WtWa emissions (g CO ₂ -eq/MJ SAF)	Net GHG reduction (% based on 100% SAF blend)	SAF yield factor (tonne/tonne feedstock)
FT-FR (Forest residues)	1	4	0	1	6	93	0.22
FT-AR (Agricultural residues)	4.3	0	0.5	1.2	6	93	0.20
FT-MSW (Municipal and industrial waste)	2	0.8	11	1	14.8	83	0.07
HEFA-UCO (Used cooking oil)	4	5	16	2	27	69	0.75
ATJ-AR (Agricultural residues)	0	0	14.9	0	14.9	83	0.26
FP-FR (Forest residues)	1	4	17	0	22	75	0.27

4.3.3 Biobased SAF supply-demand scenarios towards 2050

4.3.3.1 Biobased SAF demand scenarios towards 2050

As described in Section 4.2.3, the future national demand for aviation fuel is depicted with two diverging possibilities: a “LOW” demand trajectory and a “HIGH” demand trajectory as forecasted by Gelhausen et al. (2022). Building on such national aviation fuel demand trajectories, the present study further incorporates various SAF blending ratios to analyze the specific national demand for biobased SAF: arriving at four demand scenarios for biobased SAF towards 2050, as shown in Table 4.4.

The two Clean Sky scenarios consider two variables, namely total aviation fuel demand (“LOW” or “HIGH”) and theoretical biobased SAF blend based on several published aviation decarbonization roadmaps (van der Sman, et al., 2021; IATA, 2021; ATAG, 2021). Accordingly, the Clean Sky – LOW scenario is featured by the “LOW” demand of total aviation fuel with a lower theoretical biobased SAF blend - from 10% in 2030, to 40% in 2050, with a linear growth rate; whereas Clean Sky – HIGH scenario is featured by the “HIGH” demand of total aviation fuel with a higher theoretical biobased SAF blend - from 10% in 2030 to 80% in 2050 with a linear growth rate.

The two ReFuelEU scenarios consider only one variable, which is the total aviation fuel demand while keeping the biobased SAF blend the same as the ReFuelEU regulation requirements (EC, 2023). Therefore, the ReFuelEU – LOW scenario has the “LOW” demand of total aviation fuel with the annual progression of blend given in the directive (i.e., 6% in 2030, 20% in 2035, 34% in 2040, 42% in 2045, and 70% in 2050 of the “LOW” demand trajectory), while the ReFuelEU – HIGH scenario has the “HIGH” demand of total aviation fuel with the annual progression of blend given in the directive (i.e., 6% in 2030, 20% in 2035, 34% in 2040, 42% in 2045, and 70% in 2050 of the “HIGH” demand trajectory).

Table 4.4 Aviation fuel demand and SAF blending ratio in scenarios.

Scenario name	Total aviation fuel demand	Biobased-SAF blend				
		2030	2035	2040	2045	2050
Clean Sky – LOW	“LOW” national demand	10%	17.5%	25%	32.5%	40%
Clean Sky – HIGH	“HIGH” national demand	10%	27.5%	45%	62.5%	80%
ReFuelEU – LOW	“LOW” national demand	6%	20%	34%	42%	70%
ReFuelEU – HIGH	“HIGH” national demand	6%	20%	34%	42%	70%

As depicted in Figure 4.6, the total aviation fuel demand in Europe (as the sum of all national demands) is expected to grow from 61 million tonnes in 2030 to 70 and 83 million tonnes by 2050 under the LOW demand and HIGH demand scenarios, respectively, as forecasted by Gelhausen et al. (2022). Furthermore, the demand for biobased SAF is projected to increase by tenfold, from 4 – 6 million tonnes

in 2030 to 38 – 67 million tonnes in 2050. More detailed information on biobased SAF demand at the country level is presented in Table A1 in Section Appendix III.

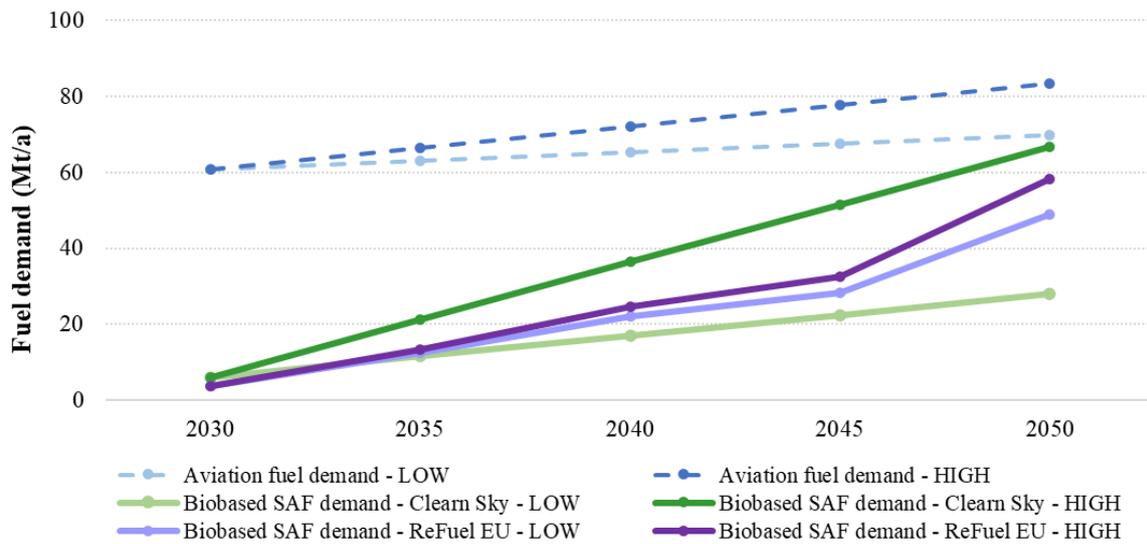


Figure 4.6 (Total) aviation fuel and biobased SAF demand scenarios (based on Gelhausen et al. 2022 and the ReFuelEU Aviation rules (as part of the “Fit for 55” package)).

4.3.3.2 Biomass availability

As shown in Table 4.4, 3 categories and 36 types of feedstocks, namely 18 specific types of forest residues (FR), 15 specific types of agricultural residues (AR), and 3 specific types of municipal solid waste (MSW) were analyzed in this study for 33 European countries.

Table 4.4 List of biomass feedstock types considered in this study (in line with the S2BIOM database).

Forest Residue (FR)	Agricultural Residue (AR)	Municipal Solid Waste (MSW)
Bark	Cereal bran	Biowaste separately collected
Black liquor	Cereals straw	Biowaste integrally collected
Final fellings from conifer trees	Maize stover	Used cooking oil
Final fellings from nonconifer trees	Olive stones	
Hazardous post-consumer wood	Oil seed rape straw	
Logging residues from final fellings from conifer trees	Pressed grapes dregs	
Logging residues from final fellings from nonconifer trees	Residues of citrus tree plantations	
Logging residues from thinnings from conifer trees	Residues of fruit tree plantations	
Logging residues from thinnings from nonconifer trees	Residues of industrial processing	
Non hazardous post-consumer wood	Residues of olives tree plantations	
Other residues (conifers)	Residues of vineyards	
Residues from further woodprocessing	Rice husk	
Sawdust from conifers trees	Rice straw	
Sawdust from non conifers trees	Sugarbeet leaves	
Stumps from final fellings from conifer trees	Sunflower straw	
Stumps from final fellings from non conifer trees		
Thinnings from fellings form conifer trees		
Thinnings from feilings from nonconifer trees		

Table 4.5 shows the total theoretical or technical potential of feedstocks availability, by type and by country, from 2030 to 2050 with 5-year intervals. The total potential of forest residues in Europe ranges from 1.24 to 89.45 million tonnes per country in 2030, and from 1.03 to 91.40 million tonnes in 2050. Sweden, Germany, Finland, France, and Poland are countries with high levels of forest residues availability, resulting from high forest biomass potential per unit area of land (Verkerk et al., 2011, Verkerk et al., 2019). Moreover, the total AR in Europe ranges from 0.03 to 72.80 million tonnes per country in 2030, and from 0.03 to 79.75 million tonnes per country in 2050. High levels of AR availability are observed in countries such as France, Germany, Ukraine, Spain, Poland, the UK, Italy, and Romania. This is because the agricultural sector is relatively well-developed due to large arable land areas and benign climate conditions in most of these countries. France and Germany, for instance, are the primary producers of cereals and oilseeds, therefore are associated with large potential of agricultural wastes (Andrea et al., 2018). In comparison, the UK and Italy show high levels of agricultural residues availability because they are key net importers of agricultural biomass (Andrea et al., 2018). In terms of MSW, its availability in Europe ranges from 0.108 to 183.40 million tonnes per country in 2030, and from 0.092 to 11.79 million tonnes per country in 2050. The UK is associated with the highest levels of MSW availability, followed by Italy, France, Germany, and Spain. MSW potential is strongly correlated with the size of the population or the economy (Rios & Picazo-Tadeo, 2021), explaining why these countries are expected to have high levels of MSW in the next few decades. On the other hand, a few highly developed countries such as The Netherlands, Belgium, and Denmark do not show high potential for biowaste due to high waste recovery rates (Bensten & Felby, 2012).

Considering that other competing uses (CU) of biomass in other biomass-based sectors such as biodiesel, biochemicals, and biomaterials production may limit its actual availability for SAF production, we consider three CU scenarios for feedstocks availability, namely: 30%, 15%, and 6% of the total technical biomass available in Europe is assumed to be allocated for SAF production (as described in Section 4.2.3).

Table 4.5 Europe (EU27 + 6 non-EU countries) biomass potential (in million tonne) per country 2030-2050.

(Austria – AT, Belgium – BE, Bulgaria – BG, Croatia – HR, Czech Republic – CZ, Germany – DE, Denmark – DK, Estonia – EE, Greece – EL, Spain – ES, Finland – FI, France – FR, Croatia – HR, Hungary – HU, Ireland – IE, Italy – IT, Lithuania – LT, Luxembourg – LU, Latvia – LV, The Netherlands – NL, Poland – PL, Portugal – PT, Romania – RO, Serbia – RS, Sweden – SE, Slovenia – SI, Slovakia – SK, and Ukraine – UA; non-EU: Albania – AL, Bosnia – BA, Moldova – MD, Montenegro – ME, Macedonia – MK, and United Kingdom – UK. FR – forest residues, AR – agricultural residues, MSW – municipal solid wastes)

Feedstock potential (million tonne)	2030			2035			2040			2045			2050		
	Country	FR	AR	MSW	FR	AR	MSW	FR	AR	MSW	FR	AR	MSW	FR	AR
AL	1.40	0.67	0.51	1.59	0.69	0.49	1.78	0.72	0.47	1.97	0.74	0.45	2.16	0.76	0.43
AT	25.17	4.06	2.16	25.69	4.16	2.07	26.21	4.26	1.98	26.73	4.37	1.89	27.25	4.47	1.80
BA	4.04	1.00	0.42	4.12	1.03	0.40	4.20	1.06	0.38	4.28	1.10	0.37	4.36	1.13	0.35
BE	5.07	2.92	2.18	5.18	2.99	2.08	5.28	3.06	1.99	5.38	3.14	1.89	5.48	3.21	1.79
BG	6.48	8.57	0.58	6.62	8.79	0.55	6.76	9.02	0.51	6.89	9.25	0.48	7.03	9.48	0.45
CZ	17.96	8.53	0.94	18.33	8.74	0.89	18.70	8.95	0.84	19.07	9.16	0.79	19.44	9.37	0.73
DE	81.39	49.44	10.25	83.07	50.66	9.74	84.74	51.88	9.23	86.41	53.09	8.73	88.08	54.31	8.22
DK	14.51	7.70	1.40	14.73	7.89	1.34	14.95	8.08	1.28	15.17	8.27	1.23	15.39	8.46	1.17
EE	8.42	1.11	0.19	8.59	1.13	0.18	8.77	1.16	0.17	8.94	1.19	0.16	9.11	1.22	0.16
EL	5.33	6.54	2.01	5.44	6.75	1.90	5.54	6.96	1.80	5.65	7.17	1.69	5.76	7.38	1.59
ES	24.90	28.83	9.69	25.41	29.67	9.23	25.93	30.51	8.77	26.44	31.34	8.31	26.95	32.18	7.85
FI	64.62	4.10	1.11	65.96	4.20	1.06	67.29	4.30	1.01	68.63	4.40	0.96	69.96	4.51	0.91
FR	67.98	57.99	14.31	69.38	59.45	13.68	70.78	60.92	13.05	72.17	62.38	12.42	73.57	63.84	11.79
HR	20.98	2.74	0.51	20.86	2.81	0.48	20.75	2.89	0.46	20.63	2.96	0.43	20.51	3.03	0.41
HU	10.69	12.45	1.12	10.91	12.77	1.07	11.13	13.09	1.02	11.35	13.42	0.97	11.57	13.74	0.91
IE	6.20	2.00	0.68	7.08	2.05	0.65	7.96	2.10	0.62	8.84	2.15	0.59	9.71	2.19	0.56
IT	24.48	20.19	12.77	22.80	20.77	12.20	21.12	21.36	11.63	19.44	21.94	11.06	17.76	22.52	10.49
LT	16.10	3.31	0.25	16.04	3.39	0.24	15.98	3.47	0.23	15.93	3.55	0.22	15.87	3.63	0.21
LU	1.90	0.13	0.20	1.94	0.13	0.19	1.98	0.13	0.18	2.02	0.14	0.17	2.06	0.14	0.16
LV	11.14	1.99	0.16	11.37	2.03	0.15	11.61	2.08	0.15	11.84	2.13	0.14	12.07	2.18	0.13
MD	4.79	0.36	0.37	4.85	0.38	0.36	4.91	0.40	0.35	4.97	0.42	0.33	5.04	0.44	0.32
ME	1.24	0.03	0.11	1.19	0.03	0.10	1.14	0.03	0.10	1.08	0.03	0.10	1.03	0.03	0.09
MK	1.38	0.56	0.27	1.31	0.58	0.26	1.24	0.60	0.25	1.17	0.61	0.24	1.10	0.63	0.23
NL	2.96	2.80	2.89	3.02	2.87	2.77	3.08	2.93	2.65	3.14	3.00	2.53	3.19	3.07	2.41
PL	38.80	24.69	3.14	39.59	25.31	3.01	40.39	25.94	2.88	41.18	26.56	2.75	41.97	27.19	2.62
PT	17.92	2.16	1.80	18.29	2.23	1.71	18.67	2.31	1.61	19.04	2.38	1.51	19.41	2.46	1.41
RO	29.25	17.01	2.27	28.53	17.45	2.18	27.80	17.89	2.09	27.08	18.32	2.00	26.35	18.76	1.91
RS	8.02	7.70	1.03	8.18	7.91	0.99	8.34	8.12	0.95	8.51	8.33	0.91	8.67	8.54	0.87
SE	89.45	4.02	2.18	89.94	4.12	2.09	90.43	4.21	1.99	90.92	4.31	1.90	91.40	4.41	1.81
SI	7.01	0.53	0.27	7.15	0.55	0.26	7.30	0.56	0.24	7.44	0.57	0.22	7.59	0.59	0.21
SK	12.53	3.15	0.54	14.14	3.23	0.51	15.75	3.31	0.49	17.36	3.39	0.46	18.96	3.46	0.43
UA	23.97	72.80	4.65	23.77	74.54	4.42	23.58	76.27	4.20	23.38	78.01	3.97	23.19	79.75	3.74
UK	25.00	21.38	183.40	25.03	21.90	140.05	25.07	22.41	96.70	25.10	22.93	53.36	25.14	23.45	10.01
Total	681	381	264	690	391	217	699	401	170	708	411	123	717	421	76

Figure 4.7 provides an overview of the total feedstock availability from 2030 to 2050 when considering different levels of feedstocks availability for SAF production. The total potential of forestry residues and agricultural residue grow slightly by 5% and 10% respectively towards 2050, due to sustainability constraints such as limiting land use change despite technological advancement in the agroforestry sector (Panoutsou & Maniatis, 2021). In contrast, the availability of MSW drops significantly by 71% in 2050, this is mainly explained by the improvement in waste management and recovery overtime, resulting in less municipal wastes (Doliente et al., 2020). In case of no competing uses (i.e., 60% of total technical feedstocks availability can be allocated to SAF production), the feedstocks potential decreases from 796 million tonnes in 2030 to 728 million tonnes in 2050. The total feedstocks availability is expected to decrease from 80 million tonnes to 73 million tonnes between 2030 and 2050 considering 6% feedstocks availability.

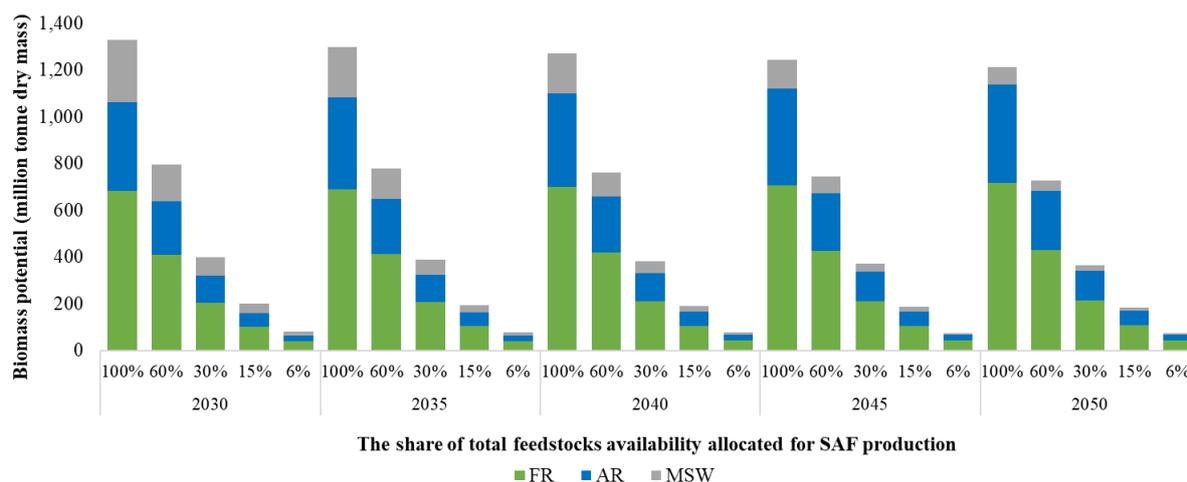


Figure 4.7 Europe's (EU27 + 6 non-EU countries) biomass potential from 2030 to 2050 for different levels of competing uses (CU). Percentages (100%, 60%, 30%, 15%, and 6%) represent the share of the total technical biomass availability allocated for SAF production.

4.3.3.3 SAF supply in different scenarios

As described in Section 4.3.2, FP-based conversion pathways lead to the highest SAF yield for forest residues (0.27 tonne SAF/tonne feedstock) while ATJ-based conversion pathways result in the highest SAF yield for agricultural residues (0.26 tonne SAF/tonne feedstock). HEFA-based pathways turn out to be the most efficient for MSW with a yield of 0.75 tonne SAF /tonne feedstock. However, given the low level of feedstock availability in the long term, HEFA-based pathways are less likely to meet future SAF demand. In terms of GHG emissions reduction, the FT-based pathways stand out with forest residues and agricultural residues, showing 83-93% life cycle GHG emissions reduction compared to fossil jet fuel, and followed by the ATJ pathways (83% reduction) and the FP pathways (75% reduction).

Given that the predominant driver for developing SAF has been to decarbonize the aviation sector, this study considers FT-FR conversion pathways as the most preferred choices for biobased SAF production due to their highest emissions reduction potential and relatively high yield, ATJ-AR (high emissions reduction potential and high yield), FT-MSW (relatively high emission reduction potential), and FP-FR (highest yield) pathways, in a decreasing order of preference when feedstocks availability is not a limiting factor. That is, in this study, we consider that the biobased SAF demand for each European country will first be covered by the FT-FR pathway, sequentially followed by the ATJ-AR pathway, the FT-MSW pathway and then the FP-FR pathway. In the case that no combination of biomass supply and conversion technology can meet the national SAF demand, the technology associated with the highest GHG emissions reduction (FT) is analyzed with the total supply of all three types of biomass feedstocks (FR+AR+MSW) to determine the maximum emissions reduction potential and the corresponding SAF supply. Therefore, the combination of conversion technology and feedstock type (i.e., SAF conversion pathway) is considered following this order: (1) FT_FR, (2) FT_FR+ATJ_AR, (3) FT_FR+ATJ_AR+FT_MS, (4) FP_FR+ATJ_AR+FT_MS, and (5) FT_FR+AR+MSW.

As shown in Figure 4.8, on the European level, SAF supply from 2030 to 2050 is expected to be higher than demand in both LOW and HIGH demand scenarios when the feedstocks availability level is no less than 30% (50% CU of usable biomass), except for 2050 in the Clean Sky – HIGH scenario where SAF supply turns out to be slightly lower than demand. In the case of 15% of the total technical feedstock availability (75% CU of usable biomass), SAF supply can meet demand in the Clean Sky – LOW scenario only, while demand surpasses supply after 2040 in the Clean Sky – HIGH scenario, and after 2045 in both ReFuelEU – LOW and ReFuelEU – HIGH scenarios. When only 6% of the total technical feedstock availability (90% CU of usable biomass) is considered for SAF production, SAF supply cannot meet demand after 2030 in the CleanSky – HIGH scenario and after 2035 in the remaining three scenarios.

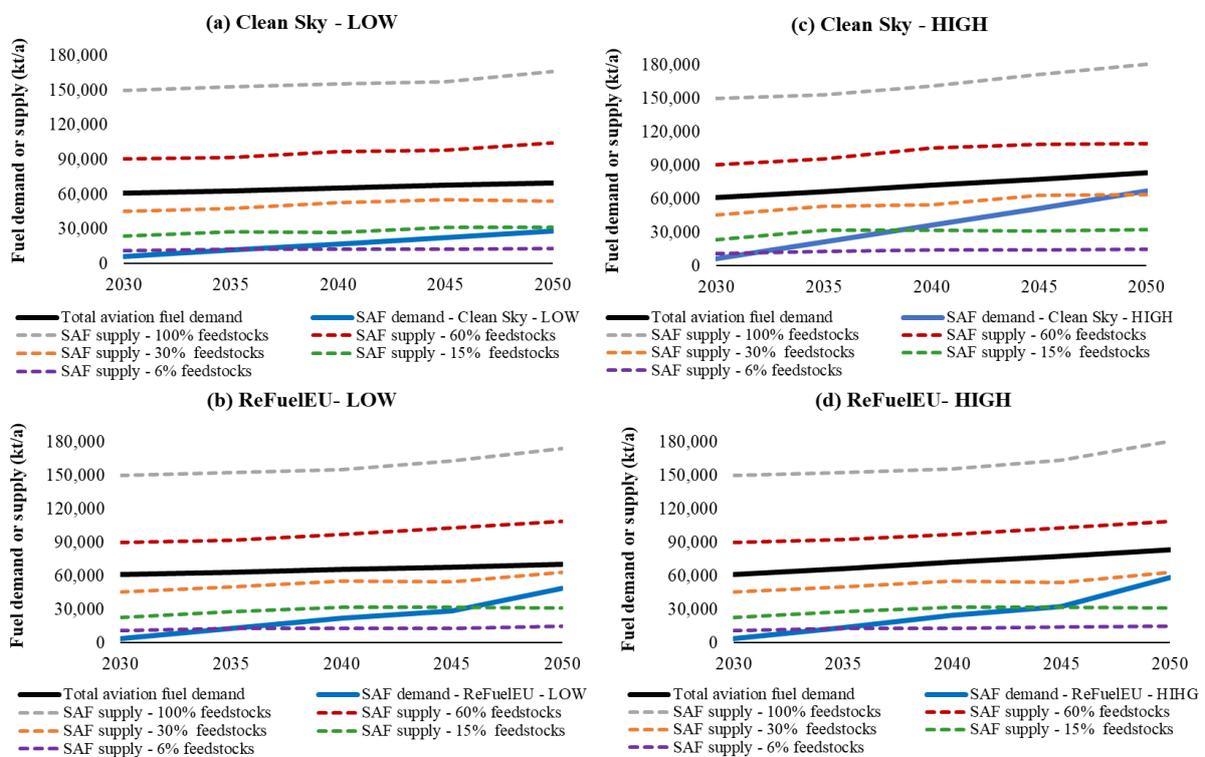


Figure 4.8 SAF supply-demand balance at the Europe level under different demand and CU scenarios. (a) Clean Sky – LOW scenario; (b) ReFuelEU – LOW scenario; (c) Clean Sky – HIGH scenario; (d) ReFuelEU – HIGH scenario^{7,8}.

It is clear that the level of CU significantly affects the projected SAF supply in all scenarios. The competing uses of biomass are driven by, for example, the current uses of biomass residues such as feed for livestock and the biochemical sector to produce higher value-added products (Davis et al., 2024;

⁷ Note that the SAF supply in percentages of feedstocks refers to the percentage of the total technical availability, as described in Section 4.2.3.

⁸ The supply curves could differ among the four scenarios for the same levels of CU because the supply reflects the sum of projected national SAF production taking into account the most suitable SAF conversion pathway (as described in Section 4.3.3.3, Paragraph 2) for each country, as shown in the Table 4.6 below.

Almena et al., 2024). It is also important to recognize the necessity of sustainable biomass harvesting and management as there is a potential risk of over-depletion of biomass residues, resulting in biodiversity losses even if 40% of biomass residues are left unutilized in the field (Davis et al., 2024; Almena et al., 2024). However, quantifying the actual impact of biomass competing uses is challenging and with uncertainties due to limitation of data availability.

Table 4.6 presents the SAF supply-demand balance at the country level from 2030 to 2050 with 5-year intervals under different SAF demand scenarios with different levels of biomass competing uses, based on the national availability of feedstocks and that no trading (imports or exports) is assumed. SAF demand varies drastically among European countries whereas the increasing trend of SAF demand is consistently observed for all countries from 2030 to 2050. To fulfill the gradually increasing demand over time, each European country will produce SAF firstly via the FT-FR pathway, subsequently supplemented by the ATJ-AR pathway and then the FT-MSW pathway; however, when these three pathways combined fail to satisfy SAF demand, the countries will utilize all types of feedstocks to produce SAF with the FT technology to maximize GHG emissions reduction. Specifically, in the ReFuelEU-LOW scenario, with 30% feedstocks availability, 32 out of 33 countries will be able to meet their national SAF demand with the FT-FR pathway (i.e., Fischer-Tropsch technology with forest residues) in 2030 (except for The Netherlands will produce SAF via the FT-FR + ATJ-AR pathways), amounting to a total 44758 kt/year production in Europe. In 2035 and 2040, the FT-FR pathway will produce SAF for 29 countries (excluding Belgium, Spain, The Netherlands and the UK) and 27 countries (excluding Belgium, Greece, Spain, The Netherlands, Italy, and the UK), leading to 41678 kt/year and 42878 kt/year SAF supply in total, respectively. By 2050, FT-FR is expected to satisfy the SAF demand for 24 countries with an annual production of 30458 kt/year while the combination of FT-FR and ATJ-AR (i.e., Alcohol-to-Jet with agricultural residues) pathways is projected to produce 20697 kt/year SAF for Germany, France and Ireland combined. Additionally, no combination of SAF production pathways could fulfill the 2050 national demand of Belgium, Greece, Spain, The Netherlands, Italy, and the UK, therefore the FT-FR+AR+MSW pathway (i.e., Fischer-Tropsch technology with forest residues, agricultural residues and municipal solid wastes) is chosen to maximize GHG emissions reduction for these countries with a combined 11889 kt/year SAF supply. In comparison, in the ReFuelEU-HIGH scenario, with 15% biomass feedstocks availability, the FT-FR pathway is expected to supply 22211, 19907, 14222, 13905, and 14380 kt/year SAF for 31, 27, 23, 22, and 20 countries, accounting for 98%, 72%, 45%, 44%, and 46% total European SAF supply in 2030, 2035, 2040, 2045, and 2050. The FT-FR and ATJ-AR pathways combined are projected to produce 281, 4001, 5417, 5637 and 61 kt/year SAF for 1, 3, 2, 2, and 1 countries, adding up to 1%, 15%, 17%, 18%, and 0.2% total European SAF supply in 2030, 2035, 2040, 2045, and 2050. The FT-FR+AR+MSW pathway is expected to produce 259, 497, 7359, 7401, and 16915 kt/year SAF for 1, 2, 7, 8, and 12 countries, amounting to 1%, 2%, 23%, 23%, and 54% total European SAF supply in 2030,

2035, 2040, 2045, and 2050. The combination of FP-FR (i.e., Fast Pyrolysis technology with forest residues), ATJ-AR, and FT-MSW is only utilized to supply 3151 kt/year SAF for The UK in 2035, 4917 kt/year SAF for Germany in 2040, and 5014 kt/year SAF for Germany in 2045, respectively.

As shown in table 4.6, at the national level, the lowest SAF demand is seen for Montenegro (ME), ranging from 2.0 – 3.3 kt in 2030 to 17 – 42 kt in 2050 where the UK has the highest SAF demand, ranging from 770 – 1284 kt in 2030 to 5928 – 13780 kt in 2050, followed by Germany (DE) (from 576 – 961 kt in 2030 to 4219 – 10081 kt in 2050), Spain (ES) (from 489 – 816 kt in 2030 to 3751 – 9041 kt in 2050), and France (FR) (from 449 – 748 kt in 2030 to 3239 – 7753 kt in 2050) across different scenarios (details see Table A1 in Section Appendix III). On the supply side, Sweden (SE) shows the highest potential of SAF production (19679 – 20109 kt across all scenarios) when feedstocks availability is at 100%; this is followed by Germany (DE), France (FR), and Finland (FI), whose SAF production potentials are 17907 – 19377 kt, 14956 – 16186 kt, and 14217 – 15392 kt, respectively for the same 100% feedstock availability. For countries with relatively low SAF demand, namely Bosnia (BA), Estonia (EE), Finland (FI), Croatia (HR), Hungary (HU), Lithuania (LT), Latvia (LV), Moldova (MD), Poland (PL), Romania (RO), Serbia (RS), Sweden (SE), Slovenia (SI), Slovakia (SK), and Ukraine (UA), SAF supply will always be sufficient from 2030 to 2050 regardless of the blending ratio nor the level of feedstock availability. In 2030, SAF supply can meet SAF demand for all countries except for Belgium (BE) and The Netherlands (NL) in the CleanSky scenarios when the level of feedstocks availability, limited by competing uses, is at 15% and 6%, and in the ReFuelEU scenarios when the degree of feedstocks availability is 6%.

Combining multiple conversion pathways can increase the total SAF supply in order to meet the national demand at a given time. For example, in the 2030 CleanSky scenarios, the SAF demand of the UK is fulfilled with FT_FR+ATJ_AR at 15% feedstocks availability and with FT-FR+ATJ_AR+FT_MS_W at 6% biomass availability. With the highest national SAF demand, it is a challenge for the UK to produce sufficient SAF locally as long as there are feedstock competing uses, especially in the CleanSky-HIGH scenario in 2050, SAF supply is insufficient even if all the theoretical feedstocks availability is mobilized regardless of the conversion pathway. For Germany (DE), SAF supply can meet demand in most cases except for the CleanSky-LOW scenario from 2040 to 2050 at 6% biomass availability and the CleanSky-HIGH scenario from 2040 to 2050 at 15% biomass availability and from 2035 to 2050 at 6% biomass availability. By leveraging multiple SAF conversion technologies (FT, ATJ, and FP) and types of feedstocks (FR, AR, and MSW), sufficient SAF can be produced for Spain (ES) and France (FR) in all scenarios throughout 2030-2050 when the degree of feedstocks availability is no less than 60% and 30%, respectively. When it comes to The Netherlands (NL), biomass availability is an apparent limiting factor for its domestic SAF supply from 2035 onwards in all scenarios and with all levels of feedstocks availability when considering biomass competing uses.

Based on the supply-demand analysis, Sweden appears to be the predominant country that produced the largest amount of SAF in Europe, leading to, for example, 1181 – 19679 kt/year in 2030 (11-13% of the total European SAF production), 1187 – 19787 kt/year in 2035 (9-13% of the total European SAF production), 1194 – 11894 kt/year in 2040 (9-13% of the total European SAF production), 1200 – 20001 kt/year in 2045 (8-12% of the total European SAF production), and 1207 – 20109 kt/year in 2050 (8-12% of the total European SAF production), when 60% of total biomass is used for SAF production. Note that SAF production in the UK declined in 2050 compared to 2045. This is because in all scenarios except for the CleanSky-LOW scenario, no combination of SAF production pathways are able to fulfill SAF demand, therefore all usable biomass is converted to SAF with the FT technology to maximize emissions reduction while resulting in a relatively lower SAF supply. Furthermore, Germany, France, and Finland are the second, third and fourth largest SAF producing countries. These three countries combined are expected to produce, for example, 2825 – 48049 kt/year in 2030 (26-36% of the total European SAF production) and 4559 – 50954 kt/year in 2050 (29-39% of the total European SAF production), when 30% of total biomass is used for SAF production. More detailed information on SAF supply and demand at the country level is presented in Tables A2-A19 in Section Appendix III.

Table 4.6 SAF supply-demand balance at the country level under different demand scenarios and with different levels of feedstocks availability. Note: all SAF supply is considered to be provided using only the feedstocks available in each country (i.e., no trading (neither imports nor exports) among countries is assumed).

CleanSky - LOW	2030						2035						2040						2045						2050							
	Demand (kt)	Supply based on feedstock availability (kt)					Demand (kt)	Supply based on feedstock availability (kt)					Demand (kt)	Supply based on feedstock availability (kt)					Demand (kt)	Supply based on feedstock availability (kt)					Demand (kt)	Supply based on feedstock availability (kt)						
		100%	60%	30%	15%	6%		100%	60%	30%	15%	6%		100%	60%	30%	15%	6%		100%	60%	30%	15%	6%		100%	60%	30%	15%	6%		
AL	3.5						7.4						11.2						15.1						18.9							
AT	80.5						153.1						225.8						298.5						371.1							
BA	3.0						6.1						9.2						12.4						15.5							
BE	346.5				277.9	111.2	770.9			564.9	282.4	113.0	1195.3			574.0	287.0	114.8	1619.7			1166.1	583.0	291.5	116.6	2044.1		1184.3	592.1	296.1	118.4	
BG	22.7						46.2						69.6						93.1						116.5							
CZ	38.2						74.9						111.6						148.4						185.1							
DE	960.7						1775.3						2589.9				1779.8		3404.5					1814.3	4219.1					1848.9		
DK	94.6						179.9						265.1						350.4					304.6	435.7					309.5		
EE	4.6						9.0						13.4						17.9						22.3							
EL	120.1						228.4					160.7	336.7				164.2	445.0					167.8	553.3				428.1	171.3			
ES	815.7						1549.5					730.2	2283.3				1862.8	745.1	3017.2				1900.1	760.0	3751.0				1937.4	774.9		
FI	82.4						155.5						228.7						301.8						375.0							
FR	748.1						1370.7						1993.4				1720.0		2616.0					1753.4	3238.6					1786.8		
HR	16.7						34.5						52.2						70.0						87.7							
HU	32.8						66.4						100.0						133.7						167.3							
IE	106.4						194.8					120.8	283.2				132.8	371.6					362.1	144.9	460.0				392.3	156.9		
IT	425.0						786.5					601.5	1147.9				583.9	1509.4					1416.0	566.4	1870.8				1372.2	548.9		
LT	11.5						22.5						33.6						44.6						55.6							
LU	6.1						11.3						16.5						21.8						27.0							
LV	12.3						23.7						35.1						46.5						57.9							
MD	6.0						12.3						18.7						25.0						31.4							
ME	3.3						6.6						9.9						13.2						16.5					14.4		
MK	4.1						8.4						12.6						16.9						21.2							
NL	396.9				212.0	84.8	733.7			429.5	214.7	85.9	1070.5			952.5	434.9	217.4	87.0	1407.2			880.6	440.3	220.1	88.1	1744.0		891.4	445.7	222.8	89.1
PL	71.9						138.4						204.9						271.4						338.0							
PT	160.1						302.0					275.4	443.9				289.2	585.8					286.3	727.7						291.7		
RO	47.5						99.1						150.7						202.4						254.0							
RS	15.3						31.3						47.3						63.3						79.3							
SE	101.0						191.1						281.2						371.2						461.3							
SI	2.5						4.9						7.4						9.9						12.3							
SK	5.1						10.1						15.2						20.2						25.2							
UA	50.6						105.7						160.8						215.9						271.1							
UK	1283.7						2444.8					1181.4	3605.8				2514.9	1006.0	4766.8					2076.5	830.6	5927.9			3276.0	1638.0	655.2	

Chapter 4

CleanSky - HIGH	2030						2035						2040						2045						2050											
	Demand	Supply based on feedstock availability (kt)					Demand	Supply based on feedstock availability (kt)					Demand	Supply based on feedstock availability (kt)					Demand	Supply based on feedstock availability (kt)					Demand	Supply based on feedstock availability (kt)										
Country	(kt)	100%	60%	30%	15%	6%	(kt)	100%	60%	30%	15%	6%	(kt)	100%	60%	30%	15%	6%	(kt)	100%	60%	30%	15%	6%	(kt)	100%	60%	30%	15%	6%	(kt)	100%	60%	30%	15%	6%
AL	3.5						14.2						24.8						35.5						46.1											39.5
AT	80.5						286.8						493.2					405.5	699.5						413.2	905.8									420.9	
BA	3.0						11.5						20.0						28.5						37.0											
BE	346.5				277.9	111.2	1463.2		1129.7	564.9	282.4	113.0	2579.9	1913.2	1147.9	574.0	287.0	114.8	3696.6	1943.5	1166.1	583.05	291.5	116.6	4813.3	1973.8	1184.3	592.1	296.1					118.4		
BG	22.7						87.5						152.2						217.0						281.7										208.4	
CZ	38.2						139.9						241.7						343.5						445.3										372.1	
DE	960.7						3240.7					1745.3	5520.7				4449.6	1779.8	7800.7					4535.8	1814.3	10080.6						4622.1			1848.9	
DK	94.6						335.2					294.74	575.9					299.6	816.6					304.6	1057.2									773.6	309.5	
EE	4.6						16.6						28.7						40.7						52.8											
EL	120.1						422.2					160.7	724.3				473.2	164.2	1026.4				838.8	419.4	167.8	1328.5					856.3	428.1			171.3	
ES	815.7						2872.1				1825.5	730.2	4928.5			3725.6	2137.4	745.1	6984.9				3800.2	1900.1	760.0	9041.3					3874.7	1937.4			774.9	
FI	82.4						290.4						498.4						706.5						914.5											
FR	748.1						2499.2					1686.7	4250.3					1720.0	6001.4					4383.5	1753.4	7752.5						4466.9			1786.8	
HR	16.7						65.5						114.2						163.0						211.7											
HU	32.8						123.9						214.9						306.0						397.1										321.4	
IE	106.4						339.0				313.5	120.8	571.5				332.0	132.8	804.1				724.3	362.1	144.9	1036.7					784.5	392.3			156.9	
IT	425.0						1449.0					601.5	2473.0				1459.9	583.9	3497.0				2832.0	1416.0	566.4	4520.9					2744.3	1372.2			548.9	
LT	11.5						41.8						72.1						102.5						132.8											
LU	6.1						21.0						35.9					28.5	50.8						65.7										29.5	
LV	12.3						44.8						77.3						109.9						142.4											
MD	6.0						23.4						40.7						58.1						75.5										73.0	
ME	3.3						12.9						22.6					15.8	32.2						41.8								36.1		14.4	
MK	4.1						16.0						27.8					24.6	39.7						51.6										23.1	
NL	396.9				212.0	84.8	1358.8		859.0	429.5	214.7	85.9	2320.7	1449.6	869.8	434.9	217.4	87.0	3282.6	1467.6	880.6	440.3	220.1	88.1	4244.4	1485.6	891.4	445.7	222.8					89.1		
PL	71.9						254.6						437.3						619.9						802.6											
PT	160.1						563.4					275.4	966.8				702.2	280.9	1370.1					715.7	286.3	1773.5					1458.6	729.3			291.7	
RO	47.5						188.7						329.9						471.1						612.3											
RS	15.3						60.7						106.2						151.7						197.1											
SE	101.0						354.1						607.1						860.1						1113.2											
SI	2.5						9.4						16.3						23.2						30.0											
SK	5.1						18.7						32.3						45.9						59.4											
UA	50.6						200.7						350.7						500.8						650.9											
UK	1283.7						4407.9					2953.4	1181.4	7532.0				5029.9	2514.9	1006.0	10656.2			8305.9	4153.0	2076.5	830.6	13780.4	10920.1	6552.1	3276.0	1638.0			655.2	

ReFuelEU - LOW	2030						2035						2040						2045						2050						
	Country	(kt)	Supply based on feedstock availability (kt)					(kt)	Supply based on feedstock availability (kt)					(kt)	Supply based on feedstock availability (kt)					(kt)	Supply based on feedstock availability (kt)										
			100%	60%	30%	15%	6%		100%	60%	30%	15%	6%		100%	60%	30%	15%	6%		100%	60%	30%	15%	6%						
AL	2.1						7.6						14.0						18.6						33.1						
AT	48.3						167.1						294.5						376.8						649.5					437.0	
BA	1.8						6.4						11.6						15.3						27.1						
BE	207.9					111.2	775.3			564.9	282.4	113.0	1457.8			574.0	287.0	114.8	1973.6			1166.1	583.0	291.5	116.6	3577.1	1973.8	1184.3	592.1	296.1	118.4
BG	13.6						48.7						88.2						115.7						204.0						
CZ	22.9						80.4						143.5						185.8						324.0					256.6	
DE	576.4						1968.5					1745.3	3426.4				1779.8	4331.3					1814.3	7383.4				4622.1	1848.9		
DK	56.7						196.3						345.9				299.64	442.4					304.6	762.5					309.5		
EE	2.7						9.6						17.2					22.3						39.0							
EL	72.0						249.3					160.7	439.3				164.2	561.8				419.4	167.8	968.3			955.9	428.1	171.3		
ES	489.4						1692.4					730.2	2980.8			1862.8	854.9	3810.4				1900.1	760.0	6564.2			3874.7	1937.4	774.9		
FI	49.4						170.5						299.4					381.8						656.2							
FR	448.9						1527.0						2648.2				1720.0	3335.9					1753.4	5667.6				4466.9	1786.8		
HR	10.0						36.0						65.7					86.6						153.5							
HU	19.7						70.1						126.8					166.2						292.7							
IE	63.8						217.0					120.8	376.3			344.35	132.8	474.0				362.1	144.9	805.1				392.3	156.9		
IT	255.0						871.4					601.5	1517.6				583.9	1919.5				1416.0	566.4	3274.0			2744.3	1372.2	548.9		
LT	6.9						24.2						43.2					55.9						97.3							
LU	3.7						12.5						21.8					27.6						47.2							
LV	7.4						25.7						45.5					58.5						101.3							
MD	3.6						12.9						23.5					31.0						54.9							
ME	2.0						7.0						12.6					16.5					15.1	28.9					14.4		
MK	2.4						8.8						15.9					21.0						37.1					23.1		
NL	238.2					84.8	813.4			429.5	214.7	85.9	1416.0		952.5	434.9	217.4	87.0	1790.2	1337.4	880.6	440.3	220.1	88.1	3052.0	1485.6	891.4	445.7	222.8	89.1	
PL	43.1						150.1						265.9					341.6						591.4					554.0		
PT	96.1						331.1					275.4	581.4				280.9	741.2				721.3	286.3	1273.5				729.3	291.7		
RO	28.5						103.0						188.6					249.9						444.5							
RS	9.2						32.8						59.7					78.5						138.7							
SE	60.6						209.2						367.8					469.4						807.3							
SI	1.5						5.3						9.5					12.3						21.6							
SK	3.1						10.8						19.4					25.2						44.1							
UA	30.3						109.7						201.2					266.6						474.4							
UK	770.2						2666.6					1181.4	4701.7			2514.9	1006.0	6016.1				4153.0	2076.5	830.6	10373.8		6552.1	3276.0	1638.0	655.2	

Chapter 4

ReFuelEU -HIGH	2030						2035						2040						2045						2050							
	Demand	Supply based on feedstock availability (kt)					Demand	Supply based on feedstock availability (kt)					Demand	Supply based on feedstock availability (kt)					Demand	Supply based on feedstock availability (kt)					Demand	Supply based on feedstock availability (kt)						
		(kt)	100%	60%	30%	15%		6%	(kt)	100%	60%	30%		15%	6%	(kt)	100%	60%		30%	15%	6%	(kt)	100%		60%	30%	15%	6%	(kt)	100%	60%
AL	2.1						8.2						15.8						21.9						40.4							
AT	48.3						177.3						329.3						441.2					421.0	792.6					420.9		
BA	1.8						6.8						12.9						17.7						32.4							
BE	207.9					111.2	820.6			564.9	282.4	113.0	1611.9			1147.9	574.0	287.0	114.8	2259.1			1166.1	583.0	291.5	116.6	4211.6	1973.8	1184.3	592.1	296.1	118.4
BG	13.6						51.7						98.5						134.8						246.5					208.4		
CZ	22.9						85.1						159.5						215.4						389.7							
DE	576.4						2071.2					1745.3	3775.4				1779.8	4978.0					1814.3	8820.6			4622.1	1848.9				
DK	56.7						207.9						385.4				299.6	515.6					304.6	925.1			773.6	309.5				
EE	2.7						10.1						19.0					25.6						46.2								
EL	72.0						263.2					160.7	486.4			410.6	164.2	649.2				419.4	167.8	1162.5			856.3	428.1	171.3			
ES	489.4						1788.6					730.2	3307.9			2137.4	745.1	4416.5				3800.2	1900.1	760.0	7911.1			3874.7	1937.4	774.9		
FI	49.4						180.7						334.4					446.6						800.2								
FR	448.9						1606.7						2919.2				1720.0	3838.1					1753.4	6783.5			4466.9	1786.8				
HR	10.0						38.3						73.4					100.9						185.3								
HU	19.7						74.0						140.1					190.8						347.4								
IE	63.8						224.3					120.8	401.1			332.01	132.8	519.9					362.1	144.9	907.1			784.5	392.3	156.9		
IT	255.0						920.1					601.5	1683.2			1459.9	583.9	2226.4					1416.0	566.4	3955.8			2744.3	1372.2	548.9		
LT	6.9						25.5						47.8					64.4						116.2								
LU	3.7						13.2						24.3					32.3					29.0	57.5					29.5			
LV	7.4						27.3						51.2					69.0						124.6								
MD	3.6						13.7						26.2					36.0						66.1								
ME	2.0						7.6						14.5					19.9					15.1	36.6			36.1	14.4				
MK	2.4						9.3						17.9					24.6						45.2					23.1			
NL	238.2					84.8	860.7			429.5	214.7	85.9	1576.7			869.8	434.9	217.4	87.0	2088.0	1467.6	880.6	440.3	220.1	88.1	3713.9	1485.6	891.4	445.7	222.8	89.1	
PL	43.1						158.0						292.8					391.5						702.3								
PT	96.1						351.0					275.4	649.0				280.9	866.4				715.7	286.3	1551.8			1473.2	729.3	291.7			
RO	28.5						109.5						210.8					290.9						535.7								
RS	9.2						35.2						67.9					93.7						172.5								
SE	60.6						221.1						408.3					544.4						974.0								
SI	1.5						5.6						10.6					14.4						26.3								
SK	3.1						11.4						21.3					28.8						52.0								
UA	30.3						116.5						224.3					309.4						569.5								
UK	770.2						2786.9					1181.4	5110.6				2514.9	1006.0	6773.9				4153.0	2076.5	830.6	12057.8		6552.1	3276.0	1638.0	655.2	

SAF supply meets demand (FT-FR)	SAF supply meets demand (FT-FR + ATJ-AR)	SAF supply meets demand (FT-FR + ATJ-AR + FT-MSW)	SAF supply meets demand (FT-FR + ATJ-AR + FT-MSW)	SAF supply cannot meet demand (FT-FR+AR+MSW)
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4.3.4 GHG emissions reduction in different scenarios

Figure 4.9 depicts the GHG emissions of the European aviation sector in the four demand scenarios with different levels of biomass competing uses. At the European level, the aviation sector will emit, from 2030 to 2050, 228 – 262 Mt CO₂-eq in the two LOW demand scenarios and 228 – 312 Mt CO₂-eq in the two HIGH demand scenarios, if jet fuel is 100% fossil-based. When considering SAF (partially) substituting fossil jet fuel, a general downward trend of total GHG emissions is observed from 2030 to 2050 for all scenarios when the level of feedstocks availability is 30% or higher despite the increase in the total aviation fuel demand. From 2030 to 2050, when feedstocks availability level is at 15%, the GHG emissions decrease from 207 Mt to 201 Mt and from 215 Mt to 185 Mt in the CleanSky-LOW scenario and ReFuelEU-LOW scenario, respectively, while increasing from 207 Mt to 228 Mt and from 215 Mt to 231 Mt in the CleanSky-HIGH scenario and ReFuelEU-HIGH scenario, respectively. In contrast, when only 6% of total biomass is used for producing SAF, the GHG emissions from the European aviation sector go up in all scenarios from 207-215 Mt in 2030 to 221-269 Mt in 2050.

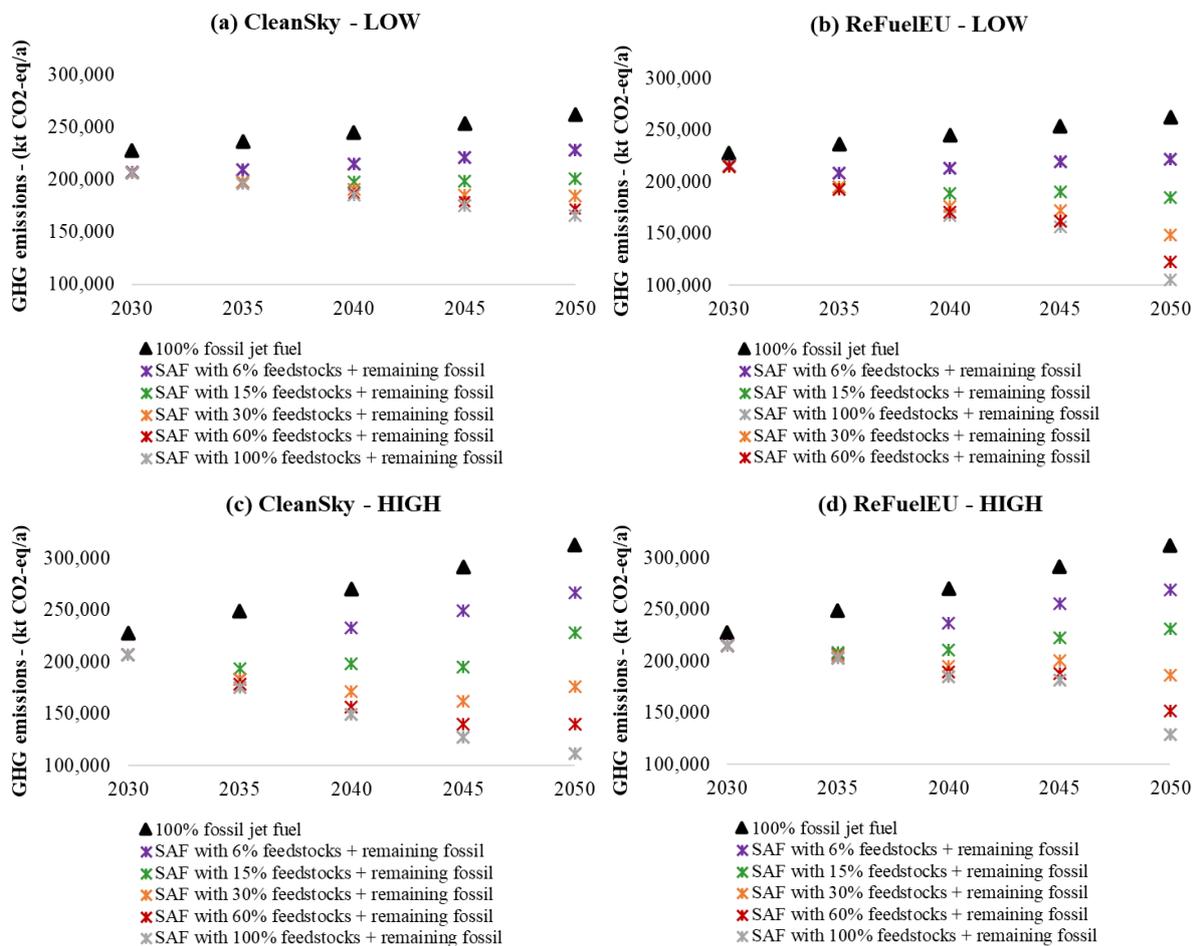


Figure 4.9 Comparison of GHG emissions from fossil jet fuel and SAF in different scenarios. (a) Clean Sky – LOW scenario; (b) ReFuelEU – LOW scenario; (c) Clean Sky – HIGH scenario; (d) ReFuelEU – HIGH scenario.

Figure 4.10 compares the absolute and relative GHG emissions reduction of the European aviation sector when considering SAF substituting fossil jet fuel in the four demand scenarios. It is worth noting that the GHG emissions reduction has an upper limit that is determined by the SAF demand. This means when SAF supply is higher than demand in certain scenarios, the maximum GHG emissions reduction is capped and calculated based on the SAF demand rather than the supply. Secondly, the relative GHG emissions reduction is calculated relative to the worst case assuming 100% of the European jet fuel is fossil-based. Therefore, the relative GHG emissions reduction will always be lower than 93%, which is the maximum theoretical percentage of GHG emissions reduction based on 100% SAF blend (as mentioned in Table 4.3).

In general, the absolute GHG emissions reduction increases as the SAF demand increases from 2030 (12 – 21 Mt) to 2050 (34 – 201 Mt) in all scenarios and at all levels of feedstocks availability with one exception each in the two high demand scenarios: (1) in the case of a 15% feedstocks availability, the emissions reduction will peak in 2045 and go down in 2050 in CleanSky – HIGH scenario; and (2) when considering a 6% feedstocks availability, the emissions reduction will peak in 2035 and become lower in the subsequent years in CleanSky – HIGH and ReFuelEU – HIGH scenarios, marking the inflection points when SAF supply fails to meet demand, meaning no combination of available feedstocks and conversion technologies can produce the required amount of SAF for Europe.

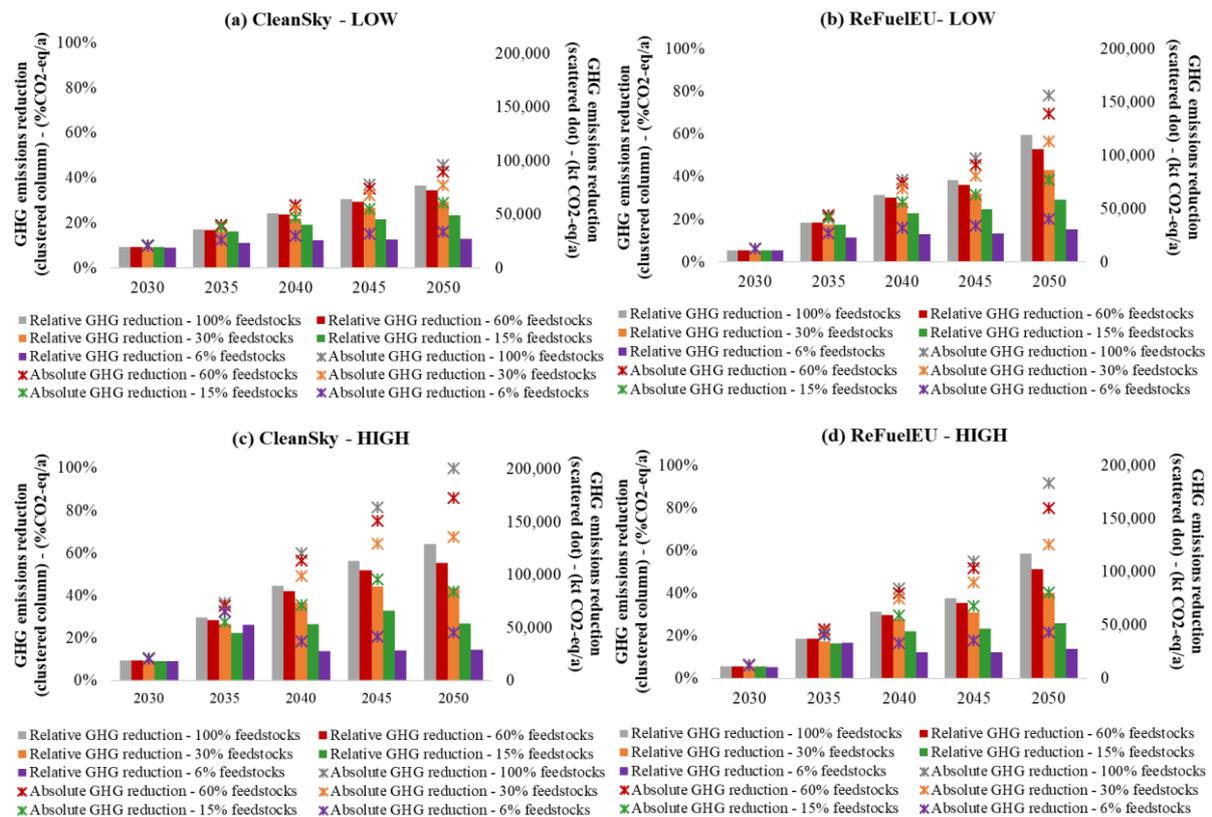


Figure 4.10 Absolute and relative GHG emissions reduction of SAF compared to fossil jet fuel in different scenarios. (a) Clean Sky – LOW scenario; (b) ReFuelEU – LOW scenario; (c) Clean Sky – HIGH scenario; (d) ReFuelEU – HIGH scenario.

CleanSky-HIGH scenario leads to the highest relative GHG emissions reduction overall, rising from 9% in 2030 to 15-64% in 2050 considering different levels of feedstocks availability. When comparing the two ReFuelEU scenarios, the absolute emissions reduction in the HIGH demand scenario is notably higher than the LOW demand scenario while the relative emissions reduction percentage is slightly lower, suggesting that (1) higher SAF demand does not necessarily lead to higher levels of relative GHG emissions, (2) higher emissions reduction percentage does not necessarily mean higher absolute emissions reduction, and (3) GHG emissions reduction is not only determined by SAF demand but also the total aviation fuel demand. In most scenarios, the absolute as well as the relative GHG emissions reduction decrease when the feedstocks availability level is reduced due to competing uses. Therefore, it is worth highlighting that in the CleanSky-HIGH and ReFuelEU – HIGH scenarios, 6% feedstocks availability results in higher absolute and relative emissions reduction than 15% feedstocks availability in 2035. This suggests that with 6% feedstocks availability, no combination of conversion technologies and feedstocks can meet SAF demand, thus all available feedstocks are converted into SAF via the FT technology in order to maximize emissions reduction. Similarly, this explains why in the ReFuelEU-LOW scenario, 15% feedstocks availability leads to slightly higher emissions reduction compared to 30% feedstocks availability in 2035.

Tables A2-A19 in Section Appendix III show the absolute and the relative GHG emissions reduction attributed to SAF for each country. At the country level, the absolute GHG emissions reduction is positively associated with the national SAF demand when feedstocks availability is sufficient. Thus, the highest level of absolute emissions reduction is expected in the UK when 100% feedstocks availability is considered for SAF supply, leading to 4478 kt to 37828 kt CO₂-eq reduction from 2030 to 2050. Furthermore, when considering 15% and 6% feedstocks availability, Germany (DE) results in the most significant GHG emissions reduction from 2040 to 2050 in the two high demand scenarios, leading to 12608 – 16090 kt CO₂-eq (15% feedstocks availability) and 6194 – 3436 kt CO₂-eq (6% feedstocks availability), respectively. This is followed by France (FR), with 9848 – 15535 kt CO₂-eq (15% feedstocks availability) and 5979 – 6214 kt CO₂-eq (6% feedstocks availability) in the high demand scenarios from 2040 – 2050. This is because as the level of feedstocks availability level decreases, less feedstocks are allocated to the SAF sector, making SAF supply the determining factor of absolute emissions reduction. In contrast, the relative GHG emissions reduction is predominantly determined by the level of feedstocks availability. The highest level of relative emissions reduction, 75%, is achieved if the national SAF demand is met by supply in the CleanSky-HIGH scenario for the following countries: Bosnia (BA), Estonia (ES), Finland (FI), Croatia (HR), Hungary (HU), Lithuania (LT), Latvia (LV), Moldova (MD), Poland (PL), Romania (RO), Serbia (RS), Sweden (SE), Slovenia (SK), Slovakia (SI), and Ukraine (UA). Regardless of the highest level of absolute GHG emissions reduction, the relative emissions reduction of the UK ranges between 4% and 59% in the same scenario due to insufficient

feedstocks availability for SAF supply. The Netherlands (NL) is the country associated with the lowest level of relative GHG emissions reduction due to relatively high SAF demand coupled with limited feedstocks availability and resulting SAF supply, especially in the long term and in the high demand scenarios. In the CleanSky-HIGH and ReFuelEU-HIGH scenarios, by 2050, the relative emissions reduction of The Netherlands (NL) is between 2% - 26% and 2% - 26% while the average relative emissions reduction of all 33 countries is between 45% - 71% and 42% -63%, relatively. More detailed information on SAF's contribution to GHG emissions reduction at the country level is presented in Section Appendix III.

4.4 Conclusions and recommendations

The objective of this study was to assess the potential demand and supply of biobased SAF in Europe for the timeframe of 2030-2050, and the contribution of SAF to Europe's transition towards climate neutrality by 2050. This has been achieved by a hybrid approach consisting of literature, expert workshop, and scenario analysis. During the literature review, a wide range of biobased SAF conversion pathways were evaluated based on their technical maturity level, economic performance, and environmental performance. Subsequently, an expert workshop was carried out to validate and conclude a shortlist of the most sustainable biobased SAF conversion pathways for Europe. Taking into account feedstocks availability as well as GHG emissions reduction potential, four SAF conversion pathways were eventually applied in the subsequent scenario analysis, namely FT-FR, ATJ-AR, FP-FR, and FT-MSW. Additionally, four SAF scenarios were analyzed based on SAF demand, SAF blending ratios, and various degrees of feedstocks availability: in the CleanSky – LOW and CleanSky – HIGH scenarios, the SAF blending percentage increases from 10% in 2030 to 40% and 80% by 2050, respectively, while in the two ReFuelEU scenarios, the SAF blending ratio rises from 6% in 2030 to 70% by 2050.

At the European level, SAF demand can be met by supply when the level of feedstocks availability is at 60% or higher in all scenarios. Based on the results of this study, the FT-FR pathway is expected to be the predominant SAF production pathway for most European countries in the next two decades. The maximum theoretical SAF supply potential increases from 150 Mt in 2030 to 181 Mt in 2050, significantly higher than the SAF demand ranging from 28 Mt in 2030 to 67 Mt in 2050. This maximum level of feedstocks availability is, however, unrealistic given other biobased sectors will compete for biomass resources. When 30% or less of feedstocks in Europe are allocated to the aviation sector, the expected SAF supply is insufficient after 2035. At the national level, for 9%, 9%, 24%, 36, and 61% of all the assessed countries, SAF supply cannot meet demand with 100%, 60%, 30%, 15%, and 6% feedstocks availability, respectively, as feedstocks potential is not distributed evenly among individual countries.

The level of GHG emissions reduction is affected by SAF demand as well as the SAF supply that is determined by the chosen SAF conversion pathways. Generally, GHG emissions reduction increases as the SAF demand goes up. The European absolute GHG emissions reduction ranges from 13 Mt (6% blending) and 21 Mt (10% blending) in 2030 to 34 – 96 MT (40% blending), 43 – 183 MT (70% blending), and 45 – 201 MT (80% blending) in 2050 with various levels of feedstocks availability. This translates into relative GHG emissions reduction of 9.0% – 9.3% (6% blending) and 5.5% – 5.6% (10% blending) in 2030 and 13% – 37% (40% blending), 14% – 59% (70% blending), and 15% – 64% (80% blending) in 2050 at different degrees of feedstocks availability, compared to 100% fossil aviation fuel. In contrast, the relative GHG emissions reduction at the country level spreads more widely, namely 5% – 6% (6% blending) and 9% – 10% (10% blending) in 2030 and 2% – 32% (40% blending), 2% – 65% (70% blending), and 2% – 75% (80% blending) in 2050 at different degrees of feedstocks availability.

It is worth highlighting that the SAF conversion pathway with the highest yield (FP-FR) does not necessarily lead to the highest level of GHG emissions reduction; similarly, the SAF conversion pathway with the highest level of GHG emissions reduction (FT-FR) requires slightly more biomass to produce the same amount of fuel compared with FP-FR. This flags a trade-off between maximizing SAF production volume versus maximizing GHG emissions reduction.

Overall, the theoretical feedstocks potential in Europe is sufficient for producing SAF in line with the demand from 2030 to 2050, however, the competing uses of biomass will be a limiting factor in the actual deployment of SAF. The highest GHG emissions reduction potential can reach 64% at the European level and 75% at the national level, confirming that biobased SAF can play a vital role in the transition towards a net zero economy and climate neutrality by 2050. While acknowledging the production cost of SAF (associated with biomass logistics and technological maturity) remains one of the main obstacles, the successful deployment of SAF will also largely depend on reliable feedstocks availability at the European level as well as at the national level. The consideration of Europe as an interactive, collaborative, and consolidated SAF market was not explored in this study due to a high level of uncertainty, nevertheless, it is worth considering developing cross-border solutions among the European countries with policy incentives, to mobilize the European biomass market in a holistic, integrated, and optimized way. In addition, further improvement of SAF conversion technologies is expected to contribute towards maximizing GHG emissions reduction for the European aviation sector.

Abbreviations

AR	Agricultural residues
ASTM	American Society for Testing and Materials
ATJ	Alcohol to Jet
CAPEX	Capital expenditures
CH-SK	Catalytic Hydrothermolysis Synthesized Kerosene
DSHC	Direct-sugar-to-hydrocarbon
EU	European Union
FP	Fast Pyrolysis
FR	Forest residues
FT	Fischer-Tropsch
GHG	Greenhouse gas
HC-HEFA	Hydroprocessed Hydrocarbons, Esters and Fatty Acids
HEFA	Hydroprocessed Esters and Fatty Acids
HFS-SIP	Hydroprocessed Fermented Sugars to Synthetic Isoparaffins
ICCT	International Council on Clean Transportation
IPCC	Intergovernmental Panel on Climate Change
LUC	Land use change
MFSP	Minimum Fuel Selling Price
MSW	Municipal solid wastes
OPEX	Operating expenditures (OPEX).
SAF	Sustainable aviation fuel
SKA	Synthetic Kerosene with Aromatics
SPK	Synthetic Paraffinic Kerosene
TRL	Technology readiness level
UCO	Used cooking oil

Chapter 5

Conclusion and Outlook

To combat climate change, renewable energy is perceived as one of the most impactful levers to drive the overarching transition towards a sustainable and zero-carbon economy. Among others, biobased sustainable aviation fuel (SAF) plays a vital role in this transition. Led by the International Air Transport Association (IATA) and the International Civil Aviation Organization (ICAO), the global aviation industry has committed to reaching net-zero carbon emissions by 2050 (IATA, 2021; ICAO, 2022). The value chain of biobased SAF interacts with a wide range of industries and intertwines with different stakeholders in society. This thesis started by recognizing the rise of biobased SAF driven by their remarkable GHG emissions reduction potential and the positive effect on socioeconomic development while revealing the under-studied non-environmental sustainability aspects such as socioeconomic effects, human health impact, and demand-supply balance. It is worth underlining that SAF is still an emerging new sector and market space where new feedstocks are being investigated, new conversion technologies are being tested, and new supply chains are being established. Therefore, having a holistic understanding beyond the environmental impacts at the early stages of technological development is a key building block of scaling up biobased SAF production. This leads to the main research question of this thesis: What is the integral sustainability performance of biobased SAF production and supply chain, focusing on the under-studied aspects of socioeconomic effects, human health impacts, and supply-demand balance? And how to quantitatively assess these aspects?

As laid out in **Chapter 1**, the main goal of this thesis is to provide in-depth insights into the integral sustainability performance of biobased SAF production and supply chains, considering the macro-socioeconomic effects, human health impacts, supply-demand balance, and the resulting GHG emissions reduction potential, which contributes to the strategic decision-making around biobased SAF. By doing so, this thesis intends to highlight the potential positive as well as negative impacts of the large-scale implementation of biobased SAF production at an early design stage while addressing the methodological challenges related to making such integral sustainability analysis operational. It is worth noting that context is crucial in understanding sustainability performance. Hence this thesis also aims to demonstrate an operational approach to establish specificities, present results, and analyze trade-offs, in order to contribute to a meaningful decision-making process focusing on biobased SAF technology and supply chain.

One of the knowledge and information gaps identified in **Chapter 1** in terms of thoroughly understanding the potential sustainability impacts and trade-offs of biobased SAF production is that empirical studies assessing socioeconomic aspects of biobased SAF are rare in scientific literature. Hence, **Chapter 2** focuses on answering the sub-research question: What are the socioeconomic sustainability effects of biobased SAF production and supply chain, and how to quantitatively assess these impacts? To address this question, a scenarios-based Input-Output (IO) analysis was conducted to evaluate the key socioeconomic effects of the biobased SAF supply chain, namely employment, GDP,

and trade balance, taking SAF demand in Brazil towards 2050 as an example. Further, to address the data uncertainty of IO analysis, a stochastic simulation approach for the technical coefficients in the IO model was proposed. The analysis in **Chapter 2** suggests that biobased SAF production would lead to significant positive net socioeconomic effects on employment and GDP, despite the type of biomass feedstock and SAF conversion technology used. Furthermore, the degree of employment and GDP increase differs among the studied feedstocks. This means that in order to harvest the desired level of socioeconomic benefits, regional policies to stimulate economic activities related to specific feedstock cultivation could be instrumental. On the other hand, a slight negative impact on the trade balance was observed, as it seems that producing biobased SAF requires more imported goods than its fossil counterpart. In addition, some of the fossil fuel sectors would be negatively affected due to the displacement of existing jobs. Despite the relatively modest scales of these negative effects, it is recommended to implement measures such as professional training for new jobs or labor re-allocation agreements to mitigate these potential negative impacts at an early stage to rebalance the displaced socioeconomic benefits in those sectors.

Chapter 3 investigates the life cycle human health impacts related to biobased SAF. Considering that life cycle impact assessment (LCIA) methods for assessing human health are often associated with high levels of uncertainty and low levels of consensus, it remains challenging to select a robust LCIA method and subsequently perform a reliable assessment of human health impacts. Therefore, **Chapter 3** focuses on answering the sub-research question: What are the human health impacts of biobased SAF production and supply chain, and what is the most appropriate methodology for assessing such impact? To address this question, a systematic comparative analysis of six commonly used LCIA methods for quantifying human health impacts was first conducted. The three biobased SAF supply chains evaluated in **Chapter 2** were used for empirically quantifying life cycle human health impacts and showing the differences in assessment results attributed to the choice of LCIA methods. The analysis in **Chapter 3** suggests that all six LCIA methods agree that biomass conversion into SAF is the predominant contributor to life cycle human health impacts due to the use of toxic chemicals, the use of primary energy, and the disposal of wastes; followed by the feedstock production stage due to the use of fertilizers and pesticides. To minimize SAF's impact on human health, it is therefore recommended to focus on the research and development of more efficient and cleaner conversion pathways that require fewer toxic chemicals or replace them fully. Attention is also needed to improve feedstock cultivation practices, especially in fertilizer and pesticide management and in yield increase (Yang, 2013; Robertson and Vitousek, 2009).

In contrast, the studied LCIA methods failed to reach a unanimous conclusion in the endpoint impacts assessment. The results were scattered and distinctly different, and it thus remains uncertain which SAF conversion technology could result in the least impact on human health. Furthermore, it also remains

challenging to draw a consensual conclusion on which LCIA method is the best. Nevertheless, lessons can be learned concerning the choice and application of LCIA methods for assessing human health in the context of biobased SAF supply chains by recognizing there is no single one-size-fits-all method in this context. In an LCA study, the first step of goal and scope definition determines the features of the study such as the geographical location as well as the value preference. Thus, the choice of methods for assessing human health effects should be made case by case, depending on each specific context. We have proposed a self-checklist and a decision tree based on the goal and scope for LCA practitioners to choose the method that best suits their LCA study.

To date, eight biobased SAF conversion pathways have been approved for commercial production thanks to accelerated technological development. On one hand, this expands the technological potential of SAF, meaning dozens of different types of biomass feedstock can potentially be used to produce SAF; on the other hand, this adds to the complexity of selecting the most sustainable conversion pathway due to unclear sustainability impacts. Furthermore, biomass production, as a key activity within the agricultural and forestry industry, is highly regulated, especially in Europe. It is worth noting that not all available biomass is expected to be used for SAF production due to competition for resources in other biobased sectors such as biodiesel, biochemicals, and biomaterials. As the sustainability criteria get increasingly stringent, second-generation feedstocks will be the main source of biomass used for SAF production. To tackle these challenges, **Chapter 4** focuses on answering the sub-research question: What are the most promising SAF production pathways using lignocellulosic and waste biomass; and will the supply of biobased SAF be sufficient to meet the demand in line with the aviation sector's climate neutral goal by 2050? To address this question, **Chapter 4** provides an up-to-date comprehensive literature review of all ASTM-approved SAF production pathways in the context of their sustainability performance, focusing on their technical maturity level, economic performance, and environmental impact. Accordingly, a shortlist of the most sustainable SAF conversion pathways was identified. Furthermore, to provide an empirical and quantitative evaluation of the supply-demand balance of biobased SAF towards 2050, a few scenarios with various levels of SAF demand, blending mandate, and biomass availability within Europe were used as the case study. The resulting GHG emissions reduction was also calculated in response to the question of whether sufficient biobased SAF can be produced to facilitate a climate-neutral aviation industry by 2050.

The analysis in **Chapter 4** suggests that theoretically, SAF supply will be sufficient to meet the demand at the European level only when the feedstock availability for SAF production is at 60% or higher. However, this level of biomass availability is unrealistic given that other biobased economy sectors will compete for local feedstock. The results also suggest that at the national level, SAF demand and supply dynamics differ drastically as biomass potential is distributed unevenly among individual countries, which again underlines the importance of context when making sustainability assessments. This means

policymakers should take into account that when decarbonizing the aviation sector, the challenges and limitations at the continental and national levels are not always aligned. Overall, Chapter 4 demonstrates that biobased SAF can lead to up to 75% GHG emissions reduction compared to its fossil counterpart. In addition, the degree of GHG emissions reduction is determined by SAF demand as well as the SAF conversion pathways selected. More specifically, emissions reduction increases as the SAF demand goes up but will reach the emissions reduction cap when supply fails to meet demand. A trade-off worth mentioning is that the SAF conversion pathway with the highest yield does not necessarily lead to the highest level of GHG emissions reduction potential, and vice versa. This is why it is important to specify the ultimate goal in the strategic planning of SAF production systems: maximizing SAF production volume or maximizing GHG emissions reduction.

Overall, this thesis has investigated a range of under-studied sustainability impacts related to biobased SAF production and supply chain, demonstrating that biobased SAF could be a promising alternative to fossil jet fuel that contributes to reducing GHG emissions, creating employment, stimulating economic development, and strengthening local energy supply while recognizing potential negative impacts on trade balance and human health. Furthermore, relatively high product costs of SAF (associated with biomass logistics and technological maturity) as well as reliable biomass feedstocks availability remain the key challenges of future SAF development. One of the limitations of this thesis is that additional sustainability concerns in such aspects as land use change, food security, biodiversity loss, and energy security were not (thoroughly) addressed due to time and data limitations. Particularly, since biobased SAF production relies heavily on activities in the agroforestry industry, more research efforts should be dedicated to the impact on land use change and biodiversity of SAF production. Secondly, as large-scale SAF deployment is still at an early phase, learning effects will lead to maturer conversion technologies, lower production costs and higher GHG emissions reduction overtime. However, due to the additional uncertainties, learning effects were not modelled by this thesis. It would be beneficial for future studies to take into account learning effects to refine the assessment. Finally, given the fact that the aviation sector was not required to implement mandatory SAF blending until very recently in Europe, biobased SAF will have to compete for sustainable biomass with other relatively mature biobased sectors such as biodiesel, biochemicals, and biomaterials. The impact and dynamics of policy incentives for these biobased economic sectors and how a cross-border international biomass and SAF market can provide flexibility and optimization were omitted in this thesis but should also be analyzed in order to form a holistic and integrated policy recommendation for advancing the European biobased economy as a whole.

To conclude, this thesis has provided a broader understanding of the integral sustainability performance of biobased SAF production and supply chain, with new insights into several under-studied aspects of sustainability, namely socioeconomic effects, human health impacts, supply-demand balance, as well as

the resulting GHG emissions reduction. It became clear that despite the substantial positive contribution to socioeconomic development and GHG emissions reduction, biobased SAF does not necessarily outperform its fossil counterpart on every front of sustainability. It might result in unintended adverse impacts on existing economic sectors such as job loss or displacement. After analyzing a wide range of SAF conversion technologies as well as types of biomass feedstocks, it remains challenging to provide a definitive answer to the question “Which biobased SAF technology is the most sustainable?” because the answer to this question relies heavily on the specific context such as but not limited to geographic location, feedstock availability, and policy goals. Nevertheless, this thesis has demonstrated an operational approach to step-by-step manifest specificities, highlight interdependencies of various elements, and eventually present results and surface trade-offs in a way that could lead to a meaningful decision-making process, for biobased SAF production and supply chain. Furthermore, this approach could also be replicated for any multidisciplinary, multi-stakeholder, and full-of-trade-off problems in general. Like any other societal issue, mitigating climate change requires multilevel collaboration of stakeholders in the public and private sectors. In the end, the right question to ask is perhaps not “Which biobased SAF technology is the most sustainable?”, but “Under a specific context, what can be done to maximize the prioritized positive impacts while minimizing the negative externalities to ensure a just and sustainable transition?”

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Appendices

Appendix I

- Scenario development

In line with the predetermined aviation fuel demand, market share of aviation biofuel is a reflection of biofuel policies and its competitiveness. Biofuel policies show large influences on the dynamics of energy market, with policy instruments such as biofuel blend mandate or emission reduction quota. The competitiveness of aviation biofuel, on the other hand, depends mainly on the maturity of conversion technologies, at early development stage. Mature conversion technologies lead to a high level of fuel readiness [1], which accelerates the commercial adaptation of aviation biofuel. In the long term, technical feasibility is the foundation for fuel performance improvement (e.g. reducing costs and emissions, and improving socioeconomic indicators). The four aforementioned certified pathways are a good starting point.

Feedstock selection is another key factor for establishing the supply chain. In addition to technical feasibility, the compatibility and suitability of different feedstocks in the local context are considered. A number of studies show that among others, sugarcane (a sugar-bearing feedstock), eucalyptus (a lignocellulosic feedstock) and macauba (an oil-bearing feedstock) are considered promising biomass sources to establish aviation biofuel industry in Brazil, due to reasons such as potential feedstock availability, techno-economic feasibility, and local climate and land conditions [2-4]. As a result, these three feedstocks were selected for the scenarios in this study.

To convert sugarcane, eucalyptus, and macauba into aviation biofuel, suitable conversion technologies (among the certified pathways) are ATJ, FT, and HEFA, respectively. ATJ pathway was selected for sugarcane-based aviation biofuel considering the maturity of sugarcane industry in Brazil. Eucalyptus-based aviation biofuel can be converted via DSHC, ATJ, and FT pathways. But most research on DSHC focuses on direct fermentation using first generation biomass [1] while ATJ has been more successful in fermentation with bioethanol derived from first generation feedstocks than lignocellulosic ones [3]. As a result, FT was selected as the production pathway for converting eucalyptus. HEFA pathway was selected for converting macauba biomass considering its oil-bearing feature.

Bioethanol and biodiesel industries have been well-established in Brazil, hence, the production of aviation biofuel will have to compete for production capacity, in other words, compete for biomass and land resources with these industries [5, 6], unless additional feedstocks dedicated to aviation biofuel supply chain are introduced (often due to policy incentives or technological breakthrough). The competition for biomass will likely drive up the prices of feedstocks [6], if not interfered by regulative schemes (such as subsidies or tax deduction).

Table A1 Total effects on employment, GDP and imports based on the stochastic simulation, represented by the simulated mean, standard deviation, relative standard deviation, and 95% confidence interval.

	Scenario 1	Scenario 2		Scenario 3			Scenario 4		
	Sugarcane-ATJ chain	Sugarcane-ATJ chain	Macauba-HEFA chain	Sugarcane-ATJ chain	Macauba-HEFA chain	Eucalyptus-FT chain	Sugarcane-ATJ chain	Macauba-HEFA chain	Eucalyptus-FT chain
Employment (jobs)-deterministic	11850	29781	34686	55840	65037	56634	38363	44740	38464
Mean	10056	24945	28908	46712	54215	47971	32406	37739	30103
SD	716	1826	1457	3312	2672	2461	2326	1849	1682
RSD	7.63%	7.31%	5.04%	7.09%	4.93%	5.13%	6.45%	4.90%	5.59%
95% lower bound	8624	21293	25995	40089	48871	43049	28157	34041	26739
95% upper bound	11488	28597	31821	53335	59559	52893	36549	41437	33467
GDP (million US\$)-deterministic	216.52	556.72	579.57	1043.86	1069.70	1086.69	708.81	719.07	736.06
Mean	166.79	427.25	455.05	801.17	852.15	802.64	544.92	584.03	542.68
SD	10.74	28.35	22.95	52.36	42.86	41.69	35.39	28.86	28.27
RSD	6.44%	6.64%	5.04%	6.54%	5.03%	5.19%	6.49%	4.94%	5.21%
95% lower bound	145.31	370.55	409.15	696.45	766.43	719.26	474.14	526.31	486.14
95% upper bound	188.27	483.95	500.95	905.89	937.87	886.02	615.70	641.75	599.22
Imports (million US\$)-deterministic	76.59	199.75	149.51	374.54	280.32	284.58	252.493	188.34	190.47
Mean	60.30	158.55	129.12	297.13	233.53	242.39	199.92	157.21	163.96
SD	4.18	11.05	7.98	21.46	14.52	14.93	14.12	9.84	10.09
RSD	0.23%	6.97%	6.18%	7.22%	6.22%	6.16%	7.06%	6.26%	6.15%
95% lower bound	60.02	136.45	113.16	254.21	204.49	212.53	171.68	137.53	143.78
95% upper bound	60.58	180.65	145.08	340.05	262.57	272.25	228.16	176.89	184.14

Table A2 Net effects on employment, GDP and imports based on the stochastic simulation, represented by the simulated mean, standard deviation, relative standard deviation, and 95% confidence interval.

	Scenario 1		Scenario 2		Scenario 3			Scenario 4		
	Sugarcane-ATJ chain	Sugarcane-ATJ chain	Macauba-HEFA chain	Sugarcane-ATJ chain	Macauba-HEFA chain	Eucalyptus-FT chain	Sugarcane-ATJ chain	Macauba-HEFA chain	Eucalyptus-FT chain	
Employment (jobs)-deterministic	9279	22926	27831	42986	52183	42869	29794	36171	29287	
Mean	9198	22635	26459	42351	49796	38685	29435	34840	26657	
SD	688	1774	1410	3281	2569	2290	2261	1793	1508	
RSD	7.48%	7.84%	5.33%	7.75%	5.16%	5.92%	7.68%	5.15%	5.66%	
95% lower bound	7822	19087	23639	35789	44658	34105	24913	31254	23641	
95% upper bound	10574	26183	29279	48913	54934	43265	33957	38426	29673	
GDP (million US\$)-deterministic	132.05	331.47	354.32	621.51	664.35	624.28	427.25	454.50	422.13	
Mean	138.99	354.25	381.41	663.63	715.36	643.49	453.06	491.01	437.54	
SD	10.43	27.86	22.91	51.39	42.98	41.10	35.06	29.93	27.67	
RSD	7.50%	7.86%	6.01%	7.74%	6.01%	6.39%	7.74%	6.10%	6.32%	
95% lower bound	118.13	298.53	335.59	560.85	629.40	561.29	382.94	431.15	382.20	
95% upper bound	159.85	409.97	427.23	766.41	801.32	725.69	523.18	550.87	492.88	
Imports (million US\$)-deterministic	51.77	133.57	83.32	250.45	156.23	143.06	169.76	105.61	96.13	
Mean	48.39	126.68	97.42	237.66	183.13	158.30	159.93	124.62	107.01	
SD	4.18	11.06	8.18	20.76	14.75	13.97	13.68	10.07	9.08	
RSD	8.64%	8.73%	8.40%	8.74%	8.05%	8.83%	8.55%	8.08%	8.49%	
95% lower bound	40.03	104.56	81.06	196.14	153.63	130.36	132.57	104.48	88.85	
95% upper bound	56.75	148.80	113.78	279.18	212.63	186.24	187.29	144.76	125.17	

Table A3 Key sectors with negative net effects on employment, GDP and imports, based on deterministic calculation and stochastic simulation, represented by the simulated mean and standard deviation.

Sector		Scenario 1	Scenario 2		Scenario 3			Scenario 4		
		Sugarcane-ATJ chain	Sugarcane-ATJ chain	Macauba-HEFA chain	Sugarcane-ATJ chain	Macauba-HEFA chain	Eucalyptus-FT chain	Sugarcane-ATJ chain	Macauba-HEFA chain	Eucalyptus-FT chain
Employment (jobs)										
Extraction of oil & gas	Deterministic	-39	-106	-108	-198	-198	-202	-131	-132	-135
	Mean	-2	-5	-11	-10	-22	-21	-7	-14	-14
	SD	5	12	11	23	20	20	16	13	14
Oil Refining	Deterministic	-9	-9	-9	-24	-23	-24	-45	-43	-45
	Mean	-5	-15	-15	-28	-29	-30	-18	-19	-20
	SD	1	2	2	3	3	3	2	2	2
GDP (million US\$)										
Extraction of oil & gas	Deterministic	-23.64	-63.50	-64.96	-119.07	-119.42	-121.81	-79.09	-79.60	-81.18
	Mean	-1.18	-3.16	-6.79	-5.94	-12.88	-13.77	-4.06	-8.21	-9.00
	SD	2.82	7.50	6.41	14.11	12.20	12.47	9.39	8.11	8.16
Oil Refining	Deterministic	-3.46	-9.29	-9.44	-17.42	-17.65	-17.70	-11.58	-11.77	-11.80
	Mean	-2.12	-5.74	-5.95	-10.73	-11.14	-11.59	-7.10	-7.39	-7.69
	SD	0.25	0.67	0.61	1.21	1.11	1.11	0.83	0.76	0.75
Imports (million US\$)										
Extraction of oil & gas	Deterministic	-8.81	-23.67	-24.22	-44.38	-44.51	-45.40	-29.48	-29.67	-30.26
	Mean	-0.43	-1.24	-2.56	-2.35	-4.58	-5.07	-1.44	-3.08	-3.30
	SD	1.04	2.85	2.45	5.28	4.42	4.70	3.51	2.97	3.02
Oil Refining	Deterministic	-5.84	-15.67	-15.93	-29.39	-29.79	-29.87	-19.53	-19.86	-19.91
	Mean	-3.58	-9.67	-10.06	-18.15	-18.80	-19.59	-11.99	-12.45	-12.98
	SD	0.43	1.11	1.04	2.07	1.92	1.92	1.41	1.27	1.27

Table A4 Top sectors with high uncertainties in the total effects on employment, GDP and imports, based on the stochastic simulation, represented by the simulated mean and relative standard deviation (RSD).

Sector	Scenario 1		Scenario 2		Scenario 3			Scenario 4		
	Sugarcane-ATJ chain	Sugarcane-ATJ chain	Macauba-HEFA chain	Sugarcane-ATJ chain	Macauba-HEFA chain	Eucalyptus-FT chain	Sugarcane-ATJ chain	Macauba-HEFA chain	Eucalyptus-FT chain	
Employment (jobs)										
Agriculture	Mean	4042	9244	1811	17292	3397	2878	12535	2347	1958
	RSD	9.56%	10.32%	33.28%	10.20%	33.23%	35.08%	9.83%	33.42%	35.49%
Livestock	Mean	404	928	634	1747	1192	800	1261	842	566
	RSD	49.72%	49.13%	36.18%	48.86%	36.56%	35.67%	49.03%	36.93%	35.05%
Forestry	Mean	75	183	10793	344	20242	10447	239	14820	7649
	RSD	23.97%	23.74%	3.23%	23.16%	3.30%	3.25%	23.95%	3.30%	3.25%
Coal extraction	Mean	35	92	114	174	214	175	115	148	120
	RSD	47.33%	47.31%	39.77%	47.05%	39.35%	37.28%	48.00%	39.94%	37.41%
Extraction of oil and gas	Mean	12	31	25	58	47	50	39	32	33
	RSD	36.00%	35.76%	34.30%	35.67%	34.13%	33.49%	35.49%	34.02%	33.92%
GDP (million US\$)										
Agriculture	Mean	33.20	75.84	14.92	142.14	27.87	16.03	102.67	19.45	16.17
	RSD	9.56%	10.58%	33.25%	10.20%	33.26%	53.22%	9.95%	33.14%	34.82%
Livestock	Mean	1.37	3.25	2.17	5.98	4.04	1.92	4.27	2.90	1.93
	RSD	49.62%	48.32%	36.91%	50.52%	36.76%	50.38%	49.68%	37.43%	35.12%
Forestry	Mean	0.61	1.51	88.53	2.82	166.11	62.74	1.95	121.69	62.81
	RSD	24.21%	23.48%	3.31%	23.71%	3.31%	4.45%	24.02%	3.27%	3.20%
Coal extraction	Mean	0.95	2.48	3.09	4.69	5.88	3.26	3.17	4.01	3.28
	RSD	48.05%	47.56%	39.57%	47.56%	39.47%	54.58%	47.44%	39.93%	36.09%
Extraction of oil and gas	Mean	7.17	18.87	15.28	35.62	28.41	19.84	23.49	19.35	19.97
	RSD	36.04%	35.78%	33.85%	35.51%	34.09%	50.14%	35.47%	34.34%	33.31%

Imports (million US\$)										
Agriculture	Mean	1.98	4.54	0.88	8.52	1.40	1.67	6.15	0.96	1.15
	RSD	9.70%	10.48%	32.72%	10.50%	35.58%	33.68%	9.88%	35.25%	32.91%
Livestock	Mean	0.0034	0.0078	0.0052	0.0147	0.0067	0.0099	0.0105	0.0047	0.0070
	RSD	49.31%	49.58%	36.87%	50.14%	34.82%	37.30%	49.84%	35.47%	37.54%
Forestry	Mean	0.08	0.19	10.96	0.35	10.61	20.54	0.24	7.78	15.06
	RSD	24.56%	23.12%	3.21%	23.44%	3.26%	3.20%	23.65%	3.32%	3.28%
Coal extraction	Mean	1.00	2.63	3.19	4.98	4.92	5.99	3.26	3.41	4.17
	RSD	46.71%	47.67%	38.60%	47.34%	37.29%	39.68%	47.10%	36.74%	40.57%
Extraction of oil and gas	Mean	2.65	7.00	5.66	13.11	11.11	10.64	8.85	7.46	7.08
	RSD	35.87%	35.65%	33.36%	36.30%	33.51%	34.11%	35.17%	33.05%	33.19%

Table A5 Costs considered for aviation biofuel production and the associated sectors in the IO table.

	IO sector name	IO sector number
Feedstock costs		
Sugarcane	Agriculture	0191
Eucalyptus	Forestry	0192
Macauba	Forestry	0192
Feedstock processing		
Electricity	Electricity, natural gas and other utilities	3500
Water	Water, sewage and waste management	3680
Chemicals	Organic and inorganic chemicals	2091
Equipment and machines	Mechanical machinery and equipment	2800
Biofuel conversion		
Electricity	Electricity, natural gas and other utilities	3500
Water	Water, sewage and waste management	3680
Chemicals	Organic and inorganic chemicals	2091
Equipment and machines	Mechanical machinery and equipment	2800

Wastewater treatment	Water, sewage and waste management	3680
Maintenance and installation	Maintenance, repair and installation of machinery and equipment	3300
Construction	Construction	4180
Transportation	Ground transportation	4900
Administration	Finance and insurance	6480
R&D	Technical analysis and R&D	7180
Sales and marketing	Advertising and other technical services	7380

Table A6 Breakdown of aviation biofuel production costs (in Million US\$₂₀₁₀), aggregated and allocated to associated economic sectors ^a

Sector	Scenario 1		Scenario 2		Scenario 3		Scenario 4		
	Sugarcane-ATJ chain	Sugarcane-ATJ chain	Macauba-HEFA chain	Sugarcane-ATJ chain	Macauba-HEFA chain	Eucalyptus-FT chain	Sugarcane-ATJ chain	Macauba-HEFA chain	Eucalyptus-FT chain
Agriculture (Feedstock)	49.32	109.61	N.A.	205.52	N.A.	N.A.	150.71	N.A.	N.A.
Forestry (Feedstock)	N.A.	N.A.	158.89	N.A.	297.91	152.57	N.A.	218.47	111.89
Organic and inorganic chemicals	110.91	295.76	179.64	554.55	336.82	328.54	369.70	224.55	219.03
Utilities	5.71	15.24	31.58	28.57	59.20	111.89	19.05	39.47	74.59
Water and waste management	6.00	16.01	7.82	30.02	14.66	56.10	20.02	9.77	37.40
Transportation	12.62	33.65	84.49	63.10	158.41	157.95	42.07	105.61	105.30
Machinery and equipment	8.06	21.50	19.83	40.32	37.18	35.59	26.88	24.79	23.73
Maintenance, repair and installation	19.65	52.39	54.72	98.23	102.60	79.20	65.49	68.40	52.80
Construction	16.28	43.42	43.27	81.41	81.13	79.46	54.27	54.09	52.97
Administration	5.91	15.76	12.10	29.55	22.68	18.36	19.70	15.12	12.24
R&D	5.91	15.76	12.10	29.55	22.68	18.36	19.70	15.12	12.24
Advertising and Marketing	8.13	21.67	16.64	40.63	31.19	25.25	27.09	20.79	16.83

^a For detailed techno-economic analysis and elaborated process design, readers are referred to the studies by Alves et al. [2] and Santos et al [3].

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Appendix II

Substance contribution analysis for each aviation biofuel alternative

Sugarcane-ATJ aviation biofuel

The substance contribution analysis reveals the key substances contributing to each impact category and key emissions to environmental compartments (i.e., air, water, and soil), as presented in **Tables S3-S7**. USEtox 2(r + i), ReCiPe 2016 (H), and TRACI show that HCT is predominantly caused by emissions of chromium VI to water compartment. Additionally, emissions of chromium VI to air and soil compartments; and nickel to air, water, and soil compartments also contribute to HCT. Further, HNCT is mainly attributed to the emissions of zinc to air, water, and soil compartments. Emissions of lead, mercury, and cadmium to air compartment; and barium to water compartment are also responsible for HNCT. These heavy metal emissions are mainly from the toxic chemicals used in sugarcane milling (e.g., phosphoric acid and polyacrylamide), and biofuel conversion (e.g., sulphuric acid, ammonia, and polyacrylamide). The use of fertilizers (e.g., urea, diammonium phosphate, potassium chloride, and ammonia) and pesticides (e.g., diuron and carbofuran) in sugarcane cultivation is also responsible for these emissions. Another main contributor is the use of primary energy processes such as diesel used in engine and for trash unbaling, electricity used for operations, and natural gas used for H₂ production. On the other hand, according to ReCiPe 2016 (H), IMPACT 2002+, and TRACI, FPM is primarily a result of emissions of ammonia, nitrogen oxides, PM_{2.5}, and sulphur dioxide to air compartment. These emissions are primarily attributed to the use of fertilizers and pesticides in sugarcane production, and toxic chemicals and primary energy used in industrial processes. The combustion of aviation biofuel also contributes largely to the emissions of PM_{2.5} and nitrogen oxides. In respect to PS, ReCiPe 2016 (H) and TRACI indicate that the emissions of nitrogen oxides and nitrogen monoxide to air compartment are predominantly responsible. These emissions are mainly from sugarcane milling and biofuel conversion, due to the use of primary energy and toxic chemicals.

Eucalyptus-FP aviation biofuel

Based on USEtox 2(r + i), ReCiPe 2016(H), and TRACI, HCT of the eucalyptus-FP supply chain is predominantly attributed to the emissions of chromium VI to water compartments. In addition, emissions of nickel to water compartment, and chromium VI to air and soil compartments also account for HCT. Moreover, HNCT is primarily caused by emissions of zinc to water compartment. Next to this, emissions of mercury to air and water compartments, and zinc and cadmium to air compartment are also responsible for HNCT. These heavy metal emissions are mainly from feedstock production due to the use of fertilizers (e.g., superphosphate, potassium chloride, and ammonium sulphate), pesticides (e.g., glyphosate herbicide and sulfloramid formicide), and diesel in the field, and from biofuel conversion due to ash disposal (assuming that ash is sent to landfill). On the other hand, according to ReCiPe 2016 (H), IMPACT 2002+, and TRACI, FPM is primarily a result of the emissions of ammonia, nitrogen

oxides, PM_{2.5}, and sulphur dioxide to air compartment, while ReCiPe 2016 (H) and TRACI suggest that PS is predominantly caused by the emissions of nitrogen oxides, and nitrogen monoxide to air compartment. The emissions responsible for FPM are primarily from the use of fertilizers, pesticides, and diesel in feedstock production; and ash disposal in biofuel conversion. Combusting biofuel is a key contributor to the emission of nitrogen oxides. With regard to PS, the emissions of nitrogen oxides and nitrogen monoxide are mainly from feedstock production and biofuel combustion.

Macauba-HEFA aviation biofuel

According to USEtox 2(r + i), ReCiPe 2016 (H), and TRACI, HCT of the macauba-HEFA supply chain is predominantly attributed to the emissions of chromium VI to water compartment, followed by the emissions of nickel to water compartment; whereas HNCT is primarily caused by the emissions of zinc to air, water, and soil compartments, followed by the emissions of lead to air compartment. The emissions of mercury to air compartment, and cadmium to soil and air compartments are also responsible for HNCT. These heavy metal emissions are mainly from the use of primary energy in H₂ SMR process, ash disposal (assuming that ash is sent to landfill) in biofuel conversion, and the use of fertilizers (e.g., superphosphate and potassium nitrate), pesticides (e.g., pyrethroid), and diesel in feedstock production. On the other hand, according to ReCiPe 2016 (H), IMPACT 2002+, and TRACI, FPM is mainly a result of the emissions of ammonia, nitrogen oxides, PM_{2.5}, and sulphur dioxide to air compartment, while ReCiPe 2016 (H) and TRACI suggest that PS is predominantly caused by the emissions of nitrogen oxides to air compartment. The emissions responsible for FPM are primarily from the use of fertilizers, pesticides, and diesel in feedstock production; primary energy used in H₂ SMR; and ash disposal in biofuel conversion. Biofuel combustion is a key contributor to the emission of nitrogen oxides. With regard to PS, the emissions of nitrogen oxides and nitrogen monoxide come predominantly from combusting biofuel.

Table S1. Life cycle inventory for the feedstock production phase, based on the functional unit of 1 L jet fuel.

Sugarcane-ATJ	Value	Unit	Eucalyptus-FP	Value	Unit	Macauba-HEFA	Value	Unit
Reference: [1, 2]]			Reference: [3, 4]			Reference: [5]		
Product			Product			Product		
Sugarcane	79	ton/ha	Eucalyptus		ton/ha	Macauba		ton/ha
Inputs			Inputs			Inputs		
Nutrients			Nutrients			Nutrients		
N (Urea, 45% N)	2.34E-02	kg	N (Urea, 45% N)	5.76E-03	kg	Urea (45% N)	2.56E-05	kg
P ₂ O ₅ (Diammonium phosphate, 20% P ₂ O ₅)	8.53E-03	kg	Ammonium sulfate (21,2% N)	2.31E-02	kg	Nitrogen fertilizer, as N	1.93E-01	kg
K ₂ O (Potassium chloride, 60% K ₂ O)	1.66E-02	kg	Superphosphate(18.5% P ₂ O ₅)	3.33E-01	kg	Potassium chloride (58% KCl), fertilizer	2.56E-05	kg
Ammonia, steam reforming, liquid	1.65E-03	kg	K ₂ O (Potassium chloride, 60% K ₂ O)	1.58E-01	kg	Magnesium sulfate (11% MgO, 13% S), fertilizer	1.37E-05	kg
Monoammonium phosphate, as P ₂ O ₅	6.12E-04	kg	Limestone (as calcium carbonate)	1.15E+00	kg	Phosphate fertilizer, as single superphosphate.	6.30E-02	kg
Monoammonium phosphate, as N	1.16E-04	kg	Mg	1.90E-02	kg	Potassium fertilizer, as K ₂ O.	2.31E-01	kg
Limestone, milled, loose	9.07E-02	kg	Water	4.90E+00	kg	Lime, at regional storehouse (soil in Brazil is low in Ca and Mg)	3.79E-01	kg
Gypsum, mineral, at mine	4.53E-02	kg	Agrochemicals			Water	1.54E+02	kg
Agrochemicals			Lubricants (oil and grease)	4.55E-05	kg	Agrochemicals		
Glyphosate	5.89E-05	kg	Glyphosate herbicide	8.88E-03	kg	Agricultural phytosanitary. Pyrethroid. Deltamethrin 2.5%.	5.98E-01	kg
Diuron, at regional storehouse/RER U	2.27E-05	kg	Sulfluramid formicide	6.45E-03	kg	Water. 500 L/ha for sprayer.	2.56E+02	kg
Carbofuran, at regional storehouse/RER U	9.52E-05	kg	Transport			Glyphosate, at storehouse. Isopropylammonium salt.	7.35E-01	kg
Growth regulators (alachlor)	2.27E-05	kg	Diesel use transport to mill	8.27E-03	kg	2,4-D, herbicide, at storehouse. Isopropylammonium salt + 2,4-D	2.45E-01	kg
Insecticides (Fenvalerat Pyrethroid)	9.07E-06	kg	Energy resources			Water. 500 L/ha for herbicide.	2.56E+02	kg
Herbicides	6.12E-05	kg	Diesel use in field	2.80E-01	kg	Transport		
Vinasse application			Electricity (seedling cultivation)	1.04E-02	MJ	Transport tractor and trailer.	2.40E+00	tkm
Vinasse pumping and storage system operation	9.47E-03	m ³	Emissions to air			Transport truck <10 t	1.54E-03	tkm
Vinasse aspersion system operation	1.42E-02	m ³	Ammonia [Inorganic emissions to air]	4.33E-03	kg	Transport. 28-t truck	2.05E+00	tkm
Machinery			Carbon dioxide [Inorganic emissions to air]	8.70E-01	kg	Emissions to air		
Harvester	9.91E-04	kg	Carbon monoxide [Inorganic emissions to air]	3.10E+00	kg	Ammonia [Inorganic emissions to air]	2.93E-02	kg
Tractor	1.73E-03	kg	Glyphosate particles	1.56E-02	kg	Carbon dioxide [Inorganic emissions to air]	5.37E-02	kg
Agricultural machinery, general, production	2.39E-03	kg	Nitrogen oxides [Inorganic emissions to air]	5.76E-04	kg	Nitrogen oxides [Inorganic emissions to air]	3.33E-03	kg
Diesel, at refinery	3.20E-02	kg	Nitrous oxide (laughing gas, nitrogen monoxide) [Inorganic emissions to air]	6.69E-03	kg	Emissions to water		
Transport			Particular matter	5.94E-04	kg	Glyphosate particles	1.10E-04	kg
Transport, lorry 16-32t, EURO3	2.66E-01	tkm	Sulphur dioxide [Inorganic emissions to air]	4.65E-04	kg	2,4-D, herbicide	3.68E-05	kg
Transport, lorry >32t, EURO3	5.80E-01	tkm	VOCNM [volatile organic compounds non-methane]	4.50E-03	kg			
Emissions to air			Emissions to soil					
Ammonia [Inorganic emissions to air]	9.02E-03	kg	Lubricants residue	1.36E-05	kg			
Benzene [Group NMVOC to air]	2.33E-07	kg	Emissions to water					

Benzo[a]pyrene [Group PAH to air]	9.59E-10	kg	Glyphosate particles [Pesticides to water]	8.30E-06	kg
Cadmium [Heavy metals to air]	3.20E-10	kg	Runoff surface (from P2O5)	6.34E-03	kg
Carbon dioxide [Inorganic emissions to air]	1.80E-01	kg	Runoff surface and percolation (from N)	5.76E-03	kg
Carbon monoxide [Inorganic emissions to air]	1.73E-04	kg			
Chromium [Heavy metals to air]	1.60E-09	kg			
Copper [Heavy metals to air]	5.44E-08	kg			
Hydrocarbons (unspecified) [Organic emissions to air (group VOC)]	9.59E-05	kg			
Methane [Organic emissions to air (group VOC)]	4.13E-06	kg			
Nickel [Heavy metals to air]	2.24E-09	kg			
Nitrogen oxides [Inorganic emissions to air]	1.36E-03	kg			
Nitrous oxide (laughing gas) [Inorganic emissions to air]	7.75E-04	kg			
Polycyclic aromatic hydrocarbons (PAH, carcinogenic) [Group PAH to air]	1.05E-07	kg			
Selenium [Heavy metals to air]	3.20E-10	kg			
Sulphur dioxide [Inorganic emissions to air]	3.24E-05	kg			
Zinc [Heavy metals to air]	3.20E-08				
Emissions to soil					
Cadmium [Heavy metals to agricultural soil]	4.28E-07	kg			
Carbofuran [Pesticides to agricultural soil]	9.39E-05	kg			
Chromium [Heavy metals to agricultural soil]	3.11E-06	kg			
Copper [Heavy metals to agricultural soil]	2.65E-06	kg			
Diuron [Pesticides to agricultural soil]	2.18E-05	kg			
Fipronil [Pesticides to agricultural soil]	8.93E-06	kg			
Glyphosate [Pesticides to agricultural soil]	5.78E-05	kg			
Hexazinone [Pesticides to agricultural soil]	6.35E-06	kg			
Lead [Heavy metals to agricultural soil]	5.71E-06	kg			
Nickel [Heavy metals to agricultural soil]	2.54E-06	kg			
Zinc [Heavy metals to agricultural soil]	1.76E-05	kg			
Emissions to water					
Carbofuran [Pesticides to fresh water]	1.43E-06	kg			
Diuron [Pesticides to fresh water]	3.31E-07	kg			
Fipronil [Pesticides to fresh water]	1.36E-07	kg			
Glyphosate [Pesticides to fresh water]	8.82E-07	kg			
Nitrate [Inorganic emissions to fresh water]	5.49E-03	kg			

Table S2. Life cycle inventory for the industrial production phase, based on the functional unit of 1 L jet fuel.

Sugarcane-ATJ	Value	Unit	Eucalyptus-FP	Value	Unit	Macauba-HEFA	Value	Unit
Reference: [1, 2]			Reference: [6]			Reference: [6]		
Outputs (co-products)			Outputs (co-products)			Outputs (co-products)		
Aviation biofuel	0.81	kg	Aviation biofuel	0.81	kg	Aviation biofuel	0.81	kg
Biodiesel	0.23	kg	Biodiesel	0.23	kg	Biodiesel	0.55	kg
Naphtha	0.11	kg	Naphtha	0.11	kg	Naphtha	0.27	kg
Propane	0.067	kg	Inputs			Inputs		
Inputs			Feedstock	17.92	kg	Feedstock	1.51	kg
Feedstock	17.92	kg	Natural gas	0.44	kg	Natural gas	0.29	kg
Water	22.43	kg	H ₂ O	0.018	kg	H ₂ O	0.44	kg
CaO (100%)	0.018	kg	Emission to soil			Emission to soil		
H ₃ PO ₄ (15wt%)	0.0042	kg	Ash to landfill	0.0042	kg	Ash to landfill	0.59	kg
Polyacrylamide (Flocculant polymer, 1wt%)	0.053	kg						
NH ₄ OH	0.023	kg						
H ₂ SO ₄	1.88	kg						
Diesel for trash unbaling	0.38	kg						
Natural gas	0.22	kg						
Emission to soil								
Ash to landfill	7.24	kg						

Table S3. Top 20 substance contribution (in %) to HCT, resulting from different LCIA methods.

Sugarcane-ATJ supply chain															
	USEtox 2 (r+i)	Compart.	Unit	ReCiPe 2016(E)	Compart.	Unit	ReCiPe 2016(H)	Compart.	Unit	IMPACT 2002+	Compart.	Unit	TRACI	Compart.	Unit
No	Substance		cases	Substance		kg 1,4-DCB	Substance		kg 1,4-DCB	Substance		kg C ₂ H ₃ Cl eq.	Substance		CTUh
	Total	All	9.68E-08	Total	All	4.80E+00	Total	All	6.89E-02	Total	All	6.43E-02	Total	All	1.43E-07
1	Chromium VI	Water	8.43E-08	Chromium VI	Water	4.67E+00	Chromium VI	Water	6.34E-02	Hydrocarbons, aromatic	Air	3.01E-02	Chromium VI	Water	1.02E-07
2	Nickel	Water	4.95E-09	Chromium VI	Soil	6.01E-02	Chromium VI	Air	1.77E-03	Benzo(a)pyrene	Air	2.59E-02	Chromium	Soil	2.54E-08
3	Benzo(a)pyrene	Air	2.97E-09	Chromium VI	Air	5.14E-02	Nickel	Air	1.36E-03	Hydrocarbons, aromatic	Water	4.13E-03	Chromium	Air	5.65E-09
4	Arsenic	Water	1.68E-09	Nickel	Water	1.04E-02	Nickel	Water	9.48E-04	Arsenic	Water	1.10E-03	Chromium	Water	4.54E-09
5	Chromium VI	Soil	5.97E-10	Nickel	Air	3.26E-03	Chromium VI	Soil	6.88E-04	Dioxin, 2,3,7,8 Tetrachlorodibenzo-p-PAH, polycyclic aromatic hydrocarbons	Air	1.03E-03	Arsenic	Water	1.88E-09
6	Mercury	Air	5.76E-10	Nickel	Soil	2.63E-03	Formaldehyde	Air	3.39E-04	PAH, polycyclic aromatic hydrocarbons	Air	7.79E-04	Nickel	Water	1.60E-09
7	Nickel	Soil	4.53E-10	Formaldehyde	Air	3.39E-04	Benzo(a)pyrene	Air	9.65E-05	Arsenic	Air	6.12E-04	Chromium VI	Soil	6.41E-10
8	Nickel	Air	3.77E-10	Mercury	Air	1.89E-04	Nickel	Soil	9.10E-05	Chromium	Air	3.27E-04	Mercury	Air	3.81E-10
9	Chromium VI	Air	2.29E-10	Mercury	Water	1.37E-04	Dioxin, 2,3,7,8 Tetrachlorodibenzo-p-	Air	5.60E-05	Arsenic	Soil	1.77E-04	Chromium VI	Air	2.93E-10
10	Arsenic	Air	1.36E-10	Lead	Soil	1.15E-04	Lead	Air	4.31E-05	PAH, polycyclic aromatic hydrocarbons	Water	3.88E-05	Nickel	Air	1.77E-10
11	Formaldehyde	Air	1.14E-10	Benzo(a)pyrene	Air	9.65E-05	Cadmium	Air	3.62E-05	Aldrin	Soil	2.57E-05	Nickel	Soil	1.46E-10
12	Lead	Air	8.64E-11	Lead	Air	6.17E-05	Mercury	Water	2.55E-05	Cadmium	Air	8.92E-06	Arsenic	Air	1.32E-10
13	Cadmium	Air	7.79E-11	Dioxin, 2,3,7,8 Tetrachlorodibenzo-p-	Air	6.03E-05	Benzene	Air	2.00E-05	Chromium VI	Air	8.53E-06	Formaldehyde	Air	1.15E-10
14	Cadmium	Water	3.62E-11	Cadmium	Air	5.96E-05	Furan	Air	1.25E-05	Formaldehyde	Air	7.00E-06	Cadmium	Air	5.35E-11
15	Cadmium	Soil	3.45E-11	Cadmium	Soil	2.84E-05	PAH, polycyclic aromatic hydrocarbons	Air	7.22E-06	Carbaryl	Soil	5.77E-06	Lead	Air	5.16E-11
16	Mercury	Water	2.79E-11	Cadmium	Water	2.18E-05	Cadmium	Soil	4.28E-06	Atrazine	Soil	4.67E-06	Benzo(a)pyrene	Air	2.51E-11
17	Dioxin, 2,3,7,8 Tetrachlorodibenzo-p-	Air	2.12E-11	Benzene	Air	2.00E-05	Lead	Water	3.84E-06	Ethane, 1,2-dichloro-	Water	3.53E-06	Mercury	Water	2.21E-11
18	Mercury	Soil	2.07E-11	Lead	Water	1.80E-05	Mercury	Air	3.79E-06	Phenol, pentachloro-	Air	2.87E-06	Dioxin, 2,3,7,8 Tetrachlorodibenzo-p-	Air	1.74E-11
19	Fluoranthene	Water	1.13E-11	Arsenic V	Water	1.79E-05	Cadmium	Water	2.86E-06	Carbaryl	Air	1.45E-06	Cadmium	Soil	1.35E-11
20	Lead	Soil	8.90E-12	Furan	Air	1.25E-05	Benzene, ethyl-	Air	2.66E-06	PAH, polycyclic aromatic hydrocarbons	Soil	8.52E-07	Mercury	Soil	1.13E-11
Eucalyptus-FP supply chain															
	USEtox 2 (r+i)	Compart.	Unit	ReCiPe 2016(E)	Compart.	Unit	ReCiPe 2016(H)	Compart.	Unit	IMPACT 2002+	Compart.	Unit	TRACI	Compart.	Unit
No	Substance		cases	Substance		kg 1,4-DCB	Substance		kg 1,4-DCB	Substance		kg C ₂ H ₃ Cl eq.	Substance		CTUh
	Total	All	1,73E-07	Total	All	8,546251	Total	All	0,124002	Total	All	0,051101	Total	All	2,45E-07
1	Chromium VI	Water	1,48E-07	Chromium VI	Water	8,22E+00	Chromium VI	Water	1,12E-01	Hydrocarbons, aromatic	Air	0,03256	Chromium VI	Water	1,59E-07
2	Nickel	Water	1,34E-08	Chromium VI	Soil	1,54E-01	Chromium VI	Air	4,75E-03	Dioxin, 2,3,7,8 Tetrachlorodibenzo-p-	Air	0,00537	Chromium	Water	5,62E-08
3	Arsenic	Water	5,45E-09	Chromium VI	Air	1,38E-01	Nickel	Water	2,56E-03	Arsenic	Water	0,003656	Chromium	Air	1,49E-08
4	Chromium VI	Soil	1,53E-09	Nickel	Water	2,80E-02	Chromium VI	Soil	1,76E-03	Hydrocarbons, aromatic	Water	0,003516	Arsenic	Water	5,90E-09
5	Mercury	Air	1,02E-09	Nickel	Air	3,88E-03	Nickel	Air	1,65E-03	Benzo(a)pyrene	Air	0,002057	Nickel	Water	4,30E-09
6	Chromium VI	Air	6,13E-10	Mercury	Water	1,61E-03	Formaldehyde	Air	8,53E-04	Arsenic	Air	0,001498	Chromium VI	Soil	1,64E-09
7	Nickel	Air	3,93E-10	Formaldehyde	Air	8,53E-04	Mercury	Water	3,03E-04	PAH, polycyclic aromatic hydrocarbons	Air	0,001217	Chromium VI	Air	7,86E-10
8	Formaldehyde	Air	3,41E-10	Mercury	Air	3,50E-04	Dioxin, 2,3,7,8 Tetrachlorodibenzo-p-	Air	2,91E-04	Chromium	Air	0,000865	Mercury	Air	6,77E-10

9	Mercury	Water	3,32E-10	Dioxin, 2,3,7,8 Tetrachlorodibenzo-p-	Air	3,13E-04	Lead	Air	9,94E-05	Arsenic	Soil	0,000196	Chromium	Soil	4,42E-10
10	Arsenic	Air	3,12E-10	Lead	Air	1,42E-04	Cadmium	Air	3,68E-05	Ethane, 1,2-dichloro-	Water	5,26E-05	Formaldehyde	Air	3,43E-10
11	Benzo(a)pyrene	Air	2,13E-10	Cadmium	Water	8,80E-05	Benzene	Air	2,02E-05	PAH, polycyclic aromatic hydrocarbons	Water	3,39E-05	Arsenic	Air	3,02E-10
12	Lead	Air	1,90E-10	Cadmium	Air	8,00E-05	Cadmium	Water	1,22E-05	Chromium VI	Air	2,29E-05	Mercury	Water	2,62E-10
13	Cadmium	Water	1,55E-10	Lead	Water	3,00E-05	PAH, polycyclic aromatic hydrocarbons	Air	1,14E-05	Cadmium	Air	1,48E-05	Nickel	Air	1,78E-10
14	Cadmium	Air	1,20E-10	Benzene	Air	2,02E-05	Methane, tetrachloro-, CFC-10	Air	8,54E-06	Formaldehyde	Air	1,46E-05	Lead	Air	1,13E-10
15	Dioxin, 2,3,7,8 Tetrachlorodibenzo-p-	Air	1,12E-10	PAH, polycyclic aromatic hydrocarbons	Air	1,14E-05	Ethane, 1,2-dichloro-	Water	7,60E-06	Aldrin	Soil	1,35E-05	Dioxin, 2,3,7,8 Tetrachlorodibenzo-p-	Air	9,18E-11
16	Nickel	Soil	7,65E-12	Nickel	Soil	9,03E-06	Benzo(a)pyrene	Air	7,45E-06	Ethane, 1,2-dichloro-	Air	5,61E-06	Cadmium	Air	8,01E-11
17	Ethane, 1,2-dichloro-	Water	6,63E-12	Methane, tetrachloro-, CFC-10	Air	8,54E-06	Mercury	Air	6,74E-06	Phenol, pentachloro-	Air	3,30E-06	Cadmium	Water	1,41E-11
18	Benzene	Air	5,31E-12	Ethane, 1,2-dichloro-	Water	7,60E-06	Lead	Water	6,15E-06	Methane, tetrachloro-, CFC-10	Air	1,26E-06	Ethane, 1,2-dichloro-	Water	6,88E-12
19	Cadmium	Soil	5,05E-12	Benzo(a)pyrene	Air	7,45E-06	Ethane, 1,2-dichloro-	Air	5,77E-06	PAH, polycyclic aromatic hydrocarbons	Soil	8,98E-07	Lead	Water	6,63E-12
20	Arsenic	Soil	3,18E-12	Ethane, 1,2-dichloro-	Air	5,77E-06	Ethene, chloro-	Air	3,63E-06	Benzene	Water	5,78E-07	Benzene	Air	6,09E-12
Macauba-HEFA supply chain															
	USEtox 2 (r+i)	Compart.	Unit	ReCiPe 2016(E)	Compart.	Unit	ReCiPe 2016(H)	Compart.	Unit	IMPACT 2002+	Compart.	Unit	TRACI	Compart.	Unit
No	Substance		cases	Substance		kg 1,4-DCB	Substance		kg 1,4-DCB	Substance		kg C ₂ H ₃ Cl eq.	Substance		CTUh
	Total	All	8,42E-08	Total	All	4,319942	Total	All	0,060524	Total	All	0,009448	Total	All	2,45E-07
1	Chromium VI	Water	7,66E-08	Chromium VI	Water	4,238418	Chromium VI	Water	0,057543	Hydrocarbons, aromatic	Air	0,005516	Chromium VI	Water	9,21E-08
2	Nickel	Water	4,64E-09	Chromium VI	Soil	0,046915	Nickel	Water	0,000889	Arsenic	Water	0,001346	Chromium	Air	8,20E-08
3	Arsenic	Water	1,35E-09	Chromium VI	Air	0,023466	Chromium VI	Air	0,000807	Dioxin, 2,3,7,8 Tetrachlorodibenzo-p-	Air	0,000643	Chromium	Water	2,44E-09
4	Chromium VI	Soil	4,66E-10	Nickel	Water	0,009714	Chromium VI	Soil	0,000537	Benzo(a)pyrene	Air	0,000636	Chromium	Soil	1,76E-09
5	Mercury	Air	4,61E-10	Nickel	Air	0,000698	Formaldehyde	Air	0,000308	PAH, polycyclic aromatic hydrocarbons	Air	0,000541	Nickel	Water	1,60E-09
6	Formaldehyde	Air	1,19E-10	Formaldehyde	Air	0,000308	Nickel	Air	0,000297	Arsenic	Air	0,000321	Arsenic	Water	1,49E-09
7	Chromium VI	Air	1,04E-10	Mercury	Air	0,000148	Dioxin, 2,3,7,8 Tetrachlorodibenzo-p-	Air	3,50E-05	Hydrocarbons, aromatic	Water	0,000228	Chromium VI	Soil	1,46E-09
8	Nickel	Air	7,05E-11	Mercury	Water	8,36E-05	Furan	Air	2,44E-05	Chromium	Air	0,00014	Mercury	Air	5,01E-10
9	Arsenic	Air	6,92E-11	Dioxin, 2,3,7,8 Tetrachlorodibenzo-p-	Air	3,77E-05	Lead	Air	2,30E-05	Arsenic	Soil	4,50E-05	Chromium VI	Air	3,03E-10
10	Benzo(a)pyrene	Air	6,66E-11	Lead	Air	3,30E-05	Mercury	Water	1,57E-05	Formaldehyde	Air	7,71E-06	Formaldehyde	Air	1,34E-10
11	Mercury	Soil	5,25E-11	Lead	Water	3,12E-05	Lead	Water	6,86E-06	Atrazine	Soil	5,66E-06	Arsenic	Air	1,21E-10
12	Cadmium	Soil	4,74E-11	Furan	Air	2,44E-05	Benzene	Air	6,50E-06	Aldrin	Soil	4,66E-06	Nickel	Air	6,71E-11
13	Lead	Air	4,59E-11	Cadmium	Soil	1,78E-05	Cadmium	Air	6,12E-06	Chromium VI	Air	3,89E-06	Mercury	Soil	3,19E-11
14	Fluoranthene	Water	2,35E-11	Cadmium	Air	1,42E-05	Cadmium	Soil	5,80E-06	Cadmium	Air	2,73E-06	Lead	Air	2,88E-11
15	Cadmium	Air	2,18E-11	Cadmium	Water	1,10E-05	PAH, polycyclic aromatic hydrocarbons	Air	4,94E-06	PAH, polycyclic aromatic hydrocarbons	Water	2,49E-06	Cadmium	Soil	2,74E-11
16	Cadmium	Water	1,93E-11	Benzene	Air	6,50E-06	Mercury	Air	3,04E-06	Phenol, pentachloro-	Air	9,70E-07	Cadmium	Air	2,54E-11
17	Mercury	Water	1,72E-11	PAH, polycyclic aromatic hydrocarbons	Air	4,94E-06	Methane, tetrachloro-, CFC-10	Air	2,40E-06	PAH, polycyclic aromatic hydrocarbons	Soil	8,28E-07	Mercury	Water	1,44E-11
18	Lead	Soil	1,68E-11	Methane, tetrachloro-, CFC-10	Air	2,40E-06	Benzo(a)pyrene	Air	2,31E-06	Ethane, 1,2-dichloro-	Water	5,90E-07	Furan	Air	1,36E-11
19	Dioxin, 2,3,7,8 Tetrachlorodibenzo-p-	Air	1,33E-11	Benzo(a)pyrene	Air	2,31E-06	Cadmium	Water	1,53E-06	Trifluralin	Soil	5,80E-07	Dioxin, 2,3,7,8 Tetrachlorodibenzo-p-	Air	1,31E-11
20	Furan	Air	1,25E-11	Formaldehyde	Water	1,23E-06	Formaldehyde	Water	1,23E-06	Methane, tetrachloro-, CFC-10	Air	3,55E-07	Lead	Soil	1,09E-11

Table S4. Top 20 substance contribution HNCT, resulting from different LCIA methods.

Sugarcane-ATJ supply chain															
	USEtox 2 (r+i)	Compart.	Unit	ReCiPe 2016(E)	Compart.	Unit	ReCiPe 2016(H)	Compart.	Unit	IMPACT 2002+	Compart.	Unit	TRACI	Compart.	Unit
No	Substance		cases	Substance		kg 1,4-DCB	Substance		kg 1,4-DCB	Substance		kg C ₂ H ₃ Cl eq.	Substance		CTUh
	Total	All	3,84E-07	Total	All	6,22E+02	Total	All	1,70E+00	Total	All	8,17E-02	Total	All	6,02E-07
1	Arsenic	Water	1,25E-07	Zinc	Water	4,83E+02	Zinc	Water	1,47E+00	Zinc	Soil	4,11E-02	Zinc	Water	2,29E-07
2	Mercury	Air	6,82E-08	Zinc	Soil	1,28E+02	Lead	Air	5,16E-02	Arsenic	Water	1,15E-02	Arsenic	Water	1,39E-07
3	Zinc	Water	4,70E-08	Zinc	Air	7,51E+00	Zinc	Air	3,93E-02	Arsenic	Air	6,14E-03	Zinc	Air	6,45E-08
4	Lead	Air	3,03E-08	Barium	Water	1,70E+00	Zinc	Soil	2,81E-02	Cadmium	Soil	6,01E-03	Zinc	Soil	5,73E-08
5	Zinc	Air	2,34E-08	Vanadium	Air	5,36E-01	Fipronil	Soil	1,61E-02	Dioxin, 2,3,7,8 Tetrachlorodibenzo-p-	Air	5,20E-03	Mercury	Air	4,51E-08
6	Cadmium	Air	1,80E-08	Vanadium	Water	4,16E-01	Carbofuran	Soil	1,51E-02	Barium	Water	3,01E-03	Lead	Air	1,81E-08
7	Zinc	Soil	1,67E-08	Barium	Soil	2,84E-01	Barium	Water	1,29E-02	Arsenic	Soil	1,84E-03	Cadmium	Air	1,13E-08
8	Barium	Water	1,00E-08	Thallium	Water	2,42E-01	Cadmium	Air	1,08E-02	Ammonia	Air	1,51E-03	Arsenic	Air	8,13E-09
9	Cadmium	Water	9,71E-09	Lead	Soil	1,38E-01	Mercury	Water	1,03E-02	Barium	Soil	6,84E-04	Barium	Water	6,90E-09
10	Cadmium	Soil	9,27E-09	Mercury	Air	7,66E-02	Vanadium	Air	6,09E-03	Zinc	Water	6,78E-04	Cadmium	Soil	3,62E-09
11	Arsenic	Air	8,54E-09	Lead	Air	7,41E-02	Barium	Soil	6,09E-03	Molybdenum	Air	6,59E-04	Mercury	Water	2,61E-09
12	Mercury	Water	3,29E-09	Mercury	Water	5,54E-02	Carbon disulfide	Air	5,80E-03	Antimony	Air	5,44E-04	Lead	Soil	2,48E-09
13	Lead	Soil	3,12E-09	Chromium VI	Water	3,59E-02	Acrolein	Air	4,88E-03	Zinc	Air	3,71E-04	Carbofuran	Soil	1,97E-09
14	Mercury	Soil	2,45E-09	Cadmium	Air	3,24E-02	Lead	Water	4,62E-03	Copper	Soil	2,74E-04	Vanadium	Water	1,64E-09
15	Vanadium	Water	1,16E-09	Barium	Air	3,11E-02	Cadmium	Soil	3,91E-03	Lead	Soil	2,66E-04	Lead	Water	1,45E-09
16	Molybdenum	Air	1,02E-09	Cadmium	Soil	2,60E-02	Vanadium	Water	3,89E-03	Nickel	Soil	2,53E-04	Mercury	Soil	1,34E-09
17	Barium	Soil	9,55E-10	Lead	Water	2,16E-02	Cadmium	Water	2,64E-03	Carbofuran	Soil	2,48E-04	Cadmium	Water	8,93E-10
18	Vanadium	Air	7,79E-10	Cadmium	Water	2,00E-02	Lead	Soil	1,76E-03	Antimony	Water	2,44E-04	Vanadium	Air	8,29E-10
19	Antimony	Water	6,53E-10	Fipronil	Soil	1,61E-02	Mercury	Air	1,42E-03	Benzene	Air	1,48E-04	Antimony	Water	6,81E-10
20	Lead	Water	6,09E-10	Carbofuran	Soil	1,51E-02	Acephate	Soil	1,32E-03	Cadmium	Air	1,37E-04	Barium	Soil	6,61E-10
Eucalyptus-FP supply chain															
	USEtox 2 (r+i)	Compart.	Unit	ReCiPe 2016(E)	Compart.	Unit	ReCiPe 2016(H)	Compart.	Unit	IMPACT 2002+	Compart.	Unit	TRACI	Compart.	Unit
No	Substance		cases	Substance		kg 1,4-DCB	Substance		kg 1,4-DCB	Substance		kg C ₂ H ₃ Cl eq.	Substance		CTUh
	Total	All	9,64E-07	Total	All	1,15E+03	Total	All	4,17E+00	Total	All	9,91E-02	Total	All	1,46E-06
1	Arsenic	Water	4,04E-07	Zinc	Water	1,11E+03	Zinc	Water	3,43E+00	Arsenic	Water	3,80E-02	Zinc	Water	5,33E-07
2	Mercury	Air	1,21E-07	Zinc	Air	3,05E+01	Glyphosate	Air	2,20E-01	Dioxin, 2,3,7,8 Tetrachlorodibenzo-p-	Air	2,71E-02	Arsenic	Water	4,36E-07
3	Zinc	Water	1,10E-07	Zinc	Soil	4,61E+00	Zinc	Air	1,57E-01	Arsenic	Air	1,50E-02	Zinc	Air	2,52E-07
4	Zinc	Air	9,39E-08	Barium	Water	2,27E+00	Mercury	Water	1,23E-01	Barium	Water	3,15E-03	Mercury	Air	8,01E-08
5	Lead	Air	6,64E-08	Vanadium	Water	1,15E+00	Lead	Air	1,19E-01	Zinc	Water	2,62E-03	Lead	Air	3,97E-08
6	Cadmium	Water	4,15E-08	Thallium	Water	7,81E-01	Cadmium	Air	1,99E-02	Zinc	Soil	2,22E-03	Mercury	Water	3,10E-08
7	Mercury	Water	3,91E-08	Mercury	Water	6,50E-01	Carbon disulfide	Air	1,77E-02	Arsenic	Soil	2,04E-03	Arsenic	Air	1,99E-08
8	Cadmium	Air	3,03E-08	Barium	Soil	2,50E-01	Barium	Water	1,75E-02	Mercury	Water	1,56E-03	Cadmium	Air	1,93E-08
9	Arsenic	Air	2,09E-08	Glyphosate	Air	2,20E-01	Cadmium	Water	1,12E-02	Zinc	Air	1,50E-03	Zinc	Soil	1,29E-08
10	Barium	Water	1,36E-08	Vanadium	Air	2,08E-01	Vanadium	Water	1,08E-02	Cadmium	Water	1,50E-03	Barium	Water	9,36E-09
11	Zinc	Soil	5,54E-09	Lead	Air	1,71E-01	Zinc	Soil	1,05E-02	Molybdenum	Air	6,67E-04	Cadmium	Water	3,78E-09
12	Vanadium	Water	3,20E-09	Mercury	Air	1,42E-01	Lead	Water	7,38E-03	Barium	Soil	6,01E-04	Vanadium	Water	3,45E-09
13	Antimony	Water	1,83E-09	Cadmium	Water	8,09E-02	Barium	Soil	5,35E-03	Antimony	Air	5,88E-04	Lead	Water	2,33E-09
14	Glyphosate	Air	1,60E-09	Chromium VI	Water	6,33E-02	Thallium	Water	4,08E-03	Antimony	Water	5,11E-04	Antimony	Water	1,91E-09
15	Cadmium	Soil	1,36E-09	Cadmium	Air	5,98E-02	Acrolein	Air	2,91E-03	Ammonia	Air	2,53E-04	Glyphosate	Air	1,26E-09
16	Thallium	Water	1,12E-09	Barium	Air	3,78E-02	Mercury	Air	2,56E-03	Cadmium	Air	2,28E-04	Thallium	Water	1,22E-09
17	Molybdenum	Air	1,03E-09	Lead	Water	3,60E-02	Vanadium	Air	2,38E-03	Benzene	Air	1,59E-04	Carbon disulfide	Air	1,10E-09
18	Molybdenum	Water	1,01E-09	Carbon disulfide	Air	1,77E-02	Barium	Air	1,58E-03	Glyphosate	Air	1,38E-04	Molybdenum	Water	7,67E-10
19	Lead	Water	9,72E-10	Molybdenum	Water	1,13E-02	Beryllium	Air	1,34E-03	Chromium	Air	1,28E-04	Cadmium	Soil	7,23E-10
20	Lead	Soil	8,74E-10	Nickel	Water	5,40E-03	Molybdenum	Air	1,07E-03	Selenium	Water	1,20E-04	Molybdenum	Air	6,69E-10

Macaubá-HEFA supply chain															
	USEtox 2 (r+i)	Compartment	Unit	ReCiPe 2016(E)	Compartment	Unit	ReCiPe 2016(H)	Compartment	Unit	IMPACT 2002+	Compartment	Unit	TRACI	Compartment	Unit
No	Substance		cases	Substance		kg 1,4-DCB	Substance		kg 1,4-DCB	Substance		kg C ₂ H ₃ Cl eq.	Substance		CTUh
	Total	All	3,14E-07	Total	All	5,29E+02	Total	All	1,76E+00	Total	All	3,22E-02	Total	All	5,33E-07
1	Arsenic	Water	1,00E-07	Zinc	Water	5,19E+02	Zinc	Water	1,62E+00	Arsenic	Water	1,40E-02	Zinc	Water	2,51E-07
2	Mercury	Air	5,45E-08	Zinc	Air	4,81E+00	Zinc	Soil	4,78E-02	Zinc	Soil	4,92E-03	Arsenic	Water	1,08E-07
3	Zinc	Water	5,18E-08	Zinc	Soil	3,84E+00	Lead	Air	2,76E-02	Dioxin, 2,3,7,8 Tetrachlorodibenzo-p-	Air	3,25E-03	Zinc	Soil	5,58E-08
4	Zinc	Soil	2,50E-08	Barium	Water	3,54E-01	Zinc	Air	2,56E-02	Arsenic	Air	3,22E-03	Zinc	Air	4,04E-08
5	Lead	Air	1,61E-08	Vanadium	Water	3,47E-01	Lead	Water	8,24E-03	Ammonia	Air	2,54E-03	Mercury	Air	3,59E-08
6	Zinc	Air	1,50E-08	Thallium	Water	1,52E-01	Mercury	Water	6,36E-03	Cadmium	Soil	9,49E-04	Lead	Air	9,61E-09
7	Cadmium	Soil	1,28E-08	Mercury	Air	6,01E-02	Cadmium	Soil	5,27E-03	Molybdenum	Air	5,56E-04	Cadmium	Soil	6,80E-09
8	Mercury	Soil	6,21E-09	Lead	Air	3,96E-02	Cadmium	Air	3,72E-03	Antimony	Air	5,24E-04	Arsenic	Air	4,27E-09
9	Lead	Soil	5,90E-09	Lead	Water	3,75E-02	Vanadium	Water	3,24E-03	Arsenic	Soil	4,68E-04	Cadmium	Air	3,55E-09
10	Cadmium	Air	5,57E-09	Mercury	Water	3,38E-02	Carbon disulfide	Air	3,08E-03	Copper	Soil	3,20E-04	Mercury	Soil	3,41E-09
11	Cadmium	Water	5,18E-09	Vanadium	Air	3,35E-02	Acephate	Soil	2,85E-03	Barium	Water	3,18E-04	Lead	Soil	2,91E-09
12	Arsenic	Air	4,48E-09	Chromium VI	Water	3,26E-02	Barium	Water	2,78E-03	Zinc	Air	2,38E-04	Lead	Water	2,59E-09
13	Barium	Water	2,15E-09	Barium	Air	3,03E-02	Acrolein	Air	2,12E-03	Zinc	Water	1,32E-04	Mercury	Water	1,61E-09
14	Mercury	Water	2,03E-09	Barium	Soil	1,96E-02	Cadmium	Water	1,40E-03	Dimethoate	Soil	1,16E-04	Barium	Water	1,48E-09
15	Lead	Water	1,09E-09	Cadmium	Soil	1,64E-02	Barium	Air	1,24E-03	Antimony	Water	1,11E-04	Vanadium	Water	1,04E-09
16	Vanadium	Water	9,65E-10	Cadmium	Air	1,11E-02	Mercury	Air	1,13E-03	Benzene	Air	5,67E-05	Molybdenum	Air	5,58E-10
17	Molybdenum	Air	8,61E-10	Cadmium	Water	1,01E-02	Molybdenum	Air	8,87E-04	Selenium	Water	4,81E-05	Antimony	Air	5,54E-10
18	Copper	Soil	5,94E-10	Molybdenum	Water	5,28E-03	Thallium	Water	7,93E-04	Barium	Soil	4,72E-05	Cadmium	Water	4,72E-10
19	Antimony	Air	5,12E-10	Copper	Water	4,13E-03	Beryllium	Air	5,76E-04	Cadmium	Air	4,19E-05	Molybdenum	Water	3,58E-10
20	Arsenic	Water	3,14E-07	Zinc	Water	5,29E+02	Zinc	Water	1,76E+00	Arsenic	Water	3,22E-02	Zinc	Water	5,33E-07

Table S5. Top 10 substance contribution FPM, resulting from different LCIA methods.

Sugarcane-ATJ supply chain												
No	ReCiPe 2016(E)	Compart.	Unit	ReCiPe 2016(H)	Compart.	Unit	IMPACT 2002+	Compart.	Unit	TRACI	Compart.	Unit
No	Substance		kg PM2.5 eq.	Substance		kg PM2.5 eq.	Substance		kg PM2.5 eq.	Substance		kg PM2.5 eq.
	Total	All	1,25E-02	Total	All	1,25E-02	Total	All	8,07E-03	Total	All	3,63E-03
1	Ammonia	Air	7,08E-03	Ammonia	Air	7,08E-03	Ammonia	Air	3,58E-03	Ammonia	Air	1,96E-03
2	Nitrate	Air	1,31E-08	Nitrogen oxides	Air	2,19E-03	Nitrogen oxides	Air	2,53E-03	Particulates, < 2.5 um	Air	1,00E-03
3	Nitrogen dioxide	Air	1,40E-06	Sulfur dioxide	Air	1,82E-03	Particulates, < 2.5 um	Air	1,01E-03	Sulfur dioxide	Air	3,85E-04
4	Nitrogen monoxide	Air	3,86E-04	Particulates, < 2.5 um	Air	1,01E-03	Sulfur dioxide	Air	4,89E-04	Nitrogen oxides	Air	1,44E-04
5	Nitrogen oxides	Air	2,19E-03	Nitrogen monoxide	Air	3,86E-04	Nitrogen monoxide	Air	4,45E-04	Particulates, > 2.5 um, and < 10um	Air	1,26E-04
6	Particulates, < 2.5 um	Air	1,01E-03	Sulfur trioxide	Air	8,69E-06	Particulates, < 10 um	Air	6,54E-06	Carbon monoxide, fossil	Air	1,96E-06
7	Sulfur dioxide	Air	1,82E-03	Nitrogen dioxide	Air	1,40E-06	Carbon monoxide	Air	3,85E-06	Carbon monoxide	Air	1,31E-06
8	Sulfur monoxide	Air	1,77E-08	Sulfur oxides	Air	2,68E-08	Sulfur trioxide	Air	2,36E-06	Nitrogen dioxide	Air	9,18E-08
9	Sulfur oxides	Air	2,68E-08	Sulfur monoxide	Air	1,77E-08	Nitrogen dioxide	Air	1,62E-06	Carbon monoxide, biogenic	Air	8,06E-08
10	Sulfur trioxide	Air	8,69E-06	Nitrate	Air	1,31E-08	Sulfur monoxide	Air	3,55E-09	N.A.	N.A.	N.A.
Eucalyptus-FP supply chain												
No	ReCiPe 2016(E)	Compart.	Unit	ReCiPe 2016(H)	Compart.	Unit	IMPACT 2002+	Compart.	Unit	TRACI	Compart.	Unit
No	Substance		kg PM2.5 eq.	Substance		kg PM2.5 eq.	Substance		kg PM2.5 eq.	Substance		kg PM2.5 eq.
	Total	All	1,07E-02	Total	All	1,07E-02	Total	All	8,00E-03	Total	All	3,65E-03
1	Ammonia	Air	1,19E-03	Sulfur dioxide	Air	3,81E-03	Nitrogen oxides	Air	2,41E-03	Particulates, < 2.5 um	Air	1,99E-03
2	Nitrate	Air	1,69E-08	Nitrogen oxides	Air	2,08E-03	Particulates, < 2.5 um	Air	1,99E-03	Sulfur dioxide	Air	8,03E-04
3	Nitrogen monoxide	Air	1,59E-03	Particulates, < 2.5 um	Air	1,99E-03	Nitrogen monoxide	Air	1,83E-03	Particulates, > 2.5 um, and < 10um	Air	3,89E-04
4	Nitrogen oxides	Air	2,08E-03	Nitrogen monoxide	Air	1,59E-03	Sulfur dioxide	Air	1,03E-03	Ammonia	Air	3,31E-04
5	Particulates, < 2.5 um	Air	1,99E-03	Ammonia	Air	1,19E-03	Ammonia	Air	6,03E-04	Nitrogen oxides	Air	1,37E-04
6	Sulfur dioxide	Air	3,81E-03	Sulfur oxides	Air	1,84E-08	Particulates	Air	1,31E-04	Carbon monoxide	Air	2,68E-06
7	Sulfur oxides	Air	1,84E-08	Nitrate	Air	1,69E-08	Carbon monoxide	Air	7,86E-06	Carbon monoxide, fossil	Air	1,34E-06
8	Sulfur trioxide	Air	3,81E-10	Sulfur trioxide	Air	3,81E-10	Particulates, < 10 um	Air	6,49E-06	Carbon monoxide, biogenic	Air	4,03E-07
9	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	Sulfur trioxide	Air	1,03E-10	N.A.	N.A.	N.A.
10	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
Macauba-HEFA supply chain												
No	ReCiPe 2016(E)	Compart.	Unit	ReCiPe 2016(H)	Compart.	Unit	IMPACT 2002+	Compart.	Unit	TRACI	Compart.	Unit
No	Substance		kg PM2.5 eq.	Substance		kg PM2.5 eq.	Substance		kg PM2.5 eq.	Substance		kg PM2.5 eq.
	Total	All	1,53E-02	Total	All	1,53E-02	Total	All	9,30E-03	Total	All	4,32E-03
1	Ammonia	Air	1,19E-02	Ammonia	Air	1,19E-02	Ammonia	Air	6,04E-03	Ammonia	Air	3,32E-03
2	Nitrate	Air	1,27E-08	Nitrogen oxides	Air	2,08E-03	Nitrogen oxides	Air	2,41E-03	Particulates, < 2.5 um	Air	6,65E-04
3	Nitrogen dioxide	Air	4,06E-09	Particulates, < 2.5 um	Air	6,65E-04	Particulates, < 2.5 um	Air	6,65E-04	Sulfur dioxide	Air	1,38E-04
4	Nitrogen monoxide	Air	1,26E-06	Sulfur dioxide	Air	6,53E-04	Sulfur dioxide	Air	1,76E-04	Nitrogen oxides	Air	1,37E-04
5	Nitrogen oxides	Air	2,08E-03	Nitrogen monoxide	Air	1,26E-06	Particulates, < 10 um	Air	6,49E-06	Particulates, > 2.5 um, and < 10um	Air	5,96E-05
6	Particulates, < 2.5 um	Air	6,65E-04	Nitrate	Air	1,27E-08	Carbon monoxide	Air	3,32E-06	Carbon monoxide	Air	1,13E-06
7	Sulfur dioxide	Air	6,53E-04	Sulfur oxides	Air	9,40E-09	Nitrogen monoxide	Air	1,45E-06	Carbon monoxide, fossil	Air	1,09E-06
8	Sulfur oxides	Air	9,40E-09	Sulfur trioxide	Air	6,27E-09	Nitrogen dioxide	Air	4,70E-09	Carbon monoxide, biogenic	Air	5,64E-08
9	Sulfur trioxide	Air	6,27E-09	Nitrogen dioxide	Air	4,06E-09	Sulfur trioxide	Air	1,70E-09	Nitrogen dioxide	Air	2,67E-10
10	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.

Table S6. Top 20 substance contribution PS, resulting from different LCIA methods.

Sugarcane-ATJ supply chain												
	ReCiPe 2016(E)	Compart.	Unit	ReCiPe 2016(H)	Compart.	Unit	IMPACT 2002+	Compart.	Unit	TRACI	Compart.	Unit
No	Substance		kg NOx eq.	Substance		kg NOx eq.	Substance		kg C2H4 eq.	Substance		kg O3 eq.
	Total	All	2,37E-02	Total	All	2,37E-02	Total	All	1,19E-03	Total	All	5,53E-01
1	Nitrogen oxides	Air	1,99E-02	1-Butanol	Air	2,16E-11	NM VOC, non-methane volatile organic compounds, unspecified origin	Air	8,80E-04	Nitrogen oxides	Air	4,94E-01
2	Nitrogen monoxide	Air	3,48E-03	1-Butene	Air	3,04E-13	VOC, volatile organic compounds	Air	1,39E-04	Nitrogen monoxide	Air	5,63E-02
3	NM VOC, non-methane volatile organic compounds, unspecified origin	Air	2,64E-04	1-Pentene	Air	8,29E-11	Pentane	Air	3,55E-05	VOC, volatile organic compounds	Air	1,65E-03
4	Pentane	Air	1,29E-05	1-Propanol	Air	4,13E-08	Butane	Air	2,53E-05	Nitrogen dioxide	Air	2,14E-04
5	Butane	Air	7,98E-06	2-Butene, 2-methyl-	Air	3,98E-14	Hexane	Air	1,66E-05	Carbon monoxide	Air	2,05E-04
6	Hexane	Air	5,03E-06	2-Methyl-1-propanol	Air	3,88E-11	Propane	Air	1,34E-05	Pentane	Air	1,16E-04
7	Propane	Air	3,78E-06	2-Propanol	Air	2,44E-08	Xylene	Air	1,14E-05	Xylene	Air	8,47E-05
8	Ethene	Air	3,06E-06	2-Propenal, 2-methyl-	Air	8,59E-12	Toluene	Air	1,02E-05	Butane	Air	8,19E-05
9	Propene	Air	2,86E-06	4-Methyl-2-pentanone	Air	1,33E-13	Ethene	Air	8,44E-06	Propene	Air	7,97E-05
10	Toluene	Air	2,56E-06	Acetaldehyde	Air	5,50E-07	Hydrocarbons, aromatic	Air	8,39E-06	Ethene	Air	7,62E-05
11	Heptane	Air	1,94E-06	Acetic acid	Air	2,09E-07	Heptane	Air	7,97E-06	Formaldehyde	Air	7,30E-05
12	Hydrocarbons, aromatic	Air	1,39E-06	Acetone	Air	3,88E-08	Propene	Air	7,53E-06	Toluene	Air	6,37E-05
13	Methanol	Air	1,30E-06	Acrolein	Air	1,02E-07	Ethane	Air	5,47E-06	Furan	Air	4,42E-05
14	Formaldehyde	Air	1,29E-06	Aldehydes, unspecified	Air	6,40E-09	Benzene	Air	4,39E-06	Hexane	Air	4,33E-05
15	Ethane	Air	1,28E-06	Benzaldehyde	Air	-2,76E-08	Hydrocarbons, aliphatic, alkanes, unspecified	Air	4,18E-06	Propane	Air	3,64E-05
16	Benzene	Air	7,25E-07	Benzene	Air	7,25E-07	Formaldehyde	Air	4,03E-06	Chlorine	Air	2,85E-05
17	Acetaldehyde	Air	5,50E-07	Benzene, 1,2,3-trimethyl-	Air	1,08E-11	Methanol	Air	3,63E-06	Methanol	Air	1,84E-05
18	Butene	Air	3,47E-07	Benzene, 1,2,4-trimethyl-	Air	3,90E-11	Butane	Air	1,77E-06	Acetaldehyde	Air	1,81E-05
19	Benzene, ethyl-	Air	2,83E-07	Benzene, 1,3,5-trimethyl-	Air	8,97E-12	Acetaldehyde	Air	1,76E-06	Heptane	Air	1,64E-05
20	Acetic acid	Air	2,09E-07	Benzene, ethyl-	Air	2,83E-07	Benzene, ethyl-	Air	1,22E-06	Benzene	Air	1,44E-05
Eucalyptus-FP supply chain												
	ReCiPe 2016(E)	Compart.	Unit	ReCiPe 2016(H)	Compart.	Unit	IMPACT 2002+	Compart.	Unit	TRACI	Compart.	Unit
No	Substance		kg NOx eq.	Substance		kg NOx eq.	Substance		kg C2H4 eq.	Substance		kg O3 eq.
	Total	All	3,38E-02	Total	All	3,38E-02	Total	All	3,81E-03	Total	All	7,27E-01
1	1-Butanol	Air	5,23E-12	Nitrogen oxides	Air	1,89E-02	VOC, volatile organic compounds	Air	2,05E-03	Nitrogen oxides	Air	4,69E-01
2	1-Pentene	Air	1,81E-11	Nitrogen monoxide	Air	1,43E-02	NM VOC, non-methane volatile organic compounds, unspecified origin	Air	1,58E-03	Nitrogen monoxide	Air	2,32E-01
3	1-Propanol	Air	2,62E-08	NM VOC, non-methane volatile organic compounds, unspecified origin	Air	4,72E-04	Pentane	Air	2,97E-05	VOC, volatile organic compounds	Air	2,43E-02
4	2-Butene, 2-methyl-	Air	1,84E-14	Pentane	Air	1,08E-05	Butane	Air	2,15E-05	Chlorine	Air	6,49E-04
5	2-Methyl-1-propanol	Air	2,76E-12	Butane	Air	6,76E-06	Hexane	Air	1,54E-05	Carbon monoxide	Air	4,19E-04
6	2-Propanol	Air	6,30E-08	Hexane	Air	4,66E-06	Xylene	Air	1,42E-05	Formaldehyde	Air	1,52E-04
7	4-Methyl-2-pentanone	Air	6,89E-14	Propane	Air	3,32E-06	Hydrocarbons, aliphatic, alkanes, unspecified	Air	1,22E-05	Xylene	Air	1,06E-04
8	Acetaldehyde	Air	1,15E-06	Ethene	Air	2,73E-06	Propane	Air	1,18E-05	Pentane	Air	9,76E-05
9	Acetic acid	Air	2,12E-06	Formaldehyde	Air	2,69E-06	Toluene	Air	9,49E-06	Butane	Air	6,95E-05
10	Acetone	Air	3,75E-08	Toluene	Air	2,38E-06	Hydrocarbons, aromatic	Air	9,07E-06	Ethene	Air	6,75E-05

11	Acrolein	Air	6,22E-08	Acetic acid	Air	2,12E-06	Formaldehyde	Air	8,40E-06	Toluene	Air	5,95E-05
12	Aldehydes, unspecified	Air	1,66E-08	Propene	Air	1,98E-06	Ethene	Air	7,51E-06	Propene	Air	5,44E-05
13	Benzaldehyde	Air	1,68E-08	Ethane	Air	1,58E-06	Ethane	Air	6,74E-06	Acetic acid	Air	4,46E-05
14	Benzene	Air	7,79E-07	Heptane	Air	1,54E-06	Acetic acid	Air	6,51E-06	Hexane	Air	4,00E-05
15	Benzene, ethyl-	Air	2,31E-07	Hydrocarbons, aromatic	Air	1,50E-06	Heptane	Air	6,32E-06	Acetaldehyde	Air	3,79E-05
16	Butadiene	Air	6,48E-12	Methanol	Air	1,20E-06	Propene	Air	5,21E-06	Propane	Air	3,20E-05
17	Butane	Air	6,76E-06	Acetaldehyde	Air	1,15E-06	Benzene	Air	4,72E-06	Methanol	Air	1,71E-05
18	Butene	Air	2,78E-07	Benzene	Air	7,79E-07	Acetaldehyde	Air	3,70E-06	Benzene	Air	1,55E-05
19	Cumene	Air	5,04E-08	Methyl ethyl ketone	Air	4,38E-07	Methanol	Air	3,35E-06	Ethane	Air	1,53E-05
20	Cyclohexane	Air	2,22E-11	Butene	Air	2,78E-07	Methyl ethyl ketone	Air	1,43E-06	Heptane	Air	1,30E-05

Macauba-HEFA supply chain

	ReCiPe 2016(E)	Compart.	Unit	ReCiPe 2016(H)	Compart.	Unit	IMPACT 2002+	Compart.	Unit	TRACI	Compart.	Unit
No	Substance		kg NOx eq.	Substance		kg NOx eq.	Substance		kg C2H4 eq.	Substance		kg O3 eq.
	Total	All	1,90E-02	Total	All	1,90E-02	Total	All	3,50E-04	Total	All	4,71E-01
1	1-Butanol	Air	2,76E-11	Nitrogen oxides	Air	1,89E-02	NM VOC, non-methane volatile organic compounds, unspecified origin	Air	1,67E-04	Nitrogen oxides	Air	4,69E-01
2	1-Pentene	Air	1,68E-10	NM VOC, non-methane volatile organic compounds, unspecified origin	Air	5,02E-05	VOC, volatile organic compounds	Air	1,39E-04	VOC, volatile organic compounds	Air	1,65E-03
3	1-Propanol	Air	8,70E-09	Nitrogen monoxide	Air	1,13E-05	Ethene	Air	7,43E-06	Nitrogen monoxide	Air	1,84E-04
4	2-Butene, 2-methyl-	Air	6,96E-14	Ethene	Air	2,70E-06	Formaldehyde	Air	4,44E-06	Carbon monoxide	Air	1,77E-04
5	2-Methyl-1-propanol	Air	1,58E-08	Formaldehyde	Air	1,42E-06	Xylene	Air	3,72E-06	Furan	Air	8,60E-05
6	2-Propanol	Air	1,74E-08	Pentane	Air	1,13E-06	Pentane	Air	3,10E-06	Chlorine	Air	8,47E-05
7	2-Propenal, 2-methyl-	Air	2,24E-12	Propene	Air	9,25E-07	Toluene	Air	3,03E-06	Formaldehyde	Air	8,05E-05
8	4-Methyl-2-pentanone	Air	2,30E-14	Toluene	Air	7,60E-07	Propene	Air	2,44E-06	Ethene	Air	6,68E-05
9	Acetaldehyde	Air	4,76E-07	Butane	Air	6,81E-07	Butane	Air	2,16E-06	Xylene	Air	2,79E-05
10	Acetic acid	Air	3,36E-07	Hexane	Air	5,14E-07	Ethane	Air	2,07E-06	Propene	Air	2,54E-05
11	Acetone	Air	3,41E-08	Ethane	Air	4,84E-07	Hydrocarbons, aliphatic, alkanes, unspecified	Air	1,92E-06	Monoethanolamine	Air	2,21E-05
12	Acrolein	Air	4,50E-08	Acetaldehyde	Air	4,76E-07	Hexane	Air	1,70E-06	Toluene	Air	1,90E-05
13	Aldehydes, unspecified	Air	4,97E-09	Propane	Air	4,23E-07	Benzene	Air	1,68E-06	Acetaldehyde	Air	1,56E-05
14	Benzaldehyde	Air	1,22E-08	Acetic acid	Air	3,36E-07	Hydrocarbons, aromatic	Air	1,54E-06	Pentane	Air	1,02E-05
15	Benzene	Air	2,77E-07	Methanol	Air	3,30E-07	Acetaldehyde	Air	1,53E-06	Acetic acid	Air	7,07E-06
16	Benzene, 1,2,3-trimethyl-	Air	2,81E-12	Benzene	Air	2,77E-07	Propane	Air	1,50E-06	Butane	Air	7,00E-06
17	Benzene, 1,2,4-trimethyl-	Air	1,02E-11	Hydrocarbons, aromatic	Air	2,54E-07	Acetic acid	Air	1,03E-06	Benzene	Air	5,51E-06
18	Benzene, 1,3,5-trimethyl-	Air	2,34E-12	Nitrate	Air	1,18E-07	Methanol	Air	9,24E-07	Methanol	Air	4,71E-06
19	Benzene, ethyl-	Air	3,31E-08	Heptane	Air	1,13E-07	Heptane	Air	4,62E-07	Ethane	Air	4,68E-06
20	Butadiene	Air	2,18E-10	Ethanol	Air	9,61E-08	Ethanol	Air	3,06E-07	Hexane	Air	4,41E-06

Table S7. Top 20 substance contribution HH, resulting from different LCIA methods.

Sugarcane-ATJ supply chain												
	USEtox 2 (r+i)	Compart.	Unit	ReCiPe 2016(E)	Compart.	Unit	ReCiPe 2016(H)	Compart.	Unit	IMPACT 2002+	Compart.	Unit
No	Substance		DALY	Substance		DALY	Substance		DALY	Substance		DALY
	Total	All	2,15E-06	Total	All	2,79E-04	Total	All	2,06E-05	Total	All	6,07E-06
1	Chromium VI	Water	9,70E-07	Zinc	Water	1,10E-04	Carbon dioxide	Air	6,30E-06	Ammonia	Air	2,51E-06
2	Arsenic	Water	3,56E-07	Carbon dioxide	Air	8,48E-05	Water, turbine use, unspecified natural origin, BR	Raw	5,43E-06	Nitrogen oxides	Air	1,77E-06
3	Mercury	Air	1,91E-07	Zinc	Soil	2,92E-05	Ammonia	Air	4,45E-06	Particulates, < 2.5 um	Air	7,04E-07
4	Zinc	Water	1,27E-07	Carbon dioxide, fossil	Air	2,39E-05	Water, turbine use, unspecified natural origin, CH	Raw	3,81E-06	Sulfur dioxide	Air	3,42E-07
5	Lead	Air	8,27E-08	Chromium VI	Water	1,55E-05	Water, river, RoW	Raw	2,58E-06	Nitrogen monoxide	Air	3,11E-07
6	Zinc	Air	6,31E-08	Water, turbine use, unspecified natural origin, BR	Raw	5,43E-06	Water, turbine use, unspecified natural origin, RoW	Raw	2,41E-06	Zinc	Soil	1,15E-07
7	Nickel	Water	5,77E-08	Ammonia	Air	4,45E-06	Water, turbine use, unspecified natural origin, CN	Raw	2,30E-06	Hydrocarbons, aromatic	Air	8,43E-08
8	Cadmium	Air	4,94E-08	Water, turbine use, unspecified natural origin, CH	Raw	3,81E-06	Carbon dioxide, fossil	Air	1,77E-06	Benzo(a)pyrene	Air	7,26E-08
9	Zinc	Soil	4,51E-08	Water, river, RoW	Raw	2,58E-06	Nitrogen oxides	Air	1,40E-06	Arsenic	Water	3,53E-08
10	Benzo(a)pyrene	Air	3,41E-08	Water, turbine use, unspecified natural origin, RoW	Raw	2,41E-06	Sulfur dioxide	Air	1,14E-06	Arsenic	Air	1,89E-08
11	Barium	Water	2,71E-08	Water, turbine use, unspecified natural origin, CN	Raw	2,30E-06	Water, river, RER	Raw	1,02E-06	Dioxin, 2,3,7,8 Tetrachlorodibenzo-p-	Air	1,74E-08
12	Cadmium	Water	2,66E-08	Zinc	Air	1,71E-06	Water, turbine use, unspecified natural origin, FR	Raw	7,65E-07	Cadmium	Soil	1,68E-08
13	Cadmium	Soil	2,54E-08	Nitrogen oxides	Air	1,40E-06	Particulates, < 2.5 um	Air	6,33E-07	Hydrocarbons, aromatic	Water	1,16E-08
14	Arsenic	Air	2,46E-08	Sulfur dioxide	Air	1,14E-06	Water, turbine use, unspecified natural origin, CA	Raw	5,45E-07	Barium	Water	8,43E-09
15	Mercury	Water	9,20E-09	Water, river, RER	Raw	1,02E-06	Water, turbine use, unspecified natural origin, US	Raw	4,53E-07	Arsenic	Soil	5,65E-09
16	Lead	Soil	8,54E-09	Water, turbine use, unspecified natural origin, FR	Raw	7,65E-07	Water, turbine use, unspecified natural origin, RU	Raw	4,02E-07	Carbon-14	Air	5,28E-09
17	Chromium VI	Soil	6,87E-09	Particulates, < 2.5 um	Air	6,33E-07	Zinc	Water	3,34E-07	Particulates, < 10 um	Air	4,58E-09
18	Mercury	Soil	6,84E-09	Water, turbine use, unspecified natural origin, CA	Raw	5,45E-07	Water, turbine use, unspecified natural origin, AT	Raw	3,21E-07	Carbon monoxide	Air	2,70E-09
19	Nickel	Soil	5,28E-09	Water, turbine use, unspecified natural origin, US	Raw	4,53E-07	Nitrogen monoxide	Air	2,46E-07	PAH, polycyclic aromatic hydrocarbons	Air	2,18E-09
20	Nickel	Air	4,40E-09	Methane, biogenic	Air	4,15E-07	Methane, biogenic	Air	2,18E-07	Barium	Soil	1,91E-09
Eucalyptus-FP supply chain												
	USEtox 2 (r+i)	Compart.	Unit	ReCiPe 2016(E)	Compart.	Unit	ReCiPe 2016(H)	Compart.	Unit	IMPACT 2002+	Compart.	Unit
No	Substance		DALY	Substance		DALY	Substance		DALY	Substance		DALY
	Total	All	4,59E-06	Total	All	3,69E-04	Total	All	1,31E-05	Total	All	6,04E-06
1	Chromium VI	Water	1,71E-06	Zinc	Water	2,53E-04	Water, turbine use, unspecified natural origin, RoW	Raw	5,66E-06	Nitrogen oxides	Air	1,69E-06
2	Arsenic	Water	1,15E-06	Carbon dioxide	Air	4,65E-05	Water, turbine use, unspecified natural origin, CN	Raw	4,48E-06	Particulates, < 2.5 um	Air	1,39E-06
3	Mercury	Air	3,39E-07	Chromium VI	Water	2,73E-05	Carbon dioxide	Air	3,45E-06	Nitrogen monoxide	Air	1,28E-06
4	Zinc	Water	2,97E-07	Carbon dioxide, fossil	Air	2,40E-05	Sulfur dioxide	Air	2,39E-06	Sulfur dioxide	Air	7,18E-07
5	Zinc	Air	2,54E-07	Zinc	Air	6,96E-06	Water, turbine use, unspecified natural origin, FR	Raw	2,31E-06	Ammonia	Air	4,23E-07

6	Lead	Air	1,81E-07	Water, turbine use, unspecified natural origin, RoW	Raw	5,66E-06	Water, turbine use, unspecified natural origin, SE	Raw	2,13E-06	Arsenic	Water	1,17E-07
7	Nickel	Water	1,56E-07	Water, turbine use, unspecified natural origin, CN	Raw	4,48E-06	Carbon dioxide, fossil	Air	1,78E-06	Particulates	Air	9,14E-08
8	Cadmium	Water	1,14E-07	Sulfur dioxide	Air	2,39E-06	Water, turbine use, unspecified natural origin, BR	Raw	1,72E-06	Hydrocarbons, aromatic	Air	9,12E-08
9	Mercury	Water	1,09E-07	Water, turbine use, unspecified natural origin, FR	Raw	2,31E-06	Water, turbine use, unspecified natural origin, AT	Raw	1,41E-06	Dioxin, 2,3,7,8 Tetrachlorodibenzo-p-	Air	9,10E-08
10	Cadmium	Air	8,31E-08	Water, turbine use, unspecified natural origin, SE	Raw	2,13E-06	Nitrogen oxides	Air	1,33E-06	Arsenic	Air	4,63E-08
11	Arsenic	Air	5,99E-08	Water, turbine use, unspecified natural origin, BR	Raw	1,72E-06	Particulates, < 2.5 um	Air	1,25E-06	Hydrocarbons, aromatic	Water	9,85E-09
12	Barium	Water	3,67E-08	Water, turbine use, unspecified natural origin, AT	Raw	1,41E-06	Nitrogen monoxide	Air	1,02E-06	Barium	Water	8,82E-09
13	Chromium VI	Soil	1,76E-08	Nitrogen oxides	Air	1,33E-06	Water, turbine use, unspecified natural origin, ES	Raw	9,80E-07	Zinc	Water	7,34E-09
14	Zinc	Soil	1,50E-08	Particulates, < 2.5 um	Air	1,25E-06	Water, turbine use, unspecified natural origin, CH	Raw	9,62E-07	Arsenic	Soil	6,26E-09
15	Vanadium	Water	8,64E-09	Zinc	Soil	1,05E-06	Water, turbine use, unspecified natural origin, RU	Raw	9,07E-07	Zinc	Soil	6,22E-09
16	Chromium VI	Air	7,09E-09	Nitrogen monoxide	Air	1,02E-06	Water, turbine use, unspecified natural origin, US	Raw	8,83E-07	Benzo(a)pyrene	Air	5,76E-09
17	Antimony	Water	4,94E-09	Water, turbine use, unspecified natural origin, ES	Raw	9,80E-07	Zinc	Water	7,82E-07	Carbon-14	Air	5,60E-09
18	Nickel	Air	4,58E-09	Water, turbine use, unspecified natural origin, CH	Raw	9,62E-07	Ammonia	Air	7,49E-07	Carbon monoxide	Air	5,50E-09
19	Glyphosate	Air	4,32E-09	Water, turbine use, unspecified natural origin, RU	Raw	9,07E-07	Water, turbine use, unspecified natural origin, DE	Raw	7,24E-07	Radon-222	Air	4,74E-09
20	Formaldehyde	Air	3,93E-09	Water, turbine use, unspecified natural origin, US	Raw	8,83E-07	Water, turbine use, unspecified natural origin, IT	Raw	7,18E-07	Particulates, < 10 um	Air	4,54E-09
Macauba-HEFA supply chain												
	USEtox 2 (r+i)	Compart.	Unit	ReCiPe 2016(E)	Compart.	Unit	ReCiPe 2016(H)	Compart.	Unit	IMPACT 2002+	Compart.	Unit
No	Substance		DALY	Substance		DALY	Substance		DALY	Substance		DALY
	Total	All	1,82E-06	Total	All	1,87E-04	Total	All	1,40E-05	Total	All	6,63E-06
1	Chromium VI	Water	8,81E-07	Zinc	Water	1,18E-04	Ammonia	Air	7,52E-06	Ammonia	Air	4,24E-06
2	Arsenic	Water	2,87E-07	Carbon dioxide	Air	3,26E-05	Water, turbine use, unspecified natural origin, CN	Raw	2,79E-06	Nitrogen oxides	Air	1,68E-06
3	Mercury	Air	1,52E-07	Chromium VI	Water	1,41E-05	Carbon dioxide	Air	2,42E-06	Particulates, < 2.5 um	Air	4,65E-07
4	Zinc	Water	1,40E-07	Carbon dioxide, fossil	Air	8,20E-06	Water, turbine use, unspecified natural origin, RoW	Raw	2,04E-06	Sulfur dioxide	Air	1,23E-07
5	Zinc	Soil	6,75E-08	Ammonia	Air	7,52E-06	Nitrogen oxides	Air	1,33E-06	Arsenic	Water	4,30E-08
6	Nickel	Water	5,41E-08	Water, turbine use, unspecified natural origin, CN	Raw	2,79E-06	Carbon dioxide, fossil	Air	6,08E-07	Hydrocarbons, aromatic	Air	1,54E-08
7	Lead	Air	4,39E-08	Water, turbine use, unspecified natural origin, RoW	Raw	2,04E-06	Water, turbine use, unspecified natural origin, US	Raw	5,45E-07	Zinc	Soil	1,38E-08
8	Zinc	Air	4,06E-08	Nitrogen oxides	Air	1,33E-06	Methane, biogenic	Air	4,90E-07	Dioxin, 2,3,7,8 Tetrachlorodibenzo-p-	Air	1,09E-08
9	Cadmium	Soil	3,50E-08	Zinc	Air	1,10E-06	Water, turbine use, unspecified natural origin, RU	Raw	4,26E-07	Arsenic	Air	9,91E-09
10	Mercury	Soil	1,74E-08	Methane, biogenic	Air	9,31E-07	Particulates, < 2.5 um	Air	4,18E-07	Particulates, < 10 um	Air	4,54E-09
11	Lead	Soil	1,61E-08	Zinc	Soil	8,75E-07	Sulfur dioxide	Air	4,10E-07	Cadmium	Soil	2,66E-09
12	Cadmium	Air	1,53E-08	Water, turbine use, unspecified natural origin, US	Raw	5,45E-07	Zinc	Water	3,69E-07	Carbon monoxide	Air	2,33E-09
13	Cadmium	Water	1,42E-08	Water, turbine use, unspecified natural origin, RU	Raw	4,26E-07	Water, turbine use, unspecified natural origin, FR	Raw	2,75E-07	Benzo(a)pyrene	Air	1,78E-09

14	Arsenic	Air	1,29E-08	Particulates, < 2.5 um	Air	4,18E-07	Water, turbine use, unspecified natural origin, CH	Raw	2,71E-07	Molybdenum	Air	1,56E-09
15	Barium	Water	5,79E-09	Sulfur dioxide	Air	4,10E-07	Water, turbine use, unspecified natural origin, CA	Raw	2,29E-07	PAH, polycyclic aromatic hydrocarbons	Air	1,52E-09
16	Mercury	Water	5,67E-09	Dinitrogen monoxide	Air	2,82E-07	Water, turbine use, unspecified natural origin, IN	Raw	2,00E-07	Antimony	Air	1,47E-09
17	Chromium VI	Soil	5,37E-09	Water, turbine use, unspecified natural origin, FR	Raw	2,75E-07	Chromium VI	Water	1,91E-07	Radon-222	Air	1,47E-09
18	Lead	Water	2,97E-09	Carbon dioxide, land transformation	Air	2,72E-07	Water, turbine use, unspecified natural origin, SE	Raw	1,90E-07	Arsenic	Soil	1,44E-09
19	Vanadium	Water	2,61E-09	Water, turbine use, unspecified natural origin, CH	Raw	2,71E-07	Water, turbine use, unspecified natural origin, BR	Raw	1,76E-07	Carbon-14	Air	1,43E-09
20	Molybdenum	Air	2,32E-09	Water, turbine use, unspecified natural origin, CA	Raw	2,29E-07	Water, turbine use, unspecified natural origin, AT	Raw	1,49E-07	Nitrogen monoxide	Air	1,02E-09

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Appendix III

Table A1 Biobased SAF demand at country level from 2030 to 2050.

Country	SAF demand - Clean Sky - LOW [kt]					SAF demand - Clean Sky - HIGH [kt]					SAF demand - ReFuel EU - LOW [kt]					SAF demand - ReFuel EU - HIGH [kt]				
	2030	2035	2040	2045	2050	2030	2035	2040	2045	2050	2030	2035	2040	2045	2050	2030	2035	2040	2045	2050
AL	3.5	7.4	11.2	15.1	18.9	3.5	14.2	24.8	35.5	46.1	2.1	7.6	14.0	18.6	33.1	2.1	8.2	15.8	21.9	40.4
AT	80.5	153.1	225.8	298.5	371.1	80.5	286.8	493.2	699.5	905.8	48.3	167.1	294.5	376.8	649.5	48.3	177.3	329.3	441.2	792.6
BA	3.0	6.1	9.2	12.4	15.5	3.0	11.5	20.0	28.5	37.0	1.8	6.4	11.6	15.3	27.1	1.8	6.8	12.9	17.7	32.4
BE	346.5	770.9	1195.3	1619.7	2044.1	346.5	1463.2	2579.9	3696.6	4813.3	207.9	775.3	1457.8	1973.6	3577.1	207.9	820.6	1611.9	2259.1	4211.6
BG	22.7	46.2	69.6	93.1	116.5	22.7	87.5	152.2	217.0	281.7	13.6	48.7	88.2	115.7	204.0	13.6	51.7	98.5	134.8	246.5
CZ	38.2	74.9	111.6	148.4	185.1	38.2	139.9	241.7	343.5	445.3	22.9	80.4	143.5	185.8	324.0	22.9	85.1	159.5	215.4	389.7
DE	960.7	1775.3	2589.9	3404.5	4219.1	960.7	3240.7	5520.7	7800.7	10080.6	576.4	1968.5	3426.4	4331.3	7383.4	576.4	2071.2	3775.4	4978.0	8820.6
DK	94.6	179.9	265.1	350.4	435.7	94.6	335.2	575.9	816.6	1057.2	56.7	196.3	345.9	442.4	762.5	56.7	207.9	385.4	515.6	925.1
EE	4.6	9.0	13.4	17.9	22.3	4.6	16.6	28.7	40.7	52.8	2.7	9.6	17.2	22.3	39.0	2.7	10.1	19.0	25.6	46.2
EL	120.1	228.4	336.7	445.0	553.3	120.1	422.2	724.3	1026.4	1328.5	72.0	249.3	439.3	561.8	968.3	72.0	263.2	486.4	649.2	1162.5
ES	815.7	1549.5	2283.3	3017.2	3751.0	815.7	2872.1	4928.5	6984.9	9041.3	489.4	1692.4	2980.8	3810.4	6564.2	489.4	1788.6	3307.9	4416.5	7911.1
FI	82.4	155.5	228.7	301.8	375.0	82.4	290.4	498.4	706.5	914.5	49.4	170.5	299.4	381.8	656.2	49.4	180.7	334.4	446.6	800.2
FR	748.1	1370.7	1993.4	2616.0	3238.6	748.1	2499.2	4250.3	6001.4	7752.5	448.9	1527.0	2648.2	3335.9	5667.6	448.9	1606.7	2919.2	3838.1	6783.5
HR	16.7	34.5	52.2	70.0	87.7	16.7	65.5	114.2	163.0	211.7	10.0	36.0	65.7	86.6	153.5	10.0	38.3	73.4	100.9	185.3
HU	32.8	66.4	100.0	133.7	167.3	32.8	123.9	214.9	306.0	397.1	19.7	70.1	126.8	166.2	292.7	19.7	74.0	140.1	190.8	347.4
IE	106.4	194.8	283.2	371.6	460.0	106.4	339.0	571.5	804.1	1036.7	63.8	217.0	376.3	474.0	805.1	63.8	224.3	401.1	519.9	907.1
IT	425.0	786.5	1147.9	1509.4	1870.8	425.0	1449.0	2473.0	3497.0	4520.9	255.0	871.4	1517.6	1919.5	3274.0	255.0	920.1	1683.2	2226.4	3955.8
LT	11.5	22.5	33.6	44.6	55.6	11.5	41.8	72.1	102.5	132.8	6.9	24.2	43.2	55.9	97.3	6.9	25.5	47.8	64.4	116.2
LU	6.1	11.3	16.5	21.8	27.0	6.1	21.0	35.9	50.8	65.7	3.7	12.5	21.8	27.6	47.2	3.7	13.2	24.3	32.3	57.5
LV	12.3	23.7	35.1	46.5	57.9	12.3	44.8	77.3	109.9	142.4	7.4	25.7	45.5	58.5	101.3	7.4	27.3	51.2	69.0	124.6
MD	6.0	12.3	18.7	25.0	31.4	6.0	23.4	40.7	58.1	75.5	3.6	12.9	23.5	31.0	54.9	3.6	13.7	26.2	36.0	66.1
ME	3.3	6.6	9.9	13.2	16.5	3.3	12.9	22.6	32.2	41.8	2.0	7.0	12.6	16.5	28.9	2.0	7.6	14.5	19.9	36.6
MK	4.1	8.4	12.6	16.9	21.2	4.1	16.0	27.8	39.7	51.6	2.4	8.8	15.9	21.0	37.1	2.4	9.3	17.9	24.6	45.2
NL	396.9	733.7	1070.5	1407.2	1744.0	396.9	1358.8	2320.7	3282.6	4244.4	238.2	813.4	1416.0	1790.2	3052.0	238.2	860.7	1576.7	2088.0	3713.9
PL	71.9	138.4	204.9	271.4	338.0	71.9	254.6	437.3	619.9	802.6	43.1	150.1	265.9	341.6	591.4	43.1	158.0	292.8	391.5	702.3
PT	160.1	302.0	443.9	585.8	727.7	160.1	563.4	966.8	1370.1	1773.5	96.1	331.1	581.4	741.2	1273.5	96.1	351.0	649.0	866.4	1551.8
RO	47.5	99.1	150.7	202.4	254.0	47.5	188.7	329.9	471.1	612.3	28.5	103.0	188.6	249.9	444.5	28.5	109.5	210.8	290.9	535.7
RS	15.3	31.3	47.3	63.3	79.3	15.3	60.7	106.2	151.7	197.1	9.2	32.8	59.7	78.5	138.7	9.2	35.2	67.9	93.7	172.5
SE	101.0	191.1	281.2	371.2	461.3	101.0	354.1	607.1	860.1	1113.2	60.6	209.2	367.8	469.4	807.3	60.6	221.1	408.3	544.4	974.0
SI	2.5	4.9	7.4	9.9	12.3	2.5	9.4	16.3	23.2	30.0	1.5	5.3	9.5	12.3	21.6	1.5	5.6	10.6	14.4	26.3
SK	5.1	10.1	15.2	20.2	25.2	5.1	18.7	32.3	45.9	59.4	3.1	10.8	19.4	25.2	44.1	3.1	11.4	21.3	28.8	52.0
UA	50.6	105.7	160.8	215.9	271.1	50.6	200.7	350.7	500.8	650.9	30.3	109.7	201.2	266.6	474.4	30.3	116.5	224.3	309.4	569.5
UK	1283.7	2444.8	3605.8	4766.8	5927.9	1283.7	4407.9	7532.0	10656.2	13780.4	770.2	2666.6	4701.7	6016.1	10373.8	770.2	2786.9	5110.6	6773.9	12057.8
Total	6079.2	11555.0	17030.8	22506.6	27982.4	6079.2	21233.6	36388.1	51542.5	66697.0	3647.5	12616.5	22227.1	28419.3	48969.2	3647.5	13287.3	24507.7	32645.0	58359.9

Table A2 2030 Clean Sky – LOW/HIGH scenario.

2030 Clean Sky - LOW / HIGH																					
Country	SAF demand (kt)	100% biomass availability				60% biomass availability				30% biomass availability				15% biomass availability				6% biomass availability			
		Conversion pathway	SAF supply (kt)	GHG emissions (kt CO2e)	GHG reduction (kt CO2e)	Conversion pathway	SAF supply (kt)	GHG emissions (kt CO2e)	GHG reduction (kt CO2e)	Conversion pathway	SAF supply (kt)	GHG emissions (kt CO2e)	GHG reduction (kt CO2e)	Conversion pathway	SAF supply (kt)	GHG emissions (kt CO2e)	GHG reduction (kt CO2e)	Conversion pathway	SAF supply (kt)	GHG emissions (kt CO2e)	GHG reduction (kt CO2e)
AL	3.5	FT_FR	308.0	0.9	12.3	FT_FR	184.8	0.9	12.3	FT_FR	92.4	0.9	12.3	FT_FR	46.2	0.9	12.3	FT_FR	18.5	0.9	12.3
AT	80.5	FT_FR	5537.8	20.7	280.7	FT_FR	3322.7	20.7	280.7	FT_FR	1661.3	20.7	280.7	FT_FR	830.7	20.7	280.7	FT_FR	332.3	20.7	280.7
BA	3.0	FT_FR	887.9	0.8	10.4	FT_FR	532.8	0.8	10.4	FT_FR	266.4	0.8	10.4	FT_FR	133.2	0.8	10.4	FT_FR	53.3	0.8	10.4
BE	346.5	FT_FR	1116.4	89.0	1208.7	FT_FR	669.8	89.0	1208.7	FT_FR+AT J_AR	562.5	95.6	1202.0	FT_FR+A R+MSW	277.9	80.0	1217.7	FT_FR+AR+ MSW	111.2	32.0	1265.7
BG	22.7	FT_FR	1426.7	5.8	79.3	FT_FR	856.0	5.8	79.3	FT_FR	428.0	5.8	79.3	FT_FR	214.0	5.8	79.3	FT_FR	85.6	5.8	79.3
CZ	38.2	FT_FR	3951.0	9.8	133.1	FT_FR	2370.6	9.8	133.1	FT_FR	1185.3	9.8	133.1	FT_FR	592.6	9.8	133.1	FT_FR	237.1	9.8	133.1
DE	960.7	FT_FR	17906.9	246.7	3351.3	FT_FR	10744.1	246.7	3351.3	FT_FR	5372.1	246.7	3351.3	FT_FR	2686.0	246.7	3351.3	FT_FR	1074.4	246.7	3351.3
DK	94.6	FT_FR	3193.1	24.3	329.9	FT_FR	1915.9	24.3	329.9	FT_FR	957.9	24.3	329.9	FT_FR	479.0	24.3	329.9	FT_FR	191.6	24.3	329.9
EE	4.6	FT_FR	1853.0	1.2	15.9	FT_FR	1111.8	1.2	15.9	FT_FR	555.9	1.2	15.9	FT_FR	277.9	1.2	15.9	FT_FR	111.2	1.2	15.9
EL	120.1	FT_FR	1172.4	30.8	418.9	FT_FR	703.4	30.8	418.9	FT_FR	351.7	30.8	418.9	FT_FR	175.9	30.8	418.9	FT_FR+ATJ AR	172.3	59.4	390.3
ES	815.7	FT_FR	5477.4	209.5	2845.3	FT_FR	3286.5	209.5	2845.3	FT_FR	1643.2	209.5	2845.3	FT_FR	821.6	209.5	2845.3	FT_FR+ATJ AR+FT_MS	819.1	481.5	2573.3
FI	82.4	FT_FR	14217.4	21.2	287.4	FT_FR	8530.4	21.2	287.4	FT_FR	4265.2	21.2	287.4	FT_FR	2132.6	21.2	287.4	FT_FR	853.0	21.2	287.4
FR	748.1	FT_FR	14955.9	192.1	2609.5	FT_FR	8973.6	192.1	2609.5	FT_FR	4486.8	192.1	2609.5	FT_FR	2243.4	192.1	2609.5	FT_FR	897.4	192.1	2609.5
HR	16.7	FT_FR	4616.3	4.3	58.2	FT_FR	2769.8	4.3	58.2	FT_FR	1384.9	4.3	58.2	FT_FR	692.4	4.3	58.2	FT_FR	277.0	4.3	58.2
HU	32.8	FT_FR	2352.3	8.4	114.4	FT_FR	1411.4	8.4	114.4	FT_FR	705.7	8.4	114.4	FT_FR	352.8	8.4	114.4	FT_FR	141.1	8.4	114.4
IE	106.4	FT_FR	1364.4	27.3	371.0	FT_FR	818.6	27.3	371.0	FT_FR	409.3	27.3	371.0	FT_FR	204.7	27.3	371.0	FT_FR+ATJ AR	113.0	41.4	357.0
IT	425.0	FT_FR	5385.1	109.1	1482.5	FT_FR	3231.0	109.1	1482.5	FT_FR	1615.5	109.1	1482.5	FT_FR	807.8	109.1	1482.5	FT_FR+ATJ AR	638.1	167.6	1424.1
LT	11.5	FT_FR	3541.4	3.0	40.1	FT_FR	2124.8	3.0	40.1	FT_FR	1062.4	3.0	40.1	FT_FR	531.2	3.0	40.1	FT_FR	212.5	3.0	40.1
LU	6.1	FT_FR	418.3	1.6	21.2	FT_FR	251.0	1.6	21.2	FT_FR	125.5	1.6	21.2	FT_FR	62.7	1.6	21.2	FT_FR	25.1	1.6	21.2
LV	12.3	FT_FR	2451.6	3.2	42.9	FT_FR	1471.0	3.2	42.9	FT_FR	735.5	3.2	42.9	FT_FR	367.7	3.2	42.9	FT_FR	147.1	3.2	42.9
MD	6.0	FT_FR	1054.0	1.5	20.9	FT_FR	632.4	1.5	20.9	FT_FR	316.2	1.5	20.9	FT_FR	158.1	1.5	20.9	FT_FR	63.2	1.5	20.9
ME	3.3	FT_FR	272.2	0.8	11.5	FT_FR	163.3	0.8	11.5	FT_FR	81.7	0.8	11.5	FT_FR	40.8	0.8	11.5	FT_FR	16.3	0.8	11.5
MK	4.1	FT_FR	303.8	1.0	14.2	FT_FR	182.3	1.0	14.2	FT_FR	91.1	1.0	14.2	FT_FR	45.6	1.0	14.2	FT_FR	18.2	1.0	14.2
NL	396.9	FT_FR	651.7	101.9	1384.5	FT_FR+AT J_AR	827.4	105.3	1381.2	FT_FR+AT J_AR	413.7	217.4	1269.0	FT_FR+A R+MSW	212.0	65.9	1420.6	FT_FR+AR+ MSW	84.8	26.4	1460.1
PL	71.9	FT_FR	8536.1	18.5	250.8	FT_FR	5121.7	18.5	250.8	FT_FR	2560.8	18.5	250.8	FT_FR	1280.4	18.5	250.8	FT_FR	512.2	18.5	250.8
PT	160.1	FT_FR	3942.5	41.1	558.5	FT_FR	2365.5	41.1	558.5	FT_FR	1182.8	41.1	558.5	FT_FR	591.4	41.1	558.5	FT_FR	236.6	41.1	558.5
RO	47.5	FT_FR	6435.1	12.2	165.6	FT_FR	3861.1	12.2	165.6	FT_FR	1930.5	12.2	165.6	FT_FR	965.3	12.2	165.6	FT_FR	386.1	12.2	165.6
RS	15.3	FT_FR	1764.8	3.9	53.3	FT_FR	1058.9	3.9	53.3	FT_FR	529.4	3.9	53.3	FT_FR	264.7	3.9	53.3	FT_FR	105.9	3.9	53.3
SE	101.0	FT_FR	19679.4	25.9	352.4	FT_FR	11807.6	25.9	352.4	FT_FR	5903.8	25.9	352.4	FT_FR	2951.9	25.9	352.4	FT_FR	1180.8	25.9	352.4
SI	2.5	FT_FR	1542.1	0.6	8.6	FT_FR	925.3	0.6	8.6	FT_FR	462.6	0.6	8.6	FT_FR	231.3	0.6	8.6	FT_FR	92.5	0.6	8.6
SK	5.1	FT_FR	2757.4	1.3	17.9	FT_FR	1654.4	1.3	17.9	FT_FR	827.2	1.3	17.9	FT_FR	413.6	1.3	17.9	FT_FR	165.4	1.3	17.9
UA	50.6	FT_FR	5273.2	13.0	176.4	FT_FR	3163.9	13.0	176.4	FT_FR	1581.9	13.0	176.4	FT_FR	791.0	13.0	176.4	FT_FR	316.4	13.0	176.4
UK	1283.7	FT_FR	5499.3	329.7	4477.9	FT_FR	3299.6	329.7	4477.9	FT_FR+AT J_AR	1649.8	329.7	4477.9	FT_FR+AT J_AR	1658.6	592.8	4214.7	FT_FR+ATJ AR+FT_MS	1433.7	754.5	4053.0

Table A3 2035 Clean Sky – LOW scenario.

2035 Clean Sky - LOW																					
Country	100% biomass availability					60% biomass availability				30% biomass availability				15% biomass availability				6% biomass availability			
	SAF demand (kt)	Conversion pathway	SAF supply (kt)	GHG emissions (kt CO2e)	GHG reduction (kt CO2e)	Conversion pathway	SAF supply (kt)	GHG emissions (kt CO2e)	GHG reduction (kt CO2e)	Conversion pathway	SAF supply (kt)	GHG emissions (kt CO2e)	GHG reduction (kt CO2e)	Conversion pathway	SAF supply (kt)	GHG emissions (kt CO2e)	GHG reduction (kt CO2e)	Conversion pathway	SAF supply (kt)	GHG emissions (kt CO2e)	GHG reduction (kt CO2e)
AL	7.4	FT_FR	349.9	1.9	25.7	FT_FR	210.0	1.9	25.7	FT_FR	105.0	1.9	25.7	FT_FR	52.5	1.9	25.7	FT_FR	21.0	1.9	25.7
AT	153.1	FT_FR	5652.1	39.3	534.2	FT_FR	3391.2	39.3	534.2	FT_FR	1695.6	39.3	534.2	FT_FR	847.8	39.3	534.2	FT_FR	339.1	39.3	534.2
BA	6.1	FT_FR	905.8	1.6	21.3	FT_FR	543.5	1.6	21.3	FT_FR	271.7	1.6	21.3	FT_FR	135.9	1.6	21.3	FT_FR	54.3	1.6	21.3
BE	770.9	FT_FR	1138.9	198.0	2689.1	FT_FR+AT J_AR	1149.9	248.2	2638.9	FT_FR+A R+MSW	564.9	933.2	1953.9	FT_FR+AR+ MSW	282.4	629.8	2257.2	FT_FR+AR+ MSW	113.0	2496.3	390.8
BG	46.2	FT_FR	1456.5	11.9	161.1	FT_FR	873.9	11.9	161.1	FT_FR	436.9	11.9	161.1	FT_FR	218.5	11.9	161.1	FT_FR	87.4	11.9	161.1
CZ	74.9	FT_FR	4032.3	19.2	261.2	FT_FR	2419.4	19.2	261.2	FT_FR	1209.7	19.2	261.2	FT_FR	604.8	19.2	261.2	FT_FR	241.9	19.2	261.2
DE	1775.3	FT_FR	18274.4	455.9	6192.7	FT_FR	10964.6	455.9	6192.7	FT_FR	5482.3	455.9	6192.7	FT_FR	2741.2	455.9	6192.7	FT_FR	1886.8	845.3	5803.4
DK	179.9	FT_FR	3241.0	46.2	627.4	FT_FR	1944.6	46.2	627.4	FT_FR	972.3	46.2	627.4	FT_FR	486.2	46.2	627.4	FT_FR	194.5	46.2	627.4
EE	9.0	FT_FR	1890.7	2.3	31.4	FT_FR	1134.4	2.3	31.4	FT_FR	567.2	2.3	31.4	FT_FR	283.6	2.3	31.4	FT_FR	113.4	2.3	31.4
EL	228.4	FT_FR	1196.1	58.6	796.7	FT_FR	717.6	58.6	796.7	FT_FR	358.8	58.6	796.7	FT_FR+ATJ_ AR	442.6	86.7	768.6	FT_FR+AR+ MSW	160.7	297.6	557.7
ES	1549.5	FT_FR	5590.5	397.9	5405.0	FT_FR	3354.3	397.9	5405.0	FT_FR	1677.2	397.9	5405.0	FT_FR+ATJ_ AR	1995.6	805.6	4997.3	FT_FR+AR+ MSW	730.2	3270.4	2532.5
FI	155.5	FT_FR	14511.0	39.9	542.5	FT_FR	8706.6	39.9	542.5	FT_FR	4353.3	39.9	542.5	FT_FR	2176.6	39.9	542.5	FT_FR	870.7	39.9	542.5
FR	1370.7	FT_FR	15263.3	352.0	4781.4	FT_FR	9158.0	352.0	4781.4	FT_FR	4579.0	352.0	4781.4	FT_FR	2289.5	352.0	4781.4	FT_FR+ATJ_ AR	1843.2	612.9	4520.5
HR	34.5	FT_FR	4590.3	8.8	120.2	FT_FR	2754.2	8.8	120.2	FT_FR	1377.1	8.8	120.2	FT_FR	688.5	8.8	120.2	FT_FR	275.4	8.8	120.2
HU	66.4	FT_FR	2400.6	17.1	231.7	FT_FR	1440.3	17.1	231.7	FT_FR	720.2	17.1	231.7	FT_FR	360.1	17.1	231.7	FT_FR	144.0	17.1	231.7
IE	194.8	FT_FR	1557.5	50.0	679.4	FT_FR	934.5	50.0	679.4	FT_FR	467.2	50.0	679.4	FT_FR	233.6	50.0	679.4	FT_FR+AR+ MSW	120.8	309.3	420.2
IT	786.5	FT_FR	5015.9	202.0	2743.3	FT_FR	3009.5	202.0	2743.3	FT_FR	1504.8	202.0	2743.3	FT_FR+ATJ_ AR	1562.6	221.5	2723.8	FT_FR+AR+ MSW	601.5	866.5	2078.8
LT	22.5	FT_FR	3528.8	5.8	78.6	FT_FR	2117.3	5.8	78.6	FT_FR	1058.6	5.8	78.6	FT_FR	529.3	5.8	78.6	FT_FR	211.7	5.8	78.6
LU	11.3	FT_FR	426.8	2.9	39.5	FT_FR	256.1	2.9	39.5	FT_FR	128.0	2.9	39.5	FT_FR	64.0	2.9	39.5	FT_FR	25.6	2.9	39.5
LV	23.7	FT_FR	2502.5	6.1	82.6	FT_FR	1501.5	6.1	82.6	FT_FR	750.7	6.1	82.6	FT_FR	375.4	6.1	82.6	FT_FR	150.1	6.1	82.6
MD	12.3	FT_FR	1067.5	3.2	43.0	FT_FR	640.5	3.2	43.0	FT_FR	320.2	3.2	43.0	FT_FR	160.1	3.2	43.0	FT_FR	64.0	3.2	43.0
ME	6.6	FT_FR	261.0	1.7	23.0	FT_FR	156.6	1.7	23.0	FT_FR	78.3	1.7	23.0	FT_FR	39.1	1.7	23.0	FT_FR	15.7	1.7	23.0
MK	8.4	FT_FR	288.5	2.1	29.1	FT_FR	173.1	2.1	29.1	FT_FR	86.5	2.1	29.1	FT_FR	43.3	2.1	29.1	FT_FR	17.3	2.1	29.1
NL	733.7	FT_FR+AT J_AR	1409.5	228.1	2519.6	FT_FR+AT J_AR	845.7	380.5	2367.1	FT_FR+A R+MSW	429.5	1271.4	1476.2	FT_FR+AR+ MSW	214.7	857.5	1890.2	FT_FR+AR+ MSW	85.9	2452.4	295.2
PL	138.4	FT_FR	8710.5	35.5	482.8	FT_FR	5226.3	35.5	482.8	FT_FR	2613.1	35.5	482.8	FT_FR	1306.6	35.5	482.8	FT_FR	522.6	35.5	482.8
PT	302.0	FT_FR	4024.7	77.6	1053.4	FT_FR	2414.8	77.6	1053.4	FT_FR	1207.4	77.6	1053.4	FT_FR	603.7	77.6	1053.4	FT_FR+AR+ MSW	275.4	172.9	958.1
RO	99.1	FT_FR	6275.8	25.4	345.7	FT_FR	3765.5	25.4	345.7	FT_FR	1882.7	25.4	345.7	FT_FR	941.4	25.4	345.7	FT_FR	376.5	25.4	345.7
RS	31.3	FT_FR	1800.3	8.0	109.1	FT_FR	1080.2	8.0	109.1	FT_FR	540.1	8.0	109.1	FT_FR	270.0	8.0	109.1	FT_FR	108.0	8.0	109.1
SE	191.1	FT_FR	19786.7	49.1	666.6	FT_FR	11872.0	49.1	666.6	FT_FR	5936.0	49.1	666.6	FT_FR	2968.0	49.1	666.6	FT_FR	1187.2	49.1	666.6
SI	4.9	FT_FR	1573.9	1.3	17.2	FT_FR	944.3	1.3	17.2	FT_FR	472.2	1.3	17.2	FT_FR	236.1	1.3	17.2	FT_FR	94.4	1.3	17.2
SK	10.1	FT_FR	3111.0	2.6	35.4	FT_FR	1866.6	2.6	35.4	FT_FR	933.3	2.6	35.4	FT_FR	466.7	2.6	35.4	FT_FR	186.7	2.6	35.4
UA	105.7	FT_FR	5230.2	27.1	368.7	FT_FR	3138.1	27.1	368.7	FT_FR	1569.0	27.1	368.7	FT_FR	784.5	27.1	368.7	FT_FR	313.8	27.1	368.7
UK	2444.8	FT_FR	5506.9	627.8	8527.8	FT_FR	3304.2	627.8	8527.8	FT_FR+AT J_AR	3359.9	1082.4	8073.2	FT_FR+ATJ_ AR+FT_MS	3150.5	1405.6	7750.0	FT_FR+AR+ MSW	1181.4	5256.3	3899.3

Table A4 2035 Clean Sky – HIGH scenario.

2035 Clean Sky - HIGH																					
Country	SAF demand (kt)	100% biomass availability				60% biomass availability				30% biomass availability				15% biomass availability				6% biomass availability			
		Conversion pathway	SAF supply (kt)	GHG emissions (kt CO2e)	GHG reduction (kt CO2e)	Conversion pathway	SAF supply (kt)	GHG emissions (kt CO2e)	GHG reduction (kt CO2e)	Conversion pathway	SAF supply (kt)	GHG emissions (kt CO2e)	GHG reduction (kt CO2e)	Conversion pathway	SAF supply (kt)	GHG emissions (kt CO2e)	GHG reduction (kt CO2e)	Conversion pathway	SAF supply (kt)	GHG emissions (kt CO2e)	GHG reduction (kt CO2e)
AL	14.2	FT_FR	349.9	3.6	49.4	FT_FR	210.0	3.6	49.4	FT_FR	105.0	3.6	49.4	FT_FR	52.5	3.6	49.4	FT_FR	21.0	3.6	49.4
AT	286.8	FT_FR	5652.1	73.7	1000.5	FT_FR	3391.2	73.7	1000.5	FT_FR	1695.6	73.7	1000.5	FT_FR	847.8	73.7	1000.5	FT_FR	339.1	73.7	1000.5
BA	11.5	FT_FR	905.8	3.0	40.1	FT_FR	543.5	3.0	40.1	FT_FR	271.7	3.0	40.1	FT_FR	135.9	3.0	40.1	FT_FR	54.3	3.0	40.1
BE	1463.2	FT_FR	1916.6	561.7	4918.0	FT_FR+A R+MSW	683.4	1572.0	3907.8	FT_FR+AR+ MSW	564.9	3525.8	1953.9	FT_FR+A R+MSW	282.4	4502.8	976.9	FT_FR+AR+ MSW	113.0	1175.7	4304.0
BG	87.5	FT_FR	1456.5	22.5	305.2	FT_FR	873.9	22.5	305.2	FT_FR	436.9	22.5	305.2	FT_FR	218.5	22.5	305.2	FT_FR+ATJ AR	224.6	22.5	305.1
CZ	139.9	FT_FR	4032.3	35.9	488.2	FT_FR	2419.4	35.9	488.2	FT_FR	1209.7	35.9	488.2	FT_FR	604.8	35.9	488.2	FT_FR	241.9	35.9	488.2
DE	3240.7	FT_FR	18274.4	832.2	11304.3	FT_FR	10964.6	832.2	11304.3	FT_FR	5482.3	832.2	11304.3	FT_FR+AT J_AR	4716.9	1118.7	11017.8	FT_FR+AR+ MSW	1745.3	2062.0	10074.5
DK	335.2	FT_FR	3241.0	86.1	1169.4	FT_FR	1944.6	86.1	1169.4	FT_FR	972.3	86.1	1169.4	FT_FR	486.2	86.1	1169.4	FT_FR+AR+ MSW	294.7	166.8	1088.6
EE	16.6	FT_FR	1890.7	4.3	58.0	FT_FR	1134.4	4.3	58.0	FT_FR	567.2	4.3	58.0	FT_FR	283.6	4.3	58.0	FT_FR	113.4	4.3	58.0
EL	422.2	FT_FR	1196.1	108.4	1472.7	FT_FR	717.6	108.4	1472.7	FT_FR+ATJ AR	885.2	144.8	1436.3	FT_FR+AT J_AR	442.6	247.7	1333.5	FT_FR+AR+ MSW	160.7	309.4	1271.7
ES	2872.1	FT_FR	5590.5	737.6	10018.4	FT_FR	3354.3	737.6	10018.4	FT_FR+ATJ AR	3991.3	1422.9	9333.1	FT_FR+A R+MSW	1825.5	4424.6	6331.3	FT_FR+AR+ MSW	730.2	2192.4	8563.6
FI	290.4	FT_FR	14511.0	74.6	1013.0	FT_FR	8706.6	74.6	1013.0	FT_FR	4353.3	74.6	1013.0	FT_FR	2176.6	74.6	1013.0	FT_FR	870.7	74.6	1013.0
FR	2499.2	FT_FR	15263.3	641.8	8717.7	FT_FR	9158.0	641.8	8717.7	FT_FR	4579.0	641.8	8717.7	FT_FR+AT J_AR	4608.1	762.1	8597.5	FT_FR+AR+ MSW	1686.7	1549.9	7809.6
HR	65.5	FT_FR	4590.3	16.8	228.3	FT_FR	2754.2	16.8	228.3	FT_FR	1377.1	16.8	228.3	FT_FR	688.5	16.8	228.3	FT_FR	275.4	16.8	228.3
HU	123.9	FT_FR	2400.6	31.8	432.0	FT_FR	1440.3	31.8	432.0	FT_FR	720.2	31.8	432.0	FT_FR	360.1	31.8	432.0	FT_FR	144.0	31.8	432.0
IE	339.0	FT_FR	1557.5	87.0	1182.3	FT_FR	934.5	87.0	1182.3	FT_FR	467.2	87.0	1182.3	FT_FR+A R+MSW	313.5	218.9	1050.5	FT_FR+AR+ MSW	120.8	227.8	1041.5
IT	1449.0	FT_FR	5015.9	372.1	5054.4	FT_FR	3009.5	372.1	5054.4	FT_FR	1504.8	372.1	5054.4	FT_FR+AT J_AR	1562.6	771.6	4654.8	FT_FR+AR+ MSW	601.5	1030.5	4395.9
LT	41.8	FT_FR	3528.8	10.7	145.9	FT_FR	2117.3	10.7	145.9	FT_FR	1058.6	10.7	145.9	FT_FR	529.3	10.7	145.9	FT_FR	211.7	10.7	145.9
LU	21.0	FT_FR	426.8	5.4	73.2	FT_FR	256.1	5.4	73.2	FT_FR	128.0	5.4	73.2	FT_FR	64.0	5.4	73.2	FT_FR	25.6	5.4	73.2
LV	44.8	FT_FR	2502.5	11.5	156.3	FT_FR	1501.5	11.5	156.3	FT_FR	750.7	11.5	156.3	FT_FR	375.4	11.5	156.3	FT_FR	150.1	11.5	156.3
MD	23.4	FT_FR	1067.5	6.0	81.5	FT_FR	640.5	6.0	81.5	FT_FR	320.2	6.0	81.5	FT_FR	160.1	6.0	81.5	FT_FR	64.0	6.0	81.5
ME	12.9	FT_FR	261.0	3.3	45.1	FT_FR	156.6	3.3	45.1	FT_FR	78.3	3.3	45.1	FT_FR	39.1	3.3	45.1	FT_FR	15.7	3.3	45.1
MK	16.0	FT_FR	288.5	4.1	55.7	FT_FR	173.1	4.1	55.7	FT_FR	86.5	4.1	55.7	FT_FR	43.3	4.1	55.7	FT_FR	17.3	4.1	55.7
NL	1358.8	FT_FR	1409.5	747.1	4341.6	FT_FR+A R+MSW	398.7	2136.3	2952.5	FT_FR+AR+ MSW	429.5	3612.5	1476.2	FT_FR+A R+MSW	214.7	4350.6	738.1	FT_FR+AR+ MSW	85.9	1105.4	3983.3
PL	254.6	FT_FR	8710.5	65.4	888.0	FT_FR	5226.3	65.4	888.0	FT_FR	2613.1	65.4	888.0	FT_FR	1306.6	65.4	888.0	FT_FR	522.6	65.4	888.0
PT	563.4	FT_FR	4024.7	144.7	1965.4	FT_FR	2414.8	144.7	1965.4	FT_FR	1207.4	144.7	1965.4	FT_FR	603.7	144.7	1965.4	FT_FR+AR+ MSW	275.4	329.3	1780.8
RO	188.7	FT_FR	6275.8	48.4	658.1	FT_FR	3765.5	48.4	658.1	FT_FR	1882.7	48.4	658.1	FT_FR	941.4	48.4	658.1	FT_FR	376.5	48.4	658.1
RS	60.7	FT_FR	1800.3	15.6	211.9	FT_FR	1080.2	15.6	211.9	FT_FR	540.1	15.6	211.9	FT_FR	270.0	15.6	211.9	FT_FR	108.0	15.6	211.9
SE	354.1	FT_FR	19786.7	90.9	1235.0	FT_FR	11872.0	90.9	1235.0	FT_FR	5936.0	90.9	1235.0	FT_FR	2968.0	90.9	1235.0	FT_FR	1187.2	90.9	1235.0
SI	9.4	FT_FR	1573.9	2.4	32.7	FT_FR	944.3	2.4	32.7	FT_FR	472.2	2.4	32.7	FT_FR	236.1	2.4	32.7	FT_FR	94.4	2.4	32.7
SK	18.7	FT_FR	3111.0	4.8	65.2	FT_FR	1866.6	4.8	65.2	FT_FR	933.3	4.8	65.2	FT_FR	466.7	4.8	65.2	FT_FR	186.7	4.8	65.2
UA	200.7	FT_FR	5230.2	51.5	699.9	FT_FR	3138.1	51.5	699.9	FT_FR	1569.0	51.5	699.9	FT_FR	784.5	51.5	699.9	FT_FR	313.8	51.5	699.9
UK	4407.9	FT_FR	5506.9	1131.9	15375.6	FT_FR+AT J_AR	6719.8	1764.9	14742.6	FT_FR+ATJ AR+FT_MS	6300.9	2506.1	14001.4	FT_FR+A R+MSW	2953.4	6759.3	9748.2	FT_FR+AR+ MSW	1181.4	3470.4	13037.1

Table A5 2040 Clean Sky – LOW scenario.

2040 Clean Sky - LOW																					
Country	SAF demand (kt)	100% biomass availability				60% biomass availability				30% biomass availability				15% biomass availability				6% biomass availability			
		Conversion pathway	SAF supply (kt)	GHG emissions (kt CO2e)	GHG reduction (kt CO2e)	Conversion pathway	SAF supply (kt)	GHG emissions (kt CO2e)	GHG reduction (kt CO2e)	Conversion pathway	SAF supply (kt)	GHG emissions (kt CO2e)	GHG reduction (kt CO2e)	Conversion pathway	SAF supply (kt)	GHG emissions (kt CO2e)	GHG reduction (kt CO2e)	Conversion pathway	SAF supply (kt)	GHG emissions (kt CO2e)	GHG reduction (kt CO2e)
AL	11.2	FT_FR	391.9	2.9	39.1	FT_FR	235.1	2.9	39.1	FT_FR	117.6	2.9	39.1	FT_FR	58.8	2.9	39.1	FT_FR	23.5	2.9	39.1
AT	225.8	FT_FR	5766.3	58.0	787.6	FT_FR	3459.8	58.0	787.6	FT_FR	1729.9	58.0	787.6	FT_FR	865.0	58.0	787.6	FT_FR	346.0	58.0	787.6
BA	9.2	FT_FR	923.6	2.4	32.2	FT_FR	554.2	2.4	32.2	FT_FR	277.1	2.4	32.2	FT_FR	138.5	2.4	32.2	FT_FR	55.4	2.4	32.2
BE	1195.3	FT_FR+AT J_AR	1958.0	326.4	4150.0	FT_FR+AT J_AR	1320.6	588.8	3887.6	FT_FR+A R+MSW	574.0	2490.0	1986.4	FT_FR+A R+MSW	287.0	3483.2	993.2	FT_FR+AR+ MSW	114.8	4079.1	397.3
BG	69.6	FT_FR	1486.3	17.9	242.9	FT_FR	891.8	17.9	242.9	FT_FR	445.9	17.9	242.9	FT_FR	222.9	17.9	242.9	FT_FR	89.2	17.9	242.9
CZ	111.6	FT_FR	4113.6	28.7	389.4	FT_FR	2468.2	28.7	389.4	FT_FR	1234.1	28.7	389.4	FT_FR	617.0	28.7	389.4	FT_FR	246.8	28.7	389.4
DE	2589.9	FT_FR	18641.9	665.1	9034.2	FT_FR	11185.1	665.1	9034.2	FT_FR	5592.6	665.1	9034.2	FT_FR	2796.3	665.1	9034.2	FT_FR+AR+ MSW	1779.8	3505.5	6193.8
DK	265.1	FT_FR	3288.9	68.1	924.9	FT_FR	1973.3	68.1	924.9	FT_FR	986.7	68.1	924.9	FT_FR	493.3	68.1	924.9	FT_FR+AR+ AR	323.3	107.0	886.0
EE	13.4	FT_FR	1928.4	3.4	46.8	FT_FR	1157.0	3.4	46.8	FT_FR	578.5	3.4	46.8	FT_FR	289.3	3.4	46.8	FT_FR	115.7	3.4	46.8
EL	336.7	FT_FR	1219.7	86.5	1174.4	FT_FR	731.8	86.5	1174.4	FT_FR	365.9	86.5	1174.4	FT_FR+AT J_AR	454.4	174.6	1086.3	FT_FR+AR+ MSW	164.2	690.8	570.1
ES	2283.3	FT_FR	5703.6	586.4	7964.7	FT_FR	3422.2	586.4	7964.7	FT_FR+AT J_AR	4090.6	914.6	7636.5	FT_FR+A R+MSW	1862.8	2087.9	6463.2	FT_FR+AR+ MSW	745.1	5965.8	2585.3
FI	228.7	FT_FR	14804.5	58.7	797.7	FT_FR	8882.7	58.7	797.7	FT_FR	4441.4	58.7	797.7	FT_FR	2220.7	58.7	797.7	FT_FR	888.3	58.7	797.7
FR	1993.4	FT_FR	15570.8	511.9	6953.3	FT_FR	9342.5	511.9	6953.3	FT_FR	4671.2	511.9	6953.3	FT_FR	2335.6	511.9	6953.3	FT_FR+AR+ MSW	1720.0	1486.0	5979.2
HR	52.2	FT_FR	4564.2	13.4	182.1	FT_FR	2738.5	13.4	182.1	FT_FR	1369.3	13.4	182.1	FT_FR	684.6	13.4	182.1	FT_FR	273.9	13.4	182.1
HU	100.0	FT_FR	2448.9	25.7	348.9	FT_FR	1469.3	25.7	348.9	FT_FR	734.7	25.7	348.9	FT_FR	367.3	25.7	348.9	FT_FR	146.9	25.7	348.9
IE	283.2	FT_FR	1750.6	72.7	987.9	FT_FR	1050.4	72.7	987.9	FT_FR	525.2	72.7	987.9	FT_FR+AT J_AR	344.4	84.5	976.1	FT_FR+AR+ MSW	132.8	598.3	462.3
IT	1147.9	FT_FR	4646.7	294.8	4004.2	FT_FR	2788.0	294.8	4004.2	FT_FR	1394.0	294.8	4004.2	FT_FR+AT J_AR	1529.9	553.4	3745.6	FT_FR+AR+ MSW	583.9	2280.4	2018.5
LT	33.6	FT_FR	3516.1	8.6	117.0	FT_FR	2109.7	8.6	117.0	FT_FR	1054.8	8.6	117.0	FT_FR	527.4	8.6	117.0	FT_FR	211.0	8.6	117.0
LU	16.5	FT_FR	435.2	4.2	57.7	FT_FR	261.1	4.2	57.7	FT_FR	130.6	4.2	57.7	FT_FR	65.3	4.2	57.7	FT_FR	26.1	4.2	57.7
LV	35.1	FT_FR	2553.3	9.0	122.4	FT_FR	1532.0	9.0	122.4	FT_FR	766.0	9.0	122.4	FT_FR	383.0	9.0	122.4	FT_FR	153.2	9.0	122.4
MD	18.7	FT_FR	1080.9	4.8	65.1	FT_FR	648.6	4.8	65.1	FT_FR	324.3	4.8	65.1	FT_FR	162.1	4.8	65.1	FT_FR	64.9	4.8	65.1
ME	9.9	FT_FR	249.8	2.5	34.5	FT_FR	149.9	2.5	34.5	FT_FR	74.9	2.5	34.5	FT_FR	37.5	2.5	34.5	FT_FR	15.0	2.5	34.5
MK	12.6	FT_FR	273.2	3.2	44.1	FT_FR	163.9	3.2	44.1	FT_FR	81.9	3.2	44.1	FT_FR	41.0	3.2	44.1	FT_FR	16.4	3.2	44.1
NL	1070.5	FT_FR+AT J_AR	1440.1	500.4	3508.5	FT_FR+A R+MSW	952.5	1016.9	2992.0	FT_FR+A R+MSW	434.9	2512.9	1496.0	FT_FR+A R+MSW	217.4	3260.9	748.0	FT_FR+AR+ MSW	87.0	3709.7	299.2
PL	204.9	FT_FR	8884.8	52.6	714.8	FT_FR	5330.9	52.6	714.8	FT_FR	2665.5	52.6	714.8	FT_FR	1332.7	52.6	714.8	FT_FR	533.1	52.6	714.8
PT	443.9	FT_FR	4106.9	114.0	1548.4	FT_FR	2464.1	114.0	1548.4	FT_FR	1232.1	114.0	1548.4	FT_FR	616.0	114.0	1548.4	FT_FR+AR+ MSW	289.2	685.2	977.2
RO	150.7	FT_FR	6116.5	38.7	525.8	FT_FR	3669.9	38.7	525.8	FT_FR	1835.0	38.7	525.8	FT_FR	917.5	38.7	525.8	FT_FR	367.0	38.7	525.8
RS	47.3	FT_FR	1835.8	12.1	164.9	FT_FR	1101.5	12.1	164.9	FT_FR	550.7	12.1	164.9	FT_FR	275.4	12.1	164.9	FT_FR	110.1	12.1	164.9
SE	281.2	FT_FR	19894.0	72.2	980.8	FT_FR	11936.4	72.2	980.8	FT_FR	5968.2	72.2	980.8	FT_FR	2984.1	72.2	980.8	FT_FR	1193.6	72.2	980.8
SI	7.4	FT_FR	1605.7	1.9	25.8	FT_FR	963.4	1.9	25.8	FT_FR	481.7	1.9	25.8	FT_FR	240.9	1.9	25.8	FT_FR	96.3	1.9	25.8
SK	15.2	FT_FR	3464.7	3.9	52.9	FT_FR	2078.8	3.9	52.9	FT_FR	1039.4	3.9	52.9	FT_FR	519.7	3.9	52.9	FT_FR	207.9	3.9	52.9
UA	160.8	FT_FR	5187.1	41.3	561.0	FT_FR	3112.3	41.3	561.0	FT_FR	1556.1	41.3	561.0	FT_FR	778.1	41.3	561.0	FT_FR	311.2	41.3	561.0
UK	3605.8	FT_FR	5514.6	926.0	12577.8	FT_FR+AT J_AR	6805.2	1096.3	12407.4	FT_FR+AT J_AR	5433.3	2005.1	11498.6	FT_FR+A R+MSW	2514.9	5113.5	8390.2	FT_FR+AR+ MSW	1006.0	10147.6	3356.1

Table A6 2040 Clean Sky – HIGH scenario.

2040 Clean Sky - HIGH																					
Country	SAF demand (kt)	100% biomass availability				60% biomass availability				30% biomass availability				15% biomass availability				6% biomass availability			
		Conversion pathway	SAF supply (kt)	GHG emissions (kt CO2e)	GHG reduction (kt CO2e)	Conversion pathway	SAF supply (kt)	GHG emissions (kt CO2e)	GHG reduction (kt CO2e)	Conversion pathway	SAF supply (kt)	GHG emissions (kt CO2e)	GHG reduction (kt CO2e)	Conversion pathway	SAF supply (kt)	GHG emissions (kt CO2e)	GHG reduction (kt CO2e)	Conversion pathway	SAF supply (kt)	GHG emissions (kt CO2e)	GHG reduction (kt CO2e)
AL	24.8	FT_FR	391.9	6.4	86.6	FT_FR	235.1	6.4	86.6	FT_FR	117.6	6.4	86.6	FT_FR	58.8	6.4	86.6	FT_FR+ATJ AR	34.7	7.1	85.8
AT	493.2	FT_FR	5766.3	126.6	1720.2	FT_FR	3459.8	126.6	1720.2	FT_FR	1729.9	126.6	1720.2	FT_FR	865.0	126.6	1720.2	MSW	405.5	435.7	1411.2
BA	20.0	FT_FR	923.6	5.1	69.8	FT_FR	554.2	5.1	69.8	FT_FR	277.1	5.1	69.8	FT_FR	138.5	5.1	69.8	FT_FR	55.4	5.1	69.8
BE	2579.9	FT_FR+A R+MSW	1913.2	3040.6	6621.2	FT_FR+A R+MSW	1147.9	5689.0	3972.7	FT_FR+A R+MSW	574.0	7675.4	1986.4	FT_FR+A R+MSW	287.0	8668.6	993.2	FT_FR+AR+ MSW	114.8	9264.5	397.3
BG	152.2	FT_FR	1486.3	39.1	531.0	FT_FR	891.8	39.1	531.0	FT_FR	445.9	39.1	531.0	FT_FR	222.9	39.1	531.0	FT_FR+ATJ AR	229.9	75.3	494.9
CZ	241.7	FT_FR	4113.6	62.1	843.2	FT_FR	2468.2	62.1	843.2	FT_FR	1234.1	62.1	843.2	FT_FR	617.0	62.1	843.2	FT_FR	246.8	62.1	843.2
DE	5520.7	FT_FR	18641.9	1417.7	19257.3	FT_FR	11185.1	1417.7	19257.3	FT_FR	5592.6	1417.7	19257.3	FT_FR+A R+MSW	4449.6	5190.6	15484.4	FT_FR+AR+ MSW	1779.8	14481.2	6193.8
DK	575.9	FT_FR	3288.9	147.9	2008.8	FT_FR	1973.3	147.9	2008.8	FT_FR	986.7	147.9	2008.8	FT_FR+AT J_AR	808.3	195.2	1961.5	FT_FR+AR+ MSW	299.6	1113.5	1043.2
EE	28.7	FT_FR	1928.4	7.4	100.1	FT_FR	1157.0	7.4	100.1	FT_FR	578.5	7.4	100.1	FT_FR	289.3	7.4	100.1	FT_FR	115.7	7.4	100.1
EL	724.3	FT_FR	1219.7	186.0	2526.5	FT_FR	731.8	186.0	2526.5	FT_FR	365.9	186.0	2526.5	FT_FR+A R+MSW	473.2	1287.3	1425.2	FT_FR+AR+ MSW	164.2	2142.4	570.1
ES	4928.5	FT_FR	5703.6	1265.6	17191.5	FT_FR+AT J_AR	8181.1	2129.5	16327.6	FT_FR+A R+MSW	3725.6	5530.8	12926.3	FT_FR+A R+MSW	2137.4	11994.0	6463.2	FT_FR+AR+ MSW	745.1	15871.9	2585.3
FI	498.4	FT_FR	14804.5	128.0	1738.7	FT_FR	8882.7	128.0	1738.7	FT_FR	4441.4	128.0	1738.7	FT_FR	2220.7	128.0	1738.7	FT_FR	888.3	128.0	1738.7
FR	4250.3	FT_FR	15570.8	1091.5	14825.9	FT_FR	9342.5	1091.5	14825.9	FT_FR	4671.2	1091.5	14825.9	FT_FR+AT J_AR	4711.3	2189.6	13727.8	FT_FR+AR+ MSW	1720.0	9938.2	5979.2
HR	114.2	FT_FR	4564.2	29.3	398.4	FT_FR	2738.5	29.3	398.4	FT_FR	1369.3	29.3	398.4	FT_FR	684.6	29.3	398.4	FT_FR	273.9	29.3	398.4
HU	214.9	FT_FR	2448.9	55.2	749.7	FT_FR	1469.3	55.2	749.7	FT_FR	734.7	55.2	749.7	FT_FR	367.3	55.2	749.7	FT_FR+ATJ AR	308.3	94.2	710.7
IE	571.5	FT_FR	1750.6	146.8	1993.7	FT_FR	1050.4	146.8	1993.7	FT_FR+AT J_AR	688.7	173.4	1967.1	FT_FR+A R+MSW	332.0	984.8	1155.7	FT_FR+AR+ MSW	132.8	1678.2	462.3
IT	2473.0	FT_FR	4646.7	635.1	8626.2	FT_FR	2788.0	635.1	8626.2	FT_FR+AT J_AR	3059.9	1253.9	8007.4	FT_FR+A R+MSW	1459.9	4215.0	5046.3	FT_FR+AR+ MSW	583.9	7242.8	2018.5
LT	72.1	FT_FR	3516.1	18.5	251.6	FT_FR	2109.7	18.5	251.6	FT_FR	1054.8	18.5	251.6	FT_FR	527.4	18.5	251.6	FT_FR	211.0	18.5	251.6
LU	35.9	FT_FR	435.2	9.2	125.1	FT_FR	261.1	9.2	125.1	FT_FR	130.6	9.2	125.1	FT_FR	65.3	9.2	125.1	FT_FR+AR+ MSW	28.5	35.3	99.1
LV	77.3	FT_FR	2553.3	19.9	269.8	FT_FR	1532.0	19.9	269.8	FT_FR	766.0	19.9	269.8	FT_FR	383.0	19.9	269.8	FT_FR	153.2	19.9	269.8
MD	40.7	FT_FR	1080.9	10.5	142.1	FT_FR	648.6	10.5	142.1	FT_FR	324.3	10.5	142.1	FT_FR	162.1	10.5	142.1	FT_FR	64.9	10.5	142.1
ME	22.6	FT_FR	249.8	5.8	78.7	FT_FR	149.9	5.8	78.7	FT_FR	74.9	5.8	78.7	FT_FR	37.5	5.8	78.7	FT_FR+AR+ MSW	15.8	29.6	54.9
MK	27.8	FT_FR	273.2	7.2	97.1	FT_FR	163.9	7.2	97.1	FT_FR	81.9	7.2	97.1	FT_FR	41.0	7.2	97.1	FT_FR+AR+ MSW	24.6	18.8	85.5
NL	2320.7	FT_FR+A R+MSW	1449.6	3704.2	4986.7	FT_FR+A R+MSW	869.8	5698.9	2992.0	FT_FR+A R+MSW	434.9	7194.9	1496.0	FT_FR+A R+MSW	217.4	7942.9	748.0	FT_FR+AR+ MSW	87.0	8391.8	299.2
PL	437.3	FT_FR	8884.8	112.3	1525.2	FT_FR	5330.9	112.3	1525.2	FT_FR	2665.5	112.3	1525.2	FT_FR	1332.7	112.3	1525.2	FT_FR	533.1	112.3	1525.2
PT	966.8	FT_FR	4106.9	248.3	3372.4	FT_FR	2464.1	248.3	3372.4	FT_FR	1232.1	248.3	3372.4	FT_FR+A R+MSW	702.2	1177.7	2442.9	FT_FR+AR+ MSW	280.9	2643.5	977.2
RO	329.9	FT_FR	6116.5	84.7	1150.6	FT_FR	3669.9	84.7	1150.6	FT_FR	1835.0	84.7	1150.6	FT_FR	917.5	84.7	1150.6	FT_FR	367.0	84.7	1150.6
RS	106.2	FT_FR	1835.8	27.3	370.4	FT_FR	1101.5	27.3	370.4	FT_FR	550.7	27.3	370.4	FT_FR	275.4	27.3	370.4	FT_FR	110.1	27.3	370.4
SE	607.1	FT_FR	19894.0	155.9	2117.7	FT_FR	11936.4	155.9	2117.7	FT_FR	5968.2	155.9	2117.7	FT_FR	2984.1	155.9	2117.7	FT_FR	1193.6	155.9	2117.7
SI	16.3	FT_FR	1605.7	4.2	56.7	FT_FR	963.4	4.2	56.7	FT_FR	481.7	4.2	56.7	FT_FR	240.9	4.2	56.7	FT_FR	96.3	4.2	56.7
SK	32.3	FT_FR	3464.7	8.3	112.6	FT_FR	2078.8	8.3	112.6	FT_FR	1039.4	8.3	112.6	FT_FR	519.7	8.3	112.6	FT_FR	207.9	8.3	112.6
UA	350.7	FT_FR	5187.1	90.1	1223.4	FT_FR	3112.3	90.1	1223.4	FT_FR	1556.1	90.1	1223.4	FT_FR	778.1	90.1	1223.4	FT_FR+ATJ AR	1501.1	112.7	1200.8
UK	7532.0	FT_FR+AT J_AR	11341.9	3091.3	25116.2	FT_FR+AT J_AR	10866.6	4213.2	23994.2	FT_FR+A R+MSW	5029.9	11427.1	16780.4	FT_FR+A R+MSW	2514.9	19817.3	8390.2	FT_FR+AR+ MSW	1006.0	24851.4	3356.1

Table A7 2045 Clean Sky – LOW scenario.

2045 Clean Sky - LOW																					
Country	SAF demand (kt)	100% biomass availability				60% biomass availability				30% biomass availability				15% biomass availability				6% biomass availability			
		Conversion pathway	SAF supply (kt)	GHG emissions (kt CO2e)	GHG reduction (kt CO2e)	Conversion pathway	SAF supply (kt)	GHG emissions (kt CO2e)	GHG reduction (kt CO2e)	Conversion pathway	SAF supply (kt)	GHG emissions (kt CO2e)	GHG reduction (kt CO2e)	Conversion pathway	SAF supply (kt)	GHG emissions (kt CO2e)	GHG reduction (kt CO2e)	Conversion pathway	SAF supply (kt)	GHG emissions (kt CO2e)	GHG reduction (kt CO2e)
AL	15.1	FT_FR	433.8	3.9	52.5	FT_FR	260.3	3.9	52.5	FT_FR	130.2	3.9	52.5	FT_FR	65.1	3.9	52.5	FT_FR	26.0	3.9	52.5
AT	298.5	FT_FR	5880.6	76.6	1041.1	FT_FR	3528.4	76.6	1041.1	FT_FR	1764.2	76.6	1041.1	FT_FR	882.1	76.6	1041.1	FT_FR	352.8	76.6	1041.1
BA	12.4	FT_FR	941.4	3.2	43.1	FT_FR	564.9	3.2	43.1	FT_FR	282.4	3.2	43.1	FT_FR	141.2	3.2	43.1	FT_FR	56.5	3.2	43.1
BE	1619.7	FT_FR+AT J_AR	1999.4	665.8	5399.9	FT_FR+A R+MSW	1166.1	2028.0	4037.7	FT_FR+A R+MSW	583.0	4046.9	2018.8	FT_FR+A R+MSW	291.5	5056.3	1009.4	FT_FR+AR+ MSW	116.6	5662.0	403.8
BG	93.1	FT_FR	1516.1	23.9	324.7	FT_FR	909.7	23.9	324.7	FT_FR	454.8	23.9	324.7	FT_FR	227.4	23.9	324.7	FT_FR+ATJ AR	235.3	25.1	323.5
CZ	148.4	FT_FR	4195.0	38.1	517.6	FT_FR	2517.0	38.1	517.6	FT_FR	1258.5	38.1	517.6	FT_FR	629.2	38.1	517.6	FT_FR	251.7	38.1	517.6
DE	3404.5	FT_FR	19009.4	874.3	11875.6	FT_FR	11405.6	874.3	11875.6	FT_FR	5702.8	874.3	11875.6	FT_FR+AT J_AR	4922.1	1191.5	11558.4	FT_FR+AR+ MSW	1814.3	6434.9	6315.0
DK	350.4	FT_FR	3336.8	90.0	1222.3	FT_FR	2002.1	90.0	1222.3	FT_FR	1001.0	90.0	1222.3	FT_FR	500.5	90.0	1222.3	MSW	304.6	251.9	1060.4
EE	17.9	FT_FR	1966.1	4.6	62.3	FT_FR	1179.6	4.6	62.3	FT_FR	589.8	4.6	62.3	FT_FR	294.9	4.6	62.3	FT_FR	118.0	4.6	62.3
EL	445.0	FT_FR	1243.4	114.3	1552.2	FT_FR	746.1	114.3	1552.2	FT_FR+AT J_AR	932.3	155.6	1511.0	FT_FR+AT J_AR	483.9	262.5	1404.0	FT_FR+AR+ MSW	167.8	1084.0	582.5
ES	3017.2	FT_FR	5816.7	774.8	10524.4	FT_FR	3490.0	774.8	10524.4	FT_FR+AT J_AR	4189.8	1504.4	9794.8	FT_FR+A R+MSW	1900.1	4704.3	6595.0	FT_FR+AR+ MSW	760.0	8661.3	2638.0
FI	301.8	FT_FR	15098.1	77.5	1052.9	FT_FR	9058.9	77.5	1052.9	FT_FR	4529.4	77.5	1052.9	FT_FR	2264.7	77.5	1052.9	FT_FR	905.9	77.5	1052.9
FR	2616.0	FT_FR	15878.2	671.8	9125.1	FT_FR	9526.9	671.8	9125.1	FT_FR	4763.5	671.8	9125.1	FT_FR+AT J_AR	4814.5	806.1	8990.8	FT_FR+AR+ MSW	1753.4	3700.3	6096.6
HR	70.0	FT_FR	4538.2	18.0	244.1	FT_FR	2722.9	18.0	244.1	FT_FR	1361.4	18.0	244.1	FT_FR	680.7	18.0	244.1	FT_FR	272.3	18.0	244.1
HU	133.7	FT_FR	2497.2	34.3	466.2	FT_FR	1498.3	34.3	466.2	FT_FR	749.2	34.3	466.2	FT_FR	374.6	34.3	466.2	FT_FR	149.8	34.3	466.2
IE	371.6	FT_FR	1943.7	95.4	1296.3	FT_FR	1166.2	95.4	1296.3	FT_FR	583.1	95.4	1296.3	FT_FR+A R+MSW	362.1	141.4	1250.4	FT_FR+AR+ MSW	144.9	887.4	504.3
IT	1509.4	FT_FR	4277.5	387.6	5265.0	FT_FR	2566.5	387.6	5265.0	FT_FR+AT J_AR	2994.6	517.3	5135.3	FT_FR+A R+MSW	1416.0	882.9	4769.7	FT_FR+AR+ MSW	566.4	3694.4	1958.2
LT	44.6	FT_FR	3503.5	11.4	155.5	FT_FR	2102.1	11.4	155.5	FT_FR	1051.1	11.4	155.5	FT_FR	525.5	11.4	155.5	FT_FR	210.2	11.4	155.5
LU	21.8	FT_FR	443.7	5.6	75.9	FT_FR	266.2	5.6	75.9	FT_FR	133.1	5.6	75.9	FT_FR	66.6	5.6	75.9	FT_FR	26.6	5.6	75.9
LV	46.5	FT_FR	2604.2	11.9	162.1	FT_FR	1562.5	11.9	162.1	FT_FR	781.3	11.9	162.1	FT_FR	390.6	11.9	162.1	FT_FR	156.3	11.9	162.1
MD	25.0	FT_FR	1094.4	6.4	87.3	FT_FR	656.6	6.4	87.3	FT_FR	328.3	6.4	87.3	FT_FR	164.2	6.4	87.3	FT_FR	65.7	6.4	87.3
ME	13.2	FT_FR	238.6	3.4	46.1	FT_FR	143.2	3.4	46.1	FT_FR	71.6	3.4	46.1	FT_FR	35.8	3.4	46.1	FT_FR	14.3	3.4	46.1
MK	16.9	FT_FR	257.8	4.3	59.0	FT_FR	154.7	4.3	59.0	FT_FR	77.4	4.3	59.0	FT_FR	38.7	4.3	59.0	FT_FR+ATJ AR	25.1	5.2	58.2
NL	1407.2	FT_FR+AT J_AR	1470.7	772.7	4497.4	FT_FR+A R+MSW	880.6	2238.5	3031.6	FT_FR+A R+MSW	440.3	3754.3	1515.8	FT_FR+A R+MSW	220.1	4512.2	757.9	FT_FR+AR+ MSW	88.1	4966.9	303.2
PL	271.4	FT_FR	9059.2	69.7	946.9	FT_FR	5435.5	69.7	946.9	FT_FR	2717.8	69.7	946.9	FT_FR	1358.9	69.7	946.9	FT_FR	543.6	69.7	946.9
PT	585.8	FT_FR	4189.0	150.4	2043.4	FT_FR	2513.4	150.4	2043.4	FT_FR	1256.7	150.4	2043.4	FT_FR	628.4	150.4	2043.4	FT_FR+AR+ MSW	286.3	1197.6	996.3
RO	202.4	FT_FR	5957.2	52.0	705.9	FT_FR	3574.3	52.0	705.9	FT_FR	1787.2	52.0	705.9	FT_FR	893.6	52.0	705.9	FT_FR	357.4	52.0	705.9
RS	63.3	FT_FR	1871.3	16.2	220.7	FT_FR	1122.8	16.2	220.7	FT_FR	561.4	16.2	220.7	FT_FR	280.7	16.2	220.7	FT_FR	112.3	16.2	220.7
SE	371.2	FT_FR	20001.3	95.3	1295.0	FT_FR	12000.8	95.3	1295.0	FT_FR	6000.4	95.3	1295.0	FT_FR	3000.2	95.3	1295.0	FT_FR	1200.1	95.3	1295.0
SI	9.9	FT_FR	1637.5	2.5	34.4	FT_FR	982.5	2.5	34.4	FT_FR	491.2	2.5	34.4	FT_FR	245.6	2.5	34.4	FT_FR	98.2	2.5	34.4
SK	20.2	FT_FR	3818.3	5.2	70.4	FT_FR	2291.0	5.2	70.4	FT_FR	1145.5	5.2	70.4	FT_FR	572.7	5.2	70.4	FT_FR	229.1	5.2	70.4
UA	215.9	FT_FR	5144.1	55.5	753.3	FT_FR	3086.5	55.5	753.3	FT_FR	1543.2	55.5	753.3	FT_FR	771.6	55.5	753.3	FT_FR	308.6	55.5	753.3
UK	4766.8	FT_FR	5522.3	1224.1	16627.7	FT_FR+AT J_AR	6890.5	2057.7	15794.1	FT_FR+A R+MSW	4942.2	3873.3	13978.5	FT_FR+A R+MSW	2076.5	10819.6	7032.2	MSW	830.6	15039.0	2812.9

Table A8 2045 Clean Sky – HIGH scenario.

2045 Clean Sky - HIGH																					
Country	SAF demand (kt)	100% biomass availability				60% biomass availability				30% biomass availability				15% biomass availability				6% biomass availability			
		Conversion pathway	SAF supply (kt)	GHG emissions (kt CO2e)	GHG reduction (kt CO2e)	Conversion pathway	SAF supply (kt)	GHG emissions (kt CO2e)	GHG reduction (kt CO2e)	Conversion pathway	SAF supply (kt)	GHG emissions (kt CO2e)	GHG reduction (kt CO2e)	Conversion pathway	SAF supply (kt)	GHG emissions (kt CO2e)	GHG reduction (kt CO2e)	Conversion pathway	SAF supply (kt)	GHG emissions (kt CO2e)	GHG reduction (kt CO2e)
AL	35.5	FT_FR	433.8	9.1	123.7	FT_FR	260.3	9.1	123.7	FT_FR	130.2	9.1	123.7	FT_FR	65.1	9.1	123.7	FT_FR+ATJ AR	37.6	14.5	118.3
AT	699.5	FT_FR	5880.6	179.6	2440.0	FT_FR	3528.4	179.6	2440.0	FT_FR	1764.2	179.6	2440.0	FT_FR	882.1	179.6	2440.0	MSW	413.2	1181.4	1438.3
BA	28.5	FT_FR	941.4	7.3	99.5	FT_FR	564.9	7.3	99.5	FT_FR	282.4	7.3	99.5	FT_FR	141.2	7.3	99.5	FT_FR	56.5	7.3	99.5
BE	3696.6	FT_FR+A R+MSW	1943.5	7114.3	6729.5	FT_FR+A R+MSW	1166.1	9806.1	4037.7	FT_FR+A R+MSW	583.0	11825.0	2018.8	FT_FR+A R+MSW	291.5	12834.4	1009.4	FT_FR+AR+ MSW	116.6	13440.0	403.8
BG	217.0	FT_FR	1516.1	55.7	756.9	FT_FR	909.7	55.7	756.9	FT_FR	454.8	55.7	756.9	FT_FR	227.4	55.7	756.9	FT_FR+ATJ AR	235.3	128.0	684.6
CZ	343.5	FT_FR	4195.0	88.2	1198.3	FT_FR	2517.0	88.2	1198.3	FT_FR	1258.5	88.2	1198.3	FT_FR	629.2	88.2	1198.3	FT_FR+ATJ AR	394.6	140.9	1145.7
DE	7800.7	FT_FR	19009.4	2003.2	27210.3	FT_FR	11405.6	2003.2	27210.3	FT_FR+AT J_AR	9844.1	3206.4	26007.1	FT_FR+A R+MSW	4535.8	4841.7	24371.8	FT_FR+AR+ MSW	1814.3	22898.5	6315.0
DK	816.6	FT_FR	3336.8	209.7	2848.3	FT_FR	2002.1	209.7	2848.3	FT_FR	1001.0	209.7	2848.3	FT_FR+AT J_AR	822.9	390.9	2667.0	FT_FR+AR+ MSW	304.6	1997.6	1060.4
EE	40.7	FT_FR	1966.1	10.5	142.1	FT_FR	1179.6	10.5	142.1	FT_FR	589.8	10.5	142.1	FT_FR	294.9	10.5	142.1	FT_FR	118.0	10.5	142.1
EL	1026.4	FT_FR	1243.4	263.6	3580.3	FT_FR+AT J_AR	1864.6	424.4	3419.5	FT_FR+A R+MSW	838.8	638.3	3205.6	FT_FR+A R+MSW	419.4	745.3	3098.6	FT_FR+AR+ MSW	167.8	3261.5	582.5
ES	6984.9	FT_FR+AT J_AR	13966.1	2463.7	23694.7	FT_FR+AT J_AR	8379.7	3798.1	22360.3	FT_FR+A R+MSW	3800.2	4798.9	21359.5	FT_FR+A R+MSW	1900.1	19563.4	6595.0	FT_FR+AR+ MSW	760.0	23520.4	2638.0
FI	706.5	FT_FR	15098.1	181.4	2464.3	FT_FR	9058.9	181.4	2464.3	FT_FR	4529.4	181.4	2464.3	FT_FR	2264.7	181.4	2464.3	FT_FR	905.9	181.4	2464.3
FR	6001.4	FT_FR	15878.2	1541.2	20934.2	FT_FR	9526.9	1541.2	20934.2	FT_FR+AT J_AR	9629.1	2251.2	20224.2	FT_FR+A R+MSW	4383.5	3617.1	18858.2	FT_FR+AR+ MSW	1753.4	16378.7	6096.6
HR	163.0	FT_FR	4538.2	41.8	568.4	FT_FR	2722.9	41.8	568.4	FT_FR	1361.4	41.8	568.4	FT_FR	680.7	41.8	568.4	FT_FR	272.3	41.8	568.4
HU	306.0	FT_FR	2497.2	78.6	1067.4	FT_FR	1498.3	78.6	1067.4	FT_FR	749.2	78.6	1067.4	FT_FR	374.6	78.6	1067.4	FT_FR+ATJ AR	359.1	168.1	977.8
IE	804.1	FT_FR	1943.7	206.5	2805.0	FT_FR	1166.2	206.5	2805.0	FT_FR+A R+MSW	724.3	333.3	2678.2	FT_FR+A R+MSW	362.1	500.5	2511.0	FT_FR+AR+ MSW	144.9	2507.2	504.3
IT	3497.0	FT_FR	4277.5	898.0	12198.1	FT_FR+AT J_AR	5989.3	1431.7	11664.4	FT_FR+A R+MSW	2832.0	2167.6	10928.5	FT_FR+A R+MSW	1416.0	8200.5	4895.6	FT_FR+AR+ MSW	566.4	11137.9	1958.2
LT	102.5	FT_FR	3503.5	26.3	357.4	FT_FR	2102.1	26.3	357.4	FT_FR	1051.1	26.3	357.4	FT_FR	525.5	26.3	357.4	FT_FR	210.2	26.3	357.4
LU	50.8	FT_FR	443.7	13.0	177.1	FT_FR	266.2	13.0	177.1	FT_FR	133.1	13.0	177.1	FT_FR	66.6	13.0	177.1	FT_FR+AR+ MSW	29.0	89.3	100.9
LV	109.9	FT_FR	2604.2	28.2	383.3	FT_FR	1562.5	28.2	383.3	FT_FR	781.3	28.2	383.3	FT_FR	390.6	28.2	383.3	FT_FR	156.3	28.2	383.3
MD	58.1	FT_FR	1094.4	14.9	202.8	FT_FR	656.6	14.9	202.8	FT_FR	328.3	14.9	202.8	FT_FR	164.2	14.9	202.8	FT_FR	65.7	14.9	202.8
ME	32.2	FT_FR	238.6	8.3	112.4	FT_FR	143.2	8.3	112.4	FT_FR	71.6	8.3	112.4	FT_FR	35.8	8.3	112.4	FT_FR+AR+ MSW	15.1	68.1	52.6
MK	39.7	FT_FR	257.8	10.2	138.6	FT_FR	154.7	10.2	138.6	FT_FR	77.4	10.2	138.6	FT_FR+AT J_AR	62.6	10.8	138.0	FT_FR+AR+ MSW	23.8	66.0	82.8
NL	3282.6	FT_FR+A R+MSW	1467.6	7240.5	5052.7	FT_FR+A R+MSW	880.6	9261.6	3031.6	FT_FR+A R+MSW	440.3	10777.4	1515.8	FT_FR+A R+MSW	220.1	11535.3	757.9	FT_FR+AR+ MSW	88.1	11990.0	303.2
PL	619.9	FT_FR	9059.2	159.2	2162.4	FT_FR	5435.5	159.2	2162.4	FT_FR	2717.8	159.2	2162.4	FT_FR	1358.9	159.2	2162.4	FT_FR+ATJ AR	958.0	203.0	2118.6
PT	1370.1	FT_FR	4189.0	351.9	4779.4	FT_FR	2513.4	351.9	4779.4	FT_FR+AT J_AR	1442.7	416.9	4714.3	FT_FR+A R+MSW	715.7	777.3	4353.9	FT_FR+AR+ MSW	286.3	4134.9	996.3
RO	471.1	FT_FR	5957.2	121.0	1643.2	FT_FR	3574.3	121.0	1643.2	FT_FR	1787.2	121.0	1643.2	FT_FR	893.6	121.0	1643.2	FT_FR+ATJ AR	643.2	186.1	1578.0
RS	151.7	FT_FR	1871.3	38.9	529.0	FT_FR	1122.8	38.9	529.0	FT_FR	561.4	38.9	529.0	FT_FR	280.7	38.9	529.0	FT_FR+ATJ AR	242.2	61.5	506.4
SE	860.1	FT_FR	20001.3	220.9	3000.3	FT_FR	12000.8	220.9	3000.3	FT_FR	6000.4	220.9	3000.3	FT_FR	3000.2	220.9	3000.3	FT_FR	1200.1	220.9	3000.3
SI	23.2	FT_FR	1637.5	5.9	80.8	FT_FR	982.5	5.9	80.8	FT_FR	491.2	5.9	80.8	FT_FR	245.6	5.9	80.8	FT_FR	98.2	5.9	80.8
SK	45.9	FT_FR	3818.3	11.8	160.0	FT_FR	2291.0	11.8	160.0	FT_FR	1145.5	11.8	160.0	FT_FR	572.7	11.8	160.0	FT_FR	229.1	11.8	160.0
UA	500.8	FT_FR	5144.1	128.6	1746.9	FT_FR	3086.5	128.6	1746.9	FT_FR	1543.2	128.6	1746.9	FT_FR	771.6	128.6	1746.9	FT_FR+ATJ AR	1525.7	238.8	1636.7
UK	10656.0	FT_FR+AT J_AR	11484.2	5680.9	34226.5	FT_FR+A R+MSW	8305.9	11778.7	28128.7	FT_FR+A R+MSW	4153.0	25843.1	14064.4	FT_FR+A R+MSW	2076.5	32875.3	7032.2	FT_FR+AR+ MSW	830.6	37094.6	2812.9

Table A9 2050 Clean Sky – LOW scenario.

2050 Clean Sky - LOW																					
Country	SAF demand (kt)	100% biomass availability				60% biomass availability				30% biomass availability				15% biomass availability				6% biomass availability			
		Conversion pathway	SAF supply (kt)	GHG emissions (kt CO2e)	GHG reduction (kt CO2e)	Conversion pathway	SAF supply (kt)	GHG emissions (kt CO2e)	GHG reduction (kt CO2e)	Conversion pathway	SAF supply (kt)	GHG emissions (kt CO2e)	GHG reduction (kt CO2e)	Conversion pathway	SAF supply (kt)	GHG emissions (kt CO2e)	GHG reduction (kt CO2e)	Conversion pathway	SAF supply (kt)	GHG emissions (kt CO2e)	GHG reduction (kt CO2e)
AL	18.9	FT_FR	475.8	4.9	65.9	FT_FR	285.5	4.9	65.9	FT_FR	142.7	4.9	65.9	FT_FR	71.4	4.9	65.9	FT_FR	28.5	4.9	65.9
AT	371.1	FT_FR	5994.9	95.3	1294.6	FT_FR	3596.9	95.3	1294.6	FT_FR	1798.5	95.3	1294.6	FT_FR	899.2	95.3	1294.6	FT_FR+ATJ AR	429.5	101.9	1288.0
BA	15.5	FT_FR	959.3	4.0	54.0	FT_FR	575.6	4.0	54.0	FT_FR	287.8	4.0	54.0	FT_FR	143.9	4.0	54.0	FT_FR	57.6	4.0	54.0
BE	2044.1	FT_FR+A R+MSW	2166.3	1004.6	6650.5	FT_FR+A R+MSW	1184.3	3552.4	4102.7	FT_FR+A R+MSW	592.1	5603.8	2051.3	FT_FR+A R+MSW	296.1	6629.4	1025.7	MSW	118.4	7244.8	410.3
BG	116.5	FT_FR	1545.9	29.9	406.5	FT_FR	927.6	29.9	406.5	FT_FR	463.8	29.9	406.5	FT_FR	231.9	29.9	406.5	FT_FR+ATJ AR	240.6	43.6	392.9
CZ	185.1	FT_FR	4276.3	47.5	645.7	FT_FR	2565.8	47.5	645.7	FT_FR	1282.9	47.5	645.7	FT_FR	641.4	47.5	645.7	FT_FR	256.6	47.5	645.7
DE	4219.1	FT_FR	19376.9	1083.5	14717.1	FT_FR	11626.1	1083.5	14717.1	FT_FR	5813.1	1083.5	14717.1	FT_FR+AT J_AR	5024.6	1836.3	13964.3	FT_FR+AR+ MSW	1848.9	9364.4	6436.2
DK	435.7	FT_FR	3384.7	111.9	1519.8	FT_FR	2030.8	111.9	1519.8	FT_FR	1015.4	111.9	1519.8	FT_FR	507.7	111.9	1519.8	MSW	309.5	554.1	1077.6
EE	22.3	FT_FR	2003.8	5.7	77.8	FT_FR	1202.3	5.7	77.8	FT_FR	601.1	5.7	77.8	FT_FR	300.6	5.7	77.8	FT_FR	120.2	5.7	77.8
EL	553.3	FT_FR	1267.1	142.1	1930.0	FT_FR	760.3	142.1	1930.0	FT_FR+AT J_AR	955.9	241.4	1830.7	FT_FR+A R+MSW	428.1	584.9	1487.2	MSW	171.3	1477.2	594.9
ES	3751.0	FT_FR	5929.8	963.3	13084.2	FT_FR+AT J_AR	8578.3	1074.0	12973.4	FT_FR+AT J_AR	4289.1	2094.3	11953.2	FT_FR+A R+MSW	1937.4	7320.6	6726.8	FT_FR+AR+ MSW	774.9	11356.7	2690.7
FI	375.0	FT_FR	15391.7	96.3	1308.0	FT_FR	9235.0	96.3	1308.0	FT_FR	4617.5	96.3	1308.0	FT_FR	2308.8	96.3	1308.0	FT_FR	923.5	96.3	1308.0
FR	3238.6	FT_FR	16185.6	831.7	11297.0	FT_FR	9711.4	831.7	11297.0	FT_FR	4855.7	831.7	11297.0	FT_FR+AT J_AR	4917.7	1296.7	10832.0	FT_FR+AR+ MSW	1786.8	5914.7	6214.0
HR	87.7	FT_FR	4512.1	22.5	306.0	FT_FR	2707.3	22.5	306.0	FT_FR	1353.6	22.5	306.0	FT_FR	676.8	22.5	306.0	FT_FR	270.7	22.5	306.0
HU	167.3	FT_FR	2545.5	43.0	583.5	FT_FR	1527.3	43.0	583.5	FT_FR	763.7	43.0	583.5	FT_FR	381.8	43.0	583.5	FT_FR+ATJ AR	367.0	51.3	575.2
IE	460.0	FT_FR	2136.9	118.1	1604.7	FT_FR	1282.1	118.1	1604.7	FT_FR	641.1	118.1	1604.7	FT_FR+A R+MSW	392.3	356.8	1366.1	FT_FR+AR+ MSW	156.9	1176.5	546.4
IT	1870.8	FT_FR	3908.3	480.4	6525.8	FT_FR	2345.0	480.4	6525.8	FT_FR+AT J_AR	2929.4	880.9	6125.3	FT_FR+A R+MSW	1372.2	2261.4	4744.9	FT_FR+AR+ MSW	548.9	5108.3	1897.9
LT	55.6	FT_FR	3490.9	14.3	194.0	FT_FR	2094.5	14.3	194.0	FT_FR	1047.3	14.3	194.0	FT_FR	523.6	14.3	194.0	FT_FR	209.5	14.3	194.0
LU	27.0	FT_FR	452.2	6.9	94.1	FT_FR	271.3	6.9	94.1	FT_FR	135.7	6.9	94.1	FT_FR	67.8	6.9	94.1	FT_FR	27.1	6.9	94.1
LV	57.9	FT_FR	2655.1	14.9	201.9	FT_FR	1593.1	14.9	201.9	FT_FR	796.5	14.9	201.9	FT_FR	398.3	14.9	201.9	FT_FR	159.3	14.9	201.9
MD	31.4	FT_FR	1107.8	8.1	109.4	FT_FR	664.7	8.1	109.4	FT_FR	332.3	8.1	109.4	FT_FR	166.2	8.1	109.4	FT_FR	66.5	8.1	109.4
ME	16.5	FT_FR	227.4	4.2	57.6	FT_FR	136.4	4.2	57.6	FT_FR	68.2	4.2	57.6	FT_FR	34.1	4.2	57.6	FT_FR+AR+ MSW	14.4	11.6	50.2
MK	21.2	FT_FR	242.5	5.4	73.9	FT_FR	145.5	5.4	73.9	FT_FR	72.8	5.4	73.9	FT_FR	36.4	5.4	73.9	FT_FR+ATJ AR	24.4	9.3	70.1
NL	1744.0	FT_FR+A R+MSW	1829.6	1474.7	5056.6	FT_FR+A R+MSW	891.4	3460.1	3071.2	FT_FR+A R+MSW	445.7	4995.7	1535.6	FT_FR+A R+MSW	222.8	5763.5	767.8	FT_FR+AR+ MSW	89.1	6224.2	307.1
PL	338.0	FT_FR	9233.6	86.8	1178.9	FT_FR	5540.1	86.8	1178.9	FT_FR	2770.1	86.8	1178.9	FT_FR	1385.0	86.8	1178.9	FT_FR	554.0	86.8	1178.9
PT	727.7	FT_FR	4271.2	186.9	2538.4	FT_FR	2562.7	186.9	2538.4	FT_FR	1281.4	186.9	2538.4	FT_FR+AT J_AR	736.6	236.8	2488.5	FT_FR+AR+ MSW	291.7	1709.9	1015.4
RO	254.0	FT_FR	5797.9	65.2	886.0	FT_FR	3478.7	65.2	886.0	FT_FR	1739.4	65.2	886.0	FT_FR	869.7	65.2	886.0	FT_FR	347.9	65.2	886.0
RS	79.3	FT_FR	1906.8	20.4	276.5	FT_FR	1144.1	20.4	276.5	FT_FR	572.0	20.4	276.5	FT_FR	286.0	20.4	276.5	FT_FR	114.4	20.4	276.5
SE	461.3	FT_FR	20108.6	118.5	1609.1	FT_FR	12065.2	118.5	1609.1	FT_FR	6032.6	118.5	1609.1	FT_FR	3016.3	118.5	1609.1	FT_FR	1206.5	118.5	1609.1
SI	12.3	FT_FR	1669.2	3.2	43.0	FT_FR	1001.5	3.2	43.0	FT_FR	500.8	3.2	43.0	FT_FR	250.4	3.2	43.0	FT_FR	100.2	3.2	43.0
SK	25.2	FT_FR	4172.0	6.5	87.9	FT_FR	2503.2	6.5	87.9	FT_FR	1251.6	6.5	87.9	FT_FR	625.8	6.5	87.9	FT_FR	250.3	6.5	87.9
UA	271.1	FT_FR	5101.1	69.6	945.6	FT_FR	3060.7	69.6	945.6	FT_FR	1530.3	69.6	945.6	FT_FR	765.2	69.6	945.6	FT_FR	306.1	69.6	945.6
UK	5927.9	FT_FR+AT J_AR	11626.4	1750.5	20449.4	FT_FR+AT J_AR	6975.9	3019.1	19180.8	FT_FR+A R+MSW	3276.0	10851.6	11348.3	FT_FR+A R+MSW	1638.0	16525.8	5674.2	MSW	655.2	19930.3	2269.7

Table A10 2050 Clean Sky – HIGH scenario.

2050 Clean Sky - HIGH																					
Country	SAF demand (kt)	100% biomass availability				60% biomass availability				30% biomass availability				15% biomass availability				6% biomass availability			
		Conversion pathway	SAF supply (kt)	GHG emissions (kt CO2e)	GHG reduction (kt CO2e)	Conversion pathway	SAF supply (kt)	GHG emissions (kt CO2e)	GHG reduction (kt CO2e)	Conversion pathway	SAF supply (kt)	GHG emissions (kt CO2e)	GHG reduction (kt CO2e)	Conversion pathway	SAF supply (kt)	GHG emissions (kt CO2e)	GHG reduction (kt CO2e)	Conversion pathway	SAF supply (kt)	GHG emissions (kt CO2e)	GHG reduction (kt CO2e)
AL	46.1	FT_FR	475.8	11.8	160.9	FT_FR	285.5	11.8	160.9	FT_FR	142.7	11.8	160.9	FT_FR	71.4	11.8	160.9	FT_FR+AR+MSW	39.5	35.6	137.2
AT	905.8	FT_FR	5994.9	232.6	3159.8	FT_FR	3596.9	232.6	3159.8	FT_FR	1798.5	232.6	3159.8	J_AR	1073.6	236.4	3156.0	MSW	420.9	1927.1	1465.3
BA	37.0	FT_FR	959.3	9.5	129.2	FT_FR	575.6	9.5	129.2	FT_FR	287.8	9.5	129.2	FT_FR	143.9	9.5	129.2	FT_FR	57.6	9.5	129.2
BE	4813.3	FT_FR+A R+MSW	1973.8	11188.1	6837.8	FT_FR+A R+MSW	1184.3	13923.2	4102.7	FT_FR+A R+MSW	592.1	15974.5	2051.3	FT_FR+A R+MSW	296.1	17000.2	1025.7	MSW	118.4	17615.6	410.3
BG	281.7	FT_FR	1545.9	72.4	982.8	FT_FR	927.6	72.4	982.8	FT_FR	463.8	72.4	982.8	J_AR	601.5	100.9	954.2	MSW	208.4	328.9	726.2
CZ	445.3	FT_FR	4276.3	114.4	1553.4	FT_FR	2565.8	114.4	1553.4	FT_FR	1282.9	114.4	1553.4	FT_FR	641.4	114.4	1553.4	FT_FR+AR+MSW	372.1	371.1	1296.7
DE	10080.6	FT_FR	19376.9	2588.7	35163.3	FT_FR	11626.1	2588.7	35163.3	FT_FR+A R+MSW	10221.9	5030.1	32721.9	FT_FR+A R+MSW	4622.1	21661.5	16090.4	FT_FR+AR+MSW	1848.9	31315.8	6436.2
DK	1057.2	FT_FR	3384.7	271.5	3687.8	FT_FR	2030.8	271.5	3687.8	FT_FR+AT J_AR	1674.9	295.5	3663.3	FT_FR+A R+MSW	773.6	1265.2	2694.0	MSW	309.5	2881.6	1077.6
EE	52.8	FT_FR	2003.8	13.6	184.2	FT_FR	1202.3	13.6	184.2	FT_FR	601.1	13.6	184.2	FT_FR	300.6	13.6	184.2	FT_FR	120.2	13.6	184.2
EL	1328.5	FT_FR+AT J_AR	3186.2	376.4	4598.9	FT_FR+AT J_AR	1911.7	667.1	4308.3	FT_FR+A R+MSW	856.3	2001.0	2974.4	FT_FR+A R+MSW	428.1	3488.2	1487.2	MSW	171.3	4380.5	594.9
ES	9041.3	FT_FR+AT J_AR	14297.1	4106.3	29753.3	FT_FR+A R+MSW	9716.6	7792.9	26066.7	FT_FR+A R+MSW	3874.7	20405.9	13453.7	FT_FR+A R+MSW	1937.4	27132.7	6726.8	MSW	774.9	31168.8	2690.7
FI	914.5	FT_FR	15391.7	234.8	3190.0	FT_FR	9235.0	3514.1	-89.3	FT_FR	4617.5	234.8	3190.0	FT_FR	2308.8	234.8	3190.0	FT_FR	923.5	234.8	3190.0
FR	7752.5	FT_FR	16185.6	1990.8	27042.4	FT_FR	9711.4	1990.8	27042.4	FT_FR+AT J_AR	9835.5	3652.3	25381.0	FT_FR+A R+MSW	4466.9	13498.2	15535.0	MSW	1786.8	22819.2	6214.0
HR	211.7	FT_FR	4512.1	54.4	738.5	FT_FR	2707.3	54.4	738.5	FT_FR	1353.6	54.4	738.5	FT_FR	676.8	54.4	738.5	FT_FR	270.7	54.4	738.5
HU	397.1	FT_FR	2545.5	102.0	1385.0	FT_FR	1527.3	102.0	1385.0	FT_FR	763.7	102.0	1385.0	FT_FR+AT J_AR	917.6	110.7	1376.3	MSW	321.4	367.3	1119.7
IE	1036.7	FT_FR	2136.9	266.2	3616.3	FT_FR	1282.1	266.2	3616.3	FT_FR+A R+MSW	784.5	1150.4	2732.1	FT_FR+A R+MSW	392.3	2516.5	1366.1	MSW	156.9	3336.1	546.4
IT	4520.9	FT_FR+AT J_AR	9764.6	1512.4	15418.6	FT_FR+AT J_AR	5858.8	2408.9	14522.0	FT_FR+A R+MSW	2744.3	7441.2	9489.7	FT_FR+A R+MSW	1372.2	12186.0	4744.9	MSW	548.9	15033.0	1897.9
LT	132.8	FT_FR	3490.9	34.1	463.2	FT_FR	2094.5	34.1	463.2	FT_FR	1047.3	34.1	463.2	FT_FR	523.6	34.1	463.2	FT_FR	209.5	34.1	463.2
LU	65.7	FT_FR	452.2	16.9	229.0	FT_FR	271.3	16.9	229.0	FT_FR	135.7	16.9	229.0	FT_FR	67.8	16.9	229.0	MSW	29.5	143.2	102.7
LV	142.4	FT_FR	2655.1	36.6	496.8	FT_FR	1593.1	36.6	496.8	FT_FR	796.5	36.6	496.8	FT_FR	398.3	36.6	496.8	FT_FR	159.3	36.6	496.8
MD	75.5	FT_FR	1107.8	19.4	263.4	FT_FR	664.7	19.4	263.4	FT_FR	332.3	19.4	263.4	FT_FR	166.2	19.4	263.4	FT_FR+AR+MSW	73.0	28.6	254.2
ME	41.8	FT_FR	227.4	10.7	146.0	FT_FR	136.4	10.7	146.0	FT_FR	68.2	10.7	146.0	FT_FR+A R+MSW	36.1	31.2	125.6	MSW	14.4	106.5	50.2
MK	51.6	FT_FR	242.5	13.3	180.1	FT_FR	145.5	13.3	180.1	FT_FR	72.8	13.3	180.1	FT_FR+AT J_AR	61.0	22.0	171.3	MSW	23.1	113.2	80.2
NL	4244.4	FT_FR+A R+MSW	1485.6	10776.8	5118.7	FT_FR+A R+MSW	891.4	12824.3	3071.2	FT_FR+A R+MSW	445.7	14359.9	1535.6	FT_FR+A R+MSW	222.8	15127.7	767.8	MSW	89.1	15588.3	307.1
PL	802.6	FT_FR	9233.6	206.1	2799.6	FT_FR	5540.1	206.1	2799.6	FT_FR	2770.1	206.1	2799.6	FT_FR	1385.0	206.1	2799.6	FT_FR+ATJ AR	978.2	348.7	2657.1
PT	1773.5	FT_FR	4271.2	455.4	6186.3	FT_FR	2562.7	455.4	6186.3	FT_FR+A R+MSW	1458.6	1565.0	5076.8	FT_FR+A R+MSW	729.3	4103.4	2538.4	MSW	291.7	5626.4	1015.4
RO	612.3	FT_FR	5797.9	157.2	2135.7	FT_FR	3478.7	157.2	2135.7	FT_FR	1739.4	157.2	2135.7	FT_FR	869.7	157.2	2135.7	FT_FR+ATJ AR	640.5	308.9	1984.0
RS	197.1	FT_FR	1906.8	50.6	687.6	FT_FR	1144.1	50.6	687.6	FT_FR	572.0	50.6	687.6	FT_FR	286.0	50.6	687.6	AR	247.6	98.1	640.1
SE	1113.2	FT_FR	20108.6	285.9	3882.9	FT_FR	12065.2	285.9	3882.9	FT_FR	6032.6	285.9	3882.9	FT_FR	3016.3	285.9	3882.9	FT_FR	1206.5	285.9	3882.9
SI	30.0	FT_FR	1669.2	7.7	104.8	FT_FR	1001.5	7.7	104.8	FT_FR	500.8	7.7	104.8	FT_FR	250.4	7.7	104.8	FT_FR	100.2	7.7	104.8
SK	59.4	FT_FR	4172.0	15.3	207.3	FT_FR	2503.2	15.3	207.3	FT_FR	1251.6	15.3	207.3	FT_FR	625.8	15.3	207.3	FT_FR	250.3	15.3	207.3
UA	650.9	FT_FR	5101.1	167.1	2270.4	FT_FR	3060.7	167.1	2270.4	FT_FR	1530.3	167.1	2270.4	FT_FR	765.2	167.1	2270.4	FT_FR+ATJ AR	1550.2	364.9	2072.7
UK	13780.4	FT_FR+A R+MSW	10920.1	13779.6	37827.8	FT_FR+A R+MSW	6552.1	28910.7	22696.7	FT_FR+A R+MSW	3276.0	40259.1	11348.3	FT_FR+A R+MSW	1638.0	45933.2	5674.2	MSW	655.2	49337.7	2269.7

Table A11 2030 ReFuelEU – LOW/HIGH scenario.

2030 ReFuelEU - LOW / HIGH																							
Country	100% biomass availability					60% biomass availability					30% biomass availability					15% biomass availability				6% biomass availability			
	SAF demand (kt)	Conversion pathway	SAF supply (kt)	GHG emissions (kt CO2e)	GHG reduction (kt CO2e)	Conversion pathway	SAF supply (kt)	GHG emissions (kt CO2e)	GHG reduction (kt CO2e)	Conversion pathway	SAF supply (kt)	GHG emissions (kt CO2e)	GHG reduction (kt CO2e)	Conversion pathway	SAF supply (kt)	GHG emissions (kt CO2e)	GHG reduction (kt CO2e)	Conversion pathway	SAF supply (kt)	GHG emissions (kt CO2e)	GHG reduction (kt CO2e)		
AL	2.1	FT_FR	308.0	0.5	7.4	FT_FR	184.8	0.5	7.4	FT_FR	92.4	0.5	7.4	FT_FR	46.2	0.5	7.4	FT_FR	18.5	0.5	7.4		
AT	48.3	FT_FR	5537.8	12.4	168.4	FT_FR	3322.7	12.4	168.4	FT_FR	1661.3	12.4	168.4	FT_FR	830.7	12.4	168.4	FT_FR	332.3	12.4	168.4		
BA	1.8	FT_FR	887.9	0.5	6.2	FT_FR	532.8	0.5	6.2	FT_FR	266.4	0.5	6.2	FT_FR	133.2	0.5	6.2	FT_FR	53.3	0.5	6.2		
BE	207.9	FT_FR	1116.4	53.4	725.2	FT_FR	669.8	53.4	725.2	FT_FR	334.9	53.4	725.2	FT_FR+AT J_AR	281.3	76.6	702.0	FT_FR+AR+ MSW	111.2	32.0	746.6		
BG	13.6	FT_FR	1426.7	3.5	47.6	FT_FR	856.0	3.5	47.6	FT_FR	428.0	3.5	47.6	FT_FR	214.0	3.5	47.6	FT_FR	85.6	3.5	47.6		
CZ	22.9	FT_FR	3951.0	5.9	79.8	FT_FR	2370.6	5.9	79.8	FT_FR	1185.3	5.9	79.8	FT_FR	592.6	5.9	79.8	FT_FR	237.1	5.9	79.8		
DE	576.4	FT_FR	17906.9	148.0	2010.8	FT_FR	10744.1	148.0	2010.8	FT_FR	5372.1	148.0	2010.8	FT_FR	2686.0	148.0	2010.8	FT_FR	1074.4	148.0	2010.8		
DK	56.7	FT_FR	3193.1	14.6	197.9	FT_FR	1915.9	14.6	197.9	FT_FR	957.9	14.6	197.9	FT_FR	479.0	14.6	197.9	FT_FR	191.6	14.6	197.9		
EE	2.7	FT_FR	1853.0	0.7	9.5	FT_FR	1111.8	0.7	9.5	FT_FR	555.9	0.7	9.5	FT_FR	277.9	0.7	9.5	FT_FR	111.2	0.7	9.5		
EL	72.0	FT_FR	1172.4	18.5	251.3	FT_FR	703.4	18.5	251.3	FT_FR	351.7	18.5	251.3	FT_FR	175.9	18.5	251.3	FT_FR+ATJ_ AR	172.3	19.5	250.3		
ES	489.4	FT_FR	5477.4	125.7	1707.2	FT_FR	3286.5	125.7	1707.2	FT_FR	1643.2	125.7	1707.2	FT_FR	821.6	125.7	1707.2	FT_FR+ATJ_ AR	778.4	217.9	1615.0		
FI	49.4	FT_FR	14217.4	12.7	172.4	FT_FR	8530.4	12.7	172.4	FT_FR	4265.2	12.7	172.4	FT_FR	2132.6	12.7	172.4	FT_FR	853.0	12.7	172.4		
FR	448.9	FT_FR	14955.9	115.3	1565.7	FT_FR	8973.6	115.3	1565.7	FT_FR	4486.8	115.3	1565.7	FT_FR	2243.4	115.3	1565.7	FT_FR	897.4	115.3	1565.7		
HR	10.0	FT_FR	4616.3	2.6	34.9	FT_FR	2769.8	2.6	34.9	FT_FR	1384.9	2.6	34.9	FT_FR	692.4	2.6	34.9	FT_FR	277.0	2.6	34.9		
HU	19.7	FT_FR	2352.3	5.1	68.6	FT_FR	1411.4	5.1	68.6	FT_FR	705.7	5.1	68.6	FT_FR	352.8	5.1	68.6	FT_FR	141.1	5.1	68.6		
IE	63.8	FT_FR	1364.4	16.4	222.6	FT_FR	818.6	16.4	222.6	FT_FR	409.3	16.4	222.6	FT_FR	204.7	16.4	222.6	FT_FR	81.9	16.4	222.6		
IT	255.0	FT_FR	5385.1	65.5	889.5	FT_FR	3231.0	65.5	889.5	FT_FR	1615.5	65.5	889.5	FT_FR	807.8	65.5	889.5	FT_FR	323.1	65.5	889.5		
LT	6.9	FT_FR	3541.4	1.8	24.1	FT_FR	2124.8	1.8	24.1	FT_FR	1062.4	1.8	24.1	FT_FR	531.2	1.8	24.1	FT_FR	212.5	1.8	24.1		
LU	3.7	FT_FR	418.3	0.9	12.7	FT_FR	251.0	0.9	12.7	FT_FR	125.5	0.9	12.7	FT_FR	62.7	0.9	12.7	FT_FR	25.1	0.9	12.7		
LV	7.4	FT_FR	2451.6	1.9	25.7	FT_FR	1471.0	1.9	25.7	FT_FR	735.5	1.9	25.7	FT_FR	367.7	1.9	25.7	FT_FR	147.1	1.9	25.7		
MD	3.6	FT_FR	1054.0	0.9	12.5	FT_FR	632.4	0.9	12.5	FT_FR	316.2	0.9	12.5	FT_FR	158.1	0.9	12.5	FT_FR	63.2	0.9	12.5		
ME	2.0	FT_FR	272.2	0.5	6.9	FT_FR	163.3	0.5	6.9	FT_FR	81.7	0.5	6.9	FT_FR	40.8	0.5	6.9	FT_FR	16.3	0.5	6.9		
MK	2.4	FT_FR	303.8	0.6	8.5	FT_FR	182.3	0.6	8.5	FT_FR	91.1	0.6	8.5	FT_FR	45.6	0.6	8.5	FT_FR	18.2	0.6	8.5		
NL	238.2	FT_FR	651.7	61.2	830.7	FT_FR	391.0	61.2	830.7	FT_FR+AT J_AR	413.7	85.6	806.3	FT_FR+A R+MSW	259.4	201.9	689.9	FT_FR+AR+ MSW	84.8	26.4	865.5		
PL	43.1	FT_FR	8536.1	11.1	150.5	FT_FR	5121.7	11.1	150.5	FT_FR	2560.8	11.1	150.5	FT_FR	1280.4	11.1	150.5	FT_FR	512.2	11.1	150.5		
PT	96.1	FT_FR	3942.5	24.7	335.1	FT_FR	2365.5	24.7	335.1	FT_FR	1182.8	24.7	335.1	FT_FR	591.4	24.7	335.1	FT_FR	236.6	24.7	335.1		
RO	28.5	FT_FR	6435.1	7.3	99.4	FT_FR	3861.1	7.3	99.4	FT_FR	1930.5	7.3	99.4	FT_FR	965.3	7.3	99.4	FT_FR	386.1	7.3	99.4		
RS	9.2	FT_FR	1764.8	2.4	32.0	FT_FR	1058.9	2.4	32.0	FT_FR	529.4	2.4	32.0	FT_FR	264.7	2.4	32.0	FT_FR	105.9	2.4	32.0		
SE	60.6	FT_FR	19679.4	15.6	211.5	FT_FR	11807.6	15.6	211.5	FT_FR	5903.8	15.6	211.5	FT_FR	2951.9	15.6	211.5	FT_FR	1180.8	15.6	211.5		
SI	1.5	FT_FR	1542.1	0.4	5.2	FT_FR	925.3	0.4	5.2	FT_FR	462.6	0.4	5.2	FT_FR	231.3	0.4	5.2	FT_FR	92.5	0.4	5.2		
SK	3.1	FT_FR	2757.4	0.8	10.7	FT_FR	1654.4	0.8	10.7	FT_FR	827.2	0.8	10.7	FT_FR	413.6	0.8	10.7	FT_FR	165.4	0.8	10.7		
UA	30.3	FT_FR	5273.2	7.8	105.9	FT_FR	3163.9	7.8	105.9	FT_FR	1581.9	7.8	105.9	FT_FR	791.0	7.8	105.9	FT_FR	316.4	7.8	105.9		
UK	770.2	FT_FR	5499.3	197.8	2686.7	FT_FR	3299.6	197.8	2686.7	FT_FR	1649.8	197.8	2686.7	FT_FR	824.9	197.8	2686.7	FT_FR+ATJ_ AR+FT_MS	1433.7	429.3	2455.2		

Table A12 2035 ReFuelEU – LOW scenario.

2035 ReFuelEU - LOW																					
Country	SAF demand (kt)	100% biomass availability				60% biomass availability				30% biomass availability				15% biomass availability				6% biomass availability			
		Conversion pathway	SAF supply (kt)	GHG emissions (kt CO2e)	GHG reduction (kt CO2e)	Conversion pathway	SAF supply (kt)	GHG emissions (kt CO2e)	GHG reduction (kt CO2e)	Conversion pathway	SAF supply (kt)	GHG emissions (kt CO2e)	GHG reduction (kt CO2e)	Conversion pathway	SAF supply (kt)	GHG emissions (kt CO2e)	GHG reduction (kt CO2e)	Conversion pathway	SAF supply (kt)	GHG emissions (kt CO2e)	GHG reduction (kt CO2e)
AL	7.6	FT_FR	349.9	2.0	26.7	FT_FR	210.0	2.0	26.7	FT_FR	105.0	2.0	26.7	FT_FR	52.5	2.0	26.7	FT_FR	21.0	2.0	26.7
AT	167.1	FT_FR	5652.1	42.9	582.9	FT_FR	3391.2	42.9	582.9	FT_FR	1695.6	42.9	582.9	FT_FR	847.8	42.9	582.9	FT_FR	339.1	42.9	582.9
BA	6.4	FT_FR	905.8	1.6	22.4	FT_FR	543.5	1.6	22.4	FT_FR	271.7	1.6	22.4	FT_FR	135.9	1.6	22.4	FT_FR	54.3	1.6	22.4
BE	775.3	FT_FR	1138.9	199.1	2704.3	FT_FR+AT J_AR	1149.9	251.8	2651.6	FT_FR+AT R+MSW	564.9	949.5	1953.9	FT_FR+AR+ MSW	282.4	634.2	2269.2	FT_FR+AR+ MSW	113.0	2512.6	390.8
BG	48.7	FT_FR	1456.5	12.5	169.8	FT_FR	873.9	12.5	169.8	FT_FR	436.9	12.5	169.8	FT_FR	218.5	12.5	169.8	FT_FR	87.4	12.5	169.8
CZ	80.4	FT_FR	4032.3	20.6	280.3	FT_FR	2419.4	20.6	280.3	FT_FR	1209.7	20.6	280.3	FT_FR	604.8	20.6	280.3	FT_FR	241.9	20.6	280.3
DE	1968.5	FT_FR	18274.4	505.5	6866.5	FT_FR	10964.6	505.5	6866.5	FT_FR	5482.3	505.5	6866.5	FT_FR	2741.2	505.5	6866.5	FT_FR+AR+ MSW	1745.3	1299.5	6072.6
DK	196.3	FT_FR	3241.0	50.4	684.8	FT_FR	1944.6	50.4	684.8	FT_FR	972.3	50.4	684.8	FT_FR	486.2	50.4	684.8	FT_FR+ATJ AR	317.5	51.5	683.7
EE	9.6	FT_FR	1890.7	2.5	33.6	FT_FR	1134.4	2.5	33.6	FT_FR	567.2	2.5	33.6	FT_FR	283.6	2.5	33.6	FT_FR	113.4	2.5	33.6
EL	249.3	FT_FR	1196.1	64.0	869.5	FT_FR	717.6	64.0	869.5	FT_FR	358.8	64.0	869.5	FT_FR+ATJ AR	442.6	104.1	829.5	FT_FR+AR+ MSW	160.7	375.9	557.7
ES	1692.4	FT_FR	5590.5	434.6	5903.5	FT_FR	3354.3	434.6	5903.5	FT_FR+AT J_AR	3991.3	443.4	5894.7	FT_FR+ATJ AR	1995.6	924.3	5413.8	FT_FR+AR+ MSW	730.2	3805.5	2532.5
FI	170.5	FT_FR	14511.0	43.8	594.6	FT_FR	8706.6	43.8	594.6	FT_FR	4353.3	43.8	594.6	FT_FR	2176.6	43.8	594.6	FT_FR	870.7	43.8	594.6
FR	1527.0	FT_FR	15263.3	392.1	5326.4	FT_FR	9158.0	392.1	5326.4	FT_FR	4579.0	392.1	5326.4	FT_FR	2289.5	392.1	5326.4	FT_FR+ATJ AR	1843.2	742.7	4975.9
HR	36.0	FT_FR	4590.3	9.2	125.6	FT_FR	2754.2	9.2	125.6	FT_FR	1377.1	9.2	125.6	FT_FR	688.5	9.2	125.6	FT_FR	275.4	9.2	125.6
HU	70.1	FT_FR	2400.6	18.0	244.5	FT_FR	1440.3	18.0	244.5	FT_FR	720.2	18.0	244.5	FT_FR	360.1	18.0	244.5	FT_FR	144.0	18.0	244.5
IE	217.0	FT_FR	1557.5	55.7	757.1	FT_FR	934.5	55.7	757.1	FT_FR	467.2	55.7	757.1	FT_FR	233.6	55.7	757.1	FT_FR+AR+ MSW	120.8	392.7	420.2
IT	871.4	FT_FR	5015.9	223.8	3039.5	FT_FR	3009.5	223.8	3039.5	FT_FR	1504.8	223.8	3039.5	FT_FR+ATJ AR	1562.6	292.0	2971.2	FT_FR+AR+ MSW	601.5	1184.4	2078.8
LT	24.2	FT_FR	3528.8	6.2	84.4	FT_FR	2117.3	6.2	84.4	FT_FR	1058.6	6.2	84.4	FT_FR	529.3	6.2	84.4	FT_FR	211.7	6.2	84.4
LU	12.5	FT_FR	426.8	3.2	43.6	FT_FR	256.1	3.2	43.6	FT_FR	128.0	3.2	43.6	FT_FR	64.0	3.2	43.6	FT_FR	25.6	3.2	43.6
LV	25.7	FT_FR	2502.5	6.6	89.5	FT_FR	1501.5	6.6	89.5	FT_FR	750.7	6.6	89.5	FT_FR	375.4	6.6	89.5	FT_FR	150.1	6.6	89.5
MD	12.9	FT_FR	1067.5	3.3	45.0	FT_FR	640.5	3.3	45.0	FT_FR	320.2	3.3	45.0	FT_FR	160.1	3.3	45.0	FT_FR	64.0	3.3	45.0
ME	7.0	FT_FR	261.0	1.8	24.5	FT_FR	156.6	1.8	24.5	FT_FR	78.3	1.8	24.5	FT_FR	39.1	1.8	24.5	FT_FR	15.7	1.8	24.5
MK	8.8	FT_FR	288.5	2.2	30.5	FT_FR	173.1	2.2	30.5	FT_FR	86.5	2.2	30.5	FT_FR	43.3	2.2	30.5	FT_FR	17.3	2.2	30.5
NL	813.4	FT_FR+AT J_AR	1409.5	294.3	2751.8	FT_FR+AT J_AR	845.7	446.7	2599.4	FT_FR+AT R+MSW	429.5	1569.9	1476.2	FT_FR+AR+ MSW	214.7	937.1	2109.0	FT_FR+AR+ MSW	85.9	2750.9	295.2
PL	150.1	FT_FR	8710.5	38.5	523.6	FT_FR	5226.3	38.5	523.6	FT_FR	2613.1	38.5	523.6	FT_FR	1306.6	38.5	523.6	FT_FR	522.6	38.5	523.6
PT	331.1	FT_FR	4024.7	85.0	1155.0	FT_FR	2414.8	85.0	1155.0	FT_FR	1207.4	85.0	1155.0	FT_FR	603.7	85.0	1155.0	FT_FR+AR+ MSW	275.4	281.9	958.1
RO	103.0	FT_FR	6275.8	26.4	359.1	FT_FR	3765.5	26.4	359.1	FT_FR	1882.7	26.4	359.1	FT_FR	941.4	26.4	359.1	FT_FR	376.5	26.4	359.1
RS	32.8	FT_FR	1800.3	8.4	114.5	FT_FR	1080.2	8.4	114.5	FT_FR	540.1	8.4	114.5	FT_FR	270.0	8.4	114.5	FT_FR	108.0	8.4	114.5
SE	209.2	FT_FR	19786.7	53.7	729.8	FT_FR	11872.0	53.7	729.8	FT_FR	5936.0	53.7	729.8	FT_FR	2968.0	53.7	729.8	FT_FR	1187.2	53.7	729.8
SI	5.3	FT_FR	1573.9	1.3	18.3	FT_FR	944.3	1.3	18.3	FT_FR	472.2	1.3	18.3	FT_FR	236.1	1.3	18.3	FT_FR	94.4	1.3	18.3
SK	10.8	FT_FR	3111.0	2.8	37.8	FT_FR	1866.6	2.8	37.8	FT_FR	933.3	2.8	37.8	FT_FR	466.7	2.8	37.8	FT_FR	186.7	2.8	37.8
UA	109.7	FT_FR	5230.2	28.2	382.8	FT_FR	3138.1	28.2	382.8	FT_FR	1569.0	28.2	382.8	FT_FR	784.5	28.2	382.8	FT_FR	313.8	28.2	382.8
UK	2666.6	FT_FR	5506.9	684.8	9301.5	FT_FR	3304.2	684.8	9301.5	FT_FR+AT J_AR	3359.9	1266.6	8719.7	FT_FR+ATJ AR+FT_MS	3150.5	1546.1	8440.2	FT_FR+AR+ MSW	1181.4	6087.0	3899.3

Table A13 2035 ReFuelEU –HIGH scenario.

2035 ReFuel EU - HIGH																					
Country	SAF demand (kt)	100% biomass availability				60% biomass availability				30% biomass availability				15% biomass availability				6% biomass availability			
		Conversion pathway	SAF supply (kt)	GHG emissions (kt CO2e)	GHG reduction (kt CO2e)	Conversion pathway	SAF supply (kt)	GHG emissions (kt CO2e)	GHG reduction (kt CO2e)	Conversion pathway	SAF supply (kt)	GHG emissions (kt CO2e)	GHG reduction (kt CO2e)	Conversion pathway	SAF supply (kt)	GHG emissions (kt CO2e)	GHG reduction (kt CO2e)	Conversion pathway	SAF supply (kt)	GHG emissions (kt CO2e)	GHG reduction (kt CO2e)
AL	8.2	FT_FR	349.9	2.1	28.5	FT_FR	210.0	2.1	28.5	FT_FR	105.0	2.1	28.5	FT_FR	52.5	2.1	28.5	FT_FR	21.0	2.1	28.5
AT	177.3	FT_FR	5652.1	45.5	618.5	FT_FR	3391.2	45.5	618.5	FT_FR	1695.6	45.5	618.5	FT_FR	847.8	45.5	618.5	FT_FR	339.1	45.5	618.5
BA	6.8	FT_FR	905.8	1.7	23.7	FT_FR	543.5	1.7	23.7	FT_FR	271.7	1.7	23.7	FT_FR	135.9	1.7	23.7	FT_FR	54.3	1.7	23.7
BE	820.6	FT_FR	1138.9	210.7	2862.4	FT_FR+AT J_AR	1149.9	289.4	2783.7	FT_FR+A R+MSW	564.9	1119.3	1953.9	FT_FR+AR+ MSW	282.4	2096.2	976.9	FT_FR+AR+ MSW	113.0	642.2	2431.0
BG	51.7	FT_FR	1456.5	13.3	180.4	FT_FR	873.9	13.3	180.4	FT_FR	436.9	13.3	180.4	FT_FR	218.5	13.3	180.4	FT_FR	87.4	13.3	180.4
CZ	85.1	FT_FR	4032.3	21.8	296.7	FT_FR	2419.4	21.8	296.7	FT_FR	1209.7	21.8	296.7	FT_FR	604.8	21.8	296.7	FT_FR	241.9	21.8	296.7
DE	2071.2	FT_FR	18274.4	531.9	7224.6	FT_FR	10964.6	531.9	7224.6	FT_FR	5482.3	531.9	7224.6	FT_FR	2741.2	531.9	7224.6	FT_FR+AR+ MSW	1745.3	1090.9	6665.6
DK	207.9	FT_FR	3241.0	53.4	725.3	FT_FR	1944.6	53.4	725.3	FT_FR	972.3	53.4	725.3	FT_FR	486.2	53.4	725.3	FT_FR+ATJ _AR	317.5	61.1	717.6
EE	10.1	FT_FR	1890.7	2.6	35.3	FT_FR	1134.4	2.6	35.3	FT_FR	567.2	2.6	35.3	FT_FR	283.6	2.6	35.3	FT_FR	113.4	2.6	35.3
EL	263.2	FT_FR	1196.1	67.6	917.9	FT_FR	717.6	67.6	917.9	FT_FR	358.8	67.6	917.9	FT_FR+ATJ AR	442.6	115.6	869.9	FT_FR+AR+ MSW	160.7	177.3	808.2
ES	1788.6	FT_FR	5590.5	459.3	6239.0	FT_FR	3354.3	459.3	6239.0	FT_FR+AT J_AR	3991.3	523.2	6175.1	FT_FR+ATJ AR	1995.6	1004.2	5694.2	FT_FR+AR+ MSW	730.2	1292.7	5405.6
FI	180.7	FT_FR	14511.0	46.4	630.4	FT_FR	8706.6	46.4	630.4	FT_FR	4353.3	46.4	630.4	FT_FR	2176.6	46.4	630.4	FT_FR	870.7	46.4	630.4
FR	1606.7	FT_FR	15263.3	412.6	5604.4	FT_FR	9158.0	412.6	5604.4	FT_FR	4579.0	412.6	5604.4	FT_FR	2289.5	412.6	5604.4	FT_FR+ATJ AR	1843.2	808.8	5208.2
HR	38.3	FT_FR	4590.3	9.8	133.5	FT_FR	2754.2	9.8	133.5	FT_FR	1377.1	9.8	133.5	FT_FR	688.5	9.8	133.5	FT_FR	275.4	9.8	133.5
HU	74.0	FT_FR	2400.6	19.0	258.1	FT_FR	1440.3	19.0	258.1	FT_FR	720.2	19.0	258.1	FT_FR	360.1	19.0	258.1	FT_FR	144.0	19.0	258.1
IE	224.3	FT_FR	1557.5	57.6	782.5	FT_FR	934.5	57.6	782.5	FT_FR	467.2	57.6	782.5	FT_FR	233.6	57.6	782.5	FT_FR+AR+ MSW	120.8	132.7	707.5
IT	920.1	FT_FR	5015.9	236.3	3209.4	FT_FR	3009.5	236.3	3209.4	FT_FR	1504.8	236.3	3209.4	FT_FR+ATJ AR	1562.6	332.4	3113.2	FT_FR+AR+ MSW	601.5	591.3	2854.3
LT	25.5	FT_FR	3528.8	6.6	89.1	FT_FR	2117.3	6.6	89.1	FT_FR	1058.6	6.6	89.1	FT_FR	529.3	6.6	89.1	FT_FR	211.7	6.6	89.1
LU	13.2	FT_FR	426.8	3.4	46.2	FT_FR	256.1	3.4	46.2	FT_FR	128.0	3.4	46.2	FT_FR	64.0	3.4	46.2	FT_FR	25.6	3.4	46.2
LV	27.3	FT_FR	2502.5	7.0	95.3	FT_FR	1501.5	7.0	95.3	FT_FR	750.7	7.0	95.3	FT_FR	375.4	7.0	95.3	FT_FR	150.1	7.0	95.3
MD	13.7	FT_FR	1067.5	3.5	47.8	FT_FR	640.5	3.5	47.8	FT_FR	320.2	3.5	47.8	FT_FR	160.1	3.5	47.8	FT_FR	64.0	3.5	47.8
ME	7.6	FT_FR	261.0	1.9	26.4	FT_FR	156.6	1.9	26.4	FT_FR	78.3	1.9	26.4	FT_FR	39.1	1.9	26.4	FT_FR	15.7	1.9	26.4
MK	9.3	FT_FR	288.5	2.4	32.5	FT_FR	173.1	2.4	32.5	FT_FR	86.5	2.4	32.5	FT_FR	43.3	2.4	32.5	FT_FR	17.3	2.4	32.5
NL	860.7	FT_FR	1409.5	333.5	2889.6	J_AR+FT_ MSW	962.1	483.0	2740.1	FT_FR+A R+MSW	429.5	1746.9	1476.2	FT_FR+AR+ MSW	214.7	2485.0	738.1	FT_FR+AR+ MSW	85.9	691.8	2531.4
PL	158.0	FT_FR	8710.5	40.6	551.2	FT_FR	5226.3	40.6	551.2	FT_FR	2613.1	40.6	551.2	FT_FR	1306.6	40.6	551.2	FT_FR	522.6	40.6	551.2
PT	351.0	FT_FR	4024.7	90.1	1224.3	FT_FR	2414.8	90.1	1224.3	FT_FR	1207.4	90.1	1224.3	FT_FR	603.7	90.1	1224.3	FT_FR+AR+ MSW	275.4	152.9	1161.5
RO	109.5	FT_FR	6275.8	28.1	381.9	FT_FR	3765.5	28.1	381.9	FT_FR	1882.7	28.1	381.9	FT_FR	941.4	28.1	381.9	FT_FR	376.5	28.1	381.9
RS	35.2	FT_FR	1800.3	9.0	122.9	FT_FR	1080.2	9.0	122.9	FT_FR	540.1	9.0	122.9	FT_FR	270.0	9.0	122.9	FT_FR	108.0	9.0	122.9
SE	221.1	FT_FR	19786.7	56.8	771.3	FT_FR	11872.0	56.8	771.3	FT_FR	5936.0	56.8	771.3	FT_FR	2968.0	56.8	771.3	FT_FR	1187.2	56.8	771.3
SI	5.6	FT_FR	1573.9	1.4	19.5	FT_FR	944.3	1.4	19.5	FT_FR	472.2	1.4	19.5	FT_FR	236.1	1.4	19.5	FT_FR	94.4	1.4	19.5
SK	11.4	FT_FR	3111.0	2.9	39.8	FT_FR	1866.6	2.9	39.8	FT_FR	933.3	2.9	39.8	FT_FR	466.7	2.9	39.8	FT_FR	186.7	2.9	39.8
UA	116.5	FT_FR	5230.2	29.9	406.5	FT_FR	3138.1	29.9	406.5	FT_FR	1569.0	29.9	406.5	FT_FR	784.5	29.9	406.5	FT_FR	313.8	29.9	406.5
UK	2786.9	FT_FR	5506.9	715.7	9721.1	FT_FR	3304.2	715.7	9721.1	FT_FR+AT J_AR	3359.9	1366.5	9070.3	FT_FR+ATJ AR+FT_MS	3150.5	1622.3	8814.5	FT_FR+AR+ MSW	1181.4	2124.5	8312.3

Table A14 2040 ReFuelEU – LOW scenario.

2040 ReFuelEU - LOW																					
Country	SAF demand (kt)	100% biomass availability				60% biomass availability				30% biomass availability				15% biomass availability				6% biomass availability			
		Conversion pathway	SAF supply (kt)	GHG emissions (kt CO2e)	GHG reduction (kt CO2e)	Conversion pathway	SAF supply (kt)	GHG emissions (kt CO2e)	GHG reduction (kt CO2e)	Conversion pathway	SAF supply (kt)	GHG emissions (kt CO2e)	GHG reduction (kt CO2e)	Conversion pathway	SAF supply (kt)	GHG emissions (kt CO2e)	GHG reduction (kt CO2e)	Conversion pathway	SAF supply (kt)	GHG emissions (kt CO2e)	GHG reduction (kt CO2e)
AL	14.0	FT_FR	391.9	3.6	48.9	FT_FR	235.1	3.6	48.9	FT_FR	117.6	3.6	48.9	FT_FR	58.8	3.6	48.9	FT_FR	23.5	3.6	48.9
AT	294.5	FT_FR	5766.3	75.6	1027.4	FT_FR	3459.8	75.6	1027.4	FT_FR	1729.9	75.6	1027.4	FT_FR	865.0	75.6	1027.4	FT_FR	346.0	75.6	1027.4
BA	11.6	FT_FR	923.6	3.0	40.6	FT_FR	554.2	3.0	40.6	FT_FR	277.1	3.0	40.6	FT_FR	138.5	3.0	40.6	FT_FR	55.4	3.0	40.6
BE	1457.8	FT_FR+AT J_AR	1958.0	544.3	4915.1	FT_FR+A R+MSW	1478.9	1228.5	4230.9	FT_FR+A R+MSW	574.0	3473.1	1986.4	FT_FR+A R+MSW	287.0	4466.3	993.2	MSW	114.8	5062.2	397.3
BG	88.2	FT_FR	1486.3	22.6	307.6	FT_FR	891.8	22.6	307.6	FT_FR	445.9	22.6	307.6	FT_FR	222.9	22.6	307.6	FT_FR	89.2	22.6	307.6
CZ	143.5	FT_FR	4113.6	36.9	500.7	FT_FR	2468.2	36.9	500.7	FT_FR	1234.1	36.9	500.7	FT_FR	617.0	36.9	500.7	FT_FR	246.8	36.9	500.7
DE	3426.4	FT_FR	18641.9	879.9	11951.9	FT_FR	11185.1	879.9	11951.9	FT_FR	5592.6	879.9	11951.9	FT_FR+AT J_AR	4819.5	1241.3	11590.5	MSW	1779.8	6638.0	6193.8
DK	345.9	FT_FR	3288.9	88.8	1206.7	FT_FR	1973.3	88.8	1206.7	FT_FR	986.7	88.8	1206.7	FT_FR	493.3	88.8	1206.7	MSW	299.6	252.4	1043.2
EE	17.2	FT_FR	1928.4	4.4	60.1	FT_FR	1157.0	4.4	60.1	FT_FR	578.5	4.4	60.1	FT_FR	289.3	4.4	60.1	FT_FR	115.7	4.4	60.1
EL	439.3	FT_FR	1219.7	112.8	1532.3	FT_FR	731.8	112.8	1532.3	FT_FR+AT J_AR	908.7	154.9	1490.3	FT_FR+AT J_AR	454.4	259.8	1385.3	MSW	164.2	1075.1	570.1
ES	2980.8	FT_FR	5703.6	765.5	10397.8	FT_FR	3422.2	765.5	10397.8	FT_FR+AT J_AR	4090.6	1493.7	9669.5	FT_FR+A R+MSW	1862.8	4700.1	6463.2	MSW	854.9	8578.0	2585.3
FI	299.4	FT_FR	14804.5	76.9	1044.5	FT_FR	8882.7	76.9	1044.5	FT_FR	4441.4	76.9	1044.5	FT_FR	2220.7	76.9	1044.5	FT_FR	888.3	76.9	1044.5
FR	2648.2	FT_FR	15570.8	680.1	9237.4	FT_FR	9342.5	680.1	9237.4	FT_FR	4671.2	680.1	9237.4	FT_FR+AT J_AR	4711.3	859.3	9058.1	MSW	1720.0	3938.3	5979.2
HR	65.7	FT_FR	4564.2	16.9	229.0	FT_FR	2738.5	16.9	229.0	FT_FR	1369.3	16.9	229.0	FT_FR	684.6	16.9	229.0	FT_FR	273.9	16.9	229.0
HU	126.8	FT_FR	2448.9	32.6	442.4	FT_FR	1469.3	32.6	442.4	FT_FR	734.7	32.6	442.4	FT_FR	367.3	32.6	442.4	FT_FR	146.9	32.6	442.4
IE	376.3	FT_FR	1750.6	96.6	1312.7	FT_FR	1050.4	96.6	1312.7	FT_FR	525.2	96.6	1312.7	FT_FR+A R+MSW	344.4	253.7	1155.7	MSW	132.8	947.1	462.3
IT	1517.6	FT_FR	4646.7	389.7	5293.7	FT_FR	2788.0	389.7	5293.7	FT_FR+AT J_AR	3059.9	460.6	5222.8	FT_FR+AT J_AR	1529.9	860.4	4823.1	MSW	583.9	3664.9	2018.5
LT	43.2	FT_FR	3516.1	11.1	150.6	FT_FR	2109.7	11.1	150.6	FT_FR	1054.8	11.1	150.6	FT_FR	527.4	11.1	150.6	FT_FR	211.0	11.1	150.6
LU	21.8	FT_FR	435.2	5.6	76.1	FT_FR	261.1	5.6	76.1	FT_FR	130.6	5.6	76.1	FT_FR	65.3	5.6	76.1	FT_FR	26.1	5.6	76.1
LV	45.5	FT_FR	2553.3	11.7	158.7	FT_FR	1532.0	11.7	158.7	FT_FR	766.0	11.7	158.7	FT_FR	383.0	11.7	158.7	FT_FR	153.2	11.7	158.7
MD	23.5	FT_FR	1080.9	6.0	82.0	FT_FR	648.6	6.0	82.0	FT_FR	324.3	6.0	82.0	FT_FR	162.1	6.0	82.0	FT_FR	64.9	6.0	82.0
ME	12.6	FT_FR	249.8	3.2	44.0	FT_FR	149.9	3.2	44.0	FT_FR	74.9	3.2	44.0	FT_FR	37.5	3.2	44.0	FT_FR	15.0	3.2	44.0
MK	15.9	FT_FR	273.2	4.1	55.6	FT_FR	163.9	4.1	55.6	FT_FR	81.9	4.1	55.6	FT_FR	41.0	4.1	55.6	FT_FR	16.4	4.1	55.6
NL	1416.0	FT_FR+AT J_AR	1440.1	787.3	4515.5	FT_FR+A R+MSW	952.5	2310.8	2992.0	FT_FR+A R+MSW	434.9	3806.8	1496.0	FT_FR+A R+MSW	217.4	4554.8	748.0	MSW	87.0	5003.6	299.2
PL	265.9	FT_FR	8884.8	68.3	927.4	FT_FR	5330.9	68.3	927.4	FT_FR	2665.5	68.3	927.4	FT_FR	1332.7	68.3	927.4	FT_FR	533.1	68.3	927.4
PT	581.4	FT_FR	4106.9	149.3	2028.2	FT_FR	2464.1	149.3	2028.2	FT_FR	1232.1	149.3	2028.2	FT_FR	616.0	149.3	2028.2	MSW	280.9	1200.3	977.2
RO	188.6	FT_FR	6116.5	48.4	658.0	FT_FR	3669.9	48.4	658.0	FT_FR	1835.0	48.4	658.0	FT_FR	917.5	48.4	658.0	FT_FR	367.0	48.4	658.0
RS	59.7	FT_FR	1835.8	15.3	208.1	FT_FR	1101.5	15.3	208.1	FT_FR	550.7	15.3	208.1	FT_FR	275.4	15.3	208.1	FT_FR	110.1	15.3	208.1
SE	367.8	FT_FR	19894.0	94.5	1283.0	FT_FR	11936.4	94.5	1283.0	FT_FR	5968.2	94.5	1283.0	FT_FR	2984.1	94.5	1283.0	FT_FR	1193.6	94.5	1283.0
SI	9.5	FT_FR	1605.7	2.4	33.0	FT_FR	963.4	2.4	33.0	FT_FR	481.7	2.4	33.0	FT_FR	240.9	2.4	33.0	FT_FR	96.3	2.4	33.0
SK	19.4	FT_FR	3464.7	5.0	67.7	FT_FR	2078.8	5.0	67.7	FT_FR	1039.4	5.0	67.7	FT_FR	519.7	5.0	67.7	FT_FR	207.9	5.0	67.7
UA	201.2	FT_FR	5187.1	51.7	701.8	FT_FR	3112.3	51.7	701.8	FT_FR	1556.1	51.7	701.8	FT_FR	778.1	51.7	701.8	FT_FR	311.2	51.7	701.8
UK	4701.7	FT_FR	5514.6	1207.4	16400.4	FT_FR+AT J_AR	6805.2	2006.3	15601.5	FT_FR+AT J_AR	5433.3	2699.3	14908.5	FT_FR+A R+MSW	2514.9	9217.6	8390.2	MSW	1006.0	14251.7	3356.1

Table A15 2040 ReFuelEU –HIGH scenario.

2040 ReFuel EU - HIGH																					
Country	SAF demand (kt)	100% biomass availability				60% biomass availability				30% biomass availability				15% biomass availability				6% biomass availability			
		Conversion pathway	SAF supply (kt)	GHG emissions (kt CO2e)	GHG reduction (kt CO2e)	Conversion pathway	SAF supply (kt)	GHG emissions (kt CO2e)	GHG reduction (kt CO2e)	Conversion pathway	SAF supply (kt)	GHG emissions (kt CO2e)	GHG reduction (kt CO2e)	Conversion pathway	SAF supply (kt)	GHG emissions (kt CO2e)	GHG reduction (kt CO2e)	Conversion pathway	SAF supply (kt)	GHG emissions (kt CO2e)	GHG reduction (kt CO2e)
AL	15.8	FT_FR	391.9	4.1	55.1	FT_FR	235.1	4.1	55.1	FT_FR	117.6	4.1	55.1	FT_FR	58.8	4.1	55.1	FT_FR	23.5	4.1	55.1
AT	329.3	FT_FR	5766.3	84.6	1148.7	FT_FR	3459.8	84.6	1148.7	FT_FR	1729.9	84.6	1148.7	FT_FR	865.0	84.6	1148.7	FT_FR	346.0	84.6	1148.7
BA	12.9	FT_FR	923.6	3.3	45.1	FT_FR	554.2	3.3	45.1	FT_FR	277.1	3.3	45.1	FT_FR	138.5	3.3	45.1	FT_FR	55.4	3.3	45.1
BE	1611.9	FT_FR+ATJ_AR	1958.0	672.3	5364.3	FT_FR+AR+MSW	1147.9	2063.8	3972.7	FT_FR+AR+MSW	574.0	4050.2	1986.4	FT_FR+AR+MSW	287.0	5043.4	993.2	FT_FR+AR+MSW	114.8	5639.3	397.3
BG	98.5	FT_FR	1486.3	25.3	343.6	FT_FR	891.8	25.3	343.6	FT_FR	445.9	25.3	343.6	FT_FR	222.9	25.3	343.6	FT_FR+ATJ_AR	229.9	30.7	338.3
CZ	159.5	FT_FR	4113.6	41.0	556.3	FT_FR	2468.2	41.0	556.3	FT_FR	1234.1	41.0	556.3	FT_FR	617.0	41.0	556.3	FT_FR	246.8	41.0	556.3
DE	3775.4	FT_FR	18641.9	969.5	13169.4	FT_FR	11185.1	969.5	13169.4	FT_FR	5592.6	969.5	13169.4	AR+FT_MS W	4916.5	1531.1	12607.8	FT_FR+AR+MSW	1779.8	7945.1	6193.8
DK	385.4	FT_FR	3288.9	99.0	1344.5	FT_FR	1973.3	99.0	1344.5	FT_FR	986.7	99.0	1344.5	FT_FR	493.3	99.0	1344.5	MSW	299.6	400.2	1043.2
EE	19.0	FT_FR	1928.4	4.9	66.1	FT_FR	1157.0	4.9	66.1	FT_FR	578.5	4.9	66.1	FT_FR	289.3	4.9	66.1	FT_FR	115.7	4.9	66.1
EL	486.4	FT_FR	1219.7	124.9	1696.8	FT_FR	731.8	124.9	1696.8	FT_FR	365.9	124.9	1696.8	FT_FR	182.9	124.9	1696.8	FT_FR+AR+MSW	164.2	1251.7	570.1
ES	3307.9	FT_FR	5703.6	849.5	11538.8	FT_FR	3422.2	849.5	11538.8	FT_FR	1711.1	849.5	11538.8	FT_FR+AR+MSW	855.5	11538.8	6463.2	FT_FR+AR+MSW	745.1	9803.0	2585.3
FI	334.4	FT_FR	14804.5	85.9	1166.4	FT_FR	8882.7	85.9	1166.4	FT_FR	4441.4	85.9	1166.4	FT_FR	2220.7	85.9	1166.4	FT_FR	888.3	85.9	1166.4
FR	2919.2	FT_FR	15570.8	749.6	10182.7	FT_FR	9342.5	749.6	10182.7	FT_FR	4671.2	749.6	10182.7	FT_FR+ATJ_AR	4711.3	1084.3	9848.0	FT_FR+AR+MSW	1720.0	4953.1	5979.2
HR	73.4	FT_FR	4564.2	18.8	255.9	FT_FR	2738.5	18.8	255.9	FT_FR	1369.3	18.8	255.9	FT_FR	684.6	18.8	255.9	FT_FR	273.9	18.8	255.9
HU	140.1	FT_FR	2448.9	36.0	488.8	FT_FR	1469.3	36.0	488.8	FT_FR	734.7	36.0	488.8	FT_FR	367.3	36.0	488.8	FT_FR+ATJ_AR	351.2	36.0	488.8
IE	401.1	FT_FR	1750.6	103.0	1399.2	FT_FR	1050.4	103.0	1399.2	FT_FR	525.2	103.0	1399.2	FT_FR+AR+MSW	332.0	346.5	1155.7	FT_FR+AR+MSW	132.8	1039.9	462.3
IT	1683.2	FT_FR	4646.7	432.2	5871.4	FT_FR	2788.0	432.2	5871.4	FT_FR+ATJ_AR	3059.9	598.1	5705.5	FT_FR+AR+MSW	1459.9	1257.3	5046.3	FT_FR+AR+MSW	583.9	4285.1	2018.5
LT	47.8	FT_FR	3516.1	12.3	166.6	FT_FR	2109.7	12.3	166.6	FT_FR	1054.8	12.3	166.6	FT_FR	527.4	12.3	166.6	FT_FR	211.0	12.3	166.6
LU	24.3	FT_FR	435.2	6.2	84.8	FT_FR	261.1	6.2	84.8	FT_FR	130.6	6.2	84.8	FT_FR	65.3	6.2	84.8	FT_FR	26.1	6.2	84.8
LV	51.2	FT_FR	2553.3	13.1	178.4	FT_FR	1532.0	13.1	178.4	FT_FR	766.0	13.1	178.4	FT_FR	383.0	13.1	178.4	FT_FR	153.2	13.1	178.4
MD	26.2	FT_FR	1080.9	6.7	91.4	FT_FR	648.6	6.7	91.4	FT_FR	324.3	6.7	91.4	FT_FR	162.1	6.7	91.4	FT_FR	64.9	6.7	91.4
ME	14.5	FT_FR	249.8	3.7	50.6	FT_FR	149.9	3.7	50.6	FT_FR	74.9	3.7	50.6	FT_FR	37.5	3.7	50.6	FT_FR	15.0	3.7	50.6
MK	17.9	FT_FR	273.2	4.6	62.4	FT_FR	163.9	4.6	62.4	FT_FR	81.9	4.6	62.4	FT_FR	41.0	4.6	62.4	FT_FR+ATJ_AR	25.7	5.5	61.5
NL	1576.7	AR+FT_MS W	1625.7	893.8	5010.9	FT_FR+AR+MSW	869.8	2912.7	2992.0	FT_FR+AR+MSW	434.9	4408.7	1496.0	FT_FR+AR+MSW	217.4	5156.8	748.0	FT_FR+AR+MSW	87.0	5605.6	299.2
PL	292.8	FT_FR	8884.8	75.2	1021.3	FT_FR	5330.9	75.2	1021.3	FT_FR	2665.5	75.2	1021.3	FT_FR	1332.7	75.2	1021.3	FT_FR	533.1	75.2	1021.3
PT	649.0	FT_FR	4106.9	166.7	2264.0	FT_FR	2464.1	166.7	2264.0	FT_FR	1232.1	166.7	2264.0	FT_FR+ATJ_AR	706.1	185.6	2245.0	FT_FR+AR+MSW	280.9	1453.5	977.2
RO	210.8	FT_FR	6116.5	54.1	735.3	FT_FR	3669.9	54.1	735.3	FT_FR	1835.0	54.1	735.3	FT_FR	917.5	54.1	735.3	FT_FR	367.0	54.1	735.3
RS	67.9	FT_FR	1835.8	17.4	236.7	FT_FR	1101.5	17.4	236.7	FT_FR	550.7	17.4	236.7	FT_FR	275.4	17.4	236.7	FT_FR	110.1	17.4	236.7
SE	408.3	FT_FR	19894.0	104.9	1424.2	FT_FR	11936.4	104.9	1424.2	FT_FR	5968.2	104.9	1424.2	FT_FR	2984.1	104.9	1424.2	FT_FR	1193.6	104.9	1424.2
SI	10.6	FT_FR	1605.7	2.7	36.9	FT_FR	963.4	2.7	36.9	FT_FR	481.7	2.7	36.9	FT_FR	240.9	2.7	36.9	FT_FR	96.3	2.7	36.9
SK	21.3	FT_FR	3464.7	5.5	74.4	FT_FR	2078.8	5.5	74.4	FT_FR	1039.4	5.5	74.4	FT_FR	519.7	5.5	74.4	FT_FR	207.9	5.5	74.4
UA	224.3	FT_FR	5187.1	57.6	782.4	FT_FR	3112.3	57.6	782.4	FT_FR	1556.1	57.6	782.4	FT_FR	778.1	57.6	782.4	FT_FR	311.2	57.6	782.4
UK	5110.6	FT_FR	5514.6	1312.4	17827.0	AR	6805.2	2345.8	16793.5	AR+FT_MS W	5433.3	2958.4	16181.0	MSW	2514.9	10749.2	8390.2	MSW	1006.0	15783.3	3356.1

Table A16 2045 ReFuelEU – LOW scenario.

2045 ReFuel EU - LOW																					
Country	SAF demand (kt)	100% biomass availability				60% biomass availability				30% biomass availability				15% biomass availability				6% biomass availability			
		Conversion pathway	SAF supply (kt)	GHG emissions (kt CO2e)	GHG reduction (kt CO2e)	Conversion pathway	SAF supply (kt)	GHG emissions (kt CO2e)	GHG reduction (kt CO2e)	Conversion pathway	SAF supply (kt)	GHG emissions (kt CO2e)	GHG reduction (kt CO2e)	Conversion pathway	SAF supply (kt)	GHG emissions (kt CO2e)	GHG reduction (kt CO2e)	Conversion pathway	SAF supply (kt)	GHG emissions (kt CO2e)	GHG reduction (kt CO2e)
AL	18.6	FT_FR	433.8	4.8	64.8	FT_FR	260.3	4.8	64.8	FT_FR	130.2	4.8	64.8	FT_FR	65.1	4.8	64.8	FT_FR	26.0	4.8	64.8
AT	376.8	FT_FR	5880.6	96.8	1314.2	FT_FR	3528.4	96.8	1314.2	FT_FR	1764.2	96.8	1314.2	FT_FR	882.1	96.8	1314.2	FT_FR+AR	421.0	110.5	1300.5
BA	15.3	FT_FR	941.4	3.9	53.4	FT_FR	564.9	3.9	53.4	FT_FR	282.4	3.9	53.4	FT_FR	141.2	3.9	53.4	FT_FR	56.5	3.9	53.4
BE	1973.6	FT_FR+ATJ_AR	1999.4	959.6	6431.3	FT_FR+AR+MSW	1166.1	3353.3	4037.7	FT_FR+AR+MSW	583.0	5372.1	2018.8	FT_FR+AR+MSW	291.5	6381.5	1009.4	FT_FR+AR+MSW	116.6	6987.2	403.8
BG	115.7	FT_FR	1516.1	29.7	403.4	FT_FR	909.7	29.7	403.4	FT_FR	454.8	29.7	403.4	FT_FR	227.4	29.7	403.4	FT_FR+AR	235.3	43.9	389.3
CZ	185.8	FT_FR	4195.0	47.7	648.2	FT_FR	2517.0	47.7	648.2	FT_FR	1258.5	47.7	648.2	FT_FR	629.2	47.7	648.2	FT_FR	251.7	47.7	648.2
DE	4331.3	FT_FR	19009.4	1112.3	15108.5	FT_FR	11405.6	1112.3	15108.5	FT_FR	5702.8	1112.3	15108.5	FT_FR+ATJ_AR	4922.1	1961.0	14259.8	FT_FR+AR+MSW	1814.3	9905.8	6315.0
DK	442.4	FT_FR	3336.8	113.6	1543.2	FT_FR	2002.1	113.6	1543.2	FT_FR	1001.0	113.6	1543.2	FT_FR	500.5	113.6	1543.2	FT_FR+AR+MSW	304.6	596.5	1060.4
EE	22.3	FT_FR	1966.1	5.7	78.0	FT_FR	1179.6	5.7	78.0	FT_FR	589.8	5.7	78.0	FT_FR	294.9	5.7	78.0	FT_FR	118.0	5.7	78.0
EL	561.8	FT_FR	1243.4	144.3	1959.7	FT_FR	746.1	144.3	1959.7	FT_FR+ATJ_AR	932.3	252.5	1851.4	FT_FR+AR+MSW	419.4	647.8	1456.2	FT_FR+AR+MSW	167.8	1521.5	582.5
ES	3810.4	FT_FR	5816.7	978.5	13291.3	FT_FR+AR	8379.7	1162.2	13107.6	FT_FR+AR	4189.8	2163.0	12106.8	FT_FR+AR+MSW	1900.1	7674.8	6595.0	FT_FR+AR+MSW	760.0	11631.8	2638.0
FI	381.8	FT_FR	15098.1	98.0	1331.8	FT_FR	9058.9	98.0	1331.8	FT_FR	4529.4	98.0	1331.8	FT_FR	2264.7	98.0	1331.8	FT_FR	905.9	98.0	1331.8
FR	3335.9	FT_FR	15878.2	856.7	11636.4	FT_FR	9526.9	856.7	11636.4	FT_FR	4763.5	856.7	11636.4	FT_FR+ATJ_AR	4814.5	1403.9	11089.1	FT_FR+AR+MSW	1753.4	6396.5	6096.6
HR	86.6	FT_FR	4538.2	22.2	302.1	FT_FR	2722.9	22.2	302.1	FT_FR	1361.4	22.2	302.1	FT_FR	680.7	22.2	302.1	FT_FR	272.3	22.2	302.1
HU	166.2	FT_FR	2497.2	42.7	579.6	FT_FR	1498.3	42.7	579.6	FT_FR	749.2	42.7	579.6	FT_FR	374.6	42.7	579.6	FT_FR+ATJ_AR	359.1	52.0	570.2
IE	474.0	FT_FR	1943.7	121.7	1653.3	FT_FR	1166.2	121.7	1653.3	FT_FR+ATJ_AR	583.1	121.7	1653.3	FT_FR+AR+MSW	362.1	514.1	1260.9	FT_FR+AR+MSW	144.9	1270.7	504.3
IT	1919.5	FT_FR	4277.5	492.9	6695.7	FT_FR	2566.5	492.9	6695.7	FT_FR+AR	2994.6	857.9	6330.8	FT_FR+AR+MSW	1416.0	2293.1	4895.6	FT_FR+AR+MSW	566.4	5230.4	1958.2
LT	55.9	FT_FR	3503.5	14.3	194.9	FT_FR	2102.1	14.3	194.9	FT_FR	1051.1	14.3	194.9	FT_FR	525.5	14.3	194.9	FT_FR	210.2	14.3	194.9
LU	27.6	FT_FR	443.7	7.1	96.4	FT_FR	266.2	7.1	96.4	FT_FR	133.1	7.1	96.4	FT_FR	66.6	7.1	96.4	FT_FR+ATJ_AR	28.8	7.7	95.8
LV	58.5	FT_FR	2604.2	15.0	204.0	FT_FR	1562.5	15.0	204.0	FT_FR	781.3	15.0	204.0	FT_FR	390.6	15.0	204.0	FT_FR	156.3	15.0	204.0
MD	31.0	FT_FR	1094.4	8.0	108.1	FT_FR	656.6	8.0	108.1	FT_FR	328.3	8.0	108.1	FT_FR	164.2	8.0	108.1	FT_FR	65.7	8.0	108.1
ME	16.5	FT_FR	238.6	4.2	57.4	FT_FR	143.2	4.2	57.4	FT_FR	71.6	4.2	57.4	FT_FR	35.8	4.2	57.4	FT_FR+AR+MSW	15.1	9.1	52.6
MK	21.0	FT_FR	257.8	5.4	73.1	FT_FR	154.7	5.4	73.1	FT_FR	77.4	5.4	73.1	FT_FR	38.7	5.4	73.1	FT_FR+ATJ_AR	25.1	8.5	70.0
NL	1790.2	FT_FR+AR+MSW	1337.4	1651.5	5052.7	FT_FR+AR+MSW	880.6	3672.6	3031.6	FT_FR+AR+MSW	440.3	5188.4	1515.8	FT_FR+AR+MSW	220.1	5946.3	757.9	FT_FR+AR+MSW	88.1	6401.0	303.2
PL	341.6	FT_FR	9059.2	87.7	1191.7	FT_FR	5435.5	87.7	1191.7	FT_FR	2717.8	87.7	1191.7	FT_FR	1358.9	87.7	1191.7	FT_FR	543.6	87.7	1191.7
PT	741.2	FT_FR	4189.0	190.3	2585.3	FT_FR	2513.4	190.3	2585.3	FT_FR	1256.7	190.3	2585.3	FT_FR+ATJ_AR	721.3	285.0	2490.7	FT_FR+AR+MSW	286.3	1779.4	996.3
RO	249.9	FT_FR	5957.2	64.2	871.6	FT_FR	3574.3	64.2	871.6	FT_FR	1787.2	64.2	871.6	FT_FR	893.6	64.2	871.6	FT_FR	357.4	64.2	871.6
RS	78.5	FT_FR	1871.3	20.2	273.7	FT_FR	1122.8	20.2	273.7	FT_FR	561.4	20.2	273.7	FT_FR	280.7	20.2	273.7	FT_FR	112.3	20.2	273.7
SE	469.4	FT_FR	20001.3	120.5	1637.2	FT_FR	12000.8	120.5	1637.2	FT_FR	6000.4	120.5	1637.2	FT_FR	3000.2	120.5	1637.2	FT_FR	1200.1	120.5	1637.2
SI	12.3	FT_FR	1637.5	3.2	43.0	FT_FR	982.5	3.2	43.0	FT_FR	491.2	3.2	43.0	FT_FR	245.6	3.2	43.0	FT_FR	98.2	3.2	43.0
SK	25.2	FT_FR	3818.3	6.5	88.0	FT_FR	2291.0	6.5	88.0	FT_FR	1145.5	6.5	88.0	FT_FR	572.7	6.5	88.0	FT_FR	229.1	6.5	88.0
UA	266.6	FT_FR	5144.1	68.5	929.9	FT_FR	3086.5	68.5	929.9	FT_FR	1543.2	68.5	929.9	FT_FR	771.6	68.5	929.9	FT_FR	308.6	68.5	929.9
UK	6016.1	FT_FR+ATJ_AR	11484.2	1828.2	20702.2	FT_FR+ATJ_AR	6890.5	3095.0	19435.3	FT_FR+AR+MSW	4153.0	8466.0	14064.4	FT_FR+AR+MSW	2076.5	15498.2	7032.2	FT_FR+AR+MSW	830.6	19717.5	2812.9

Table A17 2045 ReFuelEU –HIGH scenario.

2045 ReFuel EU - HIGH																					
Country	SAF demand (kt)	100% biomass availability				60% biomass availability				30% biomass availability				15% biomass availability				6% biomass availability			
		Conversion pathway	SAF supply (kt)	GHG emissions (kt CO2e)	GHG reduction (kt CO2e)	Conversion pathway	SAF supply (kt)	GHG emissions (kt CO2e)	GHG reduction (kt CO2e)	Conversion pathway	SAF supply (kt)	GHG emissions (kt CO2e)	GHG reduction (kt CO2e)	Conversion pathway	SAF supply (kt)	GHG emissions (kt CO2e)	GHG reduction (kt CO2e)	Conversion pathway	SAF supply (kt)	GHG emissions (kt CO2e)	GHG reduction (kt CO2e)
AL	21.9	FT_FR	433.8	5.6	76.2	FT_FR	260.3	5.6	76.2	FT_FR	130.2	5.6	76.2	FT_FR	65.1	5.6	76.2	FT_FR	26.0	5.6	76.2
AT	441.2	FT_FR	5880.6	113.3	1538.9	FT_FR	3528.4	113.3	1538.9	FT_FR	1764.2	113.3	1538.9	FT_FR	882.1	113.3	1538.9	FT_FR+AR	421.0	213.9	1438.3
BA	17.7	FT_FR	941.4	4.5	61.8	FT_FR	564.9	4.5	61.8	FT_FR	282.4	4.5	61.8	FT_FR	141.2	4.5	61.8	FT_FR	56.5	4.5	61.8
BE	2259.1	FT_FR+AR+MSW	2400.8	1950.1	6510.2	FT_FR+AR+MSW	1166.1	4422.5	4037.7	FT_FR+AR+MSW	583.0	6441.4	2018.8	FT_FR+AR+MSW	291.5	7450.8	1009.4	FT_FR+AR+MSW	116.6	8056.5	403.8
BG	134.8	FT_FR	1516.1	34.6	470.2	FT_FR	909.7	34.6	470.2	FT_FR	454.8	34.6	470.2	FT_FR	227.4	34.6	470.2	FT_FR+AR	235.3	59.8	445.1
CZ	215.4	FT_FR	4195.0	55.3	751.4	FT_FR	2517.0	55.3	751.4	FT_FR	1258.5	55.3	751.4	FT_FR	629.2	55.3	751.4	FT_FR	251.7	55.3	751.4
DE	4978.0	FT_FR	19009.4	1278.4	17364.4	FT_FR	11405.6	1278.4	17364.4	FT_FR	5702.8	1278.4	17364.4	AR+FT_MS W	5013.7	2498.0	16144.7	FT_FR+AR+MSW	1814.3	12327.8	6315.0
DK	515.6	FT_FR	3336.8	132.4	1798.4	FT_FR	2002.1	132.4	1798.4	FT_FR	1001.0	132.4	1798.4	AR	822.9	141.0	1789.8	MSW	304.6	870.4	1060.4
EE	25.6	FT_FR	1966.1	6.6	89.2	FT_FR	1179.6	6.6	89.2	FT_FR	589.8	6.6	89.2	FT_FR	294.9	6.6	89.2	FT_FR	118.0	6.6	89.2
EL	649.2	FT_FR	1243.4	166.7	2264.5	FT_FR	746.1	166.7	2264.5	AR	932.3	325.1	2106.1	MSW	419.4	975.0	1456.2	FT_FR+AR+MSW	167.8	1848.7	582.5
ES	4416.5	FT_FR	5816.7	1134.2	15405.5	AR	8379.7	1665.5	14874.2	FT_FR+AR+MSW	3800.2	2666.3	13873.4	FT_FR+AR+MSW	1900.1	9944.7	6595.0	FT_FR+AR+MSW	760.0	13901.7	2638.0
FI	446.6	FT_FR	15098.1	114.7	1557.8	FT_FR	9058.9	114.7	1557.8	FT_FR	4529.4	114.7	1557.8	FT_FR	2264.7	114.7	1557.8	FT_FR	905.9	114.7	1557.8
FR	3838.1	FT_FR	15878.2	985.6	13387.9	FT_FR	9526.9	985.6	13387.9	FT_FR	4763.5	985.6	13387.9	AR	4814.5	1820.9	12552.7	FT_FR+AR+MSW	1753.4	8277.0	6096.6
HR	100.9	FT_FR	4538.2	25.9	351.9	FT_FR	2722.9	25.9	351.9	FT_FR	1361.4	25.9	351.9	FT_FR	680.7	25.9	351.9	FT_FR	272.3	25.9	351.9
HU	190.8	FT_FR	2497.2	49.0	665.5	FT_FR	1498.3	49.0	665.5	FT_FR	749.2	49.0	665.5	FT_FR	374.6	49.0	665.5	FT_FR+AR	359.1	72.5	642.0
IE	519.9	FT_FR	1943.7	133.5	1813.5	FT_FR	1166.2	133.5	1813.5	FT_FR	583.1	133.5	1813.5	FT_FR+AR+MSW	362.1	686.1	1260.9	FT_FR+AR+MSW	144.9	1442.6	504.3
IT	2226.4	FT_FR	4277.5	571.7	7766.0	FT_FR	2566.5	571.7	7766.0	AR	2994.6	1112.6	7225.1	MSW	1416.0	3442.2	4895.6	FT_FR+AR+MSW	566.4	6379.5	1958.2
LT	64.4	FT_FR	3503.5	16.5	224.5	FT_FR	2102.1	16.5	224.5	FT_FR	1051.1	16.5	224.5	FT_FR	525.5	16.5	224.5	FT_FR	210.2	16.5	224.5
LU	32.3	FT_FR	443.7	8.3	112.5	FT_FR	266.2	8.3	112.5	FT_FR	133.1	8.3	112.5	FT_FR	66.6	8.3	112.5	FT_FR+AR+MSW	29.0	19.9	100.9
LV	69.0	FT_FR	2604.2	17.7	240.6	FT_FR	1562.5	17.7	240.6	FT_FR	781.3	17.7	240.6	FT_FR	390.6	17.7	240.6	FT_FR	156.3	17.7	240.6
MD	36.0	FT_FR	1094.4	9.2	125.6	FT_FR	656.6	9.2	125.6	FT_FR	328.3	9.2	125.6	FT_FR	164.2	9.2	125.6	FT_FR	65.7	9.2	125.6
ME	19.9	FT_FR	238.6	5.1	69.6	FT_FR	143.2	5.1	69.6	FT_FR	71.6	5.1	69.6	FT_FR	35.8	5.1	69.6	FT_FR+AR+MSW	15.1	22.1	52.6
MK	24.6	FT_FR	257.8	6.3	85.8	FT_FR	154.7	6.3	85.8	FT_FR	77.4	6.3	85.8	FT_FR	38.7	6.3	85.8	AR	25.1	11.6	80.6
NL	2088.0	FT_FR+AR+MSW	1467.6	2766.9	5052.7	FT_FR+AR+MSW	880.6	4788.0	3031.6	FT_FR+AR+MSW	440.3	6303.8	1515.8	FT_FR+AR+MSW	220.1	7061.7	757.9	FT_FR+AR+MSW	88.1	7516.5	303.2
PL	391.5	FT_FR	9059.2	100.5	1365.7	FT_FR	5435.5	100.5	1365.7	FT_FR	2717.8	100.5	1365.7	FT_FR	1358.9	100.5	1365.7	FT_FR	543.6	100.5	1365.7
PT	866.4	FT_FR	4189.0	222.5	3022.2	FT_FR	2513.4	222.5	3022.2	FT_FR	1256.7	222.5	3022.2	FT_FR+AR+MSW	715.7	754.1	2490.7	FT_FR+AR+MSW	286.3	2248.5	996.3
RO	290.9	FT_FR	5957.2	74.7	1014.8	FT_FR	3574.3	74.7	1014.8	FT_FR	1787.2	74.7	1014.8	FT_FR	893.6	74.7	1014.8	FT_FR	357.4	74.7	1014.8
RS	93.7	FT_FR	1871.3	24.1	326.7	FT_FR	1122.8	24.1	326.7	FT_FR	561.4	24.1	326.7	FT_FR	280.7	24.1	326.7	FT_FR	112.3	24.1	326.7
SE	544.4	FT_FR	20001.3	139.8	1898.9	FT_FR	12000.8	139.8	1898.9	FT_FR	6000.4	139.8	1898.9	FT_FR	3000.2	139.8	1898.9	FT_FR	1200.1	139.8	1898.9
SI	14.4	FT_FR	1637.5	3.7	50.3	FT_FR	982.5	3.7	50.3	FT_FR	491.2	3.7	50.3	FT_FR	245.6	3.7	50.3	FT_FR	98.2	3.7	50.3
SK	28.8	FT_FR	3818.3	7.4	100.4	FT_FR	2291.0	7.4	100.4	FT_FR	1145.5	7.4	100.4	FT_FR	572.7	7.4	100.4	FT_FR	229.1	7.4	100.4
UA	309.4	FT_FR	5144.1	79.5	1079.2	FT_FR	3086.5	79.5	1079.2	FT_FR	1543.2	79.5	1079.2	FT_FR	771.6	79.5	1079.2	FT_FR+AR	1525.7	79.9	1078.8
UK	6773.9	FT_FR+AR	11484.2	2457.4	22910.9	AR	6890.5	3724.2	21644.1	MSW	4153.0	11304.0	14064.4	MSW	2076.5	18336.1	7032.2	MSW	830.6	22555.5	2812.9

Table A18 2050 ReFuelEU – LOW scenario.

2050 ReFuel EU - LOW																					
Country	SAF demand (kt)	100% biomass availability				60% biomass availability				30% biomass availability				15% biomass availability				6% biomass availability			
		Conversion pathway	SAF supply (kt)	GHG emissions (kt CO2e)	GHG reduction (kt CO2e)	Conversion pathway	SAF supply (kt)	GHG emissions (kt CO2e)	GHG reduction (kt CO2e)	Conversion pathway	SAF supply (kt)	GHG emissions (kt CO2e)	GHG reduction (kt CO2e)	Conversion pathway	SAF supply (kt)	GHG emissions (kt CO2e)	GHG reduction (kt CO2e)	Conversion pathway	SAF supply (kt)	GHG emissions (kt CO2e)	GHG reduction (kt CO2e)
AL	33.1	FT_FR	475.8	8.5	115.4	FT_FR	285.5	8.5	115.4	FT_FR	142.7	8.5	115.4	FT_FR	71.4	8.5	115.4	FT_FR+ATJ_AR	40.5	11.1	112.8
AT	649.5	FT_FR	5994.9	166.8	2265.5	FT_FR	3596.9	166.8	2265.5	FT_FR	1798.5	166.8	2265.5	FT_FR	899.2	166.8	2265.5	MSW	437.0	967.0	1465.3
BA	27.1	FT_FR	959.3	7.0	94.5	FT_FR	575.6	7.0	94.5	FT_FR	287.8	7.0	94.5	FT_FR	143.9	7.0	94.5	FT_FR	57.6	7.0	94.5
BE	3577.1	FT_FR+AR+MSW	1973.8	6558.6	6837.8	FT_FR+AR+MSW	1184.3	9293.7	4102.7	FT_FR+AR+MSW	592.1	11345.1	2051.3	FT_FR+AR+MSW	296.1	12370.7	1025.7	FT_FR+AR+MSW	118.4	12986.1	410.3
BG	204.0	FT_FR	1545.9	52.4	711.4	FT_FR	927.6	52.4	711.4	FT_FR	463.8	52.4	711.4	FT_FR	231.9	52.4	711.4	FT_FR+ATJ_AR	240.6	116.2	647.7
CZ	324.0	FT_FR	4276.3	83.2	1130.0	FT_FR	2565.8	83.2	1130.0	FT_FR	1282.9	83.2	1130.0	FT_FR	641.4	83.2	1130.0	FT_FR	256.6	121.8	1091.4
DE	7383.4	FT_FR	19376.9	1896.1	25754.9	FT_FR	11626.1	1896.1	25754.9	FT_FR+ATJ_AR	10049.2	2796.7	24854.2	FT_FR+AR+MSW	4622.1	11560.5	16090.4	FT_FR+AR+MSW	1848.9	21214.8	6436.2
DK	762.5	FT_FR	3384.7	195.8	2659.7	FT_FR	2030.8	195.8	2659.7	FT_FR	1015.4	195.8	2659.7	FT_FR+ATJ_AR	837.5	341.9	2513.6	FT_FR+AR+MSW	309.5	1777.9	1077.6
EE	39.0	FT_FR	2003.8	10.0	136.2	FT_FR	1202.3	10.0	136.2	FT_FR	601.1	10.0	136.2	FT_FR	300.6	10.0	136.2	FT_FR	120.2	10.0	136.2
EL	968.3	FT_FR	1267.1	248.7	3377.5	FT_FR+ATJ_AR	1911.7	368.0	3258.2	FT_FR+ATJ_AR	955.9	583.5	3042.7	FT_FR+AR+MSW	428.1	2139.0	1487.2	FT_FR+AR+MSW	171.3	3031.3	594.9
ES	6564.2	FT_FR+ATJ_AR	14297.1	2049.5	22533.4	FT_FR+ATJ_AR	8578.3	3409.9	21173.5	FT_FR+AR+MSW	3874.7	11129.3	13453.7	FT_FR+AR+MSW	1937.4	17856.2	6726.8	FT_FR+AR+MSW	774.9	21892.3	2690.7
FI	656.2	FT_FR	15391.7	168.5	2289.1	FT_FR	9235.0	168.5	2289.1	FT_FR	4617.5	168.5	2289.1	FT_FR	2308.8	168.5	2289.1	FT_FR	923.5	168.5	2289.1
FR	5667.6	FT_FR	16185.6	1455.4	19769.7	FT_FR	9711.4	1455.4	19769.7	FT_FR+ATJ_AR	9835.5	1921.1	19304.1	FT_FR+AR+MSW	4466.9	5690.2	15535.0	FT_FR+AR+MSW	1786.8	15011.2	6214.0
HR	153.5	FT_FR	4512.1	39.4	535.5	FT_FR	2707.3	39.4	535.5	FT_FR	1353.6	39.4	535.5	FT_FR	676.8	39.4	535.5	FT_FR	270.7	39.4	535.5
HU	292.7	FT_FR	2545.5	75.2	1021.2	FT_FR	1527.3	75.2	1021.2	FT_FR	763.7	75.2	1021.2	FT_FR	381.8	75.2	1021.2	FT_FR+ATJ_AR	367.0	155.5	940.9
IE	805.1	FT_FR	2136.9	206.7	2808.3	FT_FR	1282.1	206.7	2808.3	FT_FR+ATJ_AR	812.3	300.8	2714.2	FT_FR+AR+MSW	392.3	1649.0	1366.1	FT_FR+AR+MSW	156.9	2468.6	546.4
IT	3274.0	FT_FR	3908.3	840.8	11420.2	FT_FR	5858.8	1373.5	10887.4	FT_FR+AR+MSW	2744.3	2771.2	9489.7	FT_FR+AR+MSW	1372.2	7516.1	4744.9	FT_FR+AR+MSW	548.9	10363.0	1897.9
LT	97.3	FT_FR	3490.9	25.0	339.5	FT_FR	2094.5	25.0	339.5	FT_FR	1047.3	25.0	339.5	FT_FR	523.6	25.0	339.5	FT_FR	209.5	25.0	339.5
LU	47.2	FT_FR	452.2	12.1	164.6	FT_FR	271.3	12.1	164.6	FT_FR	135.7	12.1	164.6	FT_FR	67.8	12.1	164.6	FT_FR	29.5	74.1	102.7
LV	101.3	FT_FR	2655.1	26.0	353.2	FT_FR	1593.1	26.0	353.2	FT_FR	796.5	26.0	353.2	FT_FR	398.3	26.0	353.2	FT_FR	159.3	26.0	353.2
MD	54.9	FT_FR	1107.8	14.1	191.5	FT_FR	664.7	14.1	191.5	FT_FR	332.3	14.1	191.5	FT_FR	166.2	14.1	191.5	FT_FR	66.5	14.1	191.5
ME	28.9	FT_FR	227.4	7.4	100.7	FT_FR	136.4	7.4	100.7	FT_FR	68.2	7.4	100.7	FT_FR	34.1	7.4	100.7	FT_FR+AR+MSW	14.4	57.9	50.2
MK	37.1	FT_FR	242.5	9.5	129.4	FT_FR	145.5	9.5	129.4	FT_FR	72.8	9.5	129.4	FT_FR+ATJ_AR	61.0	9.9	129.0	FT_FR+AR+MSW	23.1	58.8	80.2
NL	3052.0	FT_FR+AR+MSW	1485.6	6311.1	5118.7	FT_FR+AR+MSW	891.4	8358.6	3071.2	FT_FR+AR+MSW	445.7	9894.2	1535.6	FT_FR+AR+MSW	222.8	10662.0	767.8	FT_FR+AR+MSW	89.1	11122.7	307.1
PL	591.4	FT_FR	9233.6	151.9	2063.0	FT_FR	5540.1	151.9	2063.0	FT_FR	2770.1	151.9	2063.0	FT_FR	1385.0	151.9	2063.0	FT_FR	554.0	173.3	2041.6
PT	1273.5	FT_FR	4271.2	327.0	4442.1	FT_FR	2562.7	327.0	4442.1	FT_FR	1281.4	327.0	4442.1	FT_FR+AR+MSW	729.3	2230.8	2538.4	FT_FR+AR+MSW	291.7	3753.8	1015.4
RO	444.5	FT_FR	5797.9	114.1	1550.5	FT_FR	3478.7	114.1	1550.5	FT_FR	1739.4	114.1	1550.5	FT_FR	869.7	114.1	1550.5	FT_FR+ATJ_AR	640.5	169.6	1495.1
RS	138.7	FT_FR	1906.8	35.6	483.9	FT_FR	1144.1	35.6	483.9	FT_FR	572.0	35.6	483.9	FT_FR	286.0	35.6	483.9	FT_FR	247.6	49.6	470.0
SE	807.3	FT_FR	20108.6	207.3	2816.0	FT_FR	12065.2	207.3	2816.0	FT_FR	6032.6	207.3	2816.0	FT_FR	3016.3	207.3	2816.0	FT_FR	1206.5	207.3	2816.0
SI	21.6	FT_FR	1669.2	5.5	75.3	FT_FR	1001.5	5.5	75.3	FT_FR	500.8	5.5	75.3	FT_FR	250.4	5.5	75.3	FT_FR	100.2	5.5	75.3
SK	44.1	FT_FR	4172.0	11.3	153.8	FT_FR	2503.2	11.3	153.8	FT_FR	1251.6	11.3	153.8	FT_FR	625.8	11.3	153.8	FT_FR	250.3	11.3	153.8
UA	474.4	FT_FR	5101.1	121.8	1654.7	FT_FR	3060.7	121.8	1654.7	FT_FR	1530.3	121.8	1654.7	FT_FR	765.2	121.8	1654.7	FT_FR+ATJ_AR	1550.2	218.3	1558.2
UK	10373.8	FT_FR+ATJ_AR	11626.4	5442.0	33407.8	FT_FR+AR+MSW	6552.1	16153.2	22696.7	FT_FR+AR+MSW	3276.0	27501.5	11348.3	FT_FR+AR+MSW	1638.0	33175.7	5674.2	FT_FR+AR+MSW	655.2	36580.2	2269.7

Table A19 2050 ReFuelEU –HIGH scenario.

2050 ReFuel EU - HIGH																					
Country	SAF demand (kt)	100% biomass availability				60% biomass availability				30% biomass availability				15% biomass availability				6% biomass availability			
		Conversion pathway	SAF supply (kt)	GHG emissions (kt CO2e)	GHG reduction (kt CO2e)	Conversion pathway	SAF supply (kt)	GHG emissions (kt CO2e)	GHG reduction (kt CO2e)	Conversion pathway	SAF supply (kt)	GHG emissions (kt CO2e)	GHG reduction (kt CO2e)	Conversion pathway	SAF supply (kt)	GHG emissions (kt CO2e)	GHG reduction (kt CO2e)	Conversion pathway	SAF supply (kt)	GHG emissions (kt CO2e)	GHG reduction (kt CO2e)
AL	40.4	FT_FR	475.8	10.4	140.8	FT_FR	285.5	10.4	140.8	FT_FR	142.7	10.4	140.8	FT_FR	71.4	10.4	140.8	FT_FR+ATJ_AR	40.5	17.1	134.0
AT	792.6	FT_FR	5994.9	203.5	2764.8	FT_FR	3596.9	203.5	2764.8	FT_FR	1798.5	203.5	2764.8	FT_FR	899.2	203.5	2764.8	MSW	420.9	1503.0	1465.3
BA	32.4	FT_FR	959.3	8.3	113.0	FT_FR	575.6	8.3	113.0	FT_FR	287.8	8.3	113.0	FT_FR	143.9	8.3	113.0	FT_FR	57.6	8.3	113.0
BE	4211.6	FT_FR+AR+MSW	1973.8	8934.8	6837.8	FT_FR+AR+MSW	1184.3	11670.0	4102.7	FT_FR+AR+MSW	592.1	13721.3	2051.3	FT_FR+AR+MSW	296.1	14747.0	1025.7	FT_FR+AR+MSW	118.4	15362.3	410.3
BG	246.5	FT_FR	1545.9	63.3	859.9	FT_FR	927.6	63.3	859.9	FT_FR	463.8	63.3	859.9	FT_FR	601.5	71.7	851.5	FT_FR+AR+MSW	208.4	197.0	726.2
CZ	389.7	FT_FR	4276.3	100.1	1359.2	FT_FR	2565.8	100.1	1359.2	FT_FR	1282.9	100.1	1359.2	FT_FR	641.4	100.1	1359.2	FT_FR+ATJ_AR	402.7	176.4	1282.9
DE	8820.6	FT_FR	19376.9	2265.1	30767.8	FT_FR	11626.1	2265.1	30767.8	FT_FR+ATJ_AR	10049.2	3990.0	29043.0	FT_FR+AR+MSW	4622.1	16942.5	16090.4	FT_FR+AR+MSW	1848.9	26596.8	6436.2
DK	925.1	FT_FR	3384.7	237.6	3226.8	FT_FR	2030.8	237.6	3226.8	FT_FR	1015.4	237.6	3226.8	MSW	773.6	770.3	2694.0	MSW	309.5	2386.7	1077.6
EE	46.2	FT_FR	2003.8	11.9	161.2	FT_FR	1202.3	11.9	161.2	FT_FR	601.1	11.9	161.2	FT_FR	300.6	11.9	161.2	FT_FR	120.2	11.9	161.2
EL	1162.5	FT_FR	1267.1	298.5	4054.9	FT_FR+ATJ_AR	1911.7	529.2	3824.2	FT_FR+AR+MSW	856.3	1379.1	2974.4	FT_FR+AR+MSW	428.1	2866.2	1487.2	FT_FR+AR+MSW	171.3	3758.5	594.9
ES	7911.1	FT_FR+ATJ_AR	14297.1	3167.9	26459.2	FT_FR+ATJ_AR	8578.3	4528.2	25098.9	FT_FR+AR+MSW	3874.7	16173.4	13453.7	FT_FR+AR+MSW	1937.4	22900.3	6726.8	FT_FR+AR+MSW	774.9	26936.4	2690.7
FI	800.2	FT_FR	15391.7	205.5	2791.2	FT_FR	9235.0	205.5	2791.2	FT_FR	4617.5	205.5	2791.2	FT_FR	2308.8	205.5	2791.2	FT_FR	923.5	205.5	2791.2
FR	6783.5	FT_FR	16185.6	1742.0	23662.1	FT_FR	9711.4	1742.0	23662.1	FT_FR+ATJ_AR	9835.5	2847.6	22556.5	FT_FR+AR+MSW	4466.9	9869.1	15535.0	FT_FR+AR+MSW	1786.8	19190.1	6214.0
HR	185.3	FT_FR	4512.1	47.6	646.2	FT_FR	2707.3	47.6	646.2	FT_FR	1353.6	47.6	646.2	FT_FR	676.8	47.6	646.2	FT_FR	270.7	47.6	646.2
HU	347.4	FT_FR	2545.5	89.2	1211.9	FT_FR	1527.3	89.2	1211.9	FT_FR	763.7	89.2	1211.9	FT_FR	381.8	89.2	1211.9	FT_FR+ATJ_AR	367.0	200.9	1100.2
IE	907.1	FT_FR	2136.9	233.0	3164.3	FT_FR	1282.1	233.0	3164.3	FT_FR+AR+MSW	784.5	665.1	2732.1	FT_FR+AR+MSW	392.3	2031.2	1366.1	FT_FR+AR+MSW	156.9	2850.8	546.4
IT	3955.8	FT_FR+ATJ_AR	9764.6	1043.1	13771.4	FT_FR+ATJ_AR	5858.8	1939.7	12874.8	FT_FR+AR+MSW	2744.3	5324.8	9489.7	FT_FR+AR+MSW	1372.2	10069.7	4744.9	FT_FR+AR+MSW	548.9	12916.6	1897.9
LT	116.2	FT_FR	3490.9	29.8	405.3	FT_FR	2094.5	29.8	405.3	FT_FR	1047.3	29.8	405.3	FT_FR	523.6	29.8	405.3	FT_FR	209.5	29.8	405.3
LU	57.5	FT_FR	452.2	14.8	200.4	FT_FR	271.3	14.8	200.4	FT_FR	135.7	14.8	200.4	FT_FR	67.8	14.8	200.4	FT_FR+AR+MSW	29.5	112.5	102.7
LV	124.6	FT_FR	2655.1	32.0	434.7	FT_FR	1593.1	32.0	434.7	FT_FR	796.5	32.0	434.7	FT_FR	398.3	32.0	434.7	FT_FR	159.3	32.0	434.7
MD	66.1	FT_FR	1107.8	17.0	230.5	FT_FR	664.7	17.0	230.5	FT_FR	332.3	17.0	230.5	FT_FR	166.2	17.0	230.5	FT_FR	66.5	17.0	230.5
ME	36.6	FT_FR	227.4	9.4	127.7	FT_FR	136.4	9.4	127.7	FT_FR	68.2	9.4	127.7	FT_FR	36.1	11.6	125.6	FT_FR+AR+MSW	14.4	86.9	50.2
MK	45.2	FT_FR	242.5	11.6	157.6	FT_FR	145.5	11.6	157.6	FT_FR	72.8	11.6	157.6	AR	61.0	16.6	152.5	FT_FR+AR+MSW	23.1	89.0	80.2
NL	3713.9	FT_FR+AR+MSW	1485.6	8789.9	5118.7	FT_FR+AR+MSW	891.4	10837.3	3071.2	FT_FR+AR+MSW	445.7	12372.9	1535.6	FT_FR+AR+MSW	222.8	13140.7	767.8	FT_FR+AR+MSW	89.1	13601.4	307.1
PL	702.3	FT_FR	9233.6	180.3	2449.7	FT_FR	5540.1	180.3	2449.7	FT_FR	2770.1	180.3	2449.7	FT_FR	1385.0	180.3	2449.7	AR	978.2	265.4	2364.6
PT	1551.8	FT_FR	4271.2	398.5	5413.0	FT_FR	2562.7	398.5	5413.0	FT_FR+ATJ_AR	1473.2	734.8	5076.8	FT_FR+AR+MSW	729.3	3273.1	2538.4	FT_FR+AR+MSW	291.7	4796.2	1015.4
RO	535.7	FT_FR	5797.9	137.6	1868.7	FT_FR	3478.7	137.6	1868.7	FT_FR	1739.4	137.6	1868.7	FT_FR	869.7	137.6	1868.7	AR	640.5	245.3	1761.0
RS	172.5	FT_FR	1906.8	44.3	601.6	FT_FR	1144.1	44.3	601.6	FT_FR	572.0	44.3	601.6	FT_FR	286.0	44.3	601.6	AR	247.6	77.6	568.3
SE	974.0	FT_FR	20108.6	250.1	3397.6	FT_FR	12065.2	250.1	3397.6	FT_FR	6032.6	250.1	3397.6	FT_FR	3016.3	250.1	3397.6	FT_FR	1206.5	250.1	3397.6
SI	26.3	FT_FR	1669.2	6.8	91.7	FT_FR	1001.5	6.8	91.7	FT_FR	500.8	6.8	91.7	FT_FR	250.4	6.8	91.7	FT_FR	100.2	6.8	91.7
SK	52.0	FT_FR	4172.0	13.4	181.4	FT_FR	2503.2	13.4	181.4	FT_FR	1251.6	13.4	181.4	FT_FR	625.8	13.4	181.4	FT_FR	250.3	13.4	181.4
UA	569.5	FT_FR	5101.1	146.3	1986.6	FT_FR	3060.7	146.3	1986.6	FT_FR	1530.3	146.3	1986.6	FT_FR	765.2	146.3	1986.6	AR	1550.2	297.4	1835.5
UK	12057.8	AR+FT_MS	12327.0	6755.4	38401.1	MSW	6552.1	22459.8	22696.7	FT_FR+AR+MSW	3276.0	33808.2	11348.3	MSW	1638.0	39482.3	5674.2	MSW	655.2	42886.8	2269.7

Curriculum Vitae

Zhizhen Wang was born on September 2, 1989, in Guizhou, China. In 2013, she graduated with a Master of Engineering degree in Environmental Engineering from Sun Yat-Sen University, in Guangzhou, China. In the same year, she continued to pursue her interest in environmental studies and began the graduate study of Environmental and Energy Management at the University of Twente, in The Netherlands. At the end of 2014, she obtained a Master of Science degree in Environmental and Energy Management. After graduation, Zhizhen worked as an independent researcher on several sustainability projects in the fields of building energy efficiency, decarbonization, and circular economy. In 2016, she started her PhD research project in the area of sustainability assessment of biobased sustainable aviation fuel (SAF) in the Biotechnology and Society Group in the Department of Biotechnology at the Delft University of Technology, with Prof. dr. P. Osseweijer as promotor and dr. J.A. Posada Duque as co-promotor. Working as a PhD candidate, she broadened her knowledge base and deepened her understanding of the integral sustainability performance of biofuels. This PhD project equipped her with a unique perspective of evaluating sustainability from the intersection of technology and society. In November 2019, she started working as the Sustainability Program Manager and became the Climate Lead in 2022 at Signify in Eindhoven, The Netherlands.

In the current era of climate anxiety coexisting with climate change optimism, the scientific consensus lands on the urgency and necessity of combating climate change. Among other solutions, renewable energy is perceived as one of the most important levers to drive the transition toward a low-carbon or even zero-carbon economy.

The aviation industry relies on biobased sustainable aviation fuel (SAF) in this transition. As the value chain of biobased aviation fuel involves a wide range of economic sectors and interacts with various stakeholders in society, decarbonizing the aviation sector requires a thorough understanding of the integral sustainability performance of biobased SAF production and supply chain beyond its emissions reduction capability.

This thesis explores the broader sustainability performance of biobased SAF production and supply chain, providing new insights into several under-studied aspects of socioeconomic effects, human health impacts, supply-demand balance and resulting GHG emissions reduction potential.

This thesis has also demonstrated an operational approach to step-by-step manifest specificities, highlight interdependencies of various elements, and eventually present results and reveal trade-offs in a way that could lead to a meaningful decision-making process for biobased SAF production and supply chain. Such an approach could be replicated to facilitate decision-making and strategic planning related to other multidisciplinary, multi-stakeholder, and full-of-trade-off problems.