Contribution of Sustainable Aviation Fuels Towards Net Zero 2050 – Using Life Cycle Analysis

Final Report

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Abstract

Many regulative bodies, such as the European Union and the International Air Transport Association (IATA), have set the goal to have net zero CO_2 emissions generated by flights by 2050. Sustainable aviation fuels (SAFs) are considered the biggest contributor to achieve this goal, as they should reduce 65% of all expected CO_2 emissions by 2050. SAFs are alternative jet-fuels that are produced from biomass or waste resources instead of fossil resources. SAFs can by blended with conventional jet-fuel kerosene up to 50% and require, therefore, minimal to no retrofitting of existing aircraft fleets. This research focusses on three conditions that SAFs must meet to achieve their contributing goal towards net zero CO_2 emissions by 2050. These conditions are that the environmental impact of SAFs must be at least 65% lower than that of kerosene, flying on 100% SAF must be possible, and enough feedstocks must be available.

The environmental impact of the entire life cycles of 4 SAFs, taking into account different possible feedstocks, are assessed using life cycle analysis (LCA). The results of these LCAs show that the ability of different SAFs to reduce emissions ranges from about 80%-10% compared to kerosene. The SAF Fischer-Tropsch has the lowest environmental impact with an emission reduction between 91% and 85%, taking into account the different feedstocks. Followed by HEFA, with an emission reduction of 82%-58%. SIP and ATJ both have a significant higher environmental impact. SIP can reduce 55%-51% of emissions, while ATJ yields 68%-7%. The reason that the environmental impacts of the different SAFs are so different is mainly due to differences in the allowable feedstock and the conversion process. It is assumed that flying with 100% SAF will be possible and allowed by 2030. This is supported by the commitments of Boeing and Airbus and their first successful test flights on 100% SAF. Availability of feedstocks seems to be the biggest challenge and requires more research. In 2025 it is estimated that 8 billion liters of SAF will be required, in 2050 it is estimated to be around 449 billion liters. A huge scale-up is needed in the production of SAF, which means an immense increase in feedstock production. It is estimated that about 10 million km^2 lands are still available on earth for feedstock production of this kind. However, these lands are considered to be of low quality and must be shared with other competing sectors. Further research is needed to determine how much land will be required annually for the production of all SAFs by 2050.

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List of Abbreviations

ASTM	American Society for Testing and Materials
ATJ	Alcohol to Jet
CAAFI	Commercial Aviation Alternative Fuels Initiative
CEF	CORSIA Eligible Fuels
CHJ	Catalytic Hydrothermolysis Jet fuel
CI	Carbon Intensity
CO2	Carbon dioxide
CORSIA.	Carbon Offsetting and Reduction Scheme for International Aviation
EASA	European Union Aviation Safety Agency
EI	Environmental Impact
FAA	Federal Aviation Administration
FRL	Fuel Readiness Level
FT-SPK/A	Fischer Tropsch synthesized isoparaffinic kerosene with aromatics
FT-SPK or FT	Fischer Tropsch synthesized isoparaffinic kerosene
GHG	Greenhouse gas
GWP	Global Warming Potential
HEFA	Hydroprocessed Esters and Fatty Acids
HH-SPK or HC-HEFA	Hydroprocessed Hydrocarbons synthesized isoparaffinic kerosene
IATA	International Air Transport Association
ICAO	The United Nation's International Civil Aviation Organization
ILUC	Induced Land Use Change
LCA	Life Cycle Analysis
LHV	Lower Heating Value
SAF	Sustainable Aviation Fuel
SIP	Synthesized iso-paraffins
SPK	Synthetic Paraffinic Kerosene
UG	University of Groningen
WtWa	Well-to-Wake

Important Definitions

Carbon Intensity (CI)

Carbon intensity is a measure of the amount of greenhouse gas (GHG) emissions emitted per measurement of energy of a fuel or feedstock. Carbon intensity is measured in gCO_2e/MJ (ICAO, 2021a).

Energy Density

The energy density of a fuel or feedstock is the amount of energy/heat that is released during combustion. It is measured in MJ/kg (Boechler et al., 2021).

Environmental Impact (EI)

The environmental impact in this research is measured by carbon intensity.

Fuel Readiness Level (FRL)

The Fuel Readiness Level is a measurement scale from 1-9 to track and classify a fuels research progression for commercial use and certification (CAAFI, 2009). FRL is an initiative of the Commercial Aviation Alternative Fuels Initiative (CAAFI) and is endorsed by CORSIA (Kolosz et al., 2020). A short explanation of each level can be found in appendix B, which is established by CAAFI (CAAFI, 2009).

Induced Land Use Change (ILUC)

ILUC involves a change in production area when the area where a specific biomass is produced is extended beyond the original land. This can be the case when the type of biomass, its quantity or its use changes (ICAO, 2021a).

Lower Heating Value (LHV)

The lower heating value is a measure of energy density.

Global Warming Potential (GWP)

GWP measures the amount of energy the emissions of a greenhouse gas absorbs compared to the emissions of the same amount of CO_2 emissions, over a given time period (US EPA, 2021).

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1. Introduction

1.1 Current Growth and Goals of the Aviation Industry

Flight travel was responsible for about 2% of total CO_2 emissions, measured globally in 2017. This represents almost 900 million tons of CO_2 (Prussi et al., 2021). The International Air Transport Association (IATA) expects air transport activity to double by 2035. This is due to urbanization and emerging wealth in Asia (Edwards et al., 2016). Growing aviation means that the impact on climate change from CO_2 emissions of air transport, also continuous to increase (Prussi et al., 2021). The COVID-19 pandemic had an enormous impact on the growth rate of aviation. However, looking at past crises, aviation always recovers very quickly and continued its previous growth rate. Therefore, the same is expected to happen after COVID-19 (Tanrıverdi et al., 2020).

The percentage of the total aviation-related carbon emissions generated by international air transport is 62%. This means that in the Paris Agreement, drafted in 2016, the majority of aviation carbon emissions are not covered and are not part of national mitigation plans (Herold et al., 2019). For this reason, the United Nation's International Civil Aviation Organization (ICAO), the European Union (EU) and the IATA have all set ambitious goals for the aviation sector to largely eliminate their carbon emissions on the long and short term.

The EU has established the Green Deal, which aims to achieve net zero CO_2 emissions by 2050 (EU, 2021). This goal corresponds to that of the IATA (IATA, 2021a). The ICAO has set the goal for international aviation to have CO_2 neutral growth upward of 2020, through their established Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA). CORSIA is concerned with either offsetting excess CO_2 emissions by purchasing carbon credits from verified carbon offset programs, or reducing CO_2 emissions by using Sustainable Aviation Fuels (SAFs) (Strouhal, 2020) (ICAO, 2019a).

CORSIA is intended to be a short- and medium-term solution to reduce CO_2 emissions to enable CO_2 neutral growth, until SAFs can be scaled up and aircraft technologies are developed far enough to achieve the ultimate long-term goal of net zero CO_2 emissions by 2050 (EU, 2021) (IATA, 2021a).

1.2 How to achieve Net Zero CO_2 Emissions by 2050

contains a graph showing the growth of CO_2 emissions of the aviation sector if no action is taken. It shows that in 2050, 1,8 Gt of CO_2 will be emitted into the atmosphere. This means, that to have net zero CO_2 emissions by 2050, 1,8 Gt of CO_2 need to be eliminated in 2050.

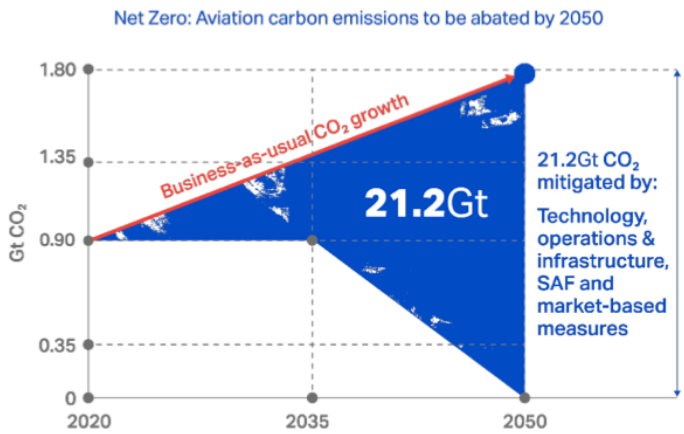

Figure 1: CO_2 emissions to be eliminated at business-as-usual growth (IATA, 2021b)

The IATA has estimated how to achieve net zero CO_2 emissions by 2050. This estimation is shown in the diagram in ***Error! Reference source not found.***. A 100% in the diagram, represents all CO_2 emissions in 2050 at business-as-usual growth, which is 1,8 Gt CO_2. The aviation sector is divided into several areas, each of which must make its own contribution to achieve net zero CO2 emissions (IATA,

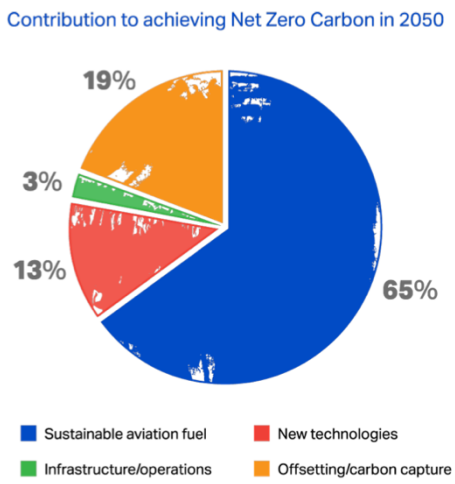

Figure 2 : Contribution of areas to achieve net zero CO_2 emissions in 2050 (IATA, 2021b).

2021b).

Improving infrastructure and operations has to do with more efficient flightpaths and reducing delays. It also includes retrofitting of wings and seating. According to IATA, improvement in infrastructure and operations should eliminate 3% of all CO_2 emissions in 2050 (Strouhal, 2020).

Improvement in new technologies consists for example of alternative options for propulsion. For example, electric, hybrid or hydrogen propulsion. These technologies become increasingly challenging or even impossible when the aircrafts get bigger and flights get longer. Certifying bodies such as the European Union Aviation Safety Agency (EASA) and Federal Aviation Administration (FAA) are unexperienced with disruptive aircraft technology. For these reasons it takes very long for these technologies to enter the market. Also, it takes 20-25 years to replace an entire fleet (van Dyk et al., 2017) (Berger, 2020). These improvements are expected to eliminate 13% of CO_2 emissions in 2050.

Usage of Sustainable Aviation Fuels (SAFs). SAFs are alternative and renewable drop-in jet fuels produced from waste and biomass resources. SAFs can be blended with conventional jet fuel to some extent, up to a maximum of 50%. Drop-in refers to the fact that SAFs can combust in the engines of existing aircrafts (Prussi et al., 2021). To achieve the goal, SAF production needs to go from 100 million liters to over 449 billion liters in 2050 (IATA, 2021b). Flying with 100% SAF is also required to reach the goal. So far, 7 different SAFs have been approved. SAFs are assigned to eliminate 65% of emissions in 2050.

Usage of approved offsetting programs and carbon capture can be done by purchasing carbon credits from verified carbon offset programs or capturing carbon from the atmosphere. These programs could consist of improved cookstoves, forestry, industrial gas, renewable energy and waste (Arendt et al., 2021). These offsetting programs and carbon capture methods are expected to set off the remaining 19% of emissions in 2050.

SAFs are expected to make the largest contribution, namely of 65%. Therefore, SAFs have the greatest impact in whether the goal of net zero CO_2 emissions can be achieved by 2050. However, SAFs face many challenges due to the required blending with kerosene, the different environmental impact that different types of SAF have, and the availability of the required feedstocks in 2050 to produce all the required SAF. This is where the focus of this research will be. To investigate if SAFs can eliminate 65% of all CO2 emissions generated by flights in 2050. The environmental impact will be estimated by doing life cycle analysis (LCAs) of different types of SAF, which will be compared to the environmental impact of kerosene.

LCA is a tool that is used to assess the impact that a product or service has on the environment during their entire life. This means from raw materials until the disposal of the final product (Ayres, 1995) (Williams, 2009).

2. Problem Analysis

2.1 System Description

There are currently 7 conversion pathways to produce SAFs, approved by the American Society for Testing and Materials (ASTM) (IATA, 2021a). SAFs are renewable jet fuels that have similar properties as conventional jet fuel, which is kerosene. Therefore, SAFs are also called Synthetic Paraffinic Kerosene (SPK) and can be blended until a certain degree with conventional jet fuel kerosene. The different types of SAFs have three main differences. These are the feedstocks that they are produced from, the processes that are used to convert the feedstock into fuel, and their Fuel Readiness Level (FRL). The FRL is a measurement scale from 1-9 to track and classify a fuels research progression for commercial use. Due to these differences, the SAFs have different environmental impacts compared to each other and compared to kerosene. (Prussi et al., 2021) (Berger, 2020) (IATA, 2021c).

The 7 SAFs are named after their conversion process and are called:
- Fischer Tropsch synthesized isoparaffinic kerosene (FT-SPK or FT)
- Fischer Tropsch synthesized isoparaffinic kerosene with aromatics (FT-SPK/A)
- Hydroprocessed Esters and Fatty Acids (HEFA)
- Hydroprocessed Hydrocarbons synthesized isoparaffinic kerosene (HH-SPK or HC-HEFA)
- Synthesized iso-paraffins (SIP)
- Alcohol to Jet (ATJ)
- Catalytic Hydrothermolysis Jet fuel (CHJ) (IATA, 2021a)

An overview of the 7 SAFs including possible feedstocks, maximum blending limit, and fuel readiness level can be found in *Table 1*.

The environmental impact of the SAFs is measured by its Greenhouse Gas (GHG) emissions in terms of their Global Warming Potential (GWP). GWP measures the global warming impact of different greenhouse gasses relative to the impact that the same amount of CO_2 emissions has over a given time period (US EPA, 2021). For a more detailed explanation of GWP can be looked in the important definitions section.

Conversion Process	Blending Limit	FRL	Possible Feedstocks
FT-SPK or FT	50%	7	Waste, coal, natural gas, lignocellulosic biomass
FT-SPK/A	50%	7	Waste, coal, natural gas, lignocellulosic biomass
HEFA	50%	9	Bio-oils, used cooking oil, animal fat
HH-SPK or HC-HEFA	10%	6	Oils produced from algae
SIP	10%	6-7	Sugar containing biomass
ATJ	50%	7	Sugar containing biomass, lignocellulosic biomass
CHJ	50%	4-6	Bio-oils, waste oils

Table 1: The approved SAFs and their corresponding blending limits, FRL, and feedstocks (IATA, 2021a) (Abrantis et al., 2021) (Kolosz et al., 2020).

2.2 Research Scope

This research consists of 3 parts. The first part includes LCAs of a selection of SAFs to determine their environmental impacts. Due to time-shortage, not all 7 SAFs are included in this research. In this research the FT, FT-SPK/A, HEFA, SIP and ATJ pathways are included. These fuels have been approved by the ASTM for the longest time (IATA, 2021a). These fuels also have the highest FRL and are therefore closest to be ready for commercial use (Abrantis et al., 2021) (Kolosz et al., 2020). The pathways that are excluded from the research are HC-HEFA and CHJ. These pathways are recommended to be investigated in further research.

The greenhouse gasses that are included in the LCAs in this research are N_2O, CH_4 and CO_2 emissions. These are measured in terms of their 100-year GWP and can be seen in *Table 2*.

Greenhouse Gas	Global Warming Potential
CO_2	1
N_2O	265-298
CH_4	28-36

Table 2: 100-year GWP of included Greenhouse Gasses (US EPA, 2021).

The second part includes an investigation into the required blending of SAFs with kerosene, if SAFs are to be used in an airplane engine. This investigation focusses on the feasibility of flying on unblended SAF in 2050. The third part of this research consists of framework containing recommendations for further research about the availability of feedstocks to produce all the needed SAF by 2050.

2.3 Stakeholder Analysis

There are multiple stakeholders in this research. These will be discussed one by one. Their interest, power and influence on each other is shown on a grid in *Figure 3*.

(a) The EU, IATA, ICAO and governments.

Goal setting and legislation making organizations and associations such as the EU, IATA, ICAO and governments, have high interest in this research. The outcome of the research will provide an insight in whether the goals that they have set are realistic and achievable in terms of the contribution of SAFs. Furthermore, it is assumed that they have medium power because they have the ability to adjust their goals.

(b) Airlines.

Airlines have high interest in the research because it provides an insight to them which SAF has the lowest environmental impact given the entire life cycle. This is valuable knowledge for airlines as they are held to certain standards regarding their CO_2 emissions. Airlines have little power because they have no influence on the outcome. Airlines are influenced by both other stakeholders (a) and (c), which can be seen in *Figure 3*. This is due to regulations that they need to adhere to, set by legislative bodies, and their dependence on available feedstocks and SAFs, produced by biorefineries and farmers.

(c) Biorefineries and farmers.

Farmers cultivate, harvest and in some cases process biomass that serves as feedstock for the production of SAFs. Biorefineries are responsible for the conversion of biomass into the fuel. Both parties have medium interest in the research because it does not directly influence their current state of business. However, is does provide opportunities for future business. Furthermore, both farmers and biorefineries have high power because they control and are responsible for the entire supply part of the life cycle of SAFs.

(d) The Green Office

The Board of the University of Groningen (UG) has appointed the Green Office to coordinate and initiate projects related to the sustainability of the University. The Green Office is the commissioning party of the research and are the stakeholder company. The Green Office, as commissioning stakeholder, has high interest and average power. They carry the responsibility of the road to sustainability of the UG, including the flight behavior of its employees. The Green office is influenced by the legislative powers of governments.

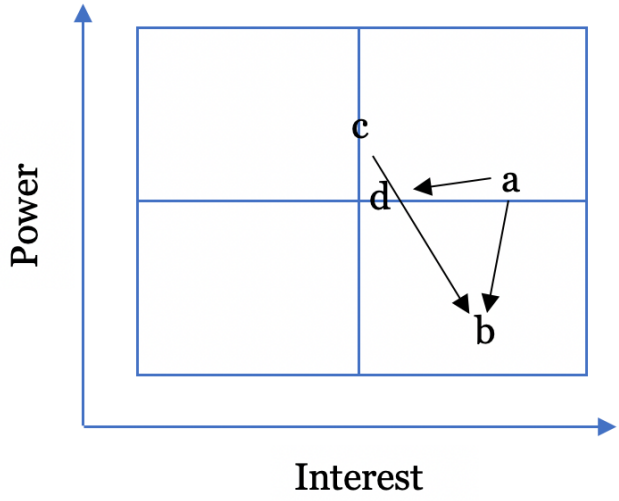

Figure 3: Power and interest grid of stakeholders.

2.4 Problem Statement

The EU, IATA and ICAO all set goals regarding reducing the CO_2 emission of international aviation. The ICAO aims for CO_2 neutral growth from 2020 upwards by means of CORSIA. The EU proposed the Green Deal, aspiring net zero CO_2 emission by the year of 2050 and corresponds to the goal of the IATA. To achieve both goals, there is a need for large scale CO_2 emission reduction. SAFs play the most important role in the clean aviation roadmap. The current contribution to CO_2 reduction of SAFs is <1% and this needs to grow to 65% by 2050 (IATA, 2019) (IATA, 2021b). However, there are many uncertainties regarding the environmental impact and feasibility of SAFs. This leads to the following problem statement:

It is unknown whether the contribution of SAFs to the reduction of CO_2 emissions of international aviation can increase from <0,5 to 65% by the year of 2050. This is due to the differences in environmental impact of the different SAFs, their required blending with kerosene and the availability of feedstocks.

2.5 Research Objective

To investigate whether SAFs can enable large scale CO_2 emission reduction, this is done by making LCAs of different SAFs taking into consideration: maximum blending limits and availability of feedstocks. The research is to be completed within 13 weeks.

2.6 Research Questions

Can SAFs achieve its contributing goal towards net zero CO_2 emission generated by the aviation sector by the year of 2050?

1. *What is the current environmental impact of kerosene?*

2. *What will be the future environmental impact of the different SAFs?*

3. *What are the prospects on flying on 100% SAF?*

4. *What is the availability of feedstocks to produce SAFs?*

2.7 Methods and Tools

2.7.1 Strategies and Materials

In this section the strategies and materials to answer the research questions are discussed. The necessary knowledge and data is gathered and processed in to answer the research questions. By answering the 4 research sub questions first, all necessary material is obtained to provide an answer to the main research question. All the methods and tools used are elaborated upon below and summarized in *Table 3*.

To answer sub question 1, scientific literature is studied by doing desk research. The environmental impact of kerosene is obtained based on multiple LCA studies, following the same LCA methodology as is used in this research. This methodology is the CORSIA methodology and will be elaborated on in the next section.

To answer the second sub question, the environmental impact of the different is SAFs determined by conducting multiple LCAs will in SimaPro. Different types of feedstocks are considered for each SAF. The LCA methodology that is followed is the CORSIA methodology. All the data that is needed for this part is extracted from the Ecoinvent 3 databases in SimaPro or from scientific literature. Furthermore, before the LCAs can be conducted, knowledge needs to be obtained on LCAs and on how to use SimaPro by investigating literature.

For the third and fourth sub questions the methods are quite similar. Desk research is conducted to gather relevant literature about blending limits with kerosene and feedstock availability to answer these two questions.

Sub question	Strategy	Material	Method
1. **What is the environmental impact of kerosene?**	- Desk research	- Scientific Literature	- Research
2. **What will be the environmental impact of different SAFs?**	- Desk research - Experiment - Calculations	- Scientific Literature - Ecoinvent 3 databases	- Research - LCA in SimaPro
3. **What are the prospects on flying on 100% SAF?**	- Desk research	- Literature	- Research
4. **What is the availability of feedstocks to produce SAFs?**	- Desk research	- Literature	- Research

Table 3: Methods and tools used to answer each sub-question.

2.7.2 Life Cycle Analysis and CORSIA

In this research life cycle analysis is used to assess the environmental impact of the entire life cycles of different types of production pathways of sustainable aviation fuels. This includes from cultivation of the biomass till the combustion of the fuel in the aircraft, which is called well-to-wake (WtWa).

The LCAs performed in this research follows the ISO 14040/44 standards, concerning the principles, framework, requirements and guidelines for LCA studies. The LCAs consist of four main phases. These phases are in sequential order: goals and scope definition, inventory analysis and collecting data, life cycle impact assessment, and interpretation of the results (Goedkoop et al., 2016).

As stated in the introduction, CORSIA stands for Carbon Offsetting and Reduction Scheme for International Aviation. It is an approach initiated by the ICAO concerning either offsetting exceeding CO_2 emissions by purchasing carbon credits from verified carbon offset programs or using reducing CO_2 emissions by using Sustainable Aviation Fuels (SAFs) (Strouhal, 2020) (ICAO, 2019a). The ICAO has established a CORSIA LCA methodology which is adopted internationally and will be followed in this research. For a fuel being eligible for use according to CORSIA, it must have an environmental impact which is at least 10% lower than the environmental impact of kerosene (Prussi et al., 2021).

3. Theory on Kerosene and SAFs

This section gives a detailed description of the production processes of kerosene and the SAFs, included in this research. *Figure 4* shows the complete overview of the conversion pathways of the SAFs, including their possible feedstocks, intermediate products, and refinery operations.

3.1 Kerosene

Kerosene is conventional jet fuel. It is produced from crude oil, which is extracted from an oil field either onshore or offshore. Crude oil is considered a fossil fuel. After extraction, the crude oil is transported to a refinery by pipelines, tanker ships or other of transportation methods capable of transporting very large amounts of oil. Refinery operations consist of refining, distillation, cracking, reforming and more. During the production of kerosene many valuable co-products are formed. These are for example: gasoline, gas oil and diesel oil. However, heavy residual oils are also a by-product and generate air emissions. After refinery operations, the kerosene is transported and distributed to its end station where it is ready to be used as jet fuel (Koroneos et al., 2005).

3.2 FT and FT-SPK/A

FT fuel is produced from syngas and some co-products. Syngas can be produced from any carbon containing material. It is mostly produced by gasification of lignocellulosic biomass feedstocks like agricultural residues or energy crops, or from municipal solid waste. This is done reacting the feedstock to air and steam under extremely high temperature and pressure. A part of the syngas is converted into wax during the FT conversion process. Another part of the syngas is used to generate electricity that is used during the FT conversion processes. Therefore, the need for externally produced electricity is relatively low (Doliente et al., 2020). Co-products are used to produce hydrogen, that is needed for hydrocracking the produced wax (Antonissen, 2016). The last step of the process is separating the product. Natural gas and coal are used most widely at the moment as feedstock for the FT process (Liu, 2010) (Berger, 2020) (Prussi et al., 2021). However, these are not considered in this research because they are considered fossil resources. The conversion process of FT and FT-SPK/A is very similar. The only difference is that for FT-SPK/A an additional process takes place, which is alkylation of light aromatics. Due to this extra process, the Produced SAF contains aromatic compounds which increases the blending ease with kerosene (Gutiérrez-Antonio et al., 2021). Due to their high similarities, FT and FT-SPK/A will be considered as equal process and will be referred to as FT from now

on in this research. FT has a fuel readiness level of 7 and a maximum blending limit with kerosene of 50% (Kolosz et al., 2020) (Abrantis et al., 2021).

3.3 HEFA

HEFA fuel uses renewable oils as feedstock. Renewable oils are oils that are extracted from plants, animal fats and waste greases (IATA, 2021c) (Prussi et al., 2021). These oils have relatively similar properties to jet fuel and therefore require an easy conversion (Antonissen, 2016). After the extraction of the oils all the oxygen needs to be removed from the oils. This is done with hydrotreatment followed by hydrocracking to form the desired carbon chains (Doliente et al., 2020). The product is then separated into jet-fuel, diesel and naphtha (Doliente et al., 2020). HEFA has a fuel readiness level of 9 and a maximum blending limit with kerosene of 50% (Kolosz et al., 2020) (IATA, 2021c) (Abrantis et al., 2021).

3.4 SIP

Feedstocks that are suitable for the SIP conversion process, are biomasses that contain sugars (IATA, 2021c). Hydrocarbons are formed during fermentation of the sugar feedstock. Hereafter the hydrocarbons are refined and catalytically upgraded to SAF (Kolosz et al., 2020). SIP has a fuel readiness level of 6-7 and a maximum blending limit with kerosene of 10% (Kolosz et al., 2020) (IATA, 2021c).

3.5 ATJ

The input into the ATJ production process is a variety of chemicals such as ethanol, methanol, butanol and other alcohols (Kolosz et al., 2020). These alcohols are produced from sugar containing feedstocks and lignocellulosic biomass by fermentation (IATA, 2021c). During the ATJ process the alcohols are dehydrated to remove water. The next step is to form hydrocarbon chains by means of oligomerization followed by a distillation step to fraction the hydrocarbons with different chain length into separate products (Antonissen, 2016). A schematic view of this system can be found in Appendix A. ATJ has a fuel readiness level of 7 and a maximum blending limit with kerosene of 50% (Kolosz et al., 2020) (IATA, 2021c) (Abrantis et al., 2021).

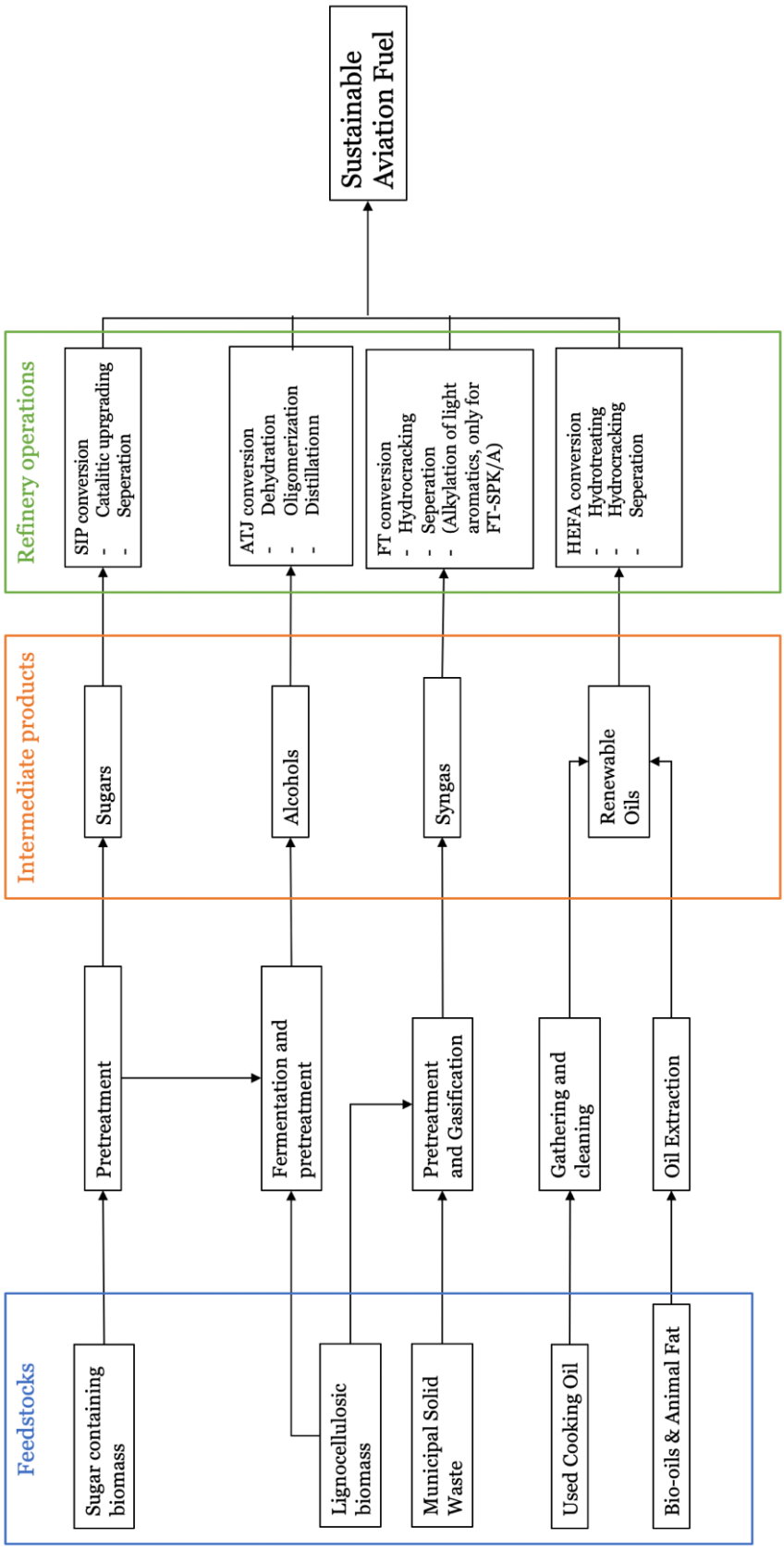

Figure 4: Overview of the conversion pathways of the SAFs included in this research. The blue block indicates the possible feedstocks. The orange block indicates intermediate products. The green block indicates the refinery operations (Antonissen, 2016) (Galvan, 2021).

4. Life Cycle Analysis of SAFs

4.1 Goal

The purpose of the LCAs of the different SAFs is to determine and compare their environmental impacts over their entire lifetime. This means from cultivation of the feedstock till the combustion of the SAF in the aircraft, also called Well-toWake (WtWa). The goal of creating multiple LCAs for each SAF, each containing a different type of feedstock, is to examine how different types of feedstocks affect the overall environmental impacts of a SAF. The goal is an emission reduction of at least 65% compared to kerosene. This will function as the reference line. Furthermore, SAFs will be assessed for eligibility using the CORSIA methodology. This is the case when the environmental impact indicates is at least 10% emission reduction compared to kerosene.

4.2 Scope

4.2.1 Boundaries

In general, each life cycle consists of 7 life cycle stages. These stages are:

a) Feedstock cultivation
b) Feedstock harvesting
c) Feedstock processing
d) Transportation
e) Fuel production
f) Transportation
g) Combustion (ICAO, 2021a) (Prussi et al., 2021)

All 7 stages are included in this WtWa research. This is indicated by the blue line in *Figure 5*.

All the life cycle stages are included in the executed LCAs in this research, on the condition that the stage is applicable to the particular SAF that the LCA represents. The total environmental impact of each LCA is calculated by adding up the values of the separate life cycle stages. All SAFs can be produced from different types of feedstocks. For this reason, multiple LCAs are created for each SAF, all using a different type of eligible feedstock. Only feedstocks that are non-fossil are included in this research.

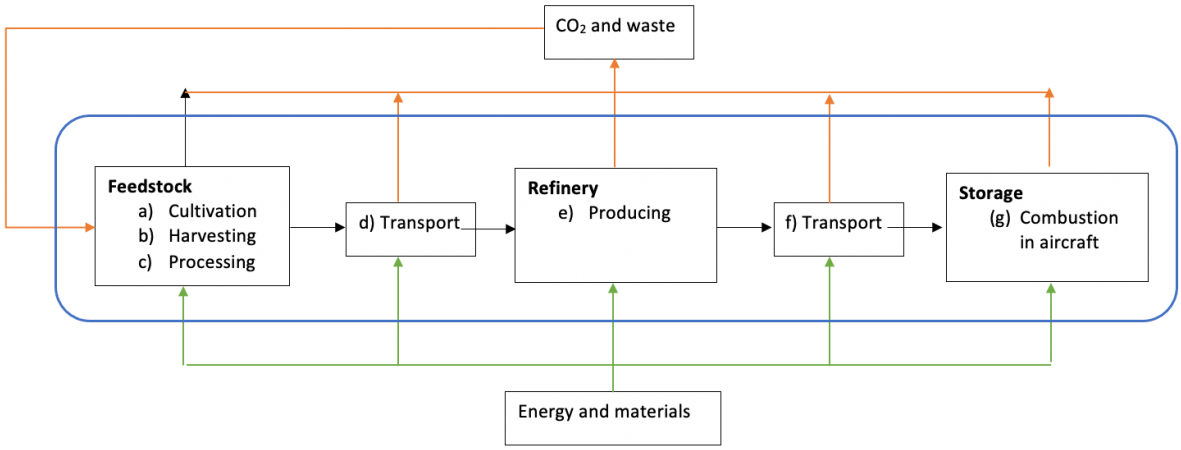

Figure 5 : The generic system of the SAFs and kerosene. The blue line indicates the scope of the LCAs. The black arrows indicate the material flow between the life cycle stages. The orange arrows indicate the output at each life cycle stage. The green arrows indicate the inputs at each stage.

All feedstocks included in this analysis are part of the approved list of feedstocks, established by the ICAO (ICAO, 2021b). Whenever a feedstock is considered low risk for land use, its emission regarding induced land use transformation is set to zero (ICAO, 2021a).

Due to the fact that most SAFs, are not yet produced on large scale globally, it is hard to estimate the distance that feedstocks have to travel to their compatible refinery. However, commercial fuel production plants do exist globally. Therefore, it is assumed that this will be possible for SAFs as well (Prussi et al., 2021). Biomass has a low bulk density and is expected to travel relative short distances to the biorefineries. Therefore, the mode of transport chosen for the LCAs are freight lorries that can carry over 32 metric tons. A distance of 250 km is chosen and used for all feedstock and fuel travel distances.

4.2.2 Induced Land Use Change

The CORSIA LCA methodology includes specific regulations regarding emissions that occur due to Induced Land Use Change (ILUC). ILUC refers to the change in production area, when the area where a specific biomass is being produced is expanded outside its original land. This could be the case when the type of biomass, quantity or its use changes (ICAO, 2021a). When a feedstock meets one of the following demands, their emissions regarding land use change can be set to zero. This is due to the fact that they form a low risk for change in land use.

- The feedstock is a residue, waste, or by-product.

- The feedstock does not require an expansion in agriculture land, measured globally.
- The feedstock provides a considerably higher gain the currently growing crop on that land (ICAO, 2021a).

4.2.3 Functional unit

The environmental impact is measured terms of carbon intensity. This is a measurement of the amount of greenhouse gas (GHG) emissions emitted per measurement of energy of the produced and combusted fuel.

The GHG emissions of all stages except the combustion stage, include CH_4, N_2O and fossil-based CO_2 emissions and are calculated in terms of the 100-year Global Warming Potential (GWP). In the combustion stage only non-biogenic CO2 emissions are considered.

It is assumed that the CO_2 that enters the atmosphere during combustion of SAFs, with biomass as feedstock, is set off by the absorption of CO_2 from the atmosphere during the growth of the biomass (Prussi et al., 2021). This approach is adopted by the ICAO and is applicable in this research. Therefore, in this research, CO_2 emissions that occur during combustion of fuels with biogenic sources are set to zero (ICAO, 2021a).

The functional unit is grams of CO_2 equivalent per MJ of produced and combusted fuel (gCO_2e/MJ). The GHG that are included in the CO_2e are non-biogenic CO_2, CH_4 and N_2O, calculated on the basis of the 100-year GWP.

Whenever SimaPro requires material inputs in terms of mass, the Lower Heating Values (LHV) of these materials are used to acquire mass values.

Emissions are allocated amongst co-products formed during different life cycle stages, according to their energy content (Prussi et al., 2021).

4.3 Inventory Analysis and Data Collection

4.3.1 Kerosene

For kerosene the life cycle is not modeled in SimaPro. The feedstock used for the production of kerosene is crude oil. Crude oil is extracted either onshore or offshore, for example in the Middle East. After extraction, the crude oil is transported by tanker, pipeline, or other modes of transport capable of carrying large quantities of oils over large distances possibly overseas, to a refinery where kerosene is produced. Many valuable co-products are formed, during production,. These include, petrol, diesel, naphtha and gasoline. After production, the kerosene is transported by truck, train, pipeline or other capable modes of transport and stored near its final destination. The final step is the combustion of kerosene in the aircraft. The environmental impact of kerosene used in this research is 89 gCO_2e/MJ. This value is an average value based on multiple global well to wake life cycle studies (Prussi et al., 2021). This value functions as a base line throughout the rest of this research. A schematic view of all stages (a)-(g) for the kerosene is provided in Appendix A.

4.3.2 FT

The FT conversion process produces sustainable jet fuel mostly from cellulosic biomass feedstocks. Using gasification, these feedstocks are converted into syngas, whereafter the syngas is converted into wax. Part of the syngas is used to generate electricity and hydrogen, both used as inputs during the FT conversion process. In this research 4 different categories of feedstocks are considered. For each category, a different life cycle is executed. This means that 4 LCAs are made for the production of jet fuel using FT conversion. The feedstock categories are forestry residues, agricultural residues, herbaceous energy crops, short rotation woody crops. A schematic view of all stages (a)-(g) for the FT pathway is provided in Appendix A.

<u>Feedstock operations, stages (a)-(c)</u>
The feedstock operations include the cultivation, harvesting, processing and collection of the feedstocks, unless stated otherwise. It is assumed that all feedstock operations take place at the fields where the feedstock has cultivated. After collecting the feedstocks, the feedstocks are transported to the biorefineries where the fuel is produced. The amount of biomass that is needed to produce 1 MJ of jet fuel can be seen in *Table 4*. The data that is used for these processes is all from the Ecoinvent 3 databases.

Bark chips are taken as the representative for the feedstock category forestry residues. Due to the fact that bark chips are considered a residue, the cultivation of

the tree is not part of this life cycle. The first stage is the harvesting stage in which the bark is taken of the stem. These operations are assumed to take place globally.

Wheat straw is taken as the representative for the feedstock category agricultural residues. Wheat straw is also considered a residue, so the cultivation stage is also not part of this life cycle. The feedstock operations for wheat straw are also assumed to take place globally.

Miscanthus chops is taken as the representative for the feedstock category herbaceous energy crops. For the miscanthus all operations activities are included. The energy crops are assumed to grow for 20 years in the EU.

Willow wood chips and particles coppice is taken as the representative for the feedstock category short rotation woody crops. For the willow wood chips also all feedstock operation activities are included. The woody crops are also assumed to grow for 20 years in the EU.

	Amount (MJ/MJ fuel)	**LHV (MJ/kg)**	**Amount (kg/MJ fuel)**
Forestry Residues	2,18 (Antonissen, 2016)	16,3 (Kolosz et al., 2020)	0,146
Agricultural Residues	2,18 (Antonissen, 2016)	16,7 (Asakereh et al., 2014)	0,143
Energy Crops	2,18 (Antonissen, 2016)	17,2 (Librenti et al., 2010)	0,138
Woody Crops	2,18 (Antonissen, 2016)	17,8 (Librenti et al., 2010)	0,134

Table 4: Feedstock amounts for FT process.

Refinery operations, stage (e)

The amounts of the different feedstocks that are to be put into the FT process to produce 1 MJ of jet fuel are stated in *Table 4*. The FT conversion process from feedstock to fuel is outside the scope of this research. Therefore, the environmental impact that this stage has on the total environmental impact is taken from a different study following the same methodology (Prussi et al., 2021). These values can be found in *Table 5*. The produced jet fuels all have a LHV of around 43 MJ/kg (Engineering ToolBox, 2003).

	Impact FT process (gCO_2e/MJ)
Forestry Residues	1,5
Agricultural Residues	0,5
Energy Crops	0,5
Woody Crops	1

Table 5: Environmental Impact of the FT conversion process (Prussi et al., 2021).

Transport operations, stages (d) & (f)
There are two transportation stages in these life cycles. Their inputs can be seen in *Table 6*.

	Distance (km)	**Mass (kg)**	**LHV (MJ/kg)**
Feedstock to refinery	250	See *Table 4Table 7*	See *Table 4*
Fuel to destination	250	0,0233	43,0 (Engineering ToolBox, 2003).

Table 6: Inputs into transport operations FT process.

4.3.3 HEFA

The HEFA process produces sustainable aviation fuel from oils. Oils are extracted from biomass resources and used as input into the HEFA process. The first step of processing the oils into fuel consists of deoxygenating the oils by means of hydrotreatment. Hereafter, long chains of hydrocarbons are formed by hydrocracking. The last step exists of separating the product into jet-fuel, diesel and naphtha. In this research, oils extracted from soybeans, palm and used cooking oil are examined. These are all considered to be renewable oils and are assumed to be similar in energy density. A schematic view of all stages (a)-(g) for the HEFA pathway is provided in Appendix A.

Feedstock operations, stages (a)-(c)
The feedstock operations include the cultivation, harvesting and extraction or collection, unless stated otherwise, of soybean oil, palm oil and used cooking oil. It is assumed that the extraction of oils takes place at an extraction plant near the field where the feedstock is grown. After extraction, the oils are transported to the refinery. The amount of the oils that is needed to produce 1 MJ of fuel can be seen in *Table 7*. The data that is used for these processes is all from the Ecoinvent 3 databases.

The soybean oil is extracted from soybeans. To extract oil from soybeans, the soybeans are first crushed and then processed into soybean oil and soybean meal as main co-product. All feedstock operations take place in Brazil.

Palm oil is extracted from palm fruits after milling and crushing of the palm fruits and their kernel. These operations all take place in Malaysia.

The used cooking oil is gathered globally and undergoes purification before it is used to produce jet fuel.

	Amount (MJ/MJ fuel)	**LHV (MJ/kg)**	**Amount (kg/MJ fuel)**
Soybean oil	1,17 (Antonissen, 2016)	36,6 (Biograce, 2011)	0,0319
Palm oil	1,17 (Antonissen, 2016)	37,0 (Biograce, 2011)	0,0316
Used cooking oil	1,17 (Antonissen, 2016)	36,0 (Biograce, 2011)	0,0325

Table 7: Feedstock amounts for HEFA process.

Refinery operations, stage (e)

The inputs into the refinery operations of the HEFA process can be seen in *Table 8*. *Table 7* contains the energy densities of the different oils used as feedstocks. It can be seen that these properties are similar to each other, which also counts for the chemical properties of the produced jet fuels. The produced jet fuels have a LHV of around 43 MJ/kg (Engineering ToolBox, 2003).

	Amount (MJ/MJ fuel)	**LHV (MJ/kg)**	**Amount (kg/MJ fuel)**
Feedstock oil	1,17 (Antonissen, 2016)	See *Table 7*	See *Table 7*
Natural Gas	0,18 (Antonissen, 2016)	47,1 (Engineering ToolBox, 2003).	0,0038
Electricity	0,50E-4 (Antonissen, 2016)		
Hydrogen	0,15 (Antonissen, 2016)	120 (Engineering ToolBox, 2003).	0,0011

Table 8: Inputs into refinery operations HEFA process.

Transport operations, stages (d) & (f)

There are two transportation stages in these life cycles. Their inputs can be seen in *Table 9*.

	Distance (km)	Mass (kg)	LHV (MJ/kg)
Feedstock to refinery	250	See *Table 7*	See *Table 7*
Fuel to destination	250	0,0233	43,0 (Engineering ToolBox, 2003).

Table 9: Inputs into transport operations HEFA process.

4.3.4 SIP

The SIP process converts biomass containing sugars into jet fuel, using fermentation and catalytical upgrading. Together with the main biomass feedstock, glucose is also required as input into the SIP process. In this research both sugarcane and sugar beet are examined as feedstocks. A schematic view of all stages (a)-(g) for the SIP pathway is provided in Appendix A.

Feedstock operations, stages (a)-(c)

The feedstock operations include the cultivation, harvesting, processing and collection of the feedstocks unless stated otherwise. Glucose is considered to be an additional feedstock added to the sugarcane and sugar beet. The feedstock operations regarding glucose are assumed to be similar to regular global glucose production. The amount of biomass that is needed to produce 1 MJ of jet fuel can be seen in *Table 10*. The data that is used for these processes is all from the Ecoinvent 3 databases.

The sugarcane production used for the analysis takes place in Brazil. It is assumed that the average lifetime of sugar cane on a plantation is five years.

The sugar beet production used is based on a production site in the Europe.

	Amount (MJ/MJ fuel)	**LHV (MJ/kg)**	**Amount (kg/MJ fuel)**
Sugarcane Glucose	0,03 0,35 (Antonissen, 2016)	15,9 15,6 (Waclawovsky et al., 2010)	0,00172 0,02249
Sugar beet Glucose	0,03 0,35 (Antonissen, 2016)	12,5 15,6 (Waclawovsky et al., 2010)	0,00214 0,02249

Table 10: Feedstock amounts for SIP process.

Refinery operations, stage (e)

The amounts of the different feedstocks that are to be put into the SIP process to produce 1 MJ of jet fuel are stated in *Table 10*. The SIP conversion process from feedstock to fuel is outside the scope of this research. Therefore, the environmental impact that this stage has on the total environmental impact is taken from a different study following the same methodology (Prussi et al., 2021). These values can be found in *Table 11*. The produced jet fuels all have a LHV of around 43 MJ/kg (Engineering ToolBox, 2003).

	EI FT process (gCO_2e/MJ)
Sugarcane	11
Sugar beet	14

Table 11: Environmental Impact of the SIP conversion process (Prussi et al., 2021).

Transport operations, stages (d) & (f)
There are two transportation stages in these life cycles. Their inputs can be seen in *Table 12*

	Distance (km)	**Mass (kg)**	**LHV (MJ/kg)**
Feedstock to refinery	250	See *Table 10*	See *Table 10*
Fuel to destination	250	0,0233	43,0 (Engineering ToolBox, 2003).

Table 12: Inputs into transport operations HEFA process.

4.4.4 ATJ

The ATJ process converts alcohols into jet fuel using oligomerization. First the alcohols that are used as input, are produced from sugar containing biomass and lignocellulosic biomass using fermentation. In this research the alcohol that is used is ethanol, produced from the feedstocks sugarcane, forestry residues, agricultural residues, energy cops and corn. It is assumed that the fermentation of biomass into ethanol is similar to the fermentation into other alcohols, and therefore the environmental impact of this process will also be similar. A schematic view of all stages (a)-(g) for the ATJ pathway is provided in Appendix A.

Feedstock operations, stages (a)-(c)
The feedstock operations include the cultivation, harvesting, processing and collection of the feedstocks, unless stated otherwise. The production of the ethanol takes place at the production site as part of the ATJ process. The data that is used for the feedstock operations is all from the Ecoinvent 3 databases. The amount of a feedstock, its energy density and the amount that is needed to produce 1 MJ of ethanol and jet fuel can be seen in *Table 14*. *Table 13* contains the properties of ethanol and the amount of ethanol that is needed to produce 1 MJ of jet fuel.

The sugarcane production used for the analysis takes place in Brazil. It is assumed that the average lifetime of sugar cane on a plantation is five years.

Bark chips are taken as the representative for the feedstock category forestry residues. Due to the fact that bark chips are considered a residue, the cultivation of the tree is not part of this life cycle. The first stage is the harvesting stage in which the bark is taken of the stem. These operations are assumed to take place globally.

Wheat straw is taken as the representative for the feedstock category agricultural residues. Wheat straw is also considered a residue, so the cultivation stage is also not part of this life cycle. The feedstock operations for wheat straw are also assumed to take place globally.

Miscanthus chops is taken as the representative for the feedstock category herbaceous energy crops. For the miscanthus all operations activities are included. The energy crops are assumed to grow for 20 years in the EU.

The feedstock operations of the corn used in the analysis is all take place in the USA.

	Amount (MJ/MJ jet fuel)	**LHV (MJ/kg)**	**Amount (kg/MJ jet fuel)**
Ethanol	1,49 (Antonissen, 2016)	26,7 (Engineering ToolBox, 2003).	0,06

Table 13: Ethanol amount for SIP process.

	Amount (MJ/MJ ethanol)	**LHV (MJ/kg)**	**Amount (kg/MJ ethanol)**	**Amount (kg/MJ jet fuel)**
Sugarcane	4 (Stojanovic et al., 2009)	15.9 (Waclawovsky et al., 2010)	0,25	0,38
Forestry Residues	2,5 (Kang et al., 2014)	16,3 (Kolosz et al., 2020)	0,15	0,22
Agricultural Residues	2,5 (Kang et al., 2014)	16,7 (Asakereh et al., 2014)	0,15	0,22
Energy Crops	2,5 (Kang et al., 2014)	17,2 (Librenti et al., 2010)	0,15	0,22
Corn			0,16 (Antonissen, 2016)	0,24

Table 14: Feedstock amounts for ATJ process.

<u>Refinery operations, stage (e)</u>

The amounts of the different feedstocks that are to be put into the ATJ process to produce 1 MJ of jet fuel are stated in *Table 14*. The ATJ conversion process from feedstock to fuel is outside the scope of this research. Therefore, the environmental impact that this stage has on the total environmental impact is taken from a different study following the same methodology (Prussi et al., 2021). These values can be found in *Table 15*. The produced jet fuels all have a LHV of around 43 MJ/kg (Engineering ToolBox, 2003).

	EI ATJ process (gCO_2e/MJ)
Sugarcane	5,5
Forestry Residues	18
Agricultural Residues	22
Energy Crops	28,5
Corn	36

Table 15: Environmental Impact of the ATJ conversion process (Prussi et al., 2021).

Transport operations, stages (d) & (f)

There are two transportation stages in these life cycles. Their inputs can be seen in *Table 16*.

	Distance (km)	**Mass (kg)**	**LHV (MJ/kg)**
Feedstock to refinery	250	See *Table 14Table 7*	See *Table 14*
Fuel to destination	250	0,0233	43,0 (Engineering ToolBox, 2003).

Table 16: Inputs into transport operations HEFA process.

4.4 Life Cycle Impact Assessment

The numerical results of the executed LCAs of the five types of SAF can be seen in *Table 17,* while the graphical results are viewed in *Figure 6*. The letter between the brackets indicated the corresponding life cycle stage. The values are obtained by adding up the CO_2e of CH_4, N_2O and non-fossil CO_2 air-borne emissions at each life cycle stage. The total environmental impact of each life cycle is obtained by adding up the environmental impacts of each life cycle stage.

Kerosene has an environmental impact of 89 gCO_2e/MJ. This is functions as the baseline and is displayed by the red line in *Figure 6*: Graphical results of LCAs of the SAFs.. SAFs need a total environmental impact of minimal 10% lower than kerosene, to be considered an eligible fuel in the CORSIA methodology. In other words, SAFs need to have an environmental impact of 80,1 gCO_2e/MJ or lower to be eligible according to CORSIA, which is shown by the green reference line in *Figure 6*: Graphical results of LCAs of the SAFs.. SAFs need a total environmental impact of less than 65% than kerosene, which is lower than 31.2 gCO_2e/MJ, to achieve its contributing goal in achieving net zero CO_2 emissions in 2050. This is shown by the blue reference line in *Figure 6*: Graphical results of LCAs of the SAFs..

Figure 6: Graphical results of LCAs of the SAFs. shows that all SAFs, produced using the Fischer-Tropsch conversion process, have an environmental impact that is lower than both reference lines. This means that for all four types of feedstocks, the FT SAF has the potential to achieve the assigned goal. Stage (a)-(c), which contain all feedstock operations, have the biggest contribution to the total environmental impact of the FT SAFs. Of the four types of feedstocks used, energy crops and woody crops have the highest emissions during feedstock operations. This is due to the fact that these crops are grown specifically to be used as fuel feedstock, while agricultural and forestry residues are left over materials. The two transportation stages of all four LCAs regarding FT, are all similar in emissions. This is due to the fact that the different feedstocks are similar in bulk density, which can be observed due to their similarity in lower heating value. The same goes for the produced jet fuel. Stage (e), which is the fuel production stage, has an extremely low contribution to the total environmental impact. Especially, compared to the SAFs following the other conversion processes. This is due to the fact that a big part of the electricity and hydrogen that is used during this part, is produced internally using co-products of the syngas production. The emissions reduction that is enabled by using FT ranges from 91%-85%.

The next results are that of the SAFs produced using the HEFA conversion process. Three different types of feedstocks are used, of which two adhere to both goals. For the HEFA process also counts that the feedstock operations have the highest

contribution to the total environmental impact. For the feedstocks soybean oil and palm oil, the extraction of the oil is considered to be a part of the feedstock operations. With used cooking oils, only some small processing has to be done to prepare the feedstock for fuel production. This, and the fact that used cooking oil is considered left over material, is part of the reason that the feedstock operations of soybean and palm oil have higher emissions. Also, both soybean oil and palm oil have a high risk in land use which increases their feedstock operations emissions. Used cooking oil has a zero ILUC value. The reason that soybean oil has such significant higher emissions than palm oil is that about two times as much soybeans are needed to produce the same amount of oil. The extracted oils are similar in energy density and also similar to the energy density of used cooking oil. Due to the similarities in energy density of the feedstocks and the produced jet fuel, the transportations stages and fuel production stage are all similar. The emissions reduction that is enabled by using HEFA ranges from 82%-58%.

Two LCAs are performed using the SIP conversion process. Both have a total environmental impact that is too high to achieve the goal of eliminating 65% of emissions that would have been generated if kerosene was used. Both are however, eligible according to CORSIA. Again, the feedstock operations account for the most emissions of the total life cycle. The reason that these operations are relatively high compared to other conversion processes is that besides the main feedstocks, also a high amount of glucose is used as input into the refinery operations. The reason that during the production of jet fuel from sugar beet more emissions appear than when sugarcane is used as feedstock, is that sugar beet has a lower energy density than sugar cane. This means that sugar beet also has a lower bulk density, which means that more sugar beet is needed to produce the same amount of jet fuel. The emissions reduction that is enabled by using SIP ranges from 55%-51%.

The next SAF, which is called ATJ, has the most diverse range of results. Forestry residues is the only feedstock that is beneath both reference lines and has the ability to achieve the goal of 65% of emission reduction. The other extreme is corn. Corn is the only feedstock that crosses both reference lines and would not even be considered an eligible fuel under CORSIA. What is notable is that unlike with all other SAF conversion processes, the feedstock operations do not have the biggest contribution to the total environmental impact. For ATJ, the fuel production stage has the highest emissions in most cases. This is due to the fact that the feedstocks first have to be converted to an alcohol, for example ethanol, before the actual ATJ process takes place and the jet fuel is produced. This extra conversion step is assumed to take place at the fuel production plant and is therefore considered to be a part of the fuel production stage. Furthermore, when looking the feedstock operations stages (a)-(c), it can be seen that the residue feedstocks have the lowest

environmental impacts. The emissions reduction that is enabled by using ATJ ranges from about 68%-7%.

Fuel	Feedstock	(a)-(c) (gCO2e/MJ)	(d) (gCO2e/MJ)	(e) (gCO2e/MJ)	(f) (gCO2e/MJ)	(g) (gCO2e/MJ)	total CI (gCO2e/MJ)
FT	Forestry Residues	2,9	3,27	1,5 (Prussi et al., 2021)	0,5	0	8,17
	Agricultural Residues	6,19	3,21	0,5 (Prussi et al., 2021)	0,5	0	10,4
	Energy Crops	8,89	3,11	0,5 (Prussi et al., 2021)	0,5	0	13
	Woody Crops	7,84	3,01	1 (Prussi et al., 2021)	0,5	0	12,35
HEFA	Soybean Oil	30,7	0,8	5,5 (Prussi et al., 2021)	0,5	0	37,5
	Palm Oil	13,2	0,8	5,5 (Prussi et al., 2021)	0,5	0	20
	Used Cooking Oil	9,18	0,8	5,5 (Prussi et al., 2021)	0,5	0	15,98
SIP	Sugar Cane	28,2	0,6	11 (Prussi et al., 2021)	0,5	0	40,3
	Sugar Beet	28,3	0,6	14 (Prussi et al., 2021)	0,5	0	43,4
ATJ	Sugar Cane	16,5	8,59	5,5 (Prussi et al., 2021)	0,5	0	31,09
	Forestry Residues	4,54	5,24	18 (Prussi et al., 2021)	0,5	0	28,28
	Agricultural Residues	10,1	5,31	22 (Prussi et al., 2021)	0,5	0	37,91
	Energy Crops	13,9	4,96	28,5 (Prussi et al., 2021)	0,5	0	47,86
	Corn	42	3,91	36 (Prussi et al., 2021)	0,5	0	82,41

Table 17: Numerical results of LCAs of the SAFs.

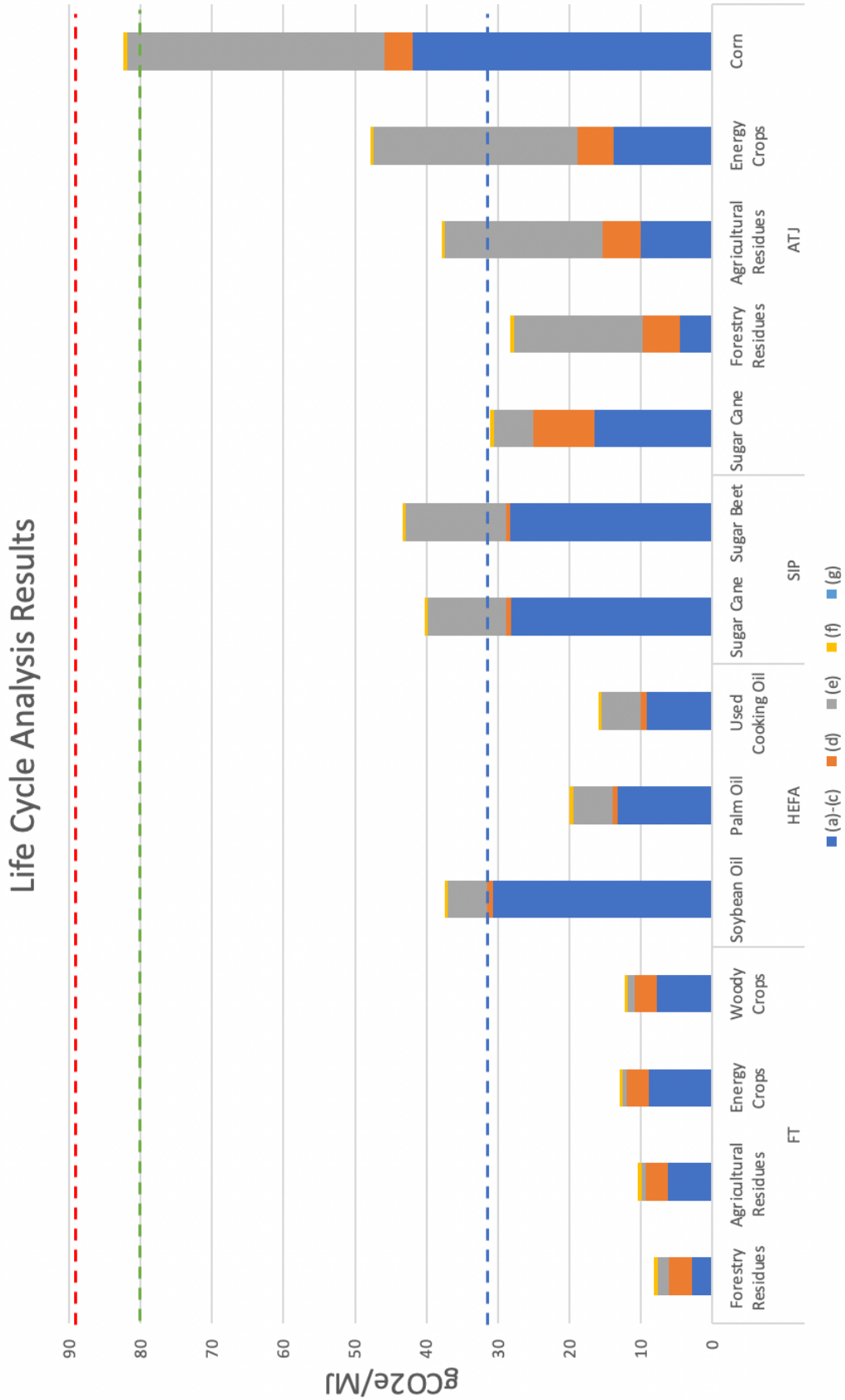

Figure 6: Graphical results of LCAs of the SAFs. The red line serves as baseline and indicates the environmental impact of kerosene. The blue and green lines are reference lines indicating 10% emissions reduction and 65% emission reduction respectively.

4.5 Sensitivity Analysis

4.5.1 Procedure

Two sensitivity analysis are performed. The first sensitivity analysis is performed to assess the impact that the yield of the produced fuel has. Yield refers to the percentage of jet fuel that is produced out of all co-products that are produced during the fuel production process. The yield could be increased by, for example, improving fuel production processes and increasing the conversion efficiency from feedstock to fuel, or by changing key parameters during the production process. The yield could decrease when non-optimal settings are used during the production process, or when a certain amount of a co-products is desired. A yield of 15% is chosen to add and subtract from the average yield, to investigate how sensitive the results are to a change in yield. The average yield is the yield that is used in the execution of the LCAs.

The second sensitivity analysis is to assess the influence of the assumption made on an average travelling distance of 250km of the feedstock to the fuel production plant. In practice, this distance could vary quite heavily. Therefore, the choice was made to do a sensitivity analysis through increasing and decreasing this traveling distance with 80%. This means that the maximum traveling distance would be 450 km and the minimal traveling distance would be 50km. Due to the different bulk densities of different feedstock types. This change in distance has a varying impact on the total environmental impact of a different fuels.

4.5.2 Results

The results of the first sensitivity analysis can be seen in *Figure 7*. This figure shows that a change in yield has a varying impact on different types of fuel. The fuels where the feedstock operations had the highest contribution to the total environmental impact are the most sensitive to a change in yield. This can be seen the best for the feedstock soybean oil using the HEFA conversion process, sugarcane and sugar beet both using the SIP conversion and corn using the ATJ conversion process. When keeping in mind the goal of 65% emission elimination in 2050, the yield sensitivity analysis is of great contribution when looking at sugarcane as feedstock for ATJ fuel. The yield difference leads to the fuel being either just above, or just below the blue reference line that indicates the achievement of the goal. Furthermore, it also shows the influence that the yield has on corn being an eligible fuel for use according to CORSIA, shown by the green line in *Figure 7*.

The results of the second sensitivity analysis can be seen in *Figure 8*. It can be seen that the biggest differences in environmental impact appear at for the

feedstocks that are required in large amounts, as is the case for all feedstocks in the ATJ conversion process. Also, feedstocks that have a low energy density, which could also be addresses with low lower heating value, appear to be sensitive for a change in travelling distance. This is the case with the feedstocks used for the FT conversion process. For the feedstock corn in the ATJ production process, a decrease in traveling distance could mean the difference for a fuel between being eligible or not according to CORSIA. For sugar cane and forestry residues in the ATJ pathway, the traveling distance has an impact on being able to reach the 65% elimination or not.

Figure 9 shows the cumulative results of both sensitivity analysis. It shows that both analyses together have a varying impact on the different pathways with corresponding feedstocks. For sugar cane, forestry residues and agricultural residues in the ATJ pathway, they have the biggest impact because it has an impact on whether or not the contribution goal towards net zero CO_2 emissions in 2050 is to be achieved. For corn in the ATJ pathway, the impact is shown non whether or not the fuel is to be labeled eligible for use according to CORSIA.

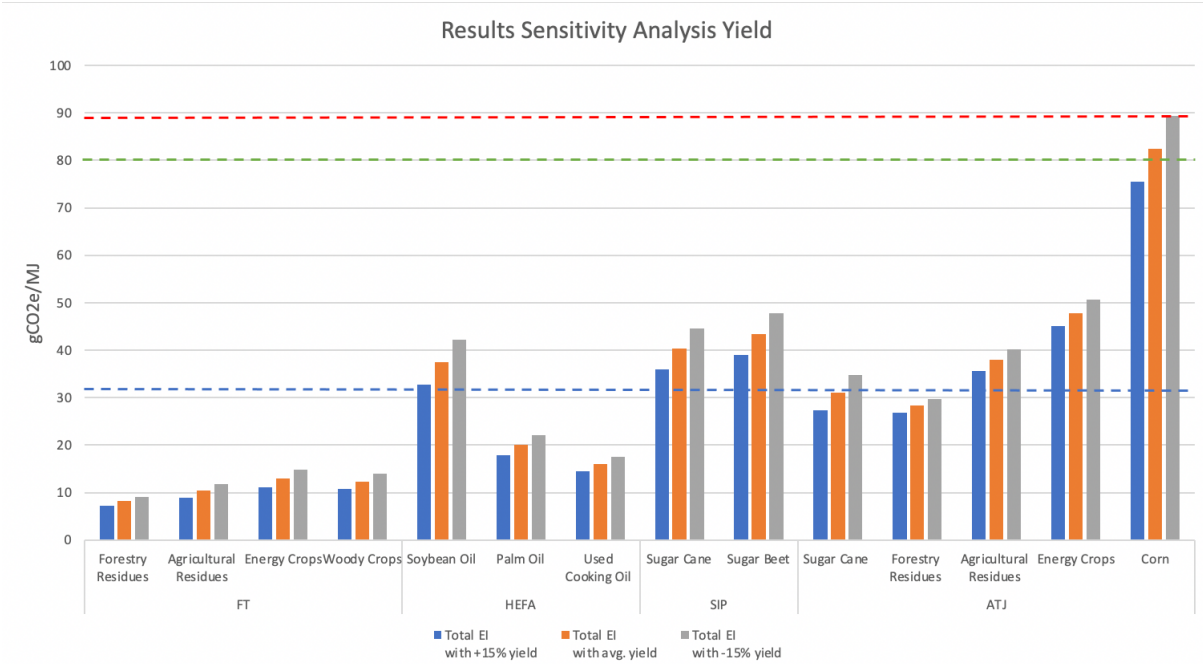

Figure 7: Results of Sensitivity Analysis concerning the yield of produced jet fuel. The red line serves as baseline and indicates the environmental impact of kerosene. The blue and green lines are reference lines indicating 10% emissions reduction and 65% emission reduction respectively.

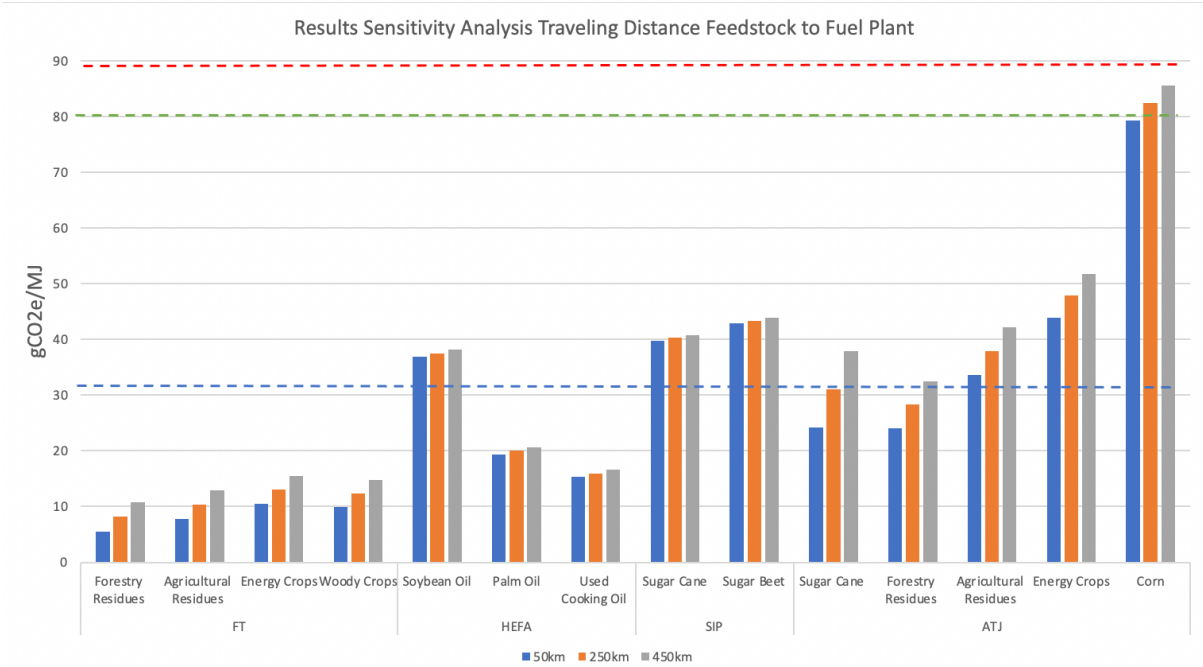

Figure 8: Results of Sensitivity Analysis concerning the traveling distance of feedstock to fuel production plant. The red line serves as baseline and indicates the environmental impact of kerosene. The blue and green lines are reference lines indicating 10% emissions reduction and 65% emission reduction respectively.

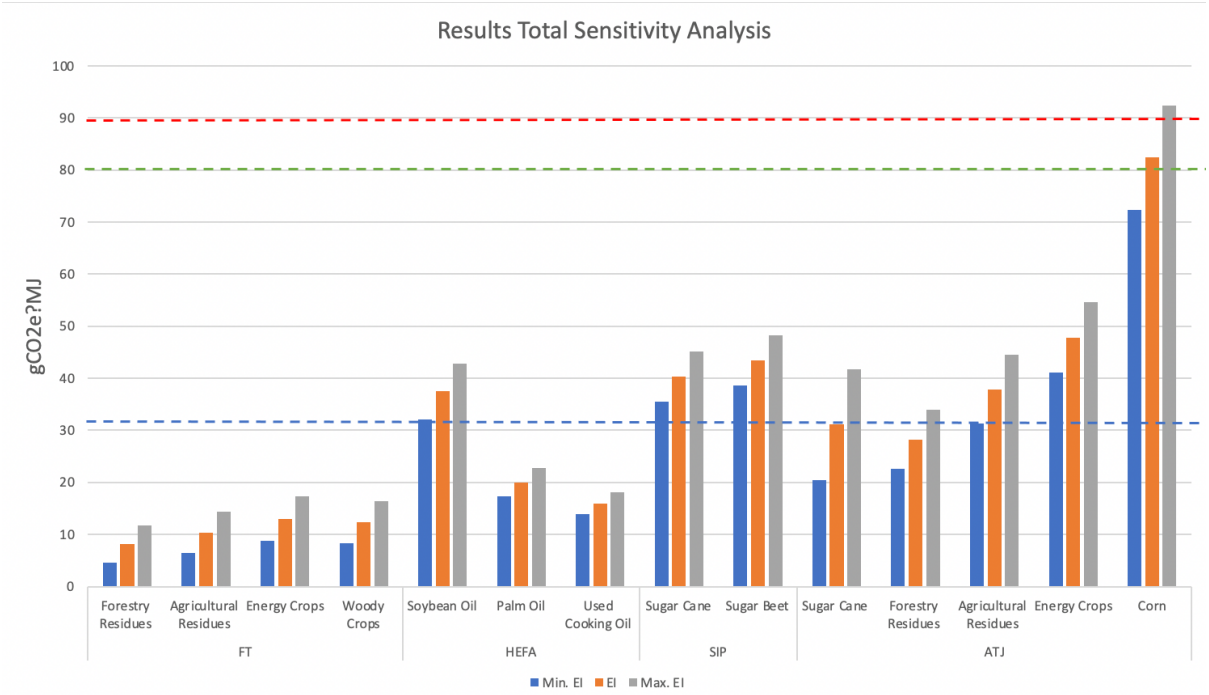

Figure 9: Results Total Sensitivity Analysis. The red line serves as baseline and indicates the environmental impact of kerosene. The blue and green lines are reference lines indicating 10% emissions reduction and 65% emission reduction respectively.

4.6 Validation

The establishment of the LCAs in this research is validated by a couple of reasons. During the establishment of the LCAs the CORSIA LCA methodology is followed. The CORSIA LCA methodology is an internationally adopted approach established by the ICAO. Furthermore, the LCAs in this research have been performed follow the ISO 14040/44 standards regarding the principles, framework, requirements and guidelines for LCA studies.

The data that is used during the LCAs comes either directly from the Ecoinvent 3 databases and scientific sources or from a secondary source which is the thesis of another student. However, this student has gathered all his data from GREET and a sensitivity analysis is performed to investigate the impact of this data.

The outcome of the LCAs is validated by looking at the list of default life cycle emissions values established by the ICAO (ICAO, 2021b). These default values are displayed by the green dots in *Figure 10*. It can be seen that the values obtained in this research follow the trend of the values established by CORSIA, with exception of a few values.

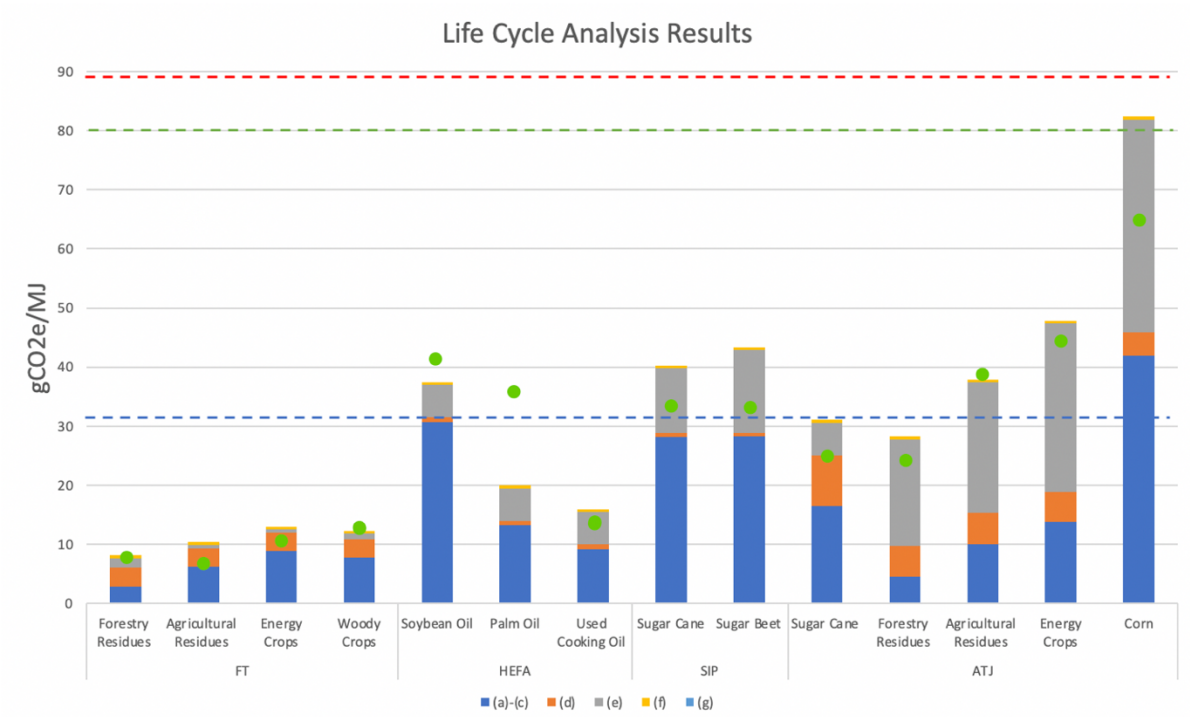

Figure 10: Comparison between life cycle result of this research and default values established by the ICAO.

5. Flying on 100% SAF

Currently, SAFs can only be used in aircraft engines if they are mixed until a certain degree with kerosene. For most SAFs this maximum blending is limited to 50%. This is due to legislation by the ASTM (IATA, 2021c). Due to this required blending SAFs would never be able to achieve their contributing goal of eliminating 65% of emissions by 2050. Therefore, it is essential that blending is no longer necessary in the near future, so that the legislation can be adjusted.

Boeing and Airbus, which are the two largest aerospace companies worldwide, are both committed to have their airplanes ready and certified by 2030 to fly on a 100% SAF (Boeing, 2021) (Singh, 2021). Both aircraft manufacturing companies have had their first successful test flights.

United Airlines has been the first airline that succeeded flying a commercial jet with passengers on board using 100% SAF in one of their two engines. The aircraft that was used to perform this flight was a Boeing 737 MAX 8 jet. By using 100% SAF in one engine and 100% conventional jet fuel in the other engine, it was shown that no modification is needed in the engines to use (unblended) SAF (Palmer, 2021).

Airbus has conducted the first in-flight of the passenger aircraft A350 with Rolls-Royce engines using 100% SAF in both engines. One of Rolls-Royce directors Simon Burr have said that they see no engineering obstacles when their engines run on 100% SAF. Furthermore, he states that flying on 100% SAF is critical for achieving full decarbonization of the aviation sector (Airbus, 2021).

Because of the high commitment of Boeing and Airbus, and their first successes on flying their aircrafts on a 100% SAF, it can be assumed that by 2050 flying on a 100% SAF is a realistic. This brings the aviation industry one step closer towards achieving net zero CO_2 emissions.

6. Feedstock availability framework for SAFs

A framework is presented in this section to estimate the availability of feedstocks in 2050. *Table 18* contains key information that needs to be gathered to estimate the feedstock availability. Due to time shortage not for all points a set-up is included in this research. For the bolt points a set-up is included in this research. The cursive point has to be investigated in more depth before it can be used in further research like the bold points.

- **The amount of SAF required in 2050.** - **The availability of land to produce SAF feedstocks.** - **Competition for the use of available lands.** - **The production capacity of biorefineries to produce SAF.**

- *The amount of land that is required to cultivate all feedstocks for all SAF production in 2050. Including:*
  - The amount of the different types of biomasses that can grow per km^2 of land.
  - The lifetime of the different types of biomasses on the fields.
  - ***The amount of biomass that is needed to produce 1 L of SAF.*** (Partly covered in this research in the inventory analysis and data collection section)

Table 18: Key knowledge to estimate the availability of feedstocks by 2050.

6.1 Amount of SAF required in 2050

This section will provide a framework containing key elements that can be used for further research into the availability of feedstocks for the production of SAFs in 2050.

Currently, less than 1% of the total jet fuel used in commercial flights is SAF (IATA, 2021a). The IATA has made an estimation on how much liters of SAF is required by 2050 to achieve net zero CO_2 emissions (IATA, 2021d). This estimation is shown in *Figure 11*.

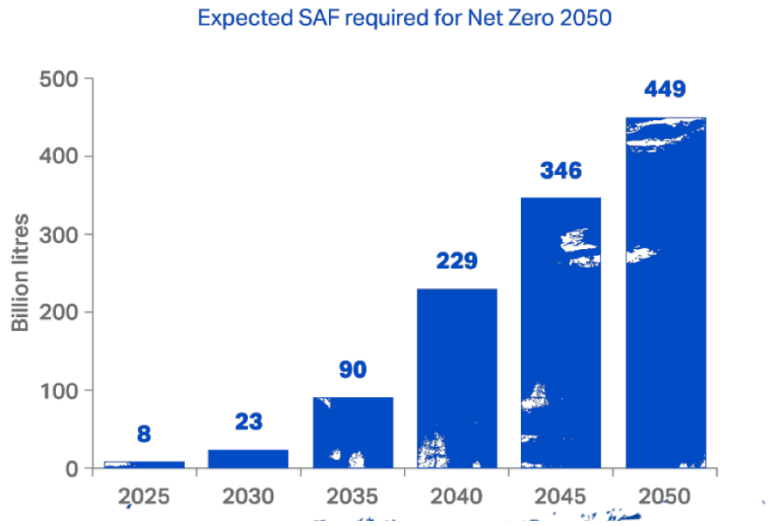

Figure 11: Estimation by IATA on required SAF by 2050 (IATA, 2021d).

In *Figure 11* can be seen that in 2050 449 billion liters of SAF is required to achieve net zero CO2 emissions. The figure shows that it is not enough to just be able to produce 449 billion liters of SAF in 2050, but that billions of SAF also need to be produced in the years before and also after 2050. This is important to take into consideration because many biomass resources take multiple years to grow. This means that lands are occupied for multiple years to provide one batch of biomass to produce SAF.

6.2 Land Availability

Figure 12 shows how all the land surface of the earth is divided between different uses. Currently, 50% of habitable land is used for agriculture. This accounts for 51 million km². 23% of these lands is currently used for crop production. This takes up about 11 million km². It can be seen that as good as all lands are currently occupied. This means that agricultural lands have to be made available for biomass production or lands that are less suitable for agriculture should be used while protecting forests (Ritchie, 2019).

The USA, China, Europe, India, Africa, South America have very big capacities of producing agriculture. It is estimated that these countries together, have between 3 and 7 million km² available lands that can be used to produce biomass feedstocks without endangering protected lands. These available lands exist of for example abandoned cropland and vegetation lands. These are considered low quality lands. The amount of available lands in these countries can be considered to be around 10km² if lands as savanna, grassland and shrubland are also taken into account. However, the quality of those lands is considered to be even lower (Cai et al., 2011).

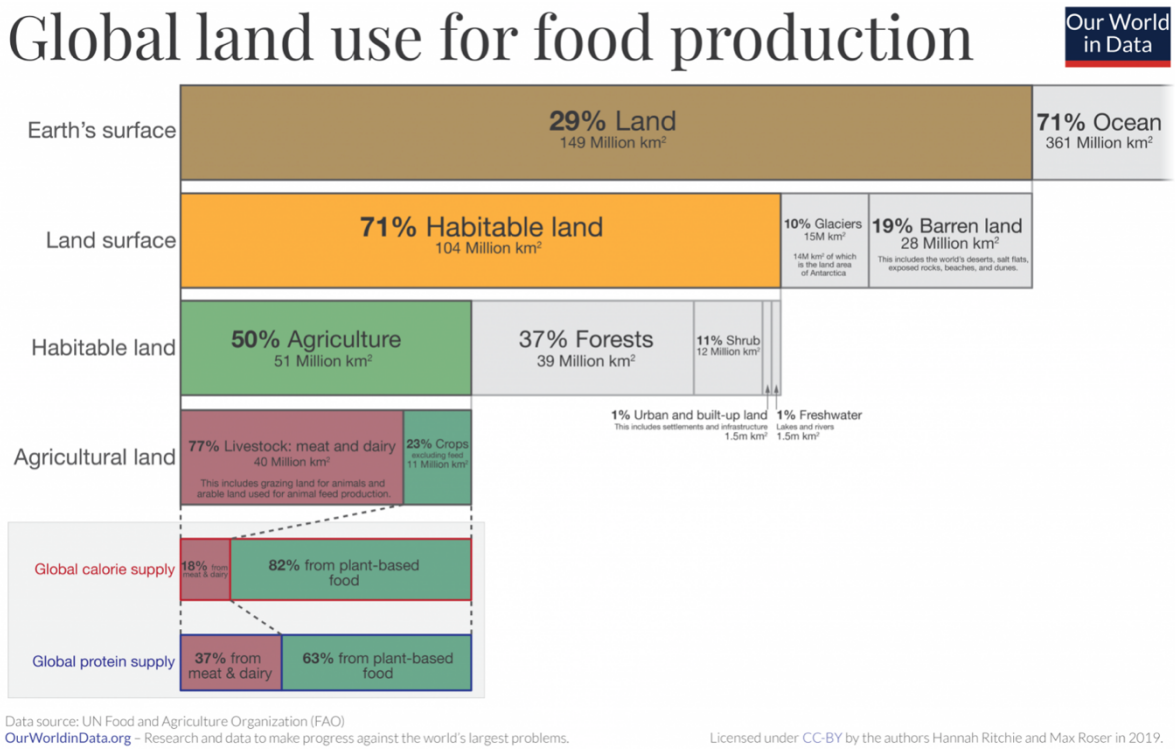

Figure 12: Global land use division (Ritchie, 2019).

6.3 Competitions for the use of available lands

Another point of consideration is that not all available land can be dedicated to production of biomass for SAF production. Many other sectors are considered with a greener future and want to make use of biomass from the same lands. For example, the road transport sector that makes use of biodiesel. Furthermore, biomass is a valuable energy resource that is used to generate electricity.

Besides other sectors wanting to make use of these lands, some SAF conversion pathways require the same feedstocks. For example, both FT and ATJ make use of forestry residues, agricultural residues and energy crops. Both SIP and ATJ, make use of sugar cane. The results of the LCAs show that lignocellulosic biomass as feedstock, in general ensure the lowest environmental impact. Therefore, it can be assumed that all conversion processes that are compatible to use these as feedstock, would prefer to make use of these feedstocks. This means that there is not only competition between different sectors, but also between different SAF refineries.

6.4 SAF production capacity of biorefineries

Currently, the only SAF that is being produced commercially is HEFA. Therefore, it is expected that HEFA will dominate the market for the coming years. Around 5 million tonne of HEFA is produced annually. However, the biggest part of the HEFA

produced fuel, is currently dedicated to the road transport sector. However, changing the production to aviation fuel, only requires small adjustments. This enables the HEFA aviation fuel production to be able to be scaled up quickly (Bauen et al., 2020). *Figure 13* shows the potential production, as of 2019, of the other types of SAF besides HEFA. This estimation is based on the extensive biofuel database of E4tech, which is an energy and sustainability consultant based in London (Bauen et al., 2020). This database contains information on plants that are being build or planned to be built by big bioenergy producing companies. For example in the USA, Fulcrum Bioenergy, and in the UK, Lanzatech and Velocys (Fulcrum Bioenergy, 2019) (LanzaTech, 2018) (Velocys, 2019).

Gasification + FT in the figure, refers to the process which in this report is called the FT process. Power to liquid FT in the figure refers to an alternative route to produce FT fuel by making use of renewable energy. This alternative route is not included in this research and is not yet approved by the ASTM. Pyrolysis is another way to produce jet fuel, which is also not jet approved by the ASTM and therefore also not included in this research. Direct sugars to hydrocarbons is in this research referred to as SIP.

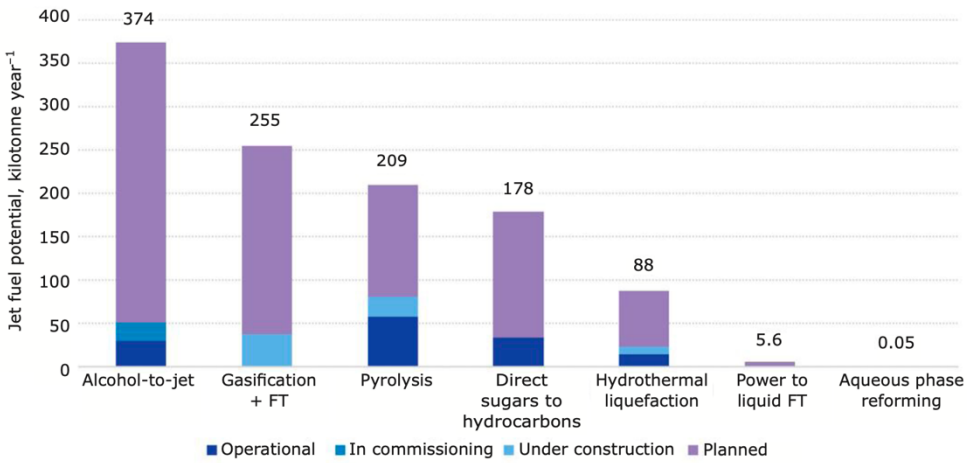

Figure 13: Potential production capacity of SAFs, estimated as of 2019 (Bauen et al., 2020).

7. Discussion

7.1 Discussion of the results

The results of the LCAs show that the environmental impact varies quite largely between the different SAFs and the different feedstocks used to produce the SAFs. All SAFs, following all different possible pathways with feedstocks, except corn in the ATJ process, are found to be eligible according to CORSIA.

The feedstocks following FT conversion have the lowest environmental impact. All feedstocks following FT are able to eliminate more than 65% of emissions compared to kerosene and are therefore suitable pathways to achieve the net zero emissions goal. For HEFA, the results are more spread. Using soybean oil it is not possible to eliminate enough emissions, while the other two feedstock do have this ability. For the SIP process, neither feedstock is able to provide enough CO_2 emission and for the ATJ process only forestry residues turn out to have this ability. When taking the average environmental impact of all SAFs following all feedstocks pathways, the average environmental impact is 30,6 gCO_2e/MJ. This shows when making use of all the feedstocks and processes used in this research, the goal of 65% emission elimination is still achieved if the SAFs were to be produced in equal amounts. This is due to the fact that the emissions of SAFs that have an environmental impact higher than the 31,2 reference line, are partly set off by the SAFs with an environmental impact below the 31,2 reference line.

Besides the feedstocks that are discussed in this research, there are many more eligible feedstocks that can be used to produce SAF. The feedstocks used in this research are only a sample and are used as representation but do not cover the entire range of possible feedstocks. Furthermore, it cannot be assumed that all SAFs are produced in equal amounts. There are many factors that play a role in determining what SAF is going to be produced in what amount. For example, the availability of the feedstocks and the costs of production.

The executed LCAs and results also contain some uncertainties. For the production processes of FT and ATJ, the feedstocks categories forestry residues and agricultural residues are used. Both categories consist of a wide range of possible residues. In this research for both categories only one type of residue is used. This is due to the fact that because they are all residues, the cultivation stage is excluded from the life cycles and all residues are assumed to be similar in energy density. However, in practice there could still be other differences. For example, the bulk density which has an important influence on the first transportation stage.

Another insecurity has to do with certain feedstock amounts that are used as input in the LCAs to produce 1 MJ of jet fuel. These values came from a thesis written

by student from the University of Utrecht. This student had obtained these values from an eligible source, which is GREET. Due to required license, these values could not be obtained directly from GREET but on good faith that the other student has extracted the correct values. However, to reduce this uncertainty, a sensitivity analysis was executed to investigate the influence that these yields had on the total outcome of the LCAs.

For all conversion processes, except HEFA, the environmental impact obtained in another research is used. This leads to the uncertainty of not knowing how exactly these values were obtained and how reliable these values are.

Furthermore, it was assumed, that all feedstocks are transported by the same mode of transport and the same distance, which, in reality, is not the case. However, the sensitivity analysis done on this assumption, shows that the first transportation stage only has a small contribution to the total environmental impact.

When investigating the life cycle stages of kerosene, it appears that the combustion stage has by far the biggest impact. The combustion stage has an environmental impact of about 71,5 gCO_2e/MJ and is accountable for about 80% of the total environmental impact (Quaschning, 2021). Due to the fact that SAFs absorb CO2 during the feedstock cultivation stage, regulatory policies state that their emissions generated during combustion are set off and equal to zero. This causes the biggest difference between the environmental impact of SAFs and kerosene. However, currently, most SAFs have a maximum blending limit of 50% with kerosene. Therefore, in practice, the combustion in an aircraft of a SAF-kerosene mixture will not be zero but will be at most half of the emissions of a full kerosene combustion.

As just stated, currently, SAFs have a maximum blending limit with kerosene. For the goal of net zero CO_2 emissions by 2050 to be achieved, it is critical that flying on 100% SAF is possible. Boeing and Airbus are committed to have their planes fly on a 100% SAF by 2030. This is supported by the fact that both aircraft manufacturers have executed their first successful test flights on 100% SAF. However, whether flying on 100% SAF is going to happen partially depends on whether legislation will allow this.

A framework to estimate the feedstock availability in 2050 was also provided in this research. This is considered an essential part. As is shown by the LCAs, the environmental impact has the potential to achieve 65% emission reduction compared to kerosene. As is explained, is that it is very likely that flying on a 100% SAFs will be possible in 2050. However, both findings do not matter if there are not enough feedstocks available to produce all the needed SAF. In the framework it is stated that 449 liters of SAF is required in 2050. Also, an estimation is given that possibly around 10 million km^2 of land is available for biomass feedstock production. However, these lands are considered low quality, and it is uncertain which feedstock

types even have the ability to grow on these lands. Furthermore, a section on competing sectors for land use and biorefinery capacity is added. The amount of land that is required to cultivate all feedstocks for all SAF production in 2050 needs more in depth-investigation.

7.2 Recommendations for further research

Due to time shortage two elements are excluded from this research. These are recommended to investigate in further research. The first element is two types of approved SAFs, named CHJ and HH-HEFA. The second element is a set-up to determine the amount of land that is needed to cultivate all feedstocks for all SAF production in 2050.

Besides the conversion processes that are included in this research, new conversion processes are being developed. Pyrolysis is one of these conversion processes under development, but not yet approved by the ASTM. The ongoing investigations into new ways of producing SAF increase the chances of SAF being able to reach that 65% CO_2 elimination. For the production of FT, an alternative route besides the route that is described in this research is under development and not yet approved. This is the power-to-liquid route that uses renewable energy to produce SAF. This pathway also has the potential of delivering a significant contribution towards achievement of the goal, due to the fact that it does not require any of the feedstocks that is used for the other conversion processes.

Some points could be derived from this research which are interesting for follow-up research. First of all, to carry out the presented in the framework to estimate feedstock availability in 2050. Furthermore, looking at the economical side of producing SAFs would be valuable, as the production of SAFs are expected to cost up till eight times as much as the production of kerosene, and varies largely between the different types of SAF (Goldstein, 2021). Also, challenges of scaling up SAF production could be an interesting addition to this research, as this also has an influence on the production costs. Lastly, besides SAFs that have to deliver a contribution of 65% elimination, there were four other areas of improvement that have to deliver to achieve net zero CO_2 emissions. These areas were operational improvement, new technologies and offsetting strategies. The ability of these other areas to deliver their contribution is also a suitable topic for further research.

8. Conclusion

The goal of this research was to investigate whether sustainable aviation fuels have the ability of eliminating 65% of CO_2 emissions in 2050. To investigate this, the research was divided into three parts. The first part consisted of estimating the environmental impact of five types of approved SAFs. The second part consisted of an investigation of the possibilities of flying on 100% SAF. The last part provided a framework for estimating the availability of feedstocks in 2050.

The results of the LCAs are based on the assumption that flying on 100% SAF is going to be possible. Due to the high commitments of Boeing and Airbus and the first test flights that have been a success, it can be assumed that this is possible by 2050.

The results of the LCAs show that the emissions reduction delivered by FT is significantly higher than the reduction any of the other SAFs can deliver. The emissions reduction of FT ranges from 91%-85%. Furthermore, the emission reduction of FT, using all feedstock pathways, is well below the goal of 65%. This cannot be said of any other SAF. Therefore, based on this research, FT is the most suitable conversion process to produce SAF. However, due to scarcity of available lands and the expected production capacity of FT biorefineries, FT cannot carry the burden of supplying the entire aviation industry with the required SAF in 2050. The fact that FT reduces more emissions than the goal, compensates for SAFs that reduce less emissions than the goal. It is recommended to produce FT to its full capacity and fill the gap as much as possible with the other SAF production processes. The most suitable for this is HEFA. HEFA is the only conversion process that is already used commercially. Furthermore, HEFA has the second lowest environmental impact and is able to reduce 82%-58% of emissions. Also, HEFA uses waste oils as feedstock, which does not require use of available lands. SIP and ATJ both have a significant higher environmental impact. SIP can reduce 55%-51% of emissions, while ATJ 68%-7% of emissions. Both processes are recommended to complement the FT and HEFA processes, where they fall short in terms of production capacity.

Some feedstocks can be used for different conversion processes. When there is scarcity of feedstocks, the feedstocks are recommended to be assigned to the conversion process that has the lowest environmental impact, as far as production capacity allows this.

Based on this research, it cannot be stated if SAFs can reduce 65% of emissions by 2050. More research needs to be done into the required lands to produce biomass feedstocks. However, it can be said that SAFs have the potential of achieving the goal according to their environmental impact, on the condition that flying on 100% SAF will be allowed.

9. Recommendations to the Green Office

As stated in the stakeholder analysis in the beginning of this research, the commissioning party of this research is the Green Office. The main message of the Green Office was that they were looking for a way to compensate for their employees' flight travel. In looking for ways to compensate for flight travel, it became clear that compensation could only help in a very limited way to reduce the carbon footprint of aviation. Therefore, it was decided to look for methods that could deliver much greater carbon reductions. Sustainable Aviation Fuels appeared to have the greatest potential to enable large-scale CO_2 emission reduction on the long and short term. The goal is to have net zero CO_2 emissions, generated by flights, by 2050. Until then, the Green Office needs a strategy to compensate for their employee flight travel. The remainder of this section will provide recommendations to the Green Office on how the University of Groningen (UG) could compensate for the flight travel of their employees until the aviation sector achieves net zero emissions. Prior to the recommendations, a brief analysis of the employee flight travel of the UG is provided.

According to the UG's annual sustainability report, 13% of their total CO2 emissions in 2019 are attributional to employee flight travel. In 2019, the UG was responsible for in total 32.6 kt CO_2 emission of which 13% is attributional to employee flight travel. This brings the total CO_2 emissions generated by flight travel in 2019 to 4.2 kt CO_2 (RUG, 2019). According to the Roadmap Sustainability, the UG aims to be CO2 neutral by 2035 (Roadmap Sustainability). The UG has introduced a policy that states that destination within 500km of Groningen or destination that can be reached within six hours by train, can only be traveled to by train (RUG, 2019).

Traveling by plane is unavoidable and air transport will continue to grow at a rapid pace. Because of, COVID-19, traveling has been prohibited for some time. Therefore, technology related to attending and organizing conferences online has evolved tremendously. However, sometimes on-site attendance at a conference overseas is unavoidable, for example due to time difference or for the social benefit.

A valid way to compensate for flight travel is to make use of approved offset programs. This is done by purchasing carbon credits from verified carbon offset programs or actively capturing carbon from the atmosphere. It is advised to only make use of verified carbon offset programs because these programs are approved by an external validator. The Carbon Offsetting and Reduction Scheme of International Aviation (CORSIA) initiated by the ICAO, has approved six offset programs (IISD, 2020) (Detterman et al., 2020). These are:

- American Carbon Registry
- Climate Action Reserve

- Verified Carbon Standards
- The Gold Standard
- China Greenhouse Gas Voluntary Emission Reduction Program
- Clean Development Mechanism

However, compensating for emissions is not going to solve the problem of the impact of aviation emissions on global warming. Looking at the bigger picture, the Green Office can have a greater impact by researching technical solutions to make aviation greener. Improvement in new technologies include alternative propulsion options. For example, electric, hybrid or hydrogen propulsion.

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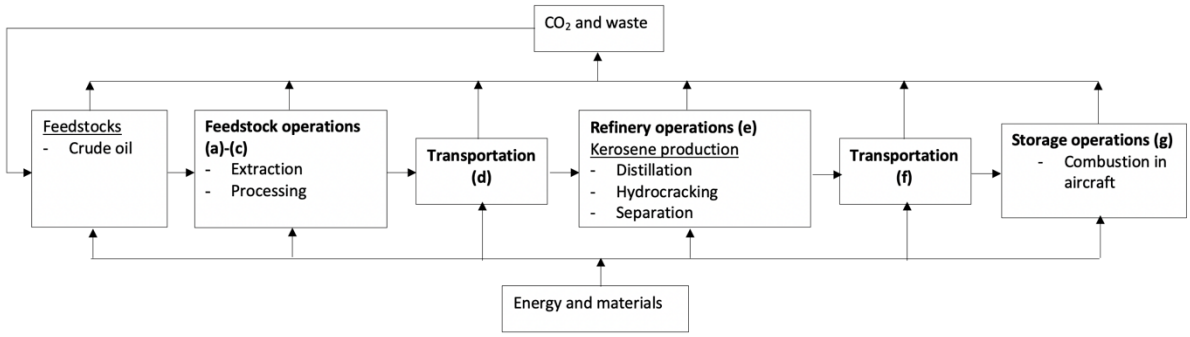
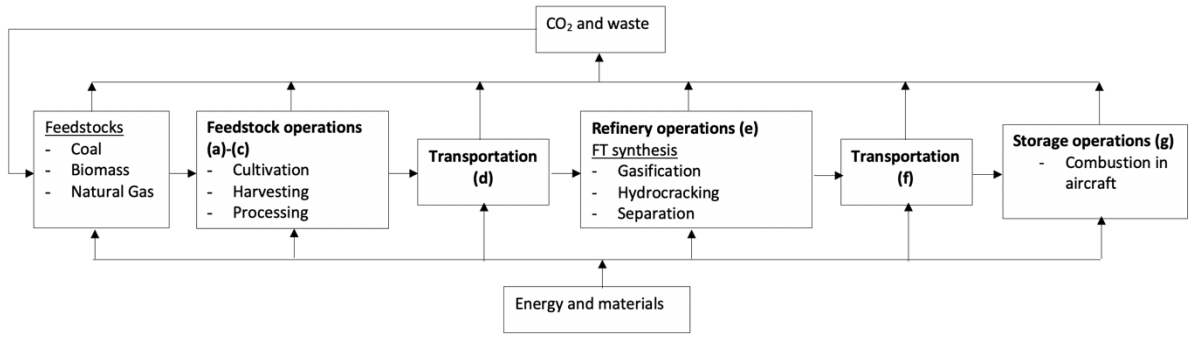
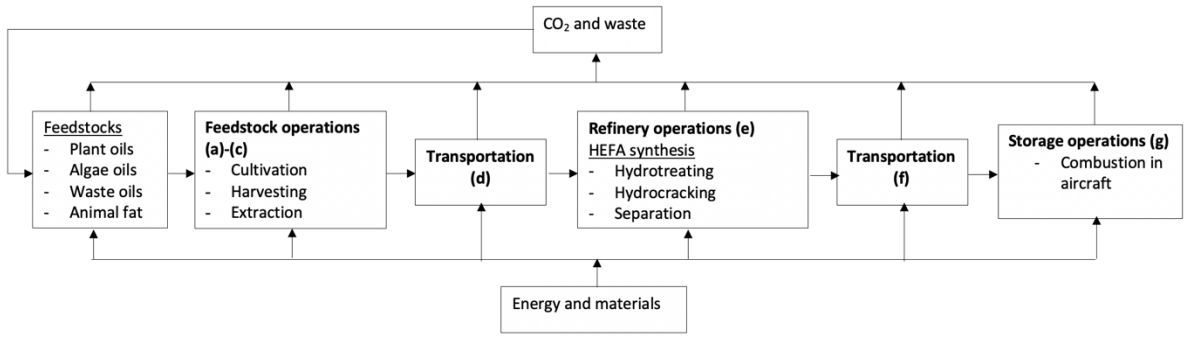
Appendix A



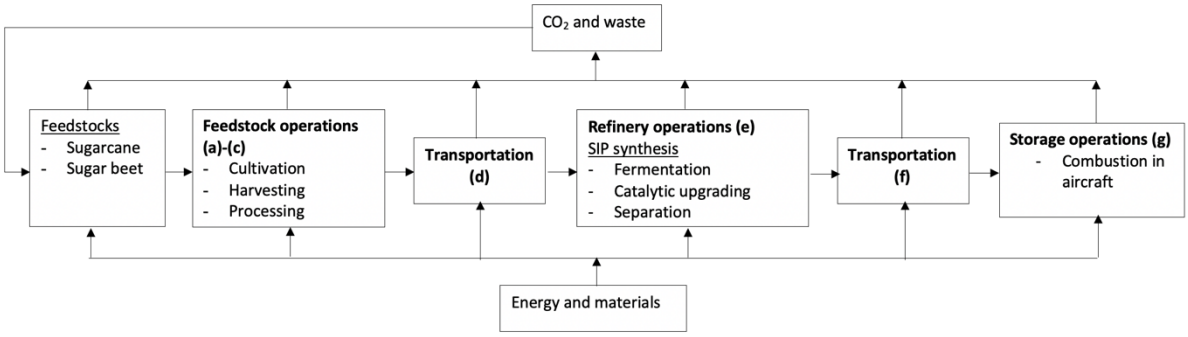
System diagram of kerosene.



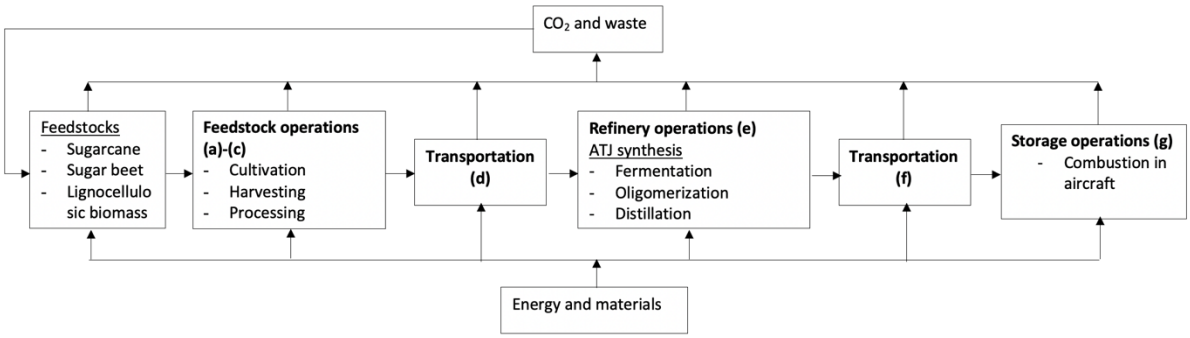
System diagram of Fischer-Tropsch.



System diagram of HEFA.



System diagram of SIP.



System diagram of ATJ.

Appendix B

FRL	Description	Toll Gate	Fuel Quantity+
1	Basic Principles Observed and Reported	Feedstock /process *principles* identified.	
2	Technology Concept Formulated	Feedstock /*complete* process identified.	
3	Proof of Concept	Lab scale fuel sample produced from realistic production feedstock. Energy balance analysis executed for initial environmental assessment. Basic fuel properties validated.	0.13 US gallons (500 ml)
4.1 4.2	Preliminary Technical Evaluation	System performance and integration studies entry criteria/specification properties evaluated (MSDS/D1655/MIL 83133)	10 US gallons (37.8 litres)
5	Process Validation	Sequential scaling from laboratory to pilot plant	80 US gallons (302.8 litres) to 225,000 US gallons (851,718 litres)
6	Full-Scale Technical Evaluation	Fitness, fuel properties, rig testing, and engine testing *	80 US gallons (302.8 litres) to 225,000 US gallons (851,718 litres)
7	Fuel Approval	Fuel class/type listed in international fuel standards**	
8	Commercialization Validated	Business model validated for production airline/military purchase agreements – Facility specific GHG assessment conducted to internationally accepted independent methodology	
9	Production Capability Established	Full scale plant operational++	

\+ Quantities required for risk mitigation reference
* As referenced in ASTM approved protocols
** As listed in original equipment manufacturers' manuals for aircraft and engines
++ color coding reference Phase of development green (technology phase), yellow (qualification phase), blue (deployment phase)

Table containing short explanation of Fuel Readiness Levels (CAAFI, 2009).