MULTI-CRITERIA ANALYSIS OF SUSTAINABLE AVIATION FUEL TECHNOLOGIES

Integrating environmental, economic, social, and technical criteria along with stakeholder perspectives to compare the fast pyrolysis, hydrothermal liquefaction and HEFA pathways

The airplane picture is generated using Canva's AI, Magic Studio™

Multi-Criteria Analysis of Sustainable Aviation Fuel Technologies

Integrating environmental, economic, social, and technical criteria along with stakeholder perspectives to compare the fast pyrolysis, HTL and HEFA pathways

By

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I've done my best to keep this thesis concise, even though I'm known for my love of lengthy explanations. I hope you enjoy the read!

Charlotte Taets van Amerongen

10th of June 2024, Delft

Executive Summary

Problem Statement

The aviation industry, responsible for approximately 2% of global anthropogenic greenhouse gas emissions, faces a significant challenge as it is expected to grow 4-6 times by 2050. This expansion is in direct conflict with the European Union's Green Deal target of a net-zero industry by 2050, highlighting the urgent need for effective emission reduction strategies. While solutions such as aircraft electrification are promising, their suitability is limited to short-haul flights due to range and weight constraints. Sustainable Aviation Fuel (SAF) is emerging as a promising alternative, particularly for long-haul flights, as it does not require new infrastructure. However, the SkyNRG Sustainable Aviation Fuel Market Outlook (2023) highlights a significant supply gap for SAF, indicating a need for increasing production and technological diversification. In response, there has been a focus on exploring new pathways to produce SAF. This study contributes to this effort by investigating thermochemical liquefaction (TL) technologies, namely HTL (HTL) and fast pyrolysis (FP), to assess their potential to contribute to a more sustainable aviation industry.

Research Objective, Knowledge Gaps, and Research Question

For this study, HTL and FP were selected from a larger set of TL technologies, a selection process described in detail in appendix C. The research objective was to evaluate these technologies against HEFA, the current standard in SAF production, using HEFA as a benchmark. This evaluation used a multi-temporal time scale and a regional focus on the EU.

A systematic literature review identified the three following main knowledge gaps in the existing literature on the evaluation of HTL and FP used for SAF production:

1. A lack of studies investigating the social impacts of HTL and FP.
2. The absence of stakeholder involvement in the evaluation of HTL and FP.
3. The need for updated data integration to effectively compare HTL and FP with established SAF technologies such as HEFA.

To fill the three gaps listed above, the following research question was addressed: *“How do HTL and FP compare to the HEFA pathway in producing SAF across technical, environmental, economic, and social aspects, while considering the perspectives of multiple stakeholders?”.*

Methodology

This study used a multi-criteria analysis (MCA) to evaluate and compare the performance of the HTL and FP pathways with the HEFA pathway. This approach was chosen in order to provide a holistic evaluation, including not only technical, economic and environmental aspects, but also social aspects.

The study was divided into four phases, as detailed in chapter 3, each corresponding to a sub question of the study:

Phase 1: Identification of stakeholders who influence or are influenced by the implementation of SAF technologies, using a power-interest grid. This phase included both a literature review and online research to clarify the stakeholder landscape.

Phase 2: Design of the MCA framework. First, relevant criteria were selected by conducting an extensive literature review on studies that used an MCA to evaluate biofuel production pathways. These criteria were then weighted using the Best-Worst Method (BWM) based on stakeholder input gathered through structured interviews. Using the BWM, stakeholders identified the most and least important criteria and conducted pairwise comparisons of these with all other criteria to assign relative weightings to each criterion considered in this study. The input-based consistency ratio, as proposed by Liang et al. (2020), was used to ensure consistency and reliability of the responses. The outcome of this phase was the establishment of the MCA framework.

Phase 3: Firstly, the technologies were analysed against the selected criteria, each with its own specific analysis, as described later in this executive summary. The data required for these analyses were obtained through interviews with technology experts from Steeper, BTG and SkyNRG. Where necessary, this was supplemented by data and/or information from relevant studies. Additionally, a detailed process model for HTL and FP was developed in Excel to estimate essential data for the criteria analyses, which is discussed in Appendix T. Subsequently, SkyNRG SAF experts participated in a focus group where they determined the performance scores for each criterion of the MCA framework for HTL, FP and HEFA based on the results of the criteria analyses and their expert knowledge. They collaboratively scored each technology on a Likert scale from 1 to 5, where 1 is the lowest performance and 5 is the highest.

Phase 4: The performance scores assigned by the SAF experts in phase 3, together with the criteria weightings awarded by the stakeholders in phase 2, were used to calculate a final MCA score for each technology per stakeholder. This was executed using the Weighted Sum Method.

Answers to research questions:

To address the main research question, it was divided into four sub questions. The first sub question stated: *Which stakeholders are involved in the implementation of HTL and FP to produce SAF, and what are their interests and influences?*

To answer this question, stakeholders involved were categorized into quadrants using a power-interest grid, which is discussed in detail in chapter 4:

- Players: High power and interest, including SAF providers, airlines, ASTM, aircraft engine manufacturers, and secondary fuel market players. They are directly involved in development and use of SAF technologies.
- Subjects: High interest but limited power, including environmental and sustainability organizations, local factory and biomass residents, R&D institutes, and feedstock suppliers.
- Context Setters: Limited interest but high power, including energy companies from the oil and gas industry, airports, the European Commission, and government agencies.
- Crowd: Limited power and interest, focusing on broader market trends, including investors and financers and SAF consumers.

Due to time constraints, only the key stakeholders from each quadrant were selected to include in this study based on their impact on the implementation of TL technologies for SAF production. Three key stakeholders were selected from the "Players" quadrant: SAF providers, airlines and ASTM. In addition, one key informant was selected from each of the remaining quadrants to ensure broad representation: environmental and sustainability organisations from 'Subjects', consumers from 'The Crowd' and energy companies from the oil and gas industry from 'Context Setters'. This ensured a balanced and feasible representation of stakeholders for this study.

The second sub question stated: *Which criteria and their respective weightings awarded by stakeholders should be considered when evaluating SAF production technologies?*

To answer this question, an extensive literature review was first carried out, in order to identify the relevant criteria for this thesis. The criteria were categorised into four dimensions: environmental, economic, technical, and social and the selection was based on their prominence in the literature and their relevance and applicability within the timeframe of this study. Environmental criteria included Global Warming Potential (GWP) and use of by-products, and economic criteria focused on capital expenditure (CAPEX), operating expenditure (OPEX), and feedstock price. The social criteria selected included safety and social impacts related to feedstock use, and technical criteria included Technology Readiness Level and efficiency. Details of the criteria selection process are described in chapter 5.1.

Next, the weightings of these selected criteria were determined by the selected stakeholders from phase one. Key takeaways were that stakeholders largely agreed on the importance of GWP but showed substantial differences in priorities for criteria such as feedstock price, TRL and social impacts related to feedstock use. Details on the criteria weightings are described in chapter 5.2. The selected criteria and their weightings together form the MCA framework for the evaluation of the HTL, FP and HEFA SAF production pathways, as presented in appendix J.

The third sub question stated: *How do HTL, FP and HEFA perform according to the criteria analyses and the performance scores assigned by SAF experts?*

The GWP analysis used a simplified 'well to wake' Life Cycle Analysis to analyse the emissions (in gCO_2eq per MJ) of three SAF technologies under different scenarios reflecting the carbon intensity of the utilities including electricity, hydrogen and heat. The results show that FP had the highest GWP in the conservative and progressive scenarios, mainly due to significant hydrogen emissions, while HTL had the highest GWP in the mixed scenario, influenced by lower hydrogen emission factors and higher heat contributions. HEFA consistently had the lowest GWP across all scenarios, benefiting from efficient use of hydrogen and heat. The experts awarded each technology a performance score of (3), considering that if the recovery of off-gases and/or char for heat generation had been included in the model, it would have led to significant reductions in GWP for HTL and FP.

The use of by-product analysis was based on an extensive literature review. This review showed that the HTL by-products, aqueous phases and solid residues, have potential uses in energy and chemical production, but their treatment can increase environmental problems such as pollution. Efficient management is therefore required to improve the circularity of HTL. FP produces biochar and gases that are highly beneficial for energy and soil enhancement, although impurities such as tar present technical and cost challenges. HEFA produces water, CO_2, propane and other gases that could be reused or sold. However, integrating advanced treatment and separation technologies to facilitate this, is costly and requires significant investment. The experts gave FP the highest score (4) because of the economically viable applications of char, HTL a neutral score (3) due to environmental challenges, and HEFA the lowest score (2), reflecting less profitable by-product valorisation.

For the economic criteria analyses, the criteria were calculated in euro per tonne of SAF to allow a direct comparison between the technologies. The economic analysis went beyond the selected MCA criteria, CAPEX, OPEX and feedstock price to include the market value of the other end-products, diesel and naphtha. This approach takes into account process inefficiencies in converting into SAF by considering the economic value of these alternative end-products. In addition, two scenarios, conservative and progressive, were defined for the OPEX assessment associated with process utilities. The research findings showed that HTL has the highest CAPEX as it requires complex equipment to process large volumes of feedstock. HEFA has lower CAPEX due to scalable and cost-optimised operations, while FP's CAPEX is also low but likely underestimated. HEFA also benefits from the lowest OPEX in both scenarios due to minimal hydrogen requirements. In contrast, HTL's OPEX is higher than HEFA's, but lower than FP's, which is the highest due to intensive operating requirements. Feedstock costs are highest for HEFA, which uses expensive used cooking oil, while HTL and FP use cheaper forest residues, with HTL being slightly less efficient in converting feedstock into SAF and therefore having a higher overall feedstock price. The expert scored HEFA high on both CAPEX and OPEX (4 each) because of its optimised operations. HTL received a (2) for CAPEX and a (3) for OPEX; FP received a (3) for CAPEX and a (2) for OPEX. For feedstock price, HEFA scored a (1), while HTL and FP both scored a (4), considering more SAF efficient operations for HTL.

The safety analysis was carried out through a detailed literature review using the methodology of Pokoo-Aikins et al. (2010), which assesses safety based on operating conditions and chemical properties. Key findings highlighted that HTL, operating at high pressures (300-340 bar), presents significant safety risks related to facility stability. FP, although operating at lower pressures, poses corrosion risks due to the unstabilised pyrolysis crude oil. HEFA, being more established, has lower safety risks due to controlled processes within the industry. The expert scores indicated that HEFA has a relatively low risk with a score of (4), while FP and HTL, with manageable risks, both received a score of (3).

The “social impact related to feedstock use” analysis was conducted through a comprehensive literature review. Key findings showed that HTL excels at processing wet biomass such as algae and sewage sludge, which contributes to waste reduction and minimises environmental risks. FP processes diverse feedstocks, including agricultural and forestry residues and non-recyclable plastics, improving soil and public health and reducing landfill waste. However, the use of non-recyclable plastics can unintentionally encourage increased plastic production, complicating efforts to achieve a sustainable society. Whereas HEFA, which uses oil-rich feedstocks such as palm oil, has been criticised for potential deforestation and food safety issues, although it also contributes to waste reduction by processing used cooking oils as a feedstock. The experts gave HTL a high score (4) for its environmental and public health benefits, FP a moderate score (3) for its balanced positive social impacts, and HEFA a low score (1) due to concerns about food-based oils.

The TRL analysis, based on the definitions of Beims (2019), assessed the level of maturity of the technologies. A comprehensive literature review identified TRLs for each technology: HTL and FP were assessed at the biocrude production plant level, while HEFA was assessed across the entire SAF production pathway. BTG's Empyro FP plant is fully mature with a TRL of 9. Steeper's Silva Green Fuel HTL plant is in late development with a TRL of 7-8. The entire HEFA pathway is fully commercial with a TRL of 9. The experts gave HEFA the highest score (5) because its pathway is fully commercial, FP a score of (3) because its overall SAF production pathway is unproven, and HTL the lowest score (2) because it is still in development and its overall SAF production pathway is unproven.

The efficiency analysis focused on calculating carbon and energy conversion efficiencies. HEFA excelled in both, showing the lowest energy losses and the highest carbon utilisation, followed by HTL and then FP. The experts awarded HEFA the highest performance score of (5) for its efficiency in converting used cooking oil into biofuel. HTL received a score of (4) for its high carbon efficiency, while FP received a score of (3) for its lower efficiencies in both areas.

Details of the criteria assessments consisting of the criteria analyses and the performance scoring of the experts are described in chapter 6.

The fourth sub question stated: *How do HTL and FP compare to the HEFA pathway when the performance scores assigned by experts are combined with the criteria weightings established by stakeholders to calculate a final MCA score?*

By combining the expert performance scores and stakeholder criteria weightings, the MCA results show that no single SAF technology consistently scores highest across all stakeholders, reflecting the different strengths and weaknesses of each technology, which are valued differently by stakeholders. HTL is preferred by the energy company in the oil and gas industry due to its relatively low feedstock price and positive social impact. The consumer favoured FP for its efficient use of by-products and feedstock price. The airline preferred HEFA for its low OPEX, CAPEX and high TRL. The environmental and sustainability organisation and the SAF supplier also preferred HTL, mainly for its positive social impact. The ASTM preferred HEFA for its efficiency and technological readiness. This analysis reveals that HTL is the most frequently preferred option among the stakeholders and that they commonly share an involvement in the production and regulatory oversight of sustainable technologies. The sensitivity analysis highlighted the impact of the feedstock price performance scores on the final MCA scores, underscoring its importance in the SAF technology evaluation. Ultimately, the choice between HTL, FP and HEFA depends on the specific priorities of each stakeholder group, highlighting the need for a balanced approach that considers different perspectives in SAF implementation decisions. Details of on the final MCA scores are shown in chapter 7.

Answer to Main Research Question

Taken together, the main research question is answered as follows. HTL and FP are potential alternatives to the HEFA pathway to produce SAF, each with different advantages and disadvantages. Technically and economically, HEFA currently outperforms due to its maturity and lower costs, while HTL and FP offer potential environmental and social benefits, particularly in terms of the kind of feedstocks used and the possibilities of by-product valorisation. The preference for each technology varies between stakeholders, indicating the need for a balanced approach that integrates multiple perspectives in SAF implementation decision-making.

Limitations and Future Research

The main limitations of this study are outlined below, and reference is made to chapter 8 for a full list of the limitations.

- Bias from collaboration with SkyNRG: working closely with SkyNRG could have introduced bias in the presentation and interpretation of results. Regular reviews with academic supervisors were conducted to minimise this possible effect.
- Limited expert and stakeholder input: the use of only two experts for the performance scoring and one interviewee per stakeholder group for the criteria weighting could have limited the depth and diversity of the findings. Future research could include a wider range of experts and stakeholders to increase the robustness and reliability of the findings.
- Selection of technology providers: The selection of just BTG and Steeper as technology providers may have biased the results. Widening the range of technology providers in future studies could improve the representativeness of the MCA.
- BWM criteria weighting: The BWM used for criteria weighting may be biased due to some stakeholders being more familiar with SAF technologies than others, potentially distorting the final MCA scores. Future studies may want to include training sessions to equalise the knowledge of all stakeholders prior to weighting.
- Temporal scale: The study used a multi-temporal timescale, which was considered suitable for this preliminary exploratory MCA. For future policy decisions, it is recommended that a single time scale is used for all analyses to improve accuracy and comparability.

Relevance of this thesis

This study meets the objectives of the CoSEM programme by developing a new MCA framework that integrates both public and private interests, using CoSEM tools and methods such as the IDEF0 diagram and the PI grid. It also provided a strong link to the energy track of the programme, as SAF is a component of the overall sustainable energy system.

The scientific relevance of this study lies in filling three key knowledge gaps in the existing literature, as outlined earlier in this executive summary. Firstly, it advanced the exploration and documentation of the social aspects of HTL and FP through comprehensive social criteria assessments. Secondly, it incorporated stakeholder opinions into the MCA framework, ensuring that the analysis was representative of their perspectives. Finally, it updated the technological data on HTL and FP by incorporating insights from recent interviews with key technology providers, ensuring relevance and accuracy.

Despite its limitations, the study provides actionable insights for decision-makers within the aviation industry and policymakers. For SAF providers considering HTL and FP technologies, a phased implementation is recommended to gradually increase production capacity while meeting the growing demand for SAF. Early adopters can test and refine the technology, build market confidence, and generate data for further investment. As these technologies mature, focus should shift to optimizing processes to increase production and efficiency thereby reducing costs. SAF providers are advised to integrate or expand facilities with dedicated by-product processing units to improve resource efficiency and capitalize on environmental advantages. Further research into by-product processing applications is recommended.

SAF providers could further enhance transparency regarding environmental impacts and commit to sustainability. For support from airlines and energy companies, optimizing supply chains and improving production efficiencies are essential. Strategies to manage stable feedstock prices could include diversifying feedstock sources and forming strategic partnerships, ensuring reliable and cost-effective SAF production.

Selecting appropriate locations for SAF production facilities can maximize environmental and social benefits, particularly in economically disadvantaged areas where waste management systems are less effective. Deploying SAF technologies in these regions can improve waste management, create economic opportunities, and enhance public health by reducing environmental hazards.

Additionally, SAF providers are advised to lobby for (more) subsidies, tax incentives, and government financial support to address higher CAPEX and OPEX associated with HTL and FP compared to HEFA. Emphasizing the long-term benefits can also attract investment from sustainability-focused funds. Therefore, policymakers are advised to provide substantial subsidies and enforce aggressive policies to make SAF competitive with conventional jet fuels and support continued investment in research and pilot projects.

In conclusion, although preliminary, this research provides fundamental insights that could contribute to the energy transition and suggests a starting point for more comprehensive investigations of SAF and other renewable energy sources.

List of Figures

List of Tables

List of Abbreviations

SAF	Sustainable Aviation Fuel
GHG	Greenhouse Gas
HTL	Hydrothermal Liquefaction
FP	Fast Pyrolysis
MCA	multi-criteria Analysis
HEFA	Hydroprocessed esters and fatty acids
GWP	Global Warming Potential
CAPEX	Capital Expenditure
OPEX	Operational Expenditure
TRL	Technology Readiness Level
IATA	International Air Transport Association
IDEF0	Integration DEFinition for Function Modelling
SPO	Stabilized Pyrolysis Oil
HPO	Hydrotreated Pyrolysis Oil
RFD	Research Flow Diagram
BWM	Best Worst Method
SMART	Simple Multi-Attribute Rating Technique
WSM	Weighted Sum Method
GFT	Gasification and Fischer-Tropsch synthesis
ATJ	Alcohol to Jet
DSHC	Direct Sugar to Hydrocarbon
TL	Thermochemical Liquefaction
ICAO	International Civil Aviation Organization
CP	Catalytic Pyrolysis
UCO	Used Cooking Oil
ASK	Available Seat Kilometre
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
LCA	Life Cycle Assessment
CCS	Carbon Capture and Storage
NG	Natural Gas
RNG	Renewable Natural Gas
EBITDA	Earnings Before Interest, Taxes, Depreciation, and Amortization
EU	European Union
UK	United Kingdom
Mt	Million metric tons
Bgal	Billion gallons
CAF	Conventional Aviation Fuel
AAF	Alternative Aviation Fuel
CHJ	Catalytic Hydrothermolysis Jet fuel
HC-HEFA-SPK	Hydro-processed Hydrocarbons,Esters,and Fatty Acids Synthetic Paraffinic Kerosene
FT-SPK	Fischer-Tropsch Synthetic Paraffin Kerosene
FT-SPK/A	Fischer-Tropsch Synthetic Paraffin Kerosene with Aromatics
SIP	Synthesized Iso-paraffin
HTL AP	HTL Aqueous Product

Table of Contents

CHAPTER 1

Introduction

The airplane picture is generated using Canva's AI, Magic Studio™

1. Introduction

1.1 Problem Statement

The aviation sector produces roughly 2% of all anthropogenic greenhouse gas (GHG) emissions and the aviation industry is only expected to grow in the decades to come. In fact, the size of the industry is estimated to increase four to six-fold by 2050 (Gonzalez-Garay et al., 2022). Therefore, there has been an increasing focus on lowering the carbon impact of the aviation industry (Gonzalez-Garay et al., 2022). One way to measure airline capacity is by looking at Available Seat Kilometre or ASK. If there is a rise in ASK, it can be assumed that there is an increase in demand for air travel (IATA, 2023). Estimates are that the aviation industry will expand to 14 million ASK by 2030 (SkyNRG, 2023a). The growing demand for air travel measured in ASK is shown in figure 1 on the left.

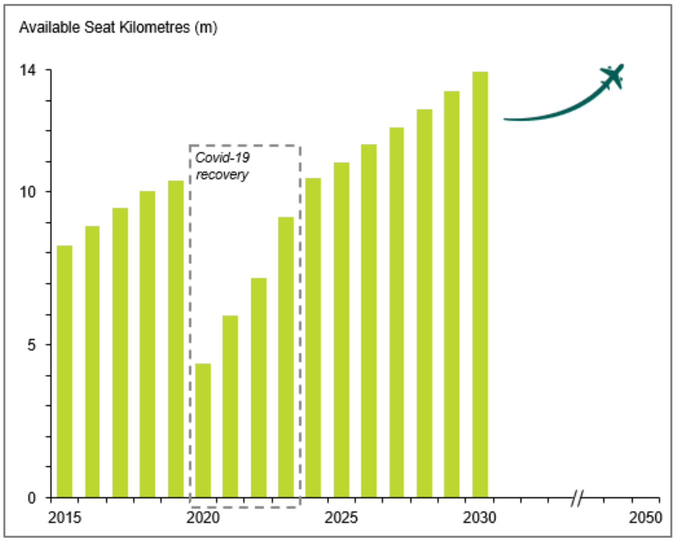

Figure 1: ASK. Source: SkyNRG, input Wall Street Research on Aerospace and Defence Data, IATA 2021, FCH JU & McKinsey Study (2020).

According to Terrenoire et al. (2019), under the most pessimistic scenario, the growth in demand for air travel could increase aviation CO_2 emissions to 2338 $MtCO_2$ per year by 2050 if no concrete mitigation measures are implemented. This increase is expected to contribute around 0.1°C to global temperatures by 2050, significantly reducing the remaining buffer of 0.3°C-0.8°C within the 1.5°C-2°C global warming limits set by climate agreements (Terrenoire et al., 2019).

1.2 Strategies for Reducing GHG Emissions in the Aviation Industry

Given the assumption that flying will remain a mode of transportation, various strategies can be employed to reduce GHG emissions in aviation, including the development of all electric aircrafts, hydrogen electric aircrafts and sustainable aviation fuels (SAF) (Sain et al., 2022).

The primary advantage of electrification technologies is their ability to operate with zero emissions. However, the current battery technology limits their range and passenger capacity, making them more suitable for short-haul flights (Sun, 2023). According to Sun (2023) this limitation is due to the significantly lower energy density of lithium-ion batteries compared to fossil fuels. Additionally, electric aircraft face challenges such as inadequate thrust from electric motors and thermal management issues at high altitudes.

SAF can reduce GHG emissions by 50% to 80% compared to conventional jet fuel, depending on the feedstock and production technology (Shehab et al., 2023). SAFs can be used without any modification to current aircraft engines (Zhang et al., 2016), allowing for immediate application with successful commercial flights demonstrating their viability (Virgin Atlantic, n.d.). They do not require significant changes to existing aviation infrastructure (Zhang et al., 2016). However, the infrastructure needs to be adjusted to accommodate the increased use of SAF (Shebab et al., 2023).

SAF is the only currently viable technology for long-haul flights (Becken et al., 2023), where battery and hydrogen technologies are not yet feasible. Although short-haul flights account for 70% of global air traffic, they are responsible for only 27% of total aviation emissions. In contrast, long-haul flights, which represent only 30% of the global fleet, are responsible for a much higher proportion, 73% of aviation GHG emissions (SkyNRG, n.d.), as shown in the figure below.

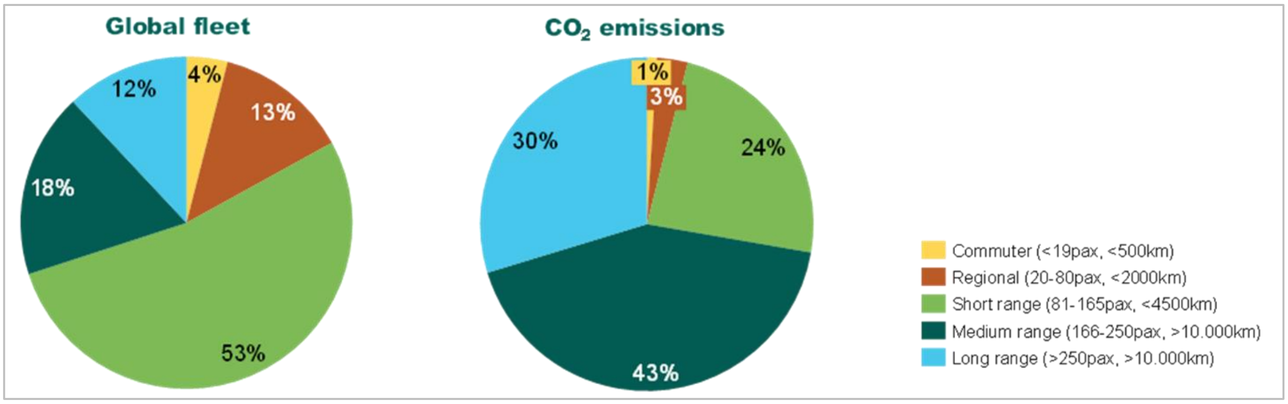

Figure 2: Global fleet distribution & corresponding CO₂ emissions. Source: SkyNRG (2023)

This highlights the impact that the implementation of SAF could have and makes it clear that the transition to these alternative fuels is key to meeting climate targets and reducing CO₂ emissions (Atsonios & Inglezakis, 2023). As a result, developments in the SAF business are currently underway. For example, on 28 November 2023, the commercial airline Virgin Atlantic completed the first transatlantic flight using 100% SAF from London Heathrow to New York JFK (Virgin Atlantic, n.d.).

1.2.1 EU Mandated Demand and Announced SAF Supply

The EU Green Deal outlines the vision and objectives for achieving a climate-neutral EU by 2050. As part of this overarching strategy, the RefuelEU Aviation initiative specifically addresses emission reduction in the aviation sector through targeted measures (European Commission, 2019; Soone & European Parliamentary Research Service, 2023). The European incremental targets for its use of SAF are as follows: at least 2% by 2025, 6% by 2030, 20% by 2035, 34% by 2040, 42% by 2045 and 70% by 2050 (Soone & European Parliamentary Research Service, 2023).

Last year, SkyNRG carried out a study, ‘Sustainable Aviation Fuel Market Outlook May 2023’ in which it outlines the SAF announced production capacity for the European Union (EU) and the United Kingdom (UK) with respect to SAF. It estimated that the commercial production of SAFs will reach 3.3 Mt/year by 2030. However, the expected mandated demand in the EU and the UK is thought to be between 4.2 and 5.4 Mt by 2030, leaving a shortfall of 0.9 to 2.1 Mt. The mismatch between supply and demand clearly indicates that in order to meet the demand for SAFs in 2030, extra capacity as well as imports from outside the EU/UK will have to be found. Apart from this, diversification of SAF pathways is required because there probably is no method of production that will be able to meet demand entirely. This clearly indicates there is a need for a multi-pathway strategy if future SAF requirements are to be met (SkyNRG, 2023).

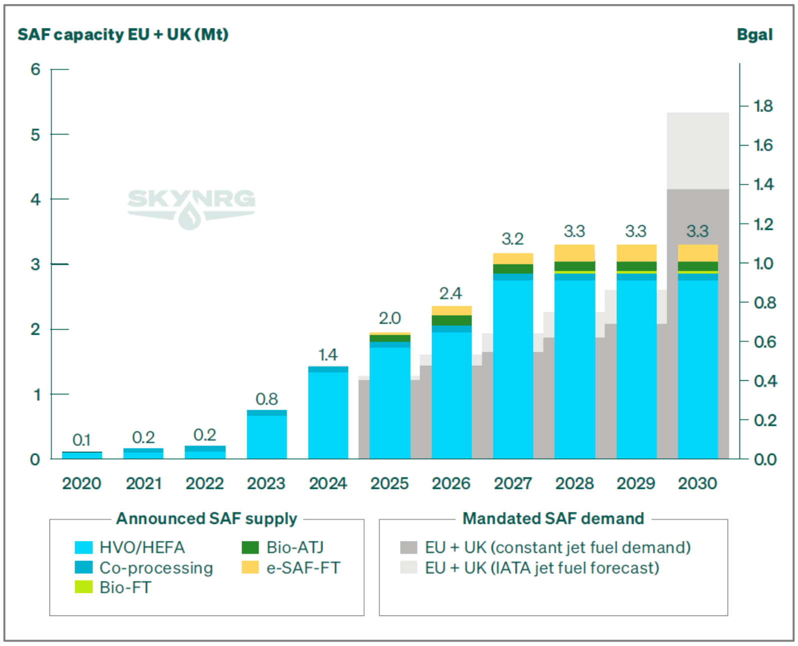

Figure 3: SAF demand and supply. Source: SkyNRG market outlook (2023)

1.2.2 Collaboration SkyNRG

In this study, SkyNRG's request to provide more extensive research on producing SAF via the "pyrolysis to SAF" pathway, a thermochemical liquefaction (TL) technology, was addressed. The Amsterdam-based company SkyNRG concentrates on the development of its specialized SAF production and provides support to other industry stakeholders. SkyNRG believes this TL technology may be one of the future pathways for their capacity development projects (SkyNRG, personal communication, 2023). The TL technology had to be investigated further to determine its usability.

Therefore, this thesis analysed and evaluated the "pyrolysis to SAF" pathway as a potential strategy for increasing the diversification of SAF production, lowering CO_2 emissions, and boosting sustainability in the aviation industry. The "pyrolysis to SAF" pathway is a broad term and consists of different alternative technologies to produce SAF. The different technologies are described in detail in appendix C. The motivation for selecting HTL and FP for in-depth evaluation is also explained here.

The collaboration with SkyNRG provided a valuable industry perspective and a better understanding of the SAF pathways, enriching the academic experience of this study.

1.3 Academic Knowledge Gaps

A systematic literature review was conducted to investigate what research has already been done on the pathway from pyrolysis to SAF. This literature review provides a comprehensive overview of the current (English-language) literature on the pathway.

Scopus was chosen as the search engine for the literature search. Scopus has search features and filters that make it easy to discover relevant findings for this research. Another advantage of using Scopus for research compared to Google Scholar, for example, is the assurance that all publications identified have been reviewed, indicating a higher degree of academic integrity and quality. In order to find information and to locate available research, the following search was carried out.

Using the search query: TITLE-ABS-KEY (("pyrolysis") AND ("SAF" OR "Sustainable Aviation Fuel") AND ("production" OR "conversion" OR "synthesis")), 22 papers were found. However, some were irrelevant as they did not focus on using pyrolysis technologies, to produce SAF, which was beyond the scope of this study. In all, based on its titles and abstracts 12 relevant papers were selected for this thesis. The inclusion/exclusion process guaranteed that the research papers used were directly linked to the focus of this study, namely the production of SAF using pyrolysis technologies. An overview of the analysed papers can be found in Appendix A.

Summarizing current knowledge, the existing literature discusses the potential benefits and challenges of various SAF technologies, including pyrolysis technologies. Tanzil et al. (2021a), Björnsson & Ericsson (2022), de Medeiros et al. (2022), Wang & Wu (2023), and Okolie et al. (2023) analyse the present performance of various SAF-production technologies, including pyrolysis technologies, focusing on their economic impact and their technical complexities. Worth noting here is that the research carried out by Okolie et al. (2023) goes into some detail on hydro-processed esters and fatty acids, the gasification and Fischer-Tropsch Process (GFT, the Alcohol to Jet (ATJ), direct sugar to hydrocarbon (DSHC) as well as fast pyrolysis (FP) SAF production methods. They use a multi-criteria evaluation, considering economic, technical, and environmental criteria. Furthermore, Van Dyk et al. (2019) evaluates different TL technologies (HTL, FP, and CP) based on their yield rates, a lifecycle assessment (LCA) and a techno-economic assessment (TEA). Moreover, different papers discuss different types of pyrolysis technologies, for example, catalytic pyrolysis (CP) and FP (Tanzil et al., 2021a; Björnsson & Ericsson, 2022; de Medeiros et al., 2022; Wang & Wu, 2023; Okolie et al., 2023). In addition to pyrolysis technologies, Björnsson & Ericsson (2022) and Van Dyk et al. (2019) also mention hydrothermal liquefaction (HTL), a technology that is very similar to pyrolysis. Although HTL is not technically a pyrolysis technology, the process has sufficient similarities to be relevant in this thesis. Since pyrolysis and HTL can both be categorized as TL, this broader term was used in this study to encompass both technologies. Following on from this literature review, three knowledge gaps were identified.

1.3.1 Absence of Social Aspects in Evaluation

The first knowledge gap is that while there are comprehensive analyses of the economic, technical, and environmental performance of TL pathways to produce SAF, there is a lack of studies examining the social impacts on local communities and individuals of these production pathways.

However, research in related fields, like the deployment of biofuel technologies, clearly underpins the relevance of social aspects in an evaluation. For example, Mangoyana et al. (2013), focuses on social issues when assessing the performance of biofuel systems.

Another study by Ribeiro (2013) stresses that assessing only the direct benefits of introducing biofuels, such as the potential to reduce GHG emissions, is insufficient. She argues that it is essential to examine the wider social issues and processes that result from such technologies. Furthermore, they stress the importance of an assessment of whether these social changes are desirable or not.

In addition, Van der Horst & Vermeylen (2011), argue that the possibility of biofuels becoming more dominant has drawn more attention to the social impacts of the production and use of biofuels for transport. For example, there have been many concerns about the negative impacts of biofuels, particularly on the rise in food prices or on land dispossession by bioenergy crop developers.

Mattioda et al. (2020) highlights the use of social life cycle analysis as an emerging tool for evaluating biofuel technologies. Using this tool makes it possible to consider social aspects, which form an important part of the decision-making process on sustainable development and energy systems. It also facilitated the evaluation of the impact on the economy and the environment as well as its technological complexities.

All in all, it is generally accepted that social aspects should form an essential part of assessing the viability of sustainable energy systems. Given the fact that a knowledge gap has been identified in the literature with regards to the social impact of TL technologies when producing SAF, this study will focus specifically on this social dimension. A detailed evaluation of these social aspects will provide a deeper understanding of the general applicability of SAF technologies as well as its social implications.

1.3.2 Lack in Stakeholder Involvement

While identifying research opportunities, it became clear that there is as of yet no study that considers the different perspectives of stakeholders when evaluating the performance of SAF applications of TL technologies.

However, research done on the evaluation of sustainable energy systems, clearly underpins the relevance of incorporating stakeholders in an evaluation. For example, Butterfoss et al. (2001) states that it has been proven that stakeholder involvement improves the quality of the evaluation findings. Furthermore, Höfer & Madlener (2020) evaluate different energy transition scenarios comprehensively, involving multiple stakeholders in each evaluation step. They involve these stakeholders in the evaluation of the scenarios to ensure the credibility of the findings.

Moreover, according to Grafakos et al. (2015), the involvement of relevant stakeholders - from energy associations and energy producers to local communities and environmental groups - is necessary for the evaluation of energy technologies and energy planning.

In summary, research in related fields recognises that stakeholder involvement in the evaluation of renewable energy systems is crucial. Given the lack of knowledge in the literature on TL technologies for SAF production and their evaluation involving stakeholders, this study will focus particularly on involving the stakeholder perspective.

1.3.3 Outdated Data HTL and FP for Benchmarking with Existing SAF Technologies

Furthermore, although Van Dyk et al. (2019) provides a detailed analysis of HTL and FP using a TEA and LCA, this study is slightly out of date, especially for a rapidly evolving industry like the SAF industry. The recent advancements in HTL and FP technologies have not been adequately used to compare the TL technologies in detail with SAF-certified pathways. To gain a full overview of the current status of TL technologies in terms of environmental, social, economic and technical aspects, this study compares these technologies with a certified pathway currently used for SAF production, while considering more recent data. The Hydroprocessed Esters and Fatty Acids (HEFA) pathway was chosen for this comparison because it is the most mature SAF production pathway (Goh et al., 2022).

1.4 Research Questions

This study aimed to address the knowledge gaps in the literature identified above and approaches this objective through a main question, which is further divided in four sub-questions. Together, these sub-questions form the structure for the study as a whole. The main research reads as follows:

"How do HTL and FP compare to the HEFA pathway in producing SAF across technical, environmental, economic, and social aspects, while considering the perspectives of multiple stakeholders?"

Taken together, the following sub-questions provide a comprehensive focus on the main question of this thesis:

1. Which stakeholders are involved in the implementation of HTL and FP to produce SAF, and what are their interests and influences?
2. Which criteria and their respective weightings awarded by stakeholders should be considered when evaluating SAF production technologies?
3. How do HTL, FP and HEFA perform according to the criteria analyses and the performance scores assigned by SAF experts?
4. How do HTL and FP compare to the HEFA pathway when the performance scores assigned by experts are combined with the criteria weightings established by stakeholders to calculate a final score?

1.5 Research Objective

The objective of this thesis was to evaluate and compare the performance of two different TL technologies, HTL and FP, by using the HEFA technology as a benchmark. This comparison was undertaken in the context of SAF applications, focusing on technical, economic, environmental, and social aspects with explicit consideration of different stakeholder's perspectives and included developing a multi-perspective framework. Unlike the TL technologies, the HEFA pathway is already commercially used, and such a comparison will highlight in which areas TL technologies stand out and where improvements need to be made in order to be able to implement them at scale. Based on this study, practical insights and recommendations were provided to support stakeholders in the deployment of SAF technologies.

1.6 Geographical Scope and Focus of the Study

A multi-temporal analysis was applied in this thesis, selecting the most appropriate timescale for each individual analysis. For example, the Technology Readiness Level analysis used the most up-to-date data to assess immediate readiness, while the costs and Global Warming Potential analyses considered different scenarios covering both current and future conditions. This approach ensured a comprehensive analysis of each SAF pathway by integrating current performance with expected developments. Moreover, the aim of this study is to explore the potential of TL technologies for its application within the current European SAF production system.

1.7 Thesis Structure

This study consists of 8 chapters, with chapter 2 focusing on the technological background and chapter 3 on the methodology. Chapter 4 discusses the stakeholders that are influenced by the implementation of new SAF technologies. Chapter 5 presents the criteria selected for this study and the weighting allocation method assigned to it. In chapter 6, the technologies are evaluated against the different criteria. Subsequently, chapter 7 assesses the technologies using the performance scores and the criteria weightings, which result in a final score per technology for each stakeholder. Chapter 8 is the conclusion and discussion chapter, which answers the research questions, outlines the relevance of this study, points out the limitations of the study and discusses suggestions for further research.

CHAPTER 2

Technological Background

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2. Technological Background

This chapter provides an overview of the technical background relevant to this thesis, which was based on an extensive literature review using the snowball method to identify key literature on SAF and TL technologies.

2.1 SAF Overview

2.1.1 What is SAF?

The 2017 Aviation and Alternative Fuels Conference distinguished three types of aviation fuel: Conventional Aviation Fuel (CAF), Alternative Aviation Fuel (AAF) and Sustainable Aviation Fuel (SAF). CAF is derived entirely from petroleum. AAF, on the other hand, is derived from sources other than petroleum, which may be non-renewable, such as natural gas, or renewable, such as biomass. SAF, a subset of AAF, refers specifically to renewable fuels and can be produced from sources such as biomass, electricity or hydrogen (Gutiérrez-Antonio, 2017). SAF is a direct 'drop-in' fuel substitute for CAF, with similar properties and characteristics. This enables it to be used without modification to aircraft engines or existing airport fuel supply infrastructure, which keeps costs down (The International Air Transport Association, 2020).

2.1.2 SAF's Role in Carbon Neutrality and Industry Challenges

It is important to note that SAF moderates the rate at which CO_2 is added to the atmosphere, rather than directly reducing the atmospheric CO_2 concentration. Although SAF emits CO_2 when burned, it achieves approximately carbon neutrality through feedstocks such as biomass, because the CO_2 absorbed during the growth of biomass is roughly equivalent to the amount of CO_2 emitted into the atmosphere when the fuel is burnt in a combustion engine. In addition, technologies that use renewable electricity and captured CO_2 to produce SAF offset the carbon emitted with the carbon absorbed from the atmosphere, minimising the net impact of SAF on atmospheric CO_2 levels (IATA, n.d). Additionally, it is important to recognise the altitude at which the emissions occur. Emissions at high altitudes, such as those produced by aviation, have a greater impact on climate change than CO_2 from fuel combustion at ground level (Jungbluth & Meili, 2019).

Despite its potential, SAF faces challenges such as high production costs and limited feedstock availability (Bauen et al., 2020). These factors question the ability of SAF to meet the growing demand of the aviation industry. Tackling these challenges will require significant investment in research and development to innovate and accelerate the market introduction of new SAF technologies (Bauen et al., 2020).

2.1.3 ASTM Certification

The American Society for Testing Materials (ASTM) provides SAF standardisation through ASTM D7566, which governs the technical certification of SAF and establishes the conditions necessary for technologies to produce industry-compliant fuel. ASTM sets for example requirements for criteria such as composition, volatility, fluidity, combustion, corrosion, thermal stability, contaminants, and additives to ensure that the fuel is compatible when mixed. This certification process is rigorous and often takes more than five years due to detailed administrative procedures and required test flights specifications (The International Air Transport Association, 2020). Among the certified SAF pathways, the HEFA pathway using lipid-based feedstocks is the most technologically advanced and currently the only commercially viable pathway, as noted by Goh et al. (2022). Appendix B provides a comprehensive overview of existing SAF pathways and specifies which are ASTM certified.

2.2 Thermochemical Liquefaction Technologies

To gain a better understanding of TL technologies, research was carried out on their operation and the different types that exist. Six types were identified: FP, HTL, hydropyrolysis, co-pyrolysis, slow pyrolysis and catalytic pyrolysis. Due to time constraints, two of these technologies were selected for detailed study. A description of all types and the reasons why some were excluded can be found in Appendix C. Based on data availability and their relevance to SAF production at the time of drafting this thesis, HTL and FP were selected for further in-depth investigation.

FP is a process that converts biomass into bio-oil, gases and char, under oxygen-free conditions. This process involves high heating rates and short hot vapor residence times at high temperatures, typically around 450–650 °C, maximizing the yield of liquid products (Li et al., 2021; Park et al., 2019). Wang & Wu (2023) discuss the use of FP for SAF production from biomass. However, they point out that there are still technical and economic barriers for large-scale implementation.

HTL is a process where the feedstock, also mainly biomass, is heated in presence of water at temperatures between 200 to 550°C and pressures from 5 to 25 MPa (Cao et al., 2017). This high-temperature, high-pressure environment breaks down complex organic molecules, resulting in the production of liquid bio-oil, along with valuable by-products such as gases and solid residues (Van Dyk et al., 2019; Björnsson & Ericsson, 2022).

2.2.1 Process Steps of FP and HTL Pathways to Produce SAF

The figure below shows the process steps for HTL and FP to produce SAF.

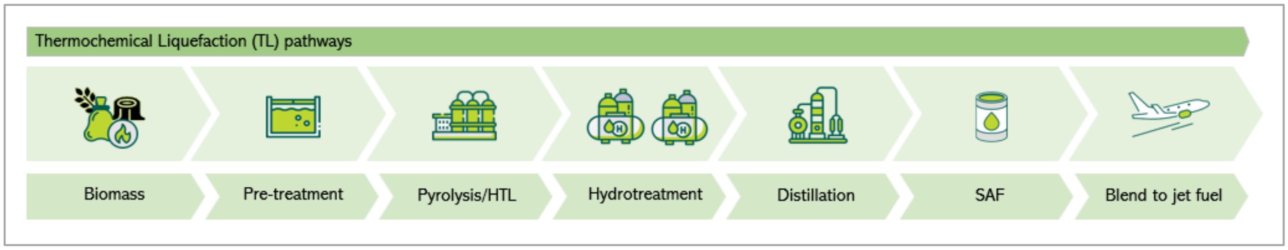

Figure 4: Process Step FP & HTL Pathways

Firstly, when FP and HTL are used for SAF production the feedstock, which is mainly biomass, must be pre-treated before it can undergo TL. This pre-treatment includes preparing the feedstock by drying and sizing (Bridgewater, 2012).

Following pre-treatment, the prepared biomass enters the reactor and undergoes the heating process, FP or HTL, where the bio-oil is produced. The reactor temperature, residence time and heating rate directly influence both the quality and quantity of the bio-oil output. In addition, the composition of the biomass itself plays an important role in the final characteristics of the resulting product (Jenkins et al., 2016).

Next, the bio-oil produced by pyrolysis and HTL requires hydrotreatment to improve its stability for use as SAF by addressing issues such as acidity, charring and high oxygen content. Hydrotreatment involves hydrocracking or hydrodeoxygenation (Burov et al., 2023).

Finally, the hydrotreated bio-oil, which now consists mainly of hydrocarbon compounds, is distilled into the final fuel products. The type of fuel depends on the length of the carbon chains in these hydrocarbons. Aviation kerosene is characterised by carbon chains between C8 and C16, so a distillate with such chain lengths is also classified as SAF (Zhang, 2020a). The resulting SAF can then be blended with CAF, with blending rates strictly regulated to meet ASTM D7566 standards (IEA, 2021).

2.2.2 Chosen Technologies from the Industry

The research into FP and HTL revealed inconsistencies in the literature on the characteristics of the technologies, such as differences in operating temperatures and residence times. Given these inconsistencies, it was decided to focus on a single industry supplier for each technology to enable in-depth investigation.

Following a review of EU technology providers, BTG was selected for the FP and Steeper Energy for the HTL, primarily based on SkyNRG's close partnerships with them, facilitating easy contact. Detailed descriptions of their bio-oil production process and IDEF0 diagrams are provided in appendices D and E.

2.2.3 HEFA

HEFA is used as the benchmark in the MCA and is a technology used to produce SAF from feedstocks consisting of oils or fats. Unlike TL technologies, the structure of these feedstocks for HEFA is similar to that of a hydrocarbon fuel. The HEFA process converts esters and/or fatty acids under high pressure and temperature using hydrogen in the presence of a catalyst. The process removes oxygen from the feedstock while converting fats and oils into (Monteiro et al., 2022).

There are a few steps involved in the HEFA pathway, which are shown in the figure below.

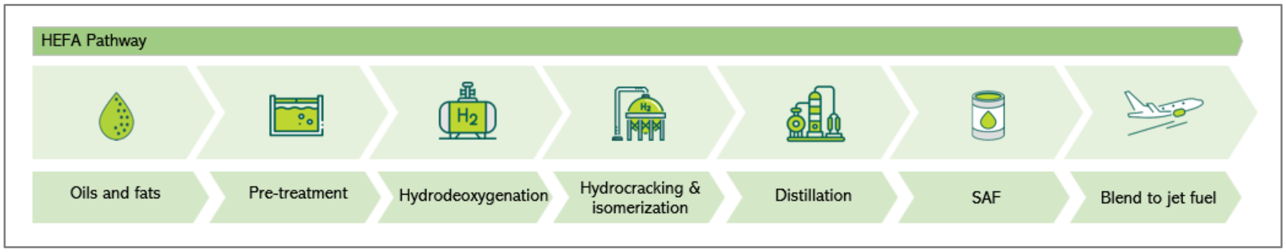

Figure 5: Process Steps HEFA pathway.

Firstly, there is the pre-treatment (Neuling & Kaltschmitt, 2015). During pre-treatment, impurities are removed, and the raw feedstock is transformed into clean feedstock. The feedstock must be pre-treated to prevent damage to the catalysts in the HEFA process. The level of impurities depends on the feedstock selected (De Greyt et al., 2022).

The clean feedstock can enter the HEFA process, which may use hydrodeoxygenation, hydrocracking or hydroisomerization depending on the chemical make-up of the feedstock and the fuel specification required (Monteiro et al., 2022).

Hydrodeoxygenation happens when the clean feedstock, which is made up of triglycerides, reacts with hydrogen to form hydrocarbons chains. The triglycerides, consisting of a glycerol molecule attached to three fatty acids, are split. The double bonds are saturated, and the oxygen is removed. Hydrocracking also involves hydrogen, but here the resulting carbon chains are cut to the required chain length. The hydrogen is also used for hydro isomerisation, where the molecule is branched to give it extra strength and density (Tao et al., 2017).

Next, distillation is used to separate the end-products according to their different boiling points, where the longer the carbon chain, the higher the boiling point. The carbon chains with a length between C6-C18 can be used for SAF. A maximum of 50% of the SAF produced by HEFA can be blended into jet fuel (Starck et al., 2016a). An IDEF0 diagram is presented in appendix F, which schematically outlines these steps.

CHAPTER 3

Methodology

The airplane picture is generated using Canva's AI, Magic Studio™

3. Methodology

The method chosen to assess the performance of the technologies in this study is Multi-Criteria Analysis (MCA). An MCA is a decision-making tool that evaluates alternatives based on both qualitative and quantitative criteria. It integrates the criteria by assigning scores to each criterion and weighting them according to their relative importance, which results in an overall assessment of the alternatives (Dean, 2020).

The choice of using an MCA was driven by its ability to address the identified knowledge gaps, outlined in chapter 1.2. In contrast to other performance analyses, such as a cost-benefit analysis, MCA allows for the inclusion of factors that cannot be easily expressed in monetary terms, such as social impacts (Bhagtani, 2008), which addresses knowledge gap one. In addition, an MCA can incorporate subjective inputs such as expert opinion and stakeholder perspectives (Dodgson et al., 2009), thereby addressing knowledge gap two.

Another advantage of an MCA is that it is a transparent analysis that can support decision-making by clearly showing how alternative SAF production technologies compare.

3.1 Research Flow of the Thesis

There were four phases to the MCA of this study. The first stage identified the stakeholders that influence or are influenced by the implementation of HTL and FP SAF production pathways within the present energy network. To get a clear picture of the stakeholders, online research was conducted.

The second phase, in which the MCA framework was designed, was divided into two sub-phases. Phase 2a, in which the criteria which were relevant for the MCA were identified based on a literature review, followed by phase 2b which built on the results of phase 1 and phase 2a and determined the weightings of the criteria through stakeholder input collected in interviews.

In the third phase, HTL and FP were assessed against HEFA using the criteria from phase 2a. A criterion analysis was carried out for each criterion. Based on the findings from these analyses and their expertise, the SAF experts assigned performance scores for each pathway.

Finally, in phase 4, the performance scores from phase 3 were integrated into the MCA framework established in phase 2. Using this framework, final scores were calculated for HTL, FP, and HEFA across all criteria. These scores were then summed to derive the final MCA score for each pathway for each stakeholder.

The research flow of this thesis is illustrated in the Research Flow Diagram (RFD) presented below.

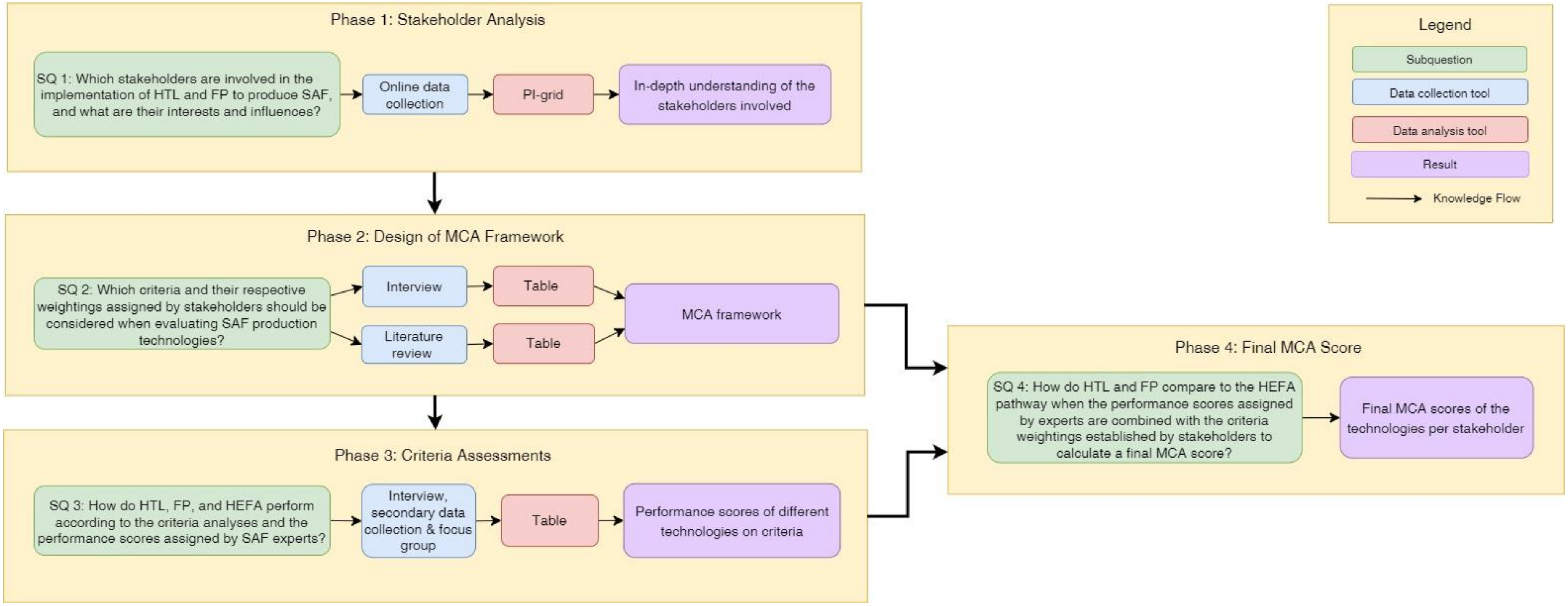

Figure 6: RFD for this thesis.

3.1.1 Phase 1: Stakeholder Analysis

Addressing the perspectives of multiple stakeholders in this MCA made a more holistic approach possible and allows the consideration of the unique interests and needs of the relevant stakeholders. The probability of a decisions outcome being broadly accepted, and the validity of the decisions made are both increased when various stakeholders are involved in the decision-making process (Huang, 2023).

To identify the stakeholders involved, a Power Interest grid (PI grid) was used as a structural stakeholder analysis tool. A PI grid is a framework for organising stakeholders by categorising them according to their level of power and interest in relation to an organisation's goal. This categorisation helps identify which stakeholders are most important to the organisation's success and therefore who to focus on. Stakeholders are grouped into four quadrants: Players (high power, high interest), Subjects (low power, high interest), Context Setters (high power, low interest) and the Crowd (low power, low interest) (Ackermann & Eden, 2011).

The PI Grid was chosen as the stakeholder analysis tool because of its efficiency and clarity, which were considered critical factors given the limited time frame of the study. A PI grid can balance the need for a broad definition of stakeholders with the need for a manageable number of stakeholders (Ackermann & Eden, 2011). Alternatives such as, Social Network Analysis, can often be complex and time-consuming because they require detailed analysis of networking relationships. Another alternative, focus groups, can provide valuable detailed insights. Nonetheless, they require substantial preparation and time to be carried out properly (Reed et al., 2009).

3.1.2 Phase 2: Design of MCA Framework

Phase 2a: Criteria Selection

To identify the relevant criteria for the MCA, an extensive literature search was conducted using Scopus. Scopus was chosen as the search engine for the reasons given previously in section 1.2. The literature review analysed which criteria were used in recent literature that assesses sustainable transport fuel or biofuel production pathways using an MCA. These criteria were also relevant for evaluating SAF, since SAF is a biofuel tailored for airplanes.

To identify the current academic literature on biofuels, an initial selection of 78 papers was collected from the Scopus database using the following search query:

(TITLE-ABS-KEY ("transport fuels" OR "alternative fuels" OR "biofuels") AND TITLE-ABS-KEY ("multi-criteria analysis" OR "mca") AND ALL (criteria OR factors OR attributes OR parameters))

To refine this initial selection of literature, the selection process was guided by clearly defined inclusion and exclusion criteria. The inclusion criteria focused on literature published between 2010 and 2024 that highlighted the latest technologies in biofuel production and MCA applications. In addition, only English language papers were selected to ensure consistent interpretation. Furthermore, the included literature had to specifically evaluate biofuel production technologies through an MCA, providing relevant insights and methodological similarities to the SAF assessment conducted in this thesis. Papers that did not meet these inclusion criteria or used methodologies other than MCA were excluded. This selection process resulted in 31 papers suitable for qualitative analysis and 47 papers that did not meet the criteria and were therefore excluded from this study. This systematic approach is shown in the figure below.

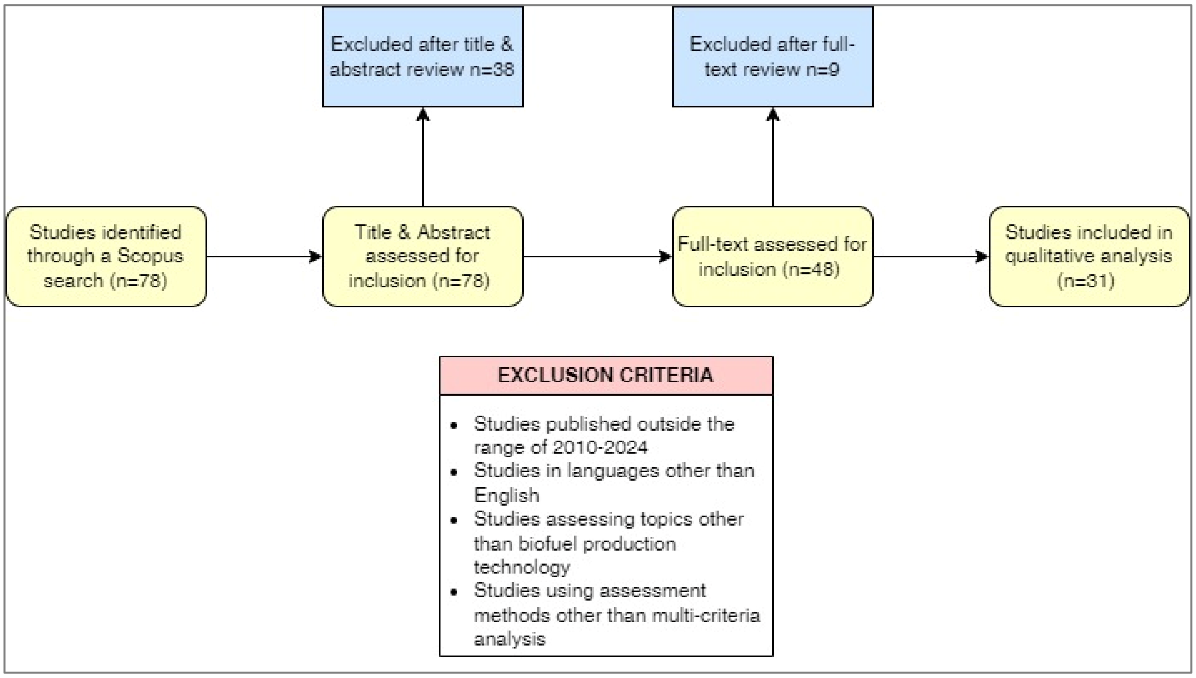

Figure 7: Literature Review Selection Process

To select the criteria for analysis, the 31 papers were reviewed in detail and the criteria used in each were catalogued in a table. Criteria that appeared frequently were considered the most relevant for the MCA of this study. In addition, the feasibility of analysing each criterion was reviewed to ensure that the analysis could be completed within the limited timeframe of this study. A comprehensive and relevant set of criteria has been selected to assess FP, HTL, HEFA and SAF production pathways in general, based on recent and relevant research in the field.

Phase 2b: Criteria Weightings

After the selection of the MCA criteria, the allocation of the weightings to these criteria was carried out by consulting the stakeholders and applying the Best Worst Method (BWM). Adherence to the TU delft Human Research Ethics Committee (HREC) guidelines was ensured, with each interviewee signing an informed consent form. An example of this form is included in appendix W.

Once the MCA criteria were selected, stakeholder consultations and the best-worst method (BWM) were used to assign the weightings. The BWM is an MCA method developed by Rezaei (2015) to solve multi-criteria decision-making (MCDM) problems, originally focusing on the preferences of a single decision-maker (Mohammadi & Rezaei, 2020). However, it was adapted within this study to include the perspectives of different stakeholders, given that Matsuura & Shiroyama (2018) highlight the importance of integrating the perspectives of different stakeholders for the effective development of sustainable biofuel strategies.

In the MCDM problem at the heart of this thesis, HTL and FP are evaluated and compared with the HEFA pathway based on the chosen set of criteria. The following steps, adopted from Rezaei (2015), were used to obtain the weightings that can be attributed to the selected set of criteria:

1. Stakeholders first identify the best (e.g. most relevant, most important) and the worst (e.g. least relevant, least important) criteria.
2. Stakeholders then express their preference for the most important (best) criterion compared to the other criteria on a scale from 1-9, with 1 indicating equal importance, and 9 a much higher importance. This provides the following Best-to-Others (BO) vector,

$$A_B = (a_{B1}, a_{B2}, \dots, a_{Bn})$$

   where, a_{Bj}, represents the preference of the most important criterion B over criterion j.

3. Stakeholders then determine the importance of each criterion relative to the least important (worst) criterion by assigning a rating between 1-9, with 1 indicating equal importance, and 9 a much higher importance. This provides the following Others-to-Worst (OW) vector,

   $$A_W = (a_{1W}, a_{2W}, \dots, a_{nW})$$

   where, a_{jW}, represents the preference of criterion j over the least important criterion W.
4. The optimal weightings (w_1^*, w_2^*, …, w_n^*) for the criteria can now be calculated by formulating a maximin problem. The objective of a maximin problem is to minimise the maximum outcome from a set of choices. The following optimization model was formulated and solved to find the optimal weightings:

   $$\min \max j \left\{ \left| \frac{w_B}{w_j} - a_{Bj} \right|, \left| \frac{w_j}{w_w} - a_{jW} \right| \right\}$$

   s.t.

   $$\sum_j w_j = 1$$

   $$w_j \geq 0, \text{for all j}$$

Rezaei's (2016) BWM linear solver, a pre-programmed tool within a spreadsheet interface, was used to solve the MCDM problem and determine the criteria weightings for each stakeholder. It normalised the 1-9 scores provided by the stakeholders during the interviews to a scale of 0-1.

The BWM was chosen for this MCA because it efficiently determines the weightings of the criteria, requiring respondents to rate only the most and least important criteria relative to others. In contrast, an alternative method, the Analytical Hierarchy Process involves comparisons between each criterion, which may lead to more inconsistencies in responses (Daghouri et al., 2018). The BWM involves fewer comparisons and more consistent calculations of weightings (Rezaei, 2015), making it preferable for this study. In addition, the smaller number of comparisons required by BWM has another advantage for this study: it makes data collection more efficient and less time-consuming for respondents (Aboutorab et al., 2018). As time is a limiting factor and it is desirable to include as many stakeholder perspectives as possible, efficient methods are preferable. The Simple Multi-Attribute Rating Technique (SMART) is another method for determining weightings in an MCA, which requires respondents to assign weightings directly to criteria without comparison (Daghouri et al., 2018). This may introduce more subjective bias as it relies solely on individual judgement. In contrast, BWM's structured comparative scoring system helps to reduce the subjective bias. Lastly, the BWM provides a consistent methodology that is easier for other researchers to replicate.

3.1.3 Phase 3: Criteria Assessments

With the criteria and their weightings established, the next step in the MCA was to conduct the criteria assessment for the SAF pathways. This assessment consisted of two parts: 1) criteria analyses and 2) performance scoring.

The criteria analyses generated research findings for all technologies against the selected criteria. Each criterion analysis has its own specific approach, which is explained in detail in chapter 6. The technical data used was collected through structured interviews with experts from BTG and Steeper on their HTL and FP technologies. Again, the HREC guidelines were adhered to, and each interviewee signed a consent form. In addition, secondary data from scientific articles, public sector reports, EU directives, company reports, etc. were collected to complement the interviews. The development of a process model for HTL and FP was necessary due to the lack of data on the required utilities of the BTG and Steeper technologies needed for the criteria analyses. This Excel model provided a simplified modelling of the steps in the HTL and FP processes and derived mass and energy flows from which the required utilities were determined. Detailed explanations are given in appendix T. For the HEFA pathway, validated data from previous studies were used, eliminating the need for a process model.

In the second part of the criteria assessment, a quantitative method was used to systematically assign performance scores to the SAF pathways. Experts from the SAF industry, specifically two experts from SkyNRG, one specialised in management and commercial strategies and the other in technical aspects of SAF, were invited to a focus group. They collaboratively assigned performance scores on a Likert Scale from 1 to 5 based on their knowledge and the research findings of the criteria analyses. The Likert scale is a widely used rating scale that helps measure people's opinions or perceptions (Likert, 1932). On this scale 1 represents the worst performance and 5 the best performance. The Likert Scale allowed the experts to apply their knowledge and insights in a simple and intuitive way. Although subjective, this method converts research findings into numeric ratings, ensuring more nuanced assessments of the technologies through expert knowledge. Consulting experts also addressed the study's limited time and resources, providing detailed information without extensive fieldwork or large surveys.

In this study, the BWM was not used to assign performance scores for several reasons. Firstly, the BWM requires the same respondents to set both the weightings and the performance scores to ensure the validity of the data. However, it was considered more effective to have only SAF experts do the performance scoring of the SAF pathways, as some stakeholders may not have the technical knowledge required for accurate scoring. Experts have the depth of understanding required to assess the complex technologies involved (Kalpoe, 2020). Secondly, although BWM effectively determines weightings through pairwise comparisons, it involves complex calculations and normalisation to establish performance scores. This complexity could hinder the directness and intuitiveness required for decision making when evaluating alternatives (Wan et al., 2021). Moreover, the normalization process in BWM can misrepresent the performance of the SAF technologies. For instance, an efficiency of 60% compared to 50% may appear less significant after normalization, which is critical for renewable energy technologies.

3.1.4 Phase 4: Final MCA Scores

The final step in the MCA was to integrate the performance scores of the SAF pathways and criteria, along with their stakeholder-determined criteria weightings. In this study, the Weighted Sum Method (WSM) was used to calculate the MCA final scores. WSM is a simple multi-criteria decision-making approach where the final score of an alternative is the weighted sum of its performance scores (San Cristóbal Mateo & Mateo, 2012). WSM was chosen for its simplicity in efficiently integrating and comparing data, avoiding the complexity of BWM for this part of the study. The WSM calculated the final MCA score of SAF pathway *i* for stakeholder *k* by multiplying the weightings of the criteria, as determined by stakeholder *k,* by the performance scores of pathway *i* on those criteria. These results were then added together for each criterion to give the final MCA score. This can be expressed in the following formula:

$$FS_{i,k} = \sum_{j=1}^{n} a_{ij} \times w_{jk}$$

- w_{jk} represents the weight for criterion j determined by stakeholder k via the BWM
- a_{ij} represents the expert assessed performance score of SAF pathway i against criterion j
- $FS_{i,k}$ represents the final MCA score of SAF pathway i according to stakeholder k and is calculated by sum of the product of w_{jk} and a_{ij} for all the criteria.

For each stakeholder, a final MCA score for each technology was calculated and presented using this formula. The results showed how stakeholder preferences and perspectives influenced the evaluation of the performance of different SAF pathways. In addition, the results showed how the TL technologies compared with

HEFA in terms of environmental, technical, economic, and social criteria according to the stakeholders and thus answered the main question of this study.

3.1.5 Aggregation of MCA Components to Final Scores

The figure below illustrates how the different components of the MCA methodology for this study relate to each other and how they eventually come together to obtain a final MCA score for each SAF pathway per stakeholder. The method/tool/approach is shown at the top, the result generated by that method/tool/approach is shown in the middle and the person involved is shown at the bottom of the block.

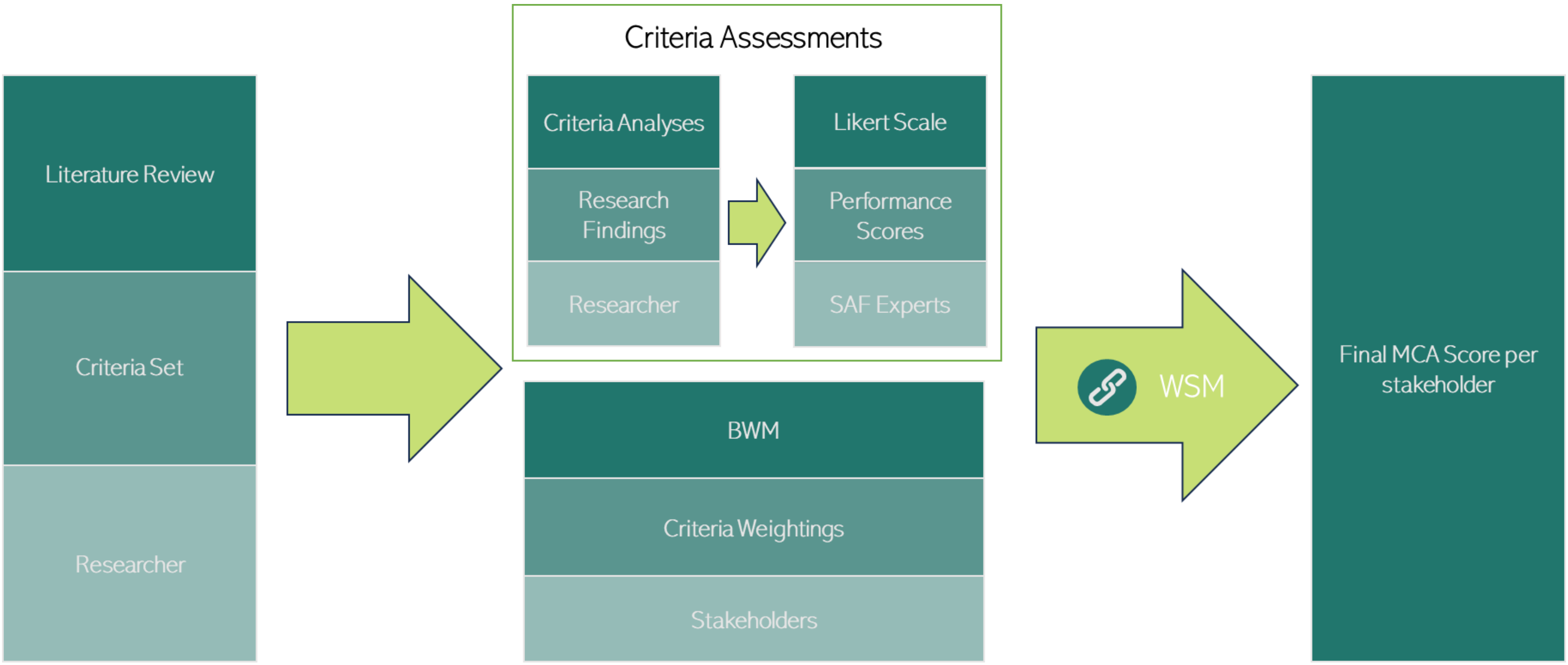

Figure 8: Aggregation of MCA Components

CHAPTER 4

Stakeholder Analysis

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4. Stakeholder’s Analysis

This chapter examined the stakeholders that influence and are influenced by the implementation of the investigated SAF technologies and selected the stakeholders to be considered for this study.

4.1 Power Interest Grid

In the PI-grid below, the stakeholders involved in the implementation of HTL and FP are grouped into the four quadrants as in Ackermann & Eden (2011): Players (high power, high interest), Subjects (low power, high interest), Context Setters (high power, low interest) and the Crowd (low power, low interest).

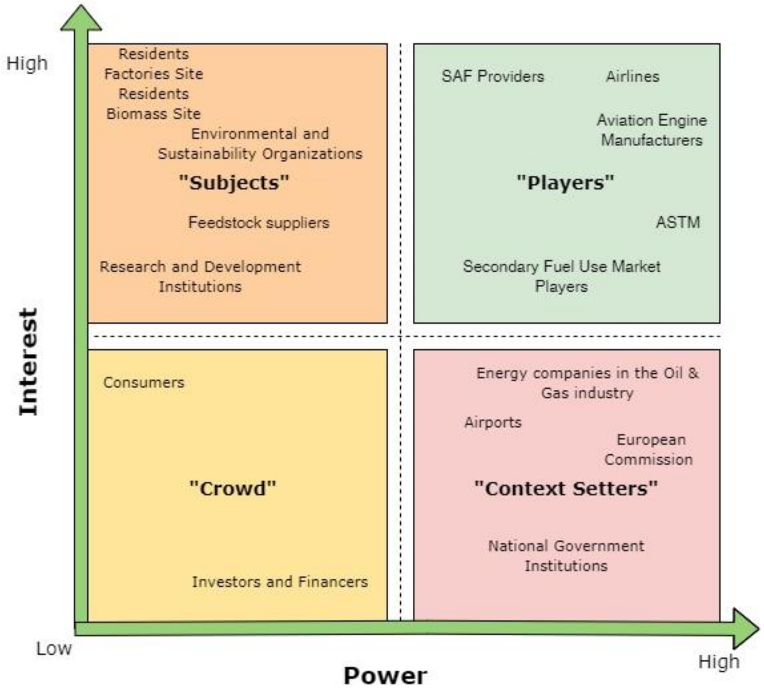

Figure 9: PI-grid

The “Subjects” stakeholders are:

- Environmental and sustainability organizations: the implementation is of great interest because they are a stakeholder that would advocate for the use of SAF over CAF because of SAF’s environmental benefits and the contribution to a cleaner aviation industry. However, these organisations do not have much power because they are not responsible for developing the technology or deciding on the laws that govern its implementation.
- Residents near factory sites: they have a high interest since it will directly affect their quality-of-life, including noise levels, air quality, and possibly property values. Additionally, these stakeholders typically lack power because they usually have no direct influence on how these manufacturing facilities operate or what regulations are made regarding their operations.
- Residents near feedstock sourcing sites: the sourcing of the feedstock can similarly impact the quality of these stakeholders. They also have little power in the decision-making processes because they usually do not have direct control over operations or regulatory decisions.
- Research and development institutions: they have great interest because these institutions focus on the development and application of new technologies and are therefore directly involved in the project. However, their power is low because they often do not manage the financial resources, have no authority over the financial resources, nor are able to enforce strategic decisions.

- Feedstock suppliers: they have a high interest because the feedstocks that these technologies often use are biomass that are currently little used elsewhere and are often even burned away without any benefit. By supplying the feedstock to the SAF market, these materials can now be put to good use (BTG, personal communication, 2024). The power of these stakeholders is currently relatively limited because the feedstock is not in short supply. Furthermore, plants focused on TL technologies are strategically located near sites with waste biomass surpluses, such as sawmills with waste sawdust, allowing a more efficient use of these previously unused feedstocks (BTG, personal communication, 2024). However, demand is expected to increase and if this leads to a shortage of biomass in the future, the power of these suppliers could increase significantly as the availability of feedstock has a direct impact on both production capacity and SAF costs.

The "Players" stakeholders are:

- ASTM: this stakeholder has a strong interest in implementation, as it is in line with its objective to develop new standards that promote technology and environmental targets. They are very powerful because they have the power to draft and approve standards that set performance, safety and quality standards for new fuels. Without ASTM approval, a SAF technology cannot gain wide acceptance, as compliance with ASTM standards is often a prerequisite for regulatory approval, market access and customer acceptance.
- SAF providers: companies like SkyNRG have a high interest because their goal is to make the aviation industry more sustainable and are therefore heavily involved in the development and innovation of SAF technologies. At the same time, they have the power to control the availability of SAF and decide which production technologies to invest in.
- Airlines: they have a high interest because using SAF can be a strategy to reduce their carbon footprint. The need to reduce their carbon footprint is driven by the international climate goals. Moreover, the use of SAF can improve their image in terms of sustainability in the eye of consumers, which is becoming more and more important. Airlines are the main users of aviation fuel and therefore have significant power over the demand and acceptance of SAF. If airlines support innovative technologies that produce SAF, this can attract investment in the market and encourage further development of these technologies.
- Aviation engine manufacturers: they have a high interest because the demand for more environmental-friendly flight options will increase and SAF can help reduce CO_2 emissions. At the same time, they have high power because it is essential for the successful implementation of SAF technologies that the fuel produced is compatible with their engines. When they support a particular SAF technology it has the potential to significantly speed up adoption across the industry.
- Secondary fuel use market players: this group, consisting of various entities within the market that use bio-oil produced by FP and HTL, have great interest in this topic. They use bio-oil as an alternative fuel source for things like industrial processes and transportation, just as the aviation industry does. Their interest is therefore in the environmental benefits of biofuel in comparison to fossil fuels. With their buying power in the biofuel market, they influence both the production dynamics and price structures of bio-oil produced by TL technologies.

The "Crowd" stakeholders are:

- Investors and financers: they have relatively low interest because their investment focus tends to be broader. Namely, the overall development of the SAF industry rather than the technical details or preference for specific technologies, like HTL and FP. Their objective may simply be to invest in the SAF market because it is profitable, and it is not important to them which technological approach ultimately becomes dominant. They also have low power because they do not really have the knowledge to judge whether a new technology is technically feasible. This means that they have little direct influence on which technologies are adopted and implemented by industry. Their role is to support through funding rather than to be involved in technical decision-making.

- Consumers: they have low power in the implementation because the average consumer do not have the technical expertise or knowledge to assess the viability or efficiency of specific SAF producing technology. Moreover, they have low interest because their decisions are often based more on general sustainability goals or pricing rather than an in-depth understanding of the technology.

The “Context Setters” stakeholders are:

- Energy companies in oil and gas industry: they have high power because they often have a lot of money and therefore play an important role in energy markets. They are also often able to influence policies and regulations. The decisions they make can therefore have a big impact on how quickly we move to more sustainable fuels such as SAF. They have a low interest because while these companies are increasingly interested in transitioning to more sustainable energy sources, their primary business models are often still based on fossil fuel production.
- Airports: they have high power due to their central role in the aviation industry. However, their interest is often low due to higher costs. Without external pressure or clear economic benefits, they are unlikely to be very interested in the implementation of SAF technologies.
- European Commission: they have low interest because their primary focus is on achieving environmental goals and driving the energy transition. They tend to leave the choice of specific technologies to the market and technical experts in the field. They nevertheless have a lot of power because their policies and regulations, such as subsidies, can stimulate the implementation of SAF technologies.
- National government institutions: the same reasoning as European Commission applies to national governments.

4.2 Selection of Stakeholders for this Study

Given the time constraints of this study, it was not feasible to include all stakeholders’ perspectives listed in chapter 4.1. Therefore, a selection has been made of the most relevant stakeholder groups for this study. Two selection criteria were used to determine the stakeholder groups to be considered for this study: 1) the level of influence a stakeholder has on the success of the implementation, and 2) whether they are easy to reach for an interview given the time constraints.

Ackermann & Eden (2011) emphasise the importance of involving “players” in the decision-making process for the long-term viability of projects. This quadrant of stakeholders, with both high power and high interest, was therefore considered to be central to the success of the implementation. Based on this, three stakeholder groups of this quadrant have been selected for inclusion in this study. The stakeholder groups selected are SAF providers, airlines, and the ASTM.

Nonetheless, for innovative energy solutions to be successfully implemented and widely accepted, it is imperative, according to Guðlaugsson et al. 2020, to fully understand the broad range of stakeholders involved in the decision-making process. This reasoning led to the decision to also include one stakeholder group from each of the other quadrants. In doing so, this study has attempted to provide the most complete representation of the relevant stakeholder groups identified in 4.1, within the timeframe constraints. For the "Subjects" the environmental and sustainability organisations were selected. For the “Crowd”, consumers and for the “Context Setters”, the energy companies in the oil and gas industry were selected.

CHAPTER 5

Design of MCA Framework

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5. Design of MCA Framework

This chapter presents the set of criteria and their associated weightings, which serve as the building blocks of the MCA framework, shown in appendix J, for this study.

5.1 Criteria Selection

In this section, the criteria selected based on the literature review are presented for each of the MCA dimensions. A table listing the analysed papers and the criteria they used in their MCA is included in appendix G.

5.1.1 Environmental Criteria

Given the wide use of **Global Warming Potential (GWP)** in various studies, including those by Perimenis et al. (2011), Torres et al. (2013), Saccheli (2016), Braz & Mariano (2018) and Mendecka et al. (2020), it was considered important and therefore included in this study. GWP provides an indication of a fuel's impact on climate change and helps to compare the relative contribution to global warming of different SAF production methods (Mendecka et al., 2020). The MCA conducted by Zorpas et al. (2016) assesses the **use of by-products** to identify the optimal alternative fuel. This criterion highlights the potential of a production process to minimise waste and improve efficiency, which is critical for overall environmental sustainability. Given the substantial amount of char and gas produced as by-products of TL technologies, this environmental criterion is considered essential for the comparison with HEFA.

Water footprint, impact on biodiversity, soil quality, land-use change and water consumption, although all relevant criteria, were excluded from this analysis. Although important in a broader ecological context, these criteria were considered less directly relevant to the specific SAF production pathways investigated in this study, and their assessment required complexities beyond the scope of this study.

5.1.2 Economic Criteria

On the economic side, the MCA focussed on **Capital Expenditure (CAPEX)**, **Operational Expenditure (OPEX)** and **feedstock price**. CAPEX are costs incurred prior to the development of the technology, whereas OPEX represent the cost made while the technology is in operation (Benali et al., 2018). Furthermore, the feedstock price is a significant cost driver of the overall cost of SAF production (de Souza et al., 2018). These criteria were preferred over others, such as employment effects or economic multipliers, because they directly affect the calculation of the production costs of SAF (Perimenis et al., 2011). In addition, criteria related to return estimates, like Net Present Value, Internal Rate of Return and Return on Capital Employed, were excluded due to their greater complexity and dependence on external factors, which introduces uncertainty into the economic dimension of the MCA.

5.1.3 Technical Criteria

The technical criteria chosen in this study are **Technological Readiness Level (TRL)** and energy and carbon conversion **efficiency**. The TRL is considered an important criterion to include in the framework for measuring the maturity of SAF technologies and their potential for deployment (Kirsnavos et al., 2023) (Cabrera & Sousa, 2022). Efficiency is considered a crucial performance criterion as it evaluates how well a technology converts feedstock into fuel (Perimenis, 2011). For this study, several technical criteria were not selected, including fuel features, engine compatibility, international technology availability and specific feedstock distributions because they increase complexity while not significantly improving the MCA for this study.

5.1.4 Social Criteria

Tavakoli & Barkdoll (2020) conducted a comprehensive study on the social impacts of a biofuel production system on stakeholders and highlighted the importance of considering the entire 'cradle to grave' life cycle, including feedstock cultivation, processing, fuel production, transportation, and fuel disposal in a social impact analysis.

Therefore, when selecting criteria for this study, the entire HTL, FP and HEFA SAF production pathways and their associated social impacts were considered. Most of the social criteria identified through the literature review were found not to differ significantly between the different pathways and were therefore excluded from this comparative MCA. For example, job creation and the visual impact of SAF production facilities are generally consistent across SAF technologies.

Nevertheless, the level of **safety** in terms of potential risks varies between the pathways studied due to the different process conditions, as discussed in chapter 2, and is therefore selected for the MCA. Furthermore, as noted by Moshiul et al. (2023) safety is one of the most important criteria to consider in a decision-making process when assessing the commercial viability of alternative fuels. Tavakoli & Barkdoll (2020), Mendecka et al. (2020) and Zorpas et al. (2016) also include safety as a key criterion in their MCA. Chapter 6.3.1 explains in detail what is included in this criterion assessment.

Another primary difference between the SAF production pathways is the type of feedstock that is used. Therefore, the second social criterion in this study focuses on the **social impacts related to feedstock use** and examines how the use of a certain feedstock can affect human well-being and social dynamics when used for SAF production. The inclusion of this criterion in the MCA framework was considered important, as it can influence the public acceptance of a SAF production pathway. For example, the food versus fuel debate highlights a case where the use of a feedstock affects public acceptance (Cabrera & Sousa, 2022) (Tomei & Helliwell, 2016). Chapter 6.3.2 explains in detail what is included in this criterion assessment.

The selected criteria, organized by dimension and their respective units of measurement, are presented in the table.

Table 1: MCA criteria.

Dimension	Criteria	Unit
Economic	CAPEX	Euro per year per ton of SAF
	OPEX	Euro per ton SAF
	Feedstock price	Euro per ton SAF
Environmental	Global Warming Potential	Grams of CO_2 equivalents per MJ product over
	Use of by-products	Qualitative
Technical	Technological Readiness Level (TRL)	Scale from 1 to 9
	Efficiency	%
Social	Social impact related to feedstocks use	Qualitative
	Safety	Qualitative

5.2 Criteria Weighting

This section presents the weightings of the criteria that resulted from the stakeholder interviews.

5.2.1 Interview Design

Through both SkyNRG's existing contacts and personal outreach, structured interviews were organised with members of each identified stakeholder group. During each interview, it was emphasised that there was no specific time frame for this study. Interviewees were asked to indicate the respective relevance of the selected criteria when assessing the performance of SAF technologies. All criteria were defined and explained prior to the interviews, trying to maximise the consistency of the responses from all stakeholders. During the interview, participants were asked to complete the Best to Other (BO) and Other to Worst (OW) vectors. The resulting data is collected and are included in appendix S. At the end of each interview, stakeholders were asked if there were any additional criteria they considered important when evaluating new SAF technologies for implementation. Due to the time constraints of the current study, suggestions for these additional criteria were included but not analysed or included in the MCA. However, they may be valuable for future studies and are therefore documented and included in appendix H for future research.

5.2.2 Stakeholders Interviewed

The following people were interviewed for the stakeholder groups selected in chapter 4.2:

- **Airline:** an employee of the merger and acquisition team of the Koninklijke Luchtvaart Maatschappij (KLM), was interviewed. KLM is the national airline of the Netherlands and was established in 1919 (KLM Royal Dutch Airlines, n.d.).
- **Environmental & sustainability organisation**: an employee of Transport and Environment (T&E) was interviewed who is an aviation policy officer. As a European non-governmental organisation, T&E advocates sustainable transport policies. Their focus is on reducing the environmental impact of transport to mitigate climate change and improve air quality (Transport & Environment, n.d.).
- **Consumer**: a person who travels for work on a monthly basis was interviewed.
- **SAF provider**: an employee of the SkyNRG commercial team.
- **American Society for Testing and Materials (ASTM):** unfortunately, it was not possible to make direct contact with a representative of ASTM itself. Instead, an individual at SkyNRG was interviewed who works closely with ASTM on a weekly basis and therefore has a good understanding of this perspective.
- **Energy company in the oil & gas industry:** an individual from Shell's Renewables & Energy Solutions team. The interview was conducted on a personal basis, independent of Shell's representation.

5.2.3 Outcomes Criteria Weightings per Stakeholder

The 'Stakeholder Criteria Weighting' bar chart below shows the results, highlighting the diversity of priorities and common themes among aviation industry stakeholders. It also shows that there is no correlation between the strength of the stakeholder opinions and their position on the PI grid. In appendix J, more detailed figures can be found.

5.2.3.1 Similarities

The bar chart shows that GWP was considered an important criterion by all the stakeholders interviewed. This may indicate a general concern about environmental impact within the aviation industry. In addition, safety was seen as an important but not dominant factor by all stakeholders. This reflects the general industry standard, which assumes that essential safety standards are met. TRL is given a lower weighting by most stakeholders, except for the ASTM. This may indicate that these stakeholders prefer to leave room for the development and integration of future technologies. Furthermore, the results show that all stakeholders consider sheer efficiency to be less relevant and that social, economic, and environmental aspects are relatively more important.

5.2.3.2 Differences

One difference between the stakeholders was that the SAF provider gave considerable priority to the feedstock price, which seemed to reflect a strategic decision to control production costs. In contrast, the ASTM and the environmental & sustainability organisation seemed to consider this criterion less important, possibly indicating a preference for long-term sustainability goals and operational performance. The energy company in the oil & gas industry and the airline shared similarities in their approach to OPEX and CAPEX, which may have indicated a shared focus on the economic drivers of SAF production. The ASTM is notable for its emphasis on TRL, which underlined their focus on current, market-ready technologies. The consumer stressed the importance of the criteria use of by-products, which may have indicated the priority on the maximisation of the value of the SAF production pathways. In contrast, the other stakeholders did not appear to assign as much importance to this criterion. Finally, the weighting given to social impacts related to feedstock use showed the most variation, with the environmental & sustainability organisation, SAF provider and the energy company in the oil & gas industry ranking this criterion as relatively very important, possibly reflecting the commitment to becoming more socially responsible or reflecting a desire to create or maintain a positive public image.

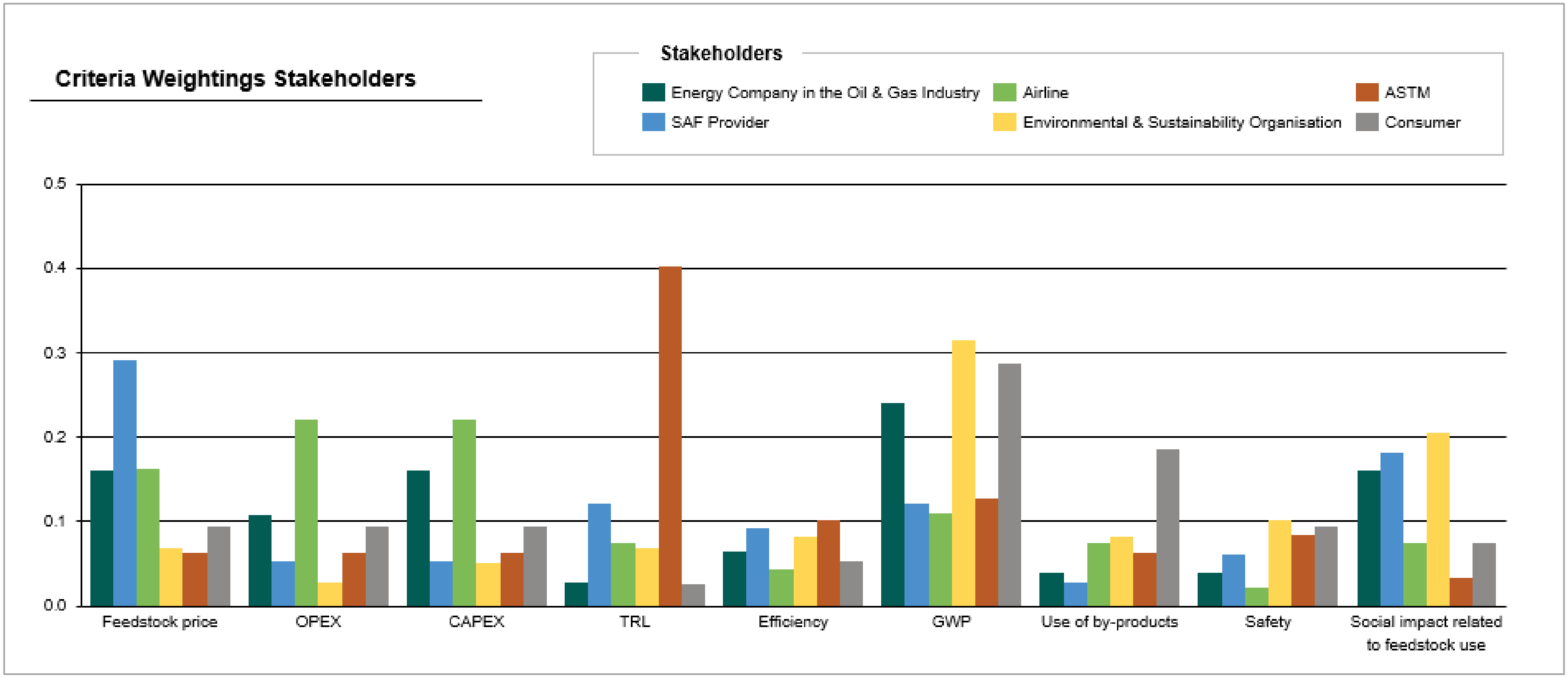

Figure 10: Criteria weightings across stakeholders.

5.2.4 Input-based Consistency Ratios

When determining the criteria weightings using the BWM, it is important to check if the stakeholder responses are consistent, as the weightings derived from these responses form the basis of the MCA. If the input is not reliable, this can lead to misrepresentation and a sub-optimal result.

In this study, the methodological approach of Liang et al. (2020) for using the input-based consistency ratio (CR^I) to check the consistency of the interviewees' responses when using the BWM has been adopted. According to this model there is a maximum level of consistency in the stakeholders' responses. Liang et al. (2020) establish specific CR^I thresholds, shown in appendix I, to measure if inconsistency between ratings stays within acceptable limits. The same thresholds were applied throughout the stakeholders' interviews so that only consistent and reliable data was used in this study.

This study chose the (CR^I) over the traditional output-based consistency ratio (CR^O) because when the CR^O is used, the consistency of the stakeholder response can only be determined after the entire optimization process of the BWM. On the other hand, CR^I enables the consistency of a stakeholder's answers to be determined during the interview, when giving input of the preferred criteria (Liang et al., 2020). This is beneficial for this study because by using the CR^I, any inconsistencies can be found and corrected immediately in the initial interview, and this reduces the likelihood that a follow-up interview is required. This increases the efficiency of the research approach of this thesis and saves time as it can be challenging to schedule a second interview to address the potential inconsistencies as stakeholders generally have limited availability.

The CR^I can be calculated using the following formula:

$$CR^I = \max_j CR_j^I$$

Where,

$$CR_j^I = \begin{cases} \dfrac{|a_{Bj} \times a_{jW} \times a_{BW}|}{a_{BW} \times a_{BW} - a_{BW}} & a_{BW} > 1 \\ 0 & a_{BW} = 1 \end{cases}$$

- a_{Bj} , represents the preference of the most important criterion B over criterion j.
- a_{jW} , represents the preference of criterion j over the least important criterion W.
- a_{BW}, represents the preference of the best criterion over the worst criterion.

During the interviews, the input-based consistency ratio (CR^I) was kept below the defined threshold in order to ensure that stakeholders maintained an acceptable level of consistency when conducting pair comparisons.

The table shows that for each stakeholder interview the CR^I was below the set threshold. Thus, confirming that the calculated weightings are reliable and accurate and can therefore be used in the MCA framework.

Table 2: Input-based consistency ratios.

Stakeholder Interview	CR^I	Threshold
Consumer	0.3036	0.3657
Energy company in the oil & gas industry	0.1429	0.3657
SAF provider	0.1429	0.3657
Airline	0.2000	0.2960
Environmental & sustainability organization	0.1429	0.3657
ASTM	0.0000	0.3662

CHAPTER 6

Criteria Assessments

The airplane picture is generated using Canva's AI, Magic Studio™

6. Criteria Assessments

A summary of all the performance scores assigned by the experts can be found in the performance matrix in appendix M.

6.1 Yields Technologies

To conduct the criteria analyses detailed information on the yields and process utilities of the SAF technologies were required. The yields for HTL and FP were obtained through interviews with experts from BTG and Steeper, while the yields for HEFA were adopted from Tao et al. (2017) and are detailed in the table below.

Table 3: Yields Technologies (rounded numbers).

	HEFA			FP			HTL		
	Feedstock			Feedstock			Feedstock		
Pre-treatment	0.85			[redacted]			1		
	Pre-treated feedstock			Pre-treated feedstock			Pre-treated feedstock		
Process	1			[redacted]			0.45		
	Bio-crude			Bio-crude			Bio-crude		
Distillation	0.05	0.65	0.25	[redacted]	[redacted]	[redacted]	0.60	0.30	0.10
	Diesel	SAF	Naphtha	Diesel	SAF	Naphtha	Diesel	SAF	Naphtha

The total yield for SAF for each technology can be calculated according to the following formula:

$$SAF_{yield,i} = \#\,Feedstock \times Ratio_{pre-treatment} \times Ratio_{process} \times Ratio_{distillation,SAF}$$

- $SAF_{yield,i}$ represents the SAF yield of technology i per amount of feedstock
- $\#\,Feedstock$ represents the amount of feedstock
- $Ratio_{pre-treatment}$ represents the conversion ratio of feedstock to clean feedstock
- $Ratio_{process}$ represents the conversion ratio from the clean feedstock to the bio-crude
- $Ratio_{distillation,SAF}$ represents the conversion ratio from bio-crude to SAF

Using this formula the following SAF yields per technology followed:

- For HTL a $SAF_{yield,HTL}$ of approximately 0.14 times the amount of feedstock
- For FP a $SAF_{yield,FP}$ of approximately 0.37 times the amount of feedstock
- For HEFA a $SAF_{yield,HEFA}$ of approximately 0.47 times the amount of feedstock

6.2 Process Model for HTL and FP

The process model constructed using Excel serves as a simplified representation of real-world operations. The starting point for this estimation was the determination of the mass and energy flows, which in turn are the basis for the estimation of the required process utilities. The computations provided the necessary information to conduct the criteria analyses for FP and HTL. Detailed documentation of how this process model was constructed can be found in appendix T.

6.2.1 Assumptions

Most of the input data for this model were derived from interviews with experts from BTG and Steeper regarding their HTL and FP technologies. Published papers available in the public domain provided additional data. When information was lacking, it was supplemented with assumptions based on literature reviews or input from SkyNRG. These assumptions affect the results, and this is analysed further in the discussion section of the thesis. The key assumptions for this model were as follows:

- Feedstock impurities, such as heavy metals were excluded from the model because they occur in small quantities only. Both interviews highlighted that most of the energy consumption in the processes of converting the feedstock is caused by oxygen removal (BTG, personal communication, 2024) (Steeper, personal communication, 2024).
- As for the energy required for pre-treatment, only the energy required for water removal was considered. The interviews revealed that this is the most energy intensive part (BTG, personal communication, 2024; Steeper, personal communication, 2024). Other energy requirements for pre-treatment were considered to be negligible for this thesis.
- No losses in process yields are assumed; these losses are considered negligible for this thesis.
- Heat generation from HTL and FP through the re-use of by-products was not included in the model because limited data about the amount of energy in these streams made modelling difficult. For the sake of coherency of the approach for HTL and FP, the element of re-use was excluded.
- In reality, processes are expected to have more heat loss. In this model, the only heat loss included is that of the water leaving the process. Moreover, there was insufficient information to model extensive heat integration.
- Although the actual capacities of the Steeper HTL and BTG FP technologies differ, the Excel model uses the larger capacity of the two for both - specifically, the capacity of the Steeper HTL technology of 2,000 barrels per day (BPD), equivalent to 13,900 kg/h of biocrude (excluding water). Modelling both processes at the same capacity ensured a clearer comparison between the technologies. Furthermore, it was decided to model the biocrude capacities without water to focus solely on the energy content of the biocrude. This enables a better illustration of how effectively each technology can produce concentrated energy carriers.

6.2.2 Mass and Energy Flows Followed from Process Model

The energy and mass Sankey diagrams for FP are shown below. These diagrams illustrate the mass flows in kilograms per hour (kg/h) and energy flows in megawatts (MW) as modelled for a biocrude capacity of 13,900 kg/h (excluding water). It is important to note that the quantities of biocrude shown in the Sankey diagram include water. Differences between inflows and outflows in the Sankey diagrams are due to model limitations and lack of detailed data, which may result in estimates differing from actual outcomes.

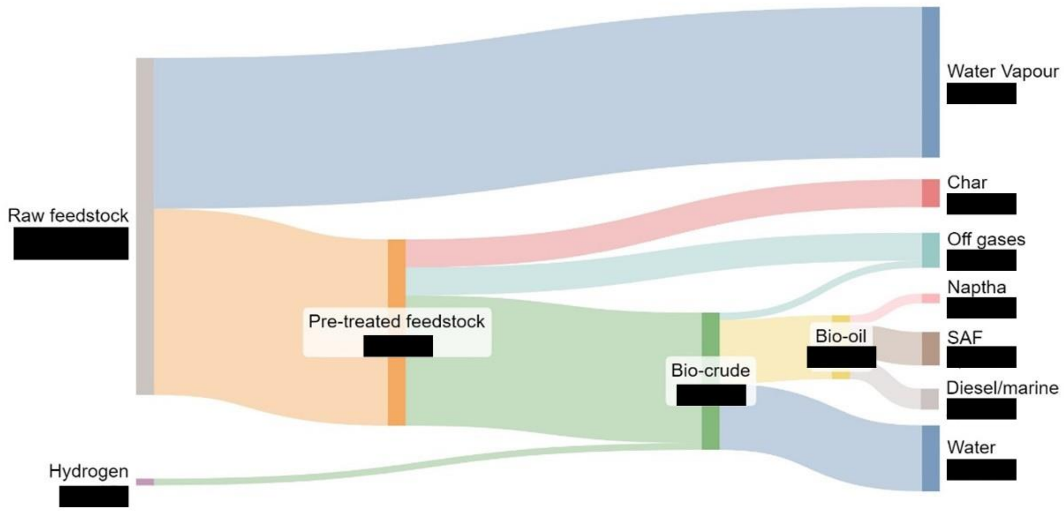

Figure 11: FP pathway mass flows in kg/h.

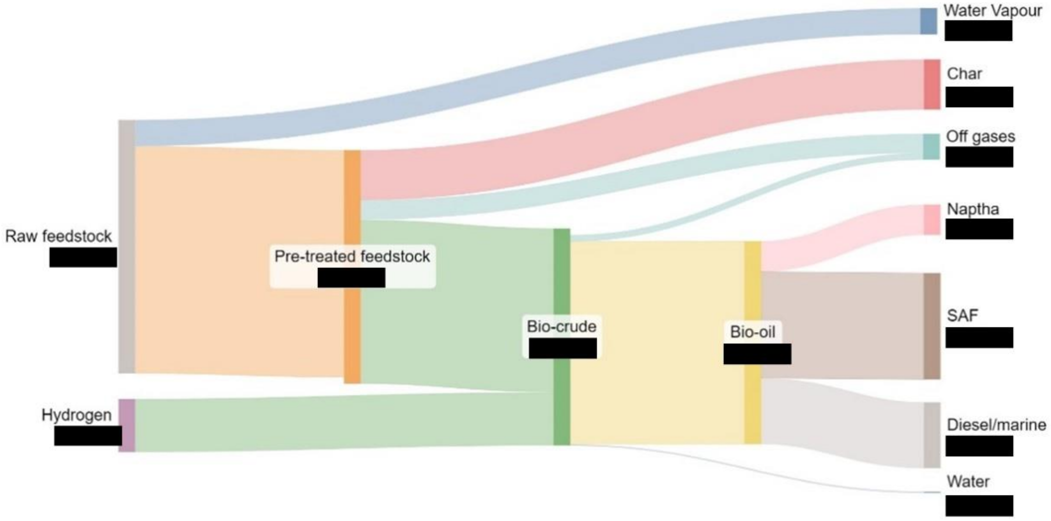

Figure 12: FP pathway energy flows in MW.

The energy and mass Sankey diagrams for HTL are shown below. These diagrams illustrate the mass flows in kilograms per hour (kg/h) and energy flows in megawatts (MW) as modelled for a biocrude capacity of 13,900 kg/h (excluding water). It is important to note that the quantities of biocrude shown in the Sankey diagram include water. Differences between inflows and outflows in the Sankey diagrams are due to model limitations and lack of detailed data, which may result in estimates differing from actual outcomes

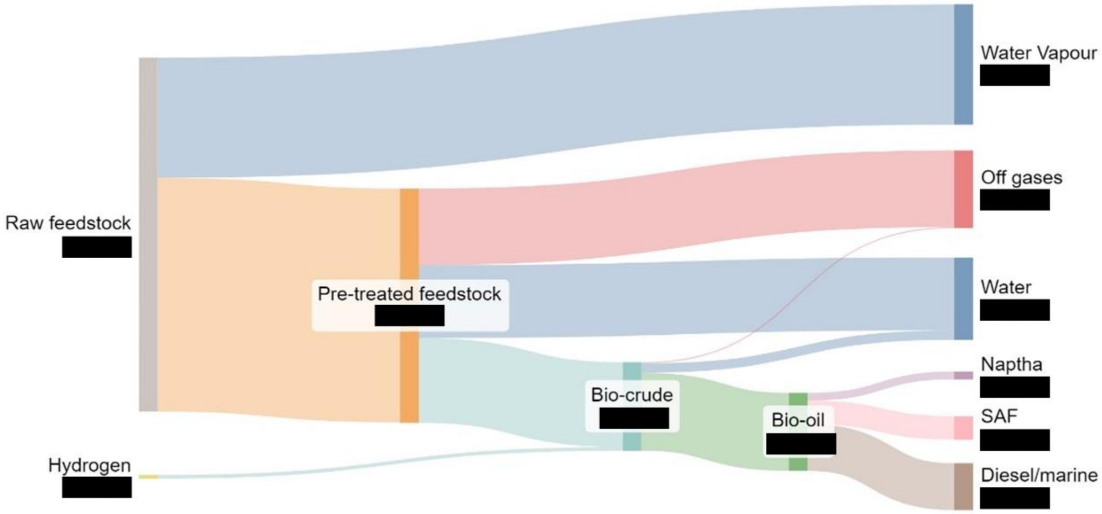

Figure 13: HTL pathway mass flows in kg/h.

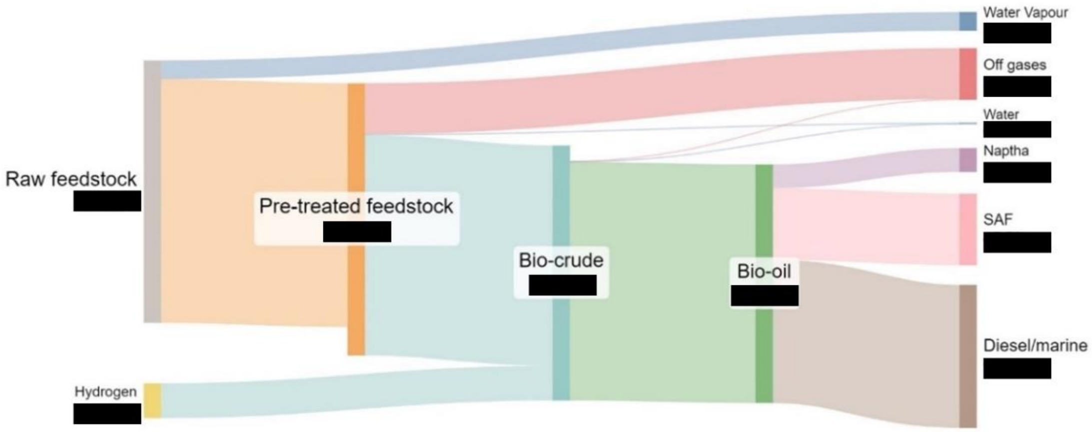

Figure 14: HTL pathway energy flows in MW.

6.3 Required Utilities Technologies

The table below outlines the required process utilities for the SAF pathways, which include electricity, heat and hydrogen. For HTL and FP, these are derived from the process model and for HEFA the process utilities are sourced from De Jong (2018). The amount of utilities required is expressed in its corresponding unit per tonne of SAF produced.

Table 4: Process utilities.

	HTL	FP	HEFA
Electricity (kWh/ ton SAF)	297	[redacted]	0.16
Heat (GJ/ ton SAF)	23	[redacted]	10
Hydrogen (ton H_2/ton SAF)	0.15	[redacted]	0.05

It is important to note that while these findings can provide insights into the operational utility requirements of the SAF technologies, they should be considered as an approximation of the actual situation. For this study, the results have been used as a basis for the criteria analyses and serve as a guideline for assessing the efficiency, sustainability, and economic performance of the SAF technologies.

6.4 Environmental Criteria Assessments

6.4.1 GWP

The GWP analysis was carried out using a simplified LCA approach. As such, the results should be considered primarily as preliminary indications. For more in-depth decision making or for a comprehensive benchmarking of the technologies in a commercial setting, additional research is required. Drawing on the findings of the analysis and their expertise, the SAF experts assigned performance scores as detailed in chapter 3.

6.4.1.1 Goal and Scope

The purpose of this LCA was to estimate the global warming potential of the entire supply chain of the HTL, FP and HEFA SAF production pathways. The total carbon footprint of the pathways was allocated to all products (char, off-gasses, diesel/marine, SAF and naphtha) using the energy allocation method. The energy content for HTL and FP was derived from the energy balance of the designed process model in which the Higher

Heating Value (HHV) was used. For HEFA, the energy content was calculated using data from De Jong (2018), also using the HHV.

The assumptions made for this analysis are set out below:

- Emissions resulting from nonrecurring construction or manufacturing activities, such as the construction of a fuel production plant or the manufacture of equipment, were not included (ICAO, 2019).
- Emissions from the blending of SAF were not included in this analysis as they are considered negligible compared to other emissions in the pathway's life cycle.
- In this LCA, emissions from particulates such as soot and aromatics were excluded.
- Specific transportation distances for feedstock and jet fuel were not considered in this analysis. It is assumed that the transport distances are the same for all the SAF technologies.
- Emissions from the catalysts used in the production pathways were not included in this LCA because they are considered negligible compared to other emissions in the pathway's life cycle.
- Indirect Land Use Change (ILUC) was outside the scope for this LCA.
- High-altitude emissions, such as those produced in aviation have a greater impact on climate change than CO_2 from fuel combustion (Jungbluth & Meili, 2019). However, this is not included in this study as it is the same for all SAF pathways.
- Similarly, he treatment of wastewater can have a large impact on the GWP assessment for FP and HTL due to the large amount of water produced in these processes, but this has also not been included in this LCA.
- The time between biomass collection and final use to produce SAF was not accounted for. However, this can have a substantial impact on the GWP calculation.

The system boundaries for this analysis were defined as well-to-wake, which included the stages of feedstock acquisition (cultivation/collection), feedstock transport, fuel production processing, fuel transport and combustion in an aircraft engine. The fuel production process includes everything from pre-treatment of the feedstock to distillation into SAF. The choice of these boundaries aligned with the CORSIA LCA methodology. The system boundaries for this analysis are visualised in the figure below.

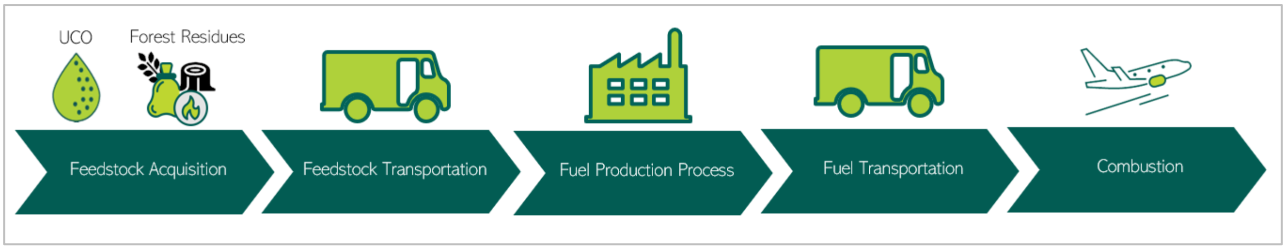

Figure 15: Well-to-Wake SAF supply chain and the system boundaries for this analysis.

6.4.1.2 Inventory Analysis

In the inventory analysis of the LCA, emissions from each step in the supply chain of the SAF pathways were identified by consulting multiple sources.

Upstream Emissions

For this LCA, the CORSIA methodology was used to estimate the upstream emissions associated with the feedstocks used in the SAF production pathways. According to CORSIA, GHG emissions from waste, residues or by-products during the cultivation phase are not attributed (ICAO, 2019). However, emissions from the collection, transport and pre-treatment of these feedstocks must be included (ICAO, 2019). It is important to note that the choice not to allocate emissions to the cultivation phase follows an economic allocation method that differs from the energy allocation method used for other parts of the LCA, as explained above.

The feedstock used for FP and HTL in this analysis was forest residues, which, according to the interviews, is the most commonly used feedstock for both technologies (BTG, personal communication, 2024; Steeper, personal communication, 2024). Used cooking oil (UCO) was used for HEFA. Emissions from the collection and transport of these feedstocks were obtained from ICAO (2019). As specific emission data for HTL and FP were not available, emission estimates from the Fischer-Tropsch pathway for forest residues were used. It was assumed that the emission profiles for forest residues for HTL and FP are not significantly different from those for the Fischer-Tropsch pathway. The emissions values are presented in the table below.

Table 5: Upstream emissions.

Component	GHG missions – typical value (gCO_2eq/MJ)	Source
Collection and transport of UCO Feedstock	0.31	ICAO (2019)
Collection and Transport of Forest Residue Feedstock	3.25	

Contrary to the approach outlined by ICAO (2019), this analysis calculates the carbon footprint of the pre-treatment step for the SAF pathways as part of the process stage, rather than the upstream stage as previously described in the goal and scope section.

Process Emissions

The process emissions were estimated based on the carbon footprint of the required utilities for the fuel production process: electricity, heat, and hydrogen. The carbon footprint was calculated by multiplying the required amounts of these utilities for each SAF pathway by their respective emission factors. The specific amounts of utilities required for each pathway are detailed in Table 6.3.

Different scenarios were formulated for the emission factors to increase the flexibility of the LCA and make it more resilient to different circumstances. The tables below give an overview of the sub-scenarios for the utilities and their corresponding emission factors. A detailed explanation of how these values were developed can be found in appendix N.

Table 6: Emissions from electricity production.

Electricity sub-scenario	Emission factor (gCO_2eq/MJ)
Green	4.1*
Mixed	54.1*
Fossil-based	196.5*

Table 7: Emissions from heat production.

Heat sub-scenario	Emission factor (gCO_2eq/MJ)
Renewable natural gas	4.1**
Natural gas	54.1***

Table 8: Emissions from hydrogen production.

Hydrogen sub-scenario	Emission factor ($kgCO_2eq/kg\ H_2$)
Green	0.60****
Blue	3.86****
Grey	9.83****

*IEA (n.d.), **Bhattacharjee (2022), ***Delegated Regulation - 2023/1185 - EN - EUR-Lex (n.d.), ****Hydrogen Council et al. (2021)

Based on these sub-scenarios, three overarching scenarios, conservative, mixed and progressive, were developed and applied in the LCA. These scenarios are shown in the table below.

Table 9: LCA scenarios.

Scenario	Electricity	Hydrogen	Heat
Progressive	Green	Green	RNG
Mixed	Mixed	Blue	NG
Conservative	Fossil-based	Grey	NG

Downstream Emissions

The downstream emissions in this study were defined as the emissions resulting from the transportation of the fuel and have been obtained from ICAO (2019). As specific emission data for HTL and FP were not available, emission estimates from the Fischer-Tropsch pathway for forest residues were used. It was assumed that the emission profiles for forest residues for HTL and FP are not significantly different from those for the Fischer-Tropsch pathway. The emissions are shown in the table below.

Table 10: Downstream emissions.

Component	GHG emissions – typical value ($g\ CO_2eq/MJ$)	Source
Fuel transport HEFA (UCO)	0.38	ICAO (2019)
Fuel transport HTL and FP (Forest residues)	0.57	

Combustion Emissions

Combustion emissions are assumed to be zero for the HTL, FP and HEFA pathways, in line with the recognised principle of biogenic CO_2 neutrality. According to the Directive 2018/2001, due to the biogenic origin of biomass, CO_2 emissions released during its combustion do not need to be included in the emissions calculation. This is based on the principle that the CO_2 released during combustion has been previously absorbed from the atmosphere by the biomass during its growth phase, thus ensuring a closed carbon cycle (European Parliament & Council of the European Union, 2018). UCO is also considered a biogenic source, as it is derived from vegetable oils or animal fats, for example, vegetable oils recovered from food-processing operations (ICAO, 2019). As already mentioned in the list of assumptions, the effects of high-altitude emissions are not considered here.

6.4.1.3 Impact Assessments: Research Findings on GWP Assessment

According to appendix V, Part C, point 4 of Directive 2018/2001, GHG other than CO_2 must be converted into CO_2 equivalents (CO_2eq). This can be achieved by multiplying their GWP by their relative value compared to CO_2 over a period of a 100 years, ensuring the inclusion of emissions such as CH4 and N2O, which are higher in GWP than CO_2. Consequently, the GWP for this analysis is determined by calculating the GHG emissions in terms of CO_2 eq. This indicated the comparative impact of the emissions produced per megajoule of energy for the end-products, relative to the impact of CO_2. Furthermore, the SAF pathway emissions were compared to the fossil fuel comparator of 94 gCO_2eq per MJ (European Parliament & Council of the European Union, 2018).

Findings for Conservative Scenario

The graphs below illustrate the total GHG emissions in gCO_2eq per MJ for the HTL, FP and HEFA pathways in the conservative scenario. At around 25 gCO_2eq per MJ, FP has the highest GWP for this scenario, followed by HTL and HEFA at around 22 and 19 gCO_2eq per MJ respectively. The majority of the GWP of FP is due to the emissions from hydrogen production. By contrast, for HTL and HEFA, the majority of the emissions are from heat production. While the emissions from electricity production contributes to the GWP of the three pathways, it does so at a significantly lower rate than the other utilities. Across all pathways, downstream activities consistently contribute the least to the total GWP, while upstream activities generally make a moderate contribution.

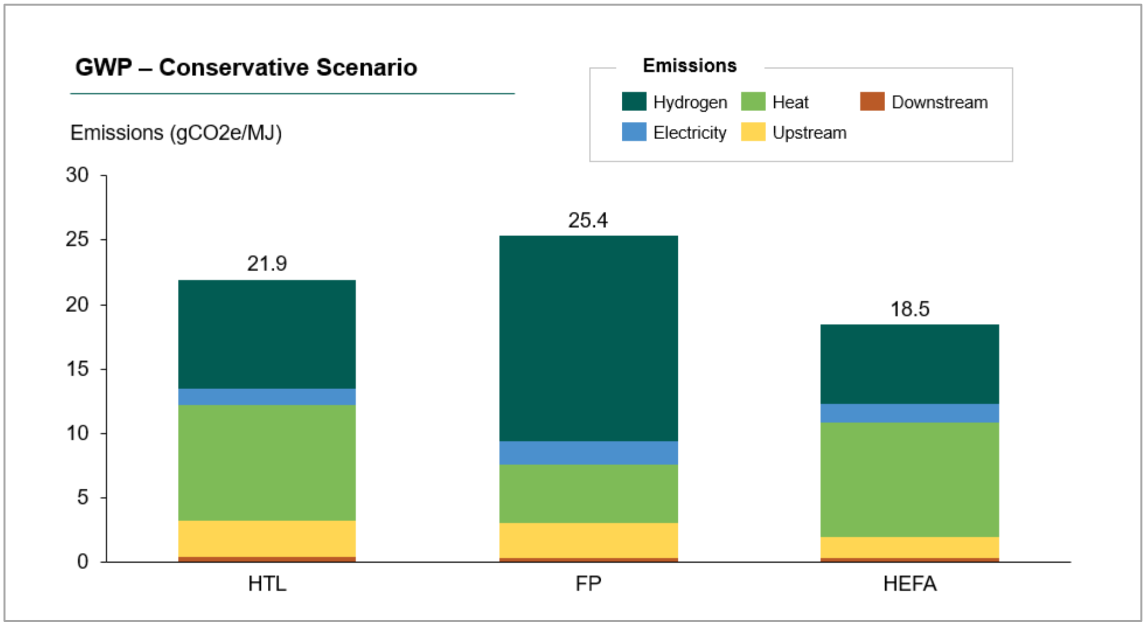

Figure 16: GWPs Conservative Scenario.

Findings for Mixed Scenario

The graphs below illustrate the total GHG emissions in gCO_2eq per MJ for the HTL, FP and HEFA pathways in the mixed scenario. At around 16 gCO_2eq per MJ, HTL has the highest GWP, followed by FP and HEFA both at around 14 gCO_2eq per MJ. In this mixed scenario, using a lower emission factor for hydrogen, the contribution of heat production emissions to total emissions becomes more prominent for FP. For both HEFA and HTL, heat production emissions are now by far the biggest source of emissions. Moreover, the upstream emissions represent a larger share of the total emissions for all pathways, whereas electricity production and downstream activities emissions contribute the least to the total GWP.

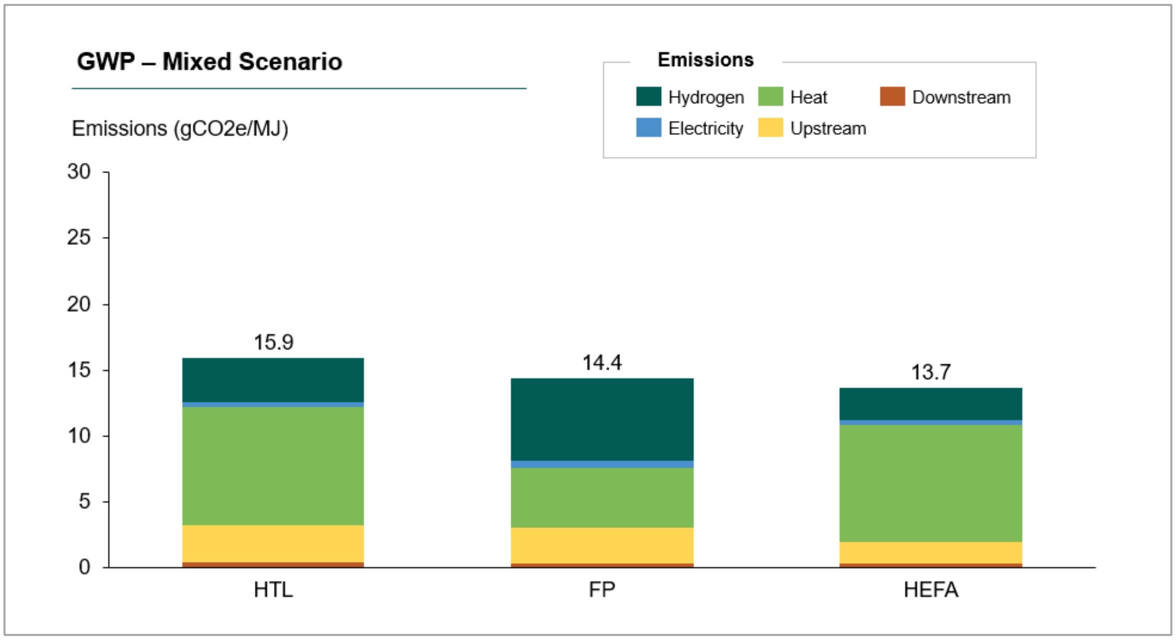

Figure 17: GWPs Mixed Scenario

Findings for Progressive Scenario

The graphs below show the total GHG emissions in gCO_2eq per MJ for the HTL, FP and HEFA pathways in the progressive scenario. FP has the highest GWP at about 4.1 gCO_2eq per MJ. HTL and HEFA follow at around 3.8 and 2.5 gCO_2eq/MJ respectively. In this scenario, based on low emission factors for hydrogen, heat and electricity, upstream emissions are dominant for all pathways. This highlights the lower upstream emissions when using UCO compared to forest residues as a feedstock. In addition, it shows that the downstream emissions are very similar for all technologies. Furthermore, the graph shows that when heat is produced using RNG, hydrogen production emissions are higher than heat production emissions for all pathways.

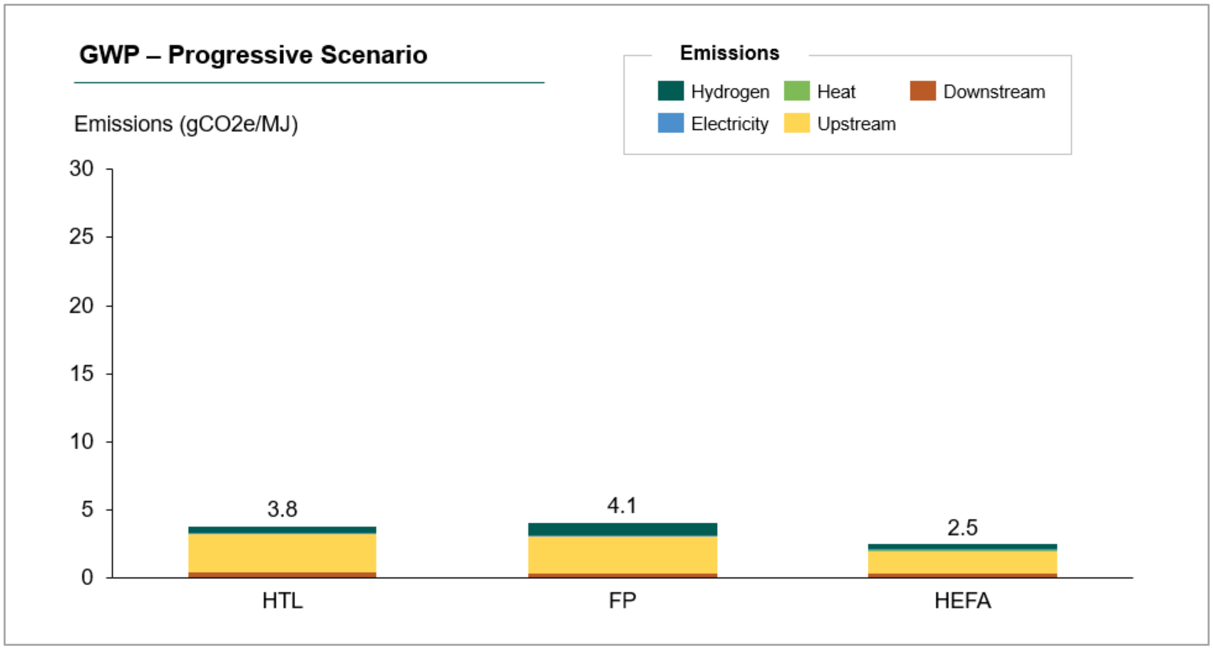

Figure 18: GWPs Progressive Scenario

6.4.1.4 Interpretation

Firstly, the results show that the lifecycle emissions for the SAF pathways are lower than the fossil fuel comparator of 94 gCO_2eq per MJ in all scenarios. In addition, it could be concluded from the impact assessment that electricity production has the lowest emissions of all energy sources in all scenarios for all pathways. Furthermore, the LCA results are dependent on the balance between hydrogen and heat production emissions. In the green scenario, hydrogen production is the main source of emissions for each pathway. In the other scenarios, it varies by pathway whether hydrogen or heat production was the main source of emissions from the utilities. The table below combines the total GWP values of each pathway for all scenarios and clearly shows that the GWP indicated that the HEFA pathway consistently has the lowest GWP emissions compared to the HTL and FP pathways across all scenarios. Furthermore, it shows that the absolute GWP difference between the pathways is rather small in all scenarios.

Table 11: GWPs across scenarios

Scenario	**Technology**	**Emissions (gCO_2eq/MJ of product)**
Grey	FP	~25.4
	HTL	~21.9
	HEFA	~18.5

Scenario	**Technology**	**Emissions (gCO₂eq/MJ of product)**
Medium	FP	~13.7
	HTL	~15.9
	HEFA	~14.4
Green	FP	~4.1
	HTL	~3.8
	HEFA	~2.5

A further conclusion that could be drawn is that technologies such as HTL and HEFA are preferable in order to reduce emissions when there is limited access to green or blue hydrogen. This is based on their lower hydrogen consumption compared to FP. HEFA, in particular stands out for its minimal hydrogen requirements. Moreover, when RNG is available, the sustainability of the SAF pathways is improved significantly by providing a low-emission heat source. When RNG is absent, FP is the preferable technology because it requires substantially less heat (6GJ/tonne of SAF) as compared to HTL (23 GJ/tonne of SAF) and HEFA (10 GJ/tonne of SAF), thereby minimizing the impact on the environment.

6.4.1.5 Expert Opinion on GWP

The following scale was used to systematically assign the performance scores for the GWP:

- Score 1 (no GHG reduction) was assigned when the GWP effect is equal to the CAF, indicating no GHG savings.
- Score 2 (low GHG savings) indicated minimal GHG savings, which represents only a small improvement.
- Score 3 (moderate GHG savings) indicated a significant reduction in GHG emissions, potentially improved by optimal conditions, such as using green electricity and green hydrogen.
- Score 3 (moderate GHG savings) indicated a significant reduction in GHG emissions, potentially improved by optimal conditions, such as using green electricity and green hydrogen.
- Score 5 (excellent GHG savings) represented a situation in which the impact of GWP is negative, implying that the SAF production pathway leads to a net removal of GHGs from the atmosphere.

The performance scores assigned by experts are shown in the table below.

Table 12: Performance scores GWP.

	FP	HTL	HEFA
Performance score	3	3	3

The SAF experts assigned a uniform GWP performance score of 3 to all SAF technologies. This decision was based on the potential of the HEFA technology to achieve significant GHG savings, when using the right feedstock. The HEFA pathway generally requires relatively low energy consumption and the GWP is mainly influenced by the choice of feedstock.

Furthermore, HTL and FP require more intensive feedstock sourcing and processing, resulting in higher upstream emissions. Also, these technologies need more processing compared to HEFA. In spite of this, depending on whether green heat and hydrogen are available, these technologies can still provide significant GHG savings. There is potential for improvement of the environmental performance of this technology through heat integration and further optimization. This was not considered in the LCA. However, this was taken into account in the performance assessment. The assigned performance scores also take into account the fact that the combustion of the by-product char for FP does not generate additional emissions when burnt and can be a potential source of energy to be re-used in the process or can be used towards decarbonization of external processes. The consistent scoring suggested that, despite varying GWP values among different SAF pathways as revealed by the LCA, these pathways could have similar potential if optimised.

6.4.2 Use of By-products

As discussed at the "IATA: What's Next?" conference (IATA, 2024) and supported by research, the effective management and utilisation of by-products generated during SAF production is crucial to advancing waste management strategies and promoting a circular economy.

Therefore, an analysis was carried out to identify the (potential) re-use and valorisation of by-products from HTL, FP and HEFA, which explored the challenges and opportunities. Only by-products resulting directly from the HTL, FP and HEFA processes are considered in this analysis. By-products from pre-treatment or refining processes are excluded. Furthermore, the products obtained after the distillation step, such as naphtha, diesel and LPG, were considered to be end-products and not by-products and were therefore not included in this analysis.

Drawing on the findings of the analysis and their expertise, the SAF experts assessed the overall impact and potential of these by-products, considering factors such as economic viability, technical feasibility, and environmental sustainability. The assessment was done by assigning performance scores as detailed in chapter 3.

6.4.2.1 Research Findings Use of By-products

This section presents the key research findings of a comprehensive literature review on the by-products of HTL, FP and HEFA and their (potential) uses and its challenges. The main research findings are presented per technology. A detailed description of the research findings related to the use of by-products from the various biofuel production technologies is provided in the appendix K.

HTL By-products

HTL produces a wide range of by-products, of which the HTL Aqueous Phase (HTL AP) is the most important, in addition to gaseous by-products and, to a lesser extent, solid residues (Peterson et al., 2008).

HTL AP

HTL AP plays a significant role in nutrient recycling and energy generation, particularly through technologies such as Microbial Fuel Cells and Microbial Electrolysis Cells, which efficiently convert organic materials into electrical energy (Watson et al., 2020). Additionally, HTL AP supports algae cultivation, providing a nutrient-rich medium that enhances biomass production and facilitates biofuel generation (Ranganathan & Savithri, 2019). It also has the capability to yield valuable chemicals such as acetic acid, phenol, and glycolic acid, which are useful for various industrial applications (Swetha et al., 2021). Furthermore, the organic content of HTL AP can be converted into methane for energy production, while its nutrient-rich content is ideal for recycling and use in fertilizers, promoting sustainable agricultural practices (Wang et al., 2021).

Gaseous By-products

Gaseous by-products that are generated in the process of HTL vary in their composition depending on what feedstock is used (Madsen et al., 2015). Madsen et al (2015) states that the main components of gaseous by-products are carbon dioxide (CO_2), carbon monoxide (CO), hydrogen (H_2,), methane (CH_4), and ethylene (C_2H_4). CO_2 is utilized in cultivating microalgae, and thereby supporting sustainable bioenergy solutions (Ranganathan and Savithri, 2019). H_2-rich gas is recirculated and utilized in the upgrading process to enhance the quality of the biocrude (Mathkander et al., 2021). Moreover, the gaseous HTL by-product can potentially be reused in generating energy and heat (Steeper, personal communication, 2024).

Solid Residues

The solid residues undergo additional treatment to be converted into hydrochar, which is used in energy storage technologies and as a soil amendment, showcasing its versatility and contribution to sustainability

(Amar et al., 2020). Additionally, after appropriate treatment and in combination with a suitable catalyst, solid residues have the potential for reuse in hydrogen production (Arun et al., 2020).

Challenges

However, managing these by-products presents several challenges. Improper handling of HTL AP can lead to environmental issues such as pollution and eutrophication, highlighting the need for effective treatment to mitigate these impacts (Zhang et al., 2020b). The presence of phenolics and ammonia complicates biological treatment processes and hinders energy recovery efforts, indicating the necessity for innovative treatment methods (Wang et al., 2021). Additionally, the complexity and high costs associated with effective treatment and disposal impact the sustainability and economic viability of HTL technology (Hong et al., 2021). Addressing these issues requires a balanced approach that emphasizes continued research and the development of efficient, ecologically responsible solutions.

The literature review did not specifically identify challenges associated with the gaseous by-products. However, considering the inherent complexities of the HTL process, it is reasonable to assume such challenges exist due to the variability in the composition of gaseous by-products, depending on the feedstock used. This necessitates flexible and adaptable treatment technologies, as standardized systems may not handle all outputs efficiently. Further research is needed to explore the design and efficacy of such systems.

Solid residues also require additional processing to tailor their properties for specific application in energy storage. The complexity of production processes and higher costs associated with this might limit their application (Amar et al., 2020). These challenges must be addressed to realize the potential of hydrochar in energy storage applications, highlighting the need for further research to develop cost-effective and efficient processing techniques. Although these aspects fall outside the scope of this thesis, they are important for future advancements.

FP By-products

FPs generates biochar and off-gasses as by-products (Pattiya, 2018).

Off-gasses

The off-gasses consist of CO, CO_2, H_2, CH_4, and other light hydrocarbons (Pattiya, 2018). These gases can be reused for energy and process heat generation (BTG, personal communication, 2024). They can serve as fuel in industrial combustion processes, providing an alternative to fossil fuels and reducing GHG emissions (Goyal et al., 2008). Additionally, off-gasses can act as fluidizing mediums or carrier gases in fluidized bed reactors, improving chemical process efficiency and serving as a source of process heat within production facilities (Bridgewater, 2000; Zhang et al., 2011).

Biochar

Biochar, a carbon-rich by-product, has multiple applications that contribute to environmental sustainability and the development of a circular economy. It can be used as a soil amendment, enhancing soil fertility and water retention, which is particularly valuable in arid regions (Mohan et al., 2018; Leng et al., 2019). Biochar also immobilizes heavy metals, reducing their environmental impact and enhancing soil and water safety (Beesley et al., 2011). Furthermore, biochar improves the composting process by absorbing odours and retaining nutrients, resulting in nutrient-rich compost that supports plant growth (Sanchez-Monedero et al., 2018). Its adsorption properties make biochar effective in wastewater treatment, removing pollutants and nutrients from wastewater before discharge into natural water bodies (Inyang et al., 2016). Additionally, biochar can be reused for generating energy and process heat (BTG, personal communication, 2024).

Challenges

Despite the potential benefits, managing these by-products presents several challenges. Off-gasses contain tar and other contaminants that must be removed through complex purification processes, which can be costly due to the need for specialized equipment and higher energy consumption (Guo et al., 2020). The presence of tar can potentially be mitigated through catalytic reforming, but this also incurs higher costs due to the need for specialized equipment and increased energy consumption (Guo et al., 2020). For biochar, additional preparation or purification is often required to achieve the desired qualities for specific applications, which also incurs extra costs (Srinivasan et al., 2015). The optimization of process parameters, such as temperature, heating rate, and residence time, plays a significant role in determining the efficiency of biochar production (Tripathi et al., 2016). Small adjustments to these parameters can significantly impact the quality and quantity of the biochar produced. The variability in biochar composition, depending on the biomass feed and pyrolysis conditions, further complicates its production and application (Srinivasan et al., 2015). Additionally, managing heavy metals in biochar is another challenge, as their presence can pose environmental risks, necessitating careful monitoring and mitigation strategies (Srinivasan et al., 2015).

HEFA By-products

The HEFA process primarily produces water and gaseous products, such as CO_2, H_2, and propane (C_3H_8), as by-products (Neuling & Kaltschmitt, 2018).

Water

During the HEFA process, water is produced as a by-product through hydrodeoxygenation, where triglycerides react with hydrogen to remove oxygen (Neuling & Kaltschmitt, 2018). According to Neuling & Kaltschmitt (2018) this water can be reused within the production facility for cooling and cleaning, enhancing operational efficiency.

CO_2 and C_3H_8

In the HEFA process, during the decarboxylation step, CO_2 and C_3H_8 are produced. C_3H_8 can be sold or used internally as an energy source, while CO_2 can be recycled back within the process or vented (Tao et al., 2017). The reuse of these by-products aligns with sustainability goals by reducing GHG emissions and providing alternative energy sources (Neuling & Kaltschmitt, 2018). The subsequent cracking and isomerizing steps further modify the hydrocarbons to meet specific biofuel specifications such as cold flow and combustion properties (Tao et al., 2017; Neuling & Kaltschmitt, 2018). In these steps, the hydrocarbon products are distilled to remove gaseous by-products, including C_3H_8, H_2, and CO_2. The reuse of C_3H_8 and CO_2 is similar to the decarboxylation step, while H_2, like CO_2, can be vented or recycled back into the process (Tao et al., 2017; Neuling & Kaltschmitt, 2018).

Challenges

Managing the by-products of HEFA presents several challenges. Treating water before reuse is costly and requires advanced treatment methods to remove contaminants and meet environmental standards (Tao et al., 2017; Davis et al., 2013). Additionally, the original design of existing facilities focuses on optimizing HEFA fuel production and may not account for the valorisation of by-products. Therefore, implementing corresponding on-site systems, such as gas separation units and storage capacities, is necessary for further processing (Neuling & Kaltschmitt, 2018).

6.4.2.2 Summary Research Findings

The table below serves as a comprehensive summary of the use of by-product analysis. It encapsulates the main considerations on sustainability benefits, technical readiness, economic viability, and operational feasibility derived from the comprehensive literature review.

Table 13: Summary research findings use of by-products.

Technology	Sustainability Benefits	Technical Feasibility	Economic Viability	Operational Feasibility
HTL	Nutrient recycling and energy generation from HTL AP; reducing emissions	Development needed for efficient use and valorisation of all by-product types.	High costs associated with processing but potential long-term benefits.	Requires high-tech solutions for integration and handling.

Technology	Sustainability Benefits	Technical Feasibility	Economic Viability	Operational Feasibility
	from gaseous by-products.			
FP	Biochar improves soil health; off-gasses reduce reliance on fossil fuels.	Proven technologies for biochar; further research needed for gas utilization.	Cost-effectiveness varies by local demand for biochar and energy reuse setups.	May need logistical and infrastructural updates for full integration.
HEFA	Water and gas reuse lowers overall environmental footprint.	Existing technologies for water and CO_2 recycling; needs optimization.	Costs vary based on scale and technology integration.	Complex integration, requiring infrastructural adjustments.

6.4.2.3 Expert Opinion on Use of By-products Performance

The following scale was used to systematically assign the performance scores for the use of by-products:

- Score 1 (very negative impact) describes situations in which the use of by-products is technically unfeasible, not economically viable, or would have a significantly negative impact on the environment, for example, because re-use would lead to the generation of more waste, higher emissions, or serious disruption of existing operational processes.
- Score 2 (negative impact) indicates that there are serious downsides connected with the use of the by-products, for example, because it would incur high costs or because there are technical obstacles that cannot be easily overcome without significant investment or risk.
- Score 3 (neutral) signifies that the use of by-products is possible, even though the benefits and downsides cancel each other out, for example, because re-use is feasible, but without significant benefits.
- Score 4 (positive impact) illustrates a feasible and beneficial use of by-products because there is a clear economic or environmental benefit, even though some minor challenges may remain that need addressing.
- Score 5 (very positive impact) shows situations in which the use of by-products is highly beneficial, with substantial environmental or economic advantages and without technical or operational obstacles.

The table below shows the performance scores assigned by the experts, with further details in the accompanying discussion.

Table 14: Performance scores use of by-products.

	FP	**HTL**	**HEFA**
Performance score	4	3	2

The rationale behind the 4 for FP was that biochar has great potential to create a negative carbon footprint. Despite its current low market value, the SAF experts emphasised that there are significant environmental benefits in agricultural applications, such as improving soil conditions and sequestering carbon.

The valorisation of HTL by-product is less attractive economically and can pose environmental problems, such as pollution and eutrophication. Therefore, HTL scored a 3 instead of a 4. In addition, the technological and operational obstacles for valorisation are higher for HTL than for FP, where biochar application is more direct and economically viable.

HEFA was assigned a 2 because, although the economic value of C_3H_8 is clear in many industries, it is not as attractive from an environmental perspective when compared to other by-products that have a greater ability to help close the carbon cycle or reduce GHG emissions. It is not currently economically viable to capture and use CO_2 produced by HEFA process due to the limited level of CO_2 production. The benefits of capturing CO_2 do not outweigh the investment that is required.

6.5 Economic Criteria Assessments

6.5.1 CAPEX, OPEX & Feedstock Price

The analysis of the economic criteria is different from the analysis of the other criteria. Instead of separate sections for each criterion, all the economic research findings are summarised in a single graph illustrating the correlations. Drawing on the findings of the analysis and their expertise, the SAF experts assigned performance scores as detailed in chapter 3. The data used for the analyses can be found in appendix U.

6.5.1.1 Approach

The values for all economic criteria were calculated per tonne of SAF to ensure a consistent unit of measurement and to allow direct comparison between the SAF pathways studied.

Although the literature review highlighted CAPEX, OPEX and feedstock price as key criteria in MCAs for biofuel production, this thesis required a broader economic analysis. Therefore, the cost price per tonne of SAF, including the market value of the co-products naphtha and diesel/marine, was also evaluated. This extended approach recognised that the HTL, FP and HEFA pathways studied may not be fully optimised for the production of SAF as the primary end product. By including the revenue of the co-products, the analysis compensated for any process inefficiencies in SAF production, providing a more balanced financial comparison of each technology. Excluding the cost price of SAF, which included the revenue of the co-products, could misrepresent the economic viability of these technologies. This comprehensive economic analysis enabled the SAF experts to make an informed assessment on the performance scores.

For the economic criteria assessments the following assumptions were made:

- Given the lack of specific operational data, a continuous operating time of 365 days per year was assumed for all the SAF technologies. This enabled consistency and comparability in the analysis.
- The economic lifetime of the SAF plants is taken to be 25 years (Makepa et al., 2023).
- Given the lack of specific data, this study did not include any chemicals (i.e. catalyst) that might be used in these processes.
- For the CAPEX and OPEX analysis, only the costs associated with biofuel production were considered. Costs related to, for example, transport, blending and other upstream or downstream processes were excluded from the scope of the analysis.

CAPEX

The CAPEX estimates were based on a 25-year operating life for the plants, consisting of the following four main components:

1. Total Installed Equipment Cost

For HEFA, the total installed equipment costs were derived from internal SkyNRG data (SkyNRG, personal communication, 2024).
For HTL and FP, specific data on the BTG and Steeper technologies were not available, mainly due to the confidential nature of this information. Consequently, the installed equipment costs were estimated using literature on other HTL and FP technologies. Six relevant studies were consulted, and their average total installed cost was adjusted for inflation at a rate of 2% per year to reflect current value. The costs derived from the literature were then scaled to match the production capacities of the BTG and Steeper processes using the formula derived from the principles outlined by Green & Southard (2018):

$$C_i = C_l \frac{{S_l}^{n}}{S_i}$$

Where,

- C_i, represents the total installed costs of technology i
- C_l, represents the average total installed costs from the literature
- S_i, represents the capacity of technology i
- S_l, represents the capacity of technology i
- n, represents the scaling factor

A scaling factor of 0.9 was applied because interviews with BTG and Steeper revealed that their HTL and FP processes use modular units (BTG, personal communication, 2024; Steeper, personal communication, 2024). This implies that the benefits of CAPEX scaling are limited, with a doubling of production capacity leading to an almost doubled (0.9 scale factor) CAPEX cost.

2. Balance of Plant/Outside System Battery Limits (OSBL)

These are the costs of infrastructure and services required to support a process unit in an industrial plant, but not directly involved in the production process (Tanzil et al, 2021b). According to SkyNRG, these costs represent approximately 40% of the total installed equipment cost, an estimate that is included for HTL, FP and HEFA in this analysis (SkyNRG, personal communication, 2024).

3. Development costs

Development costs are taken to mean all costs associated with the research, design and development of new products, services or projects and may include the labour cost of the development team, the cost of prototyping, testing, and market research as well as the cost of regulatory authorization. SkyNRG stated that these costs are equal to approximately 5% of the total cost of installed equipment and this estimate was included in the CAPEX analysis (SkyNRG, personal communication, 2024).

4. Financing costs

These costs consist mainly of interest payments on loans or bonds used to finance the construction of a plant. According to SkyNRG, these costs represent approximately 25% of total installed equipment costs, and this estimate was included in the CAPEX analysis (SkyNRG, personal communication, 2024).

OPEX

For the estimated OPEX it was assumed that it consists of the following three main components:

- Maintenance costs: according to SkyNRG, these costs constitute 2.5% of the total CAPEX and this estimate was included in the OPEX analysis (SkyNRG, personal communication, 2024).
- Operations & site costs: according to SkyNRG these costs are around €7,500,000 per year and this estimate was included in this OPEX analysis (SkyNRG, personal communication, 2024).
- Process utility costs, which include:
  - Costs of hydrogen
  - Costs of heat
  - Costs of electricity

The following two scenarios, conservative and progressive, were constructed for the cost of these utilities and the values are given in appendix U. The inclusion of the two scenarios allowed the analyses to remain more flexible and resilient to a variety of conditions.

Table 15: Scenarios economic analysis.

Scenario	Electricity	Hydrogen	Heat
Conservative	Grey	Grey	Natural Gas
Progressive	Green	Green	Renewable Natural Gas

Feedstock Price

In this analysis, forest residues were assumed to be the feedstock for the HTL and FP processes, while used cooking oil (UCO) was assumed to be the feedstock for the HEFA process. The total feedstock costs were calculated by multiplying the required amount of feedstock to produce one ton of SAF by the feedstock price. Details on feedstock prices can be found in appendix U.

Revenue from Co-products and Cost Price of SAF

In the refining process, as described in section 6.1.2, the composition of the bio-oil results in different proportions of end-products for the technologies. To facilitate a fair comparison of the cost prices of SAF between the technologies, the revenue of the co-products, specifically diesel and naphtha, was estimated and included in the cost calculations. This ensured that all costs were appropriately allocated to SAF. The assumed revenues for these co-products are detailed in appendix U. The cost price of SAF was estimated by adding the CAPEX, OPEX and feedstock price and then subtracting the revenue of the co-products as these can be sold and generate an economic return.

6.5.1.2 Research findings Economic Analysis

The graphs below show the research findings for the two scenarios of the economic analysis with further details in the accompanying discussion.

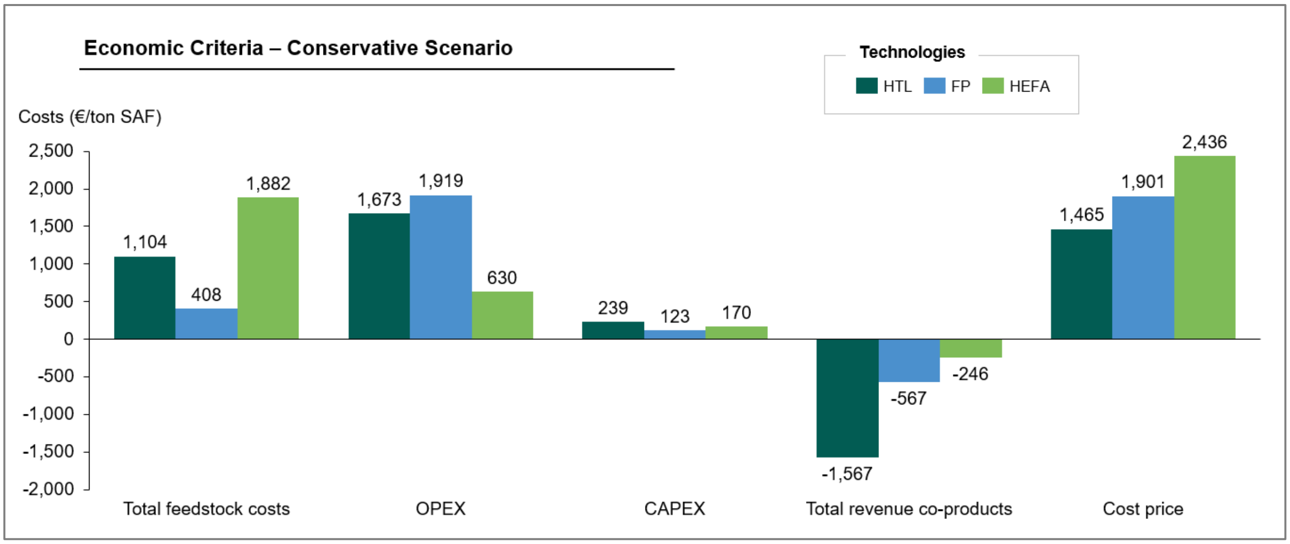

Figure 19: Economic criteria findings conservative scenario.

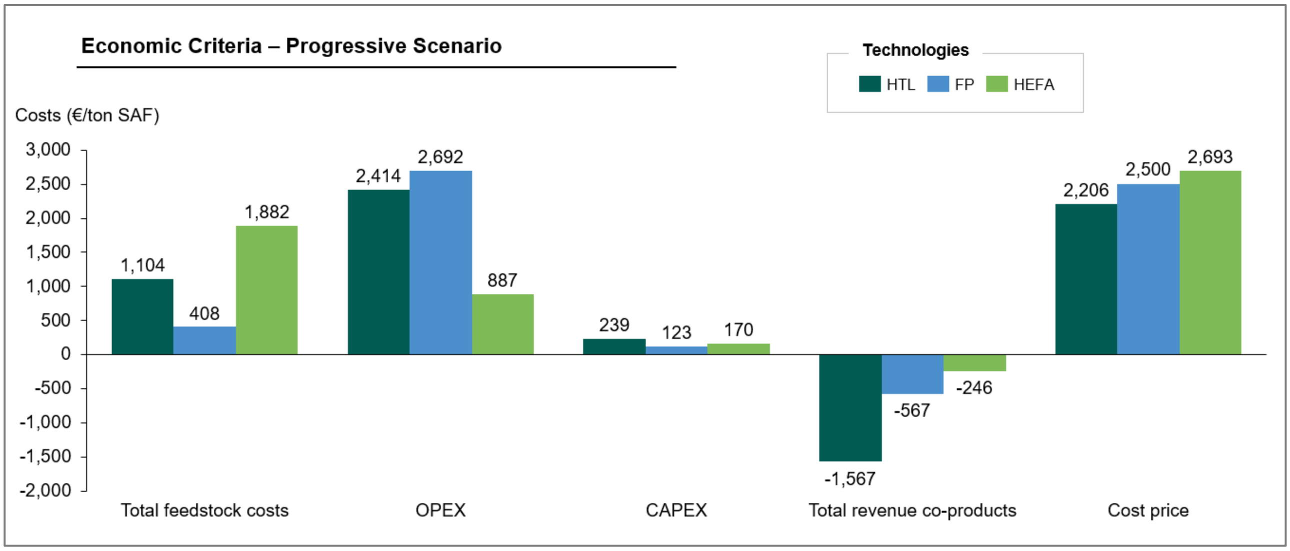

Figure 20: Economic criteria findings conservative scenario.

Feedstock Price

The total feedstock cost per tonne of SAF remains the same in both scenarios, with HEFA having the highest cost due to the more expensive UCO compared to the forest residues used in HTL and FP. Although HTL and FP use the same feedstock, the feedstock cost per tonne of SAF is higher for HTL due to its lower efficiency in producing SAF, as detailed in the table in section 6.1. For HEFA, feedstock cost is the largest component of the economic criteria.

OPEX

In both scenarios, HEFA has the lowest OPEX, mainly due to its lower hydrogen requirement. On the opposite, FP has a higher OPEX than HTL because it uses more hydrogen. In the progressive scenario, the OPEX for FP and HTL increases considerably compared to the conservative scenario, whereas the increase for HEFA is less pronounced. This difference is mainly due to the higher hydrogen consumption in the FP and HTL processes, which results in higher costs.

CAPEX

CAPEX is consistent across the two scenarios, with HTL being the highest, followed by HEFA and then FP. The reason why HTL has the highest is likely to be because of its high feedstock consumption and therefore higher machinery requirements. It should be noted that HEFA calculations are based on industrial data, whereas HTL and FP are based on academic literature, which often underestimates CAPEX, as indicated by SkyNRG (SkyNRG, personal communication, 2024). This could mean that the actual CAPEX for TL technologies could be higher than indicated in the graphs.

Revenue from Co-products

The graphs show that HTL has the highest revenue from co-products, followed by FP and then HEFA. This can be explained by the fact that, HTL produces the largest amount of usable by-products, followed by FP and then HEFA, as shown in the table in section 6.1.

Cost price

The graphs show that HEFA has the highest cost price per tonne of SAF in both scenarios, mainly due to expensive feedstock and less valuable co-products. Notably, HEFA's OPEX is significantly lower than the other two technologies, particularly in the progressive scenario where green alternatives increase costs. In this scenario, FP's cost price per tonne of SAF approaches that of HEFA, with HTL also showing a notable increase. This suggests that the costs of TL technologies such as HTL and FP are more sensitive to the use of costly green alternatives for process utilities than HEFA.

Furthermore, despite lower feedstock prices and CAPEX, FP has a higher cost price per tonne of SAF than HTL. This is mainly because HTL generates a greater amount of valuable co-products and has a lower OPEX, resulting in a comparatively lower cost price per tonne of SAF.

The analysis of the economic criteria was very preliminary and based on limited data. A more comprehensive economic analysis is recommended for an accurate decision-making process.

6.5.1.3 Expert Opinion on CAPEX, OPEX and Feedstock Costs Performance

The following scale was used to systematically assign the performance scores for the CAPEX, OPEX and feedstock price:

- Score 1 (very high cost) indicates situations in which CAPEX, OPEX and feedstock costs are very high, making it difficult to achieve a positive return on the investment.
- Score 2 (high cost) indicates that the CAPEX, OPEX, and feedstock costs are high, resulting in a less than favourable cost structure, albeit not as extreme as the levels in score 1.
- Score 3 (average cost) illustrates a cost structure that can be considered reasonable and in which CAPEX, OPEX and/or feedstock costs are such that a reduction of costs through optimization or technical improvements is possible.
- Score 4 (low cost) indicates that the CAPEX, OPEX, and/or feedstock costs is relatively low in comparison to other technologies in the SAF industry.
- Score 5 (very low cost) shows a scenario in which CAPEX, OPEX and/or feedstock costs are very low and approaching CAF cost, thereby improving greatly the feasibility of the process.

The table below shows the performance scores assigned by the experts, with further details in the accompanying discussion.

Table 16: Performance scores economic criteria.

	FP	HTL	HEFA
Performance score CAPEX	3	2	4
Performance score OPEX	2	3	4
Performance score Feedstock price	4	4	1

CAPEX

The SAF experts gave HEFA a score of 4 because it has already been widely implemented, resulting in an optimised CAPEX per tonne of SAF produced. The process is also proving to be scalable, enabling further cost efficiencies. As such, it is an attractive choice for investors looking to invest in a reliable and cost-effective SAF technology.

Despite the research findings indicating lower CAPEX for FP, it received a lower score than HEFA, mainly because it relied on academic literature, which often underestimates costs. In contrast, HEFA used industry data, which provided a more realistic picture of actual costs. As a result, FP received a score of 3, reflecting a higher perceived CAPEX than HEFA. While FP has the potential to reduce costs through economies of scale, its less mature technology currently results in a higher cost per tonne of SAF.

HTL received the lowest score of 2, indicating the highest CAPEX of the SAF technologies assessed, due to its need for complex, expensive equipment to handle high pressures and larger plant size, as it requires more feedstock to produce the same amount of SAF compared to FP and HEFA.

OPEX

HEFA's OPEX was rated 4 due to the relatively high efficiency and simplicity of the process. The HEFA technology uses a straightforward process with oil-based feedstocks that are already quite similar to the final SAF product, which helps to reduce operating and associated costs.

FP scored a 2 for OPEX due to its intensive processing requirements, resulting in higher operating costs. In contrast, HTL scored a 3 because its high-pressure processing conditions require less hydrogen, resulting in lower OPEX. Hydrogen consumption had a significant impact on OPEX scores. A reduction in the price of green hydrogen could potentially improve the OPEX of FP.

Feedstock Price

HEFA received a score of 1 for feedstock price, mainly due to the significant increase in the price of UCO in recent years. It was noted that originally UCO had a negative price and biofuel producers were "paid" to get rid of it, but with increasing demand and competition, UCO has become a high value feedstock (SkyNRG, personal communication, 2024).

HTL and FP each receive a feedstock price score of 4. Despite requiring large quantities of feedstock to produce one tonne of SAF, their costs remain lower than those of HEFA. Although the research findings showed that the total feedstock cost per tonne of SAF is higher for HTL than for FP, both were given the same score. This is because HTL technology is not yet optimised for SAF production and therefore scoring was based on absolute feedstock costs, which are identical for both HTL and FP.

6.6 Social Criteria Assessments

6.6.1 Safety

Although the literature review for this study found that safety is often quantified in terms of disability-adjusted life years (DALYs) within an MCA (Mendecka et al., 2020), this unit was not used in this study. DALYs quantify the total long-term health impact of disease and disability within a population, such as exposure to hazardous chemicals like lead, which is responsible for 1.06 million deaths and 24.4 million DALYs (International Labour Office, 2021). However, SAF production involves operational and chemical risks, such as chemical leaks, explosions and fire hazards, which pose immediate safety risks rather than long-term health effects. Furthermore, safety factors related to the end use of bio-oil for SAF were not considered in this analysis, as it is assumed that all SAF pathways must meet the strict ASTM standards. Therefore, the analysis focused on the production process itself, with emphasis on the direct impacts on worker safety and the production environment. Accordingly, this study adopted the methodology of Pokoo-Aikins et al. (2010), which categorises safety in terms of operating conditions and chemical properties, to identify specific hazards in SAF production technologies.

6.6.1.1 Potential Hazards Related to Safety Parameters

The table below presents key safety parameters for evaluating potential risks in SAF production, selected based on available data to allow for a reliable comparison between the technologies at the production level. Although other factors may also affect safety, the lack of sufficient data limited their inclusion. The selected parameters emphasise immediate risks and the need to maintain safety in the workplace and the environment, which could have a significant impact on stakeholder trust and acceptance of the technology.

Table 17: Safety parameters.

	Safety parameter	Characteristics
Operating conditions	Temperature	High temperatures can pose safety risks, potentially causing fires or explosions, especially when handling flammable substances. Therefore, careful monitoring is essential to prevent such hazards.

	Safety parameter	Characteristics
	Pressure	High pressure can lead to equipment failure, leak or even explode (López-Molina et al., 2020). Therefore, careful monitoring is essential to prevent such hazards.
Chemical properties	Density	Density impacts fuel diffusion and reaction dynamics (Pires et al., 2018). For SAF production, a low density is preferable as it eases control of the fuel, reducing spillage and leakage risks. It also decreases mechanical strain on storage tanks and pipelines, lowering the likelihood of failures and leaks.
	Flash point	The flash point is the lowest temperature at which a liquid emits enough vapor to ignite (Valenzuela, 2011). It is a crucial safety parameter in SAF production, as it indicates flammability. A high flash point is desirable as it signifies lower flammability, thereby reducing fire risks (Pires et al., 2018).
	Water content	Water content in fuel is an important safety measure, indicating potential contamination (Pires et al., 2018). In SAF production, reducing water content is crucial to minimize corrosive reactions that increase the risk of leaks and structural failures in pipework and tanks.
	Total Acid Number (TAN)	Total Acid Number (TAN) indicates the acidity of a liquid and the potential presence of corrosive components, making it a critical safety parameter (Rivera-Barrera, 2020). In SAF production, a low TAN is desirable to reduce corrosion risks in pipework and tanks, thereby minimizing the likelihood of leaks and structural failures.

6.6.1.2 Research Findings on Safety Assessment

The table below shows the values found through literature review for the chosen safety parameter for HTL, FP and HEFA.

Table 18: Safety research findings

	Operating Conditions		Chemical Properties			
	Temperature (°C)	Pressure (bar)	Density at 40 °C (kg/m^3)	Flash point (°C)	TAN (mg KOH/g)	Water content (wt%)
HEFA	300-450[e]	55-60[e]	776[d]	39[d]	10[d]	0[d]
FP	400-600[b]	1[b]*	1170[b]	50.5[c]	70[b]	25[b]
HTL	390-410[a]	300-340[a]	1057.2[a]	59[a]	8.8[a]	0.8[a]

[a] Steeper Energy Aps. (2018)., [b] Van de Beld, B. & BTG Biomass Technology Group BV. (2022), [c] Van Dyk et al. (2019), [d] Pires et al. (2018), [e] Gutiérrez-Antonio et al. (2017), *It is important to note for the comparison that the FP process step operates at atmospheric pressure, but the stabilization step occurs at 200 bar. In contrast, the HTL process does not require such a step before upgrading.

6.6.1.3 Expert Opinion on Safety Performance

The following scale was used by the SAF experts to systematically assign the performance scores for safety:

- Score 1 (very high risk) denotes technologies that can pose serious risks and hazards to both the operational setting and the environment.

- Score 2 (high risk) indicates a significant risk and potential hazards inherent in the technology, but at a manageable level if strict protocol is adhered to.
- Score 3 (medium risk) shows a standard safety risk typical for the technology in this industry.
- Score 4 (low Risk) refers to technologies that present minimal risks and hazards and are well managed by existing security protocols.
- Score 5 (very low Risk) refers to technologies that are optimised for safety, with almost no risks or hazards in their operational procedures. They provide a safe working environment and minimise environmental impact, comparable to well-managed water treatment systems that operate without significant risk to personnel or the environment.

The table below shows the performance scores assigned by the experts, with further details in the accompanying discussion.

Table 19: Performance scores safety.

	FP	HTL	HEFA
Performance score	3	3	4

During the safety performance scoring assessment, the SAF experts emphasised that while the SAF technologies are inherently safe when used correctly, pressure is identified as the primary safety concern. The high temperatures pose less of a risk, as the processes take place predominantly in liquid phases.

HTL operates at high pressures of up to 300 bar and the main operational risk is maintaining this pressure. Potential problems such as rough feedstock and potential clogging of pipelines can exacerbate these risks. However, as these risks are common in the industry and are manageable through routine inspections, HTL has been assigned a safety score of 3.

FP technology inherently carries the risk of equipment corrosion due to the acidic nature of unstabilised pyrolysis oil, which raises safety concerns. However, the biocrude stabilisation step, which operates at high pressures of 200 bar, significantly reduces these risks. Nevertheless, this high pressure poses additional concerns such as blockages and potential explosions. Despite these concerns, FP received a safety score of 3, reflecting both the reduction in acidity and the industry standard practice of operating at high pressures during the stabilisation step.

HEFA is a more established refining technology and therefore received a higher score of 4. Although there are inherent risks associated with any refining process, the industry's extensive knowledge and experience with HEFA helps to mitigate these risks, making them well understood and manageable.

6.6.2 Social Impact Related to Feedstock Use

HTL, FP and HEFA can convert a wide range of feedstocks into renewable fuels, which can have profound social impacts. Recognizing this broad social impact is essential (IATA, 2024). This criterion analysis started with defining what constitutes 'social impact' within the context of SAF technologies. Hobod & Tomei (2013) define the social impacts as anything that affects local liveability, food security and ecosystem services. The latter covers pollination, water filtration and soil fertility, which have an impact on the sustainability of agricultural practices and the quality of the living environment of the community. Griffith (1979) further emphasises the importance to include community cohesion in social impact assessments.

6.6.2.1 Social Factors Used in Analysis

The next step involved identifying the specific social factors influenced by the use of different feedstocks, which were defined for this analysis as: social cohesion, public health, food security, and overall quality of life. Social factors such as employment and economic resilience were excluded from this analysis as they occur across all biofuel projects (Allan, 2015) and do not differ along different SAF trajectories. The social factors selected and defined for this analysis are discussed in detail below.

Social Cohesion

Social cohesion focused on the trust, interconnectedness, and mutual assistance among individuals within a community, as emphasized by Chan et al. (2006). There are positive and negative effects on social cohesion within communities. On the positive side, the use of SAF feedstocks can strengthen the overall capacities of the community and promote empowerment (Schoneveld, 2014; German et al., 2011). It can also contribute to a better community spirit and foster a sense of pride (von Maltitz et al., 2014). Furthermore, it can create a sense of ownership and encourage communities to work towards sustainable development (Esenaliev et al., 2016). Negative effects on social cohesion can include land disputes and displacement, disrupting local agricultural livelihoods (Cotula et al., 2009). Additionally, social unrest may arise from uneven benefit distribution and lack of fair local participation (German et al., 2011).

Public Health

Public health examined the effects on the health of communities located in the immediate vicinity of SAF production facilities as well as those that may be indirectly affected by the activities of these facilities. Positive impacts on public health can include the use of SAF feedstocks that reduce waste and reduce pollution. One of the negative effects on public health is the impact on water quality. This is the case when there is intensive cultivation of crops for SAF which require significant water use and substances such as fertilisers and pesticides. Runoff from these substances can lead to water pollution (De Vries et al., 2010) reducing clean drinking water availability. This can lead to diseases in the local population (German, Schoneveld, & Pacheco, 2011; De Vries et al., 2010; Powers et al., 2010), especially in communities that rely on local water sources for their daily water needs (Tarrass & Benjelloun, 2012). According to Eisentraut (2010), access to fresh water is a growing problem in many countries, e.g. China, India, and South Africa. Tarrass & Benjelloun (2012) explain that water shortages can compel people to use contaminated water for drinking, cooking, or washing, leading to disease outbreaks. These outbreaks can burden the health sector, causing an overload that may deteriorate the access to and quality of medical services. Changes in land use can also cause stress and this can affect public health, in addition to food security and social cohesion. This stress can result from land loss and economic insecurity. Such social and psychological stress can lead to long-term health problems such as depression and chronic anxiety disorders (Clayton, Manning, Krygsman, & Speiser, 2017).

Food Security

Food security was about access to and availability of food. It can be influenced by the production of SAF in both positive and negative ways. When the production of SAF does not compromise the land or resources needed for food crops, thus maintaining food security, SAF production was seen in a positive light. On the other hand, it was viewed negatively if it could affect food security. The demand for SAF feedstock can reduce the land available for small-scale or subsistence farming, which is particularly concerning in areas where land is crucial to the food security of local people (Cotula et al., 2008; Hodbod & Tomei, 2013). For small farmers or livestock farmers who lose their land and are forced to relocate, this displacement can severely impact their food security (Cotula et al., 2008; International Land Coalition, 2012). Moreover, SAF production may result in higher food prices due to a decline in the production of food crops and an increase in demand for such crops (Ahmed, 2020). This may threaten the food security of poorer rural smallholder farmers and poor urban consumers in particular (Ewing & Msangi, 2009). Intensive cultivation of crops for SAF can remove important nutrients from the soil and this can lead to soil depletion (Ale et al., 2019). The eroded soil can transfer wind or rainwater to neighbouring soils. If these neighbouring soils are used to grow food crops, this can negatively affect their production capacity by degrading soil quality. Additionally, intensive water use for irrigation of biofuel crops can lead to a decrease in water availability (Powers et al., 2010). In areas where water is already scarce, this can result in a further reduction of water available for the irrigation of crops and thus negatively impact food production.

Quality-of-life

The quality-of-life factor linked environmental impact with human well-being. The focus was on the visual, odorous, and aesthetic aspects of the environment that affect the quality of life both positively and negatively.

When managed properly, SAF production can eliminate odour nuisances. For example, when using feedstocks traditionally considered odorous waste. When these materials are no longer left untreated or disposed of in landfills, the odours affecting the liveability of nearby communities are reduced. However, as noted by Holma et al. (2018), these odours can also be emitted during the SAF production process. Generally, odours are detected at very low chemical concentrations, far below the levels at which these substances might be toxic (Montrimaitė & Lapinskienė, 2012). To minimise the emission of unpleasant odours and thus reduce the impact on the environment, advanced odour control techniques, such as biofilters, closed-system processing, and chemical scrubbers can be used (Montrimaitė & Lapinskienė, 2012). The transformation of landscapes for biofuel crops can lead to visual and aesthetic changes in the environment. This occurs because of the loss of natural habitats and visual degradation of landscapes. Holma et al. (2018) and Tudge et al. (2020) highlight the visual changes in the landscape caused by the presence of renewable energy sites. Such visual changes may be perceived as undesirable by the local community. If water use to irrigate biofuel crops reduces local water resources, this affects not only agriculture, but also the availability of water for domestic and recreational use (Beringer et al. 2011). Quality of life decreases when restrictions on daily activities such as drinking and cooking happen and recreational opportunities on water decrease. The local biodiversity is also reduced when natural habitats are turned into land for the cultivation of SAF crops. The loss of these lands can result in the disruption of ecosystems or the reduction of plant and animal species varieties (Mellilo et al., 2009; Tudge et al., 2020). Not only does it impact the ecological balance, it also negatively affects the aesthetic and recreational appeal of these areas, because areas that used to have a rich variety of plants and animals, providing more opportunities for recreation, are now lost or reduced.

Drawing on the findings of the analysis and their expertise the SAF experts assessed the overall social impact of the four factors across all potential feedstocks, assigning a single performance score to each SAF pathway. The assessment was done by assigning performance scores as detailed in chapter 3.

6.6.2.2 Research Findings on Social Impact Related to Feedstock Use

This section presents the research findings of an extensive literature review on the social impacts related to feedstock use for the SAF pathways. This research included an analysis of the most used feedstocks for each of the pathways. The impacts are outlined for each pathway, illustrating how specific feedstocks either positively or negatively affect the four social factors, defined above.

HTL

Commonly used feedstocks in HTL are all the wet organic material variety, such as algae (Ovsysannikova et al., 2020), municipal sewage sludge (Seipe et al., 2020), food waste (Maddi et al., 2017) and agricultural residues (Cao et al., 2017).

Algae

Algae show great promise for use in HTL as they provide potential for the production of liquid bio-crude oil because of their high lipid content (Li et al., 2014). They also have advantages such as effective CO_2 fixation and rapid growth rate (Clarens et al., 2010). Moreover, He et al. (2019) have demonstrated that even algae with low lipid content can still produce substantial yields of bio-crude oil, validating their effectiveness as feedstock for HTL. The two most common options for algae cultivation are bioreactors and open waters (Iglina & Pashchenko (2022). Algae can be grown on different bodies of water, and this does not affect most food production (Ullman, 2021), meaning vital agricultural land is not redirected for feedstock production. Algae farming can also contribute to social cohesion by involving local communities, fostering a sense of collective responsibility and ownership.

In addition, algae use photosynthesis to extract CO_2 from their environment to grow, thereby releasing oxygen as a by-product. In water-rich environments, algae can absorb CO_2 dissolved in water, but also directly from the air (Sengupta, Gorain & Pal, 2017), thereby effectively reducing CO_2 levels. Therefore, algae can be said to be effective water and air purification tools. A study by Iglina & Pashchenko (2022) illustrates that CO_2

from industrial emissions can be used for biofuel production because it enables the algae to be used more efficiently for growth. Obviously, public health outcomes are improved when environments are cleaner.

Additionally, this can be done through the use of wastewater as algae can absorb nutrients as well as pollutants from wastewater (Chen & Qi, 2015). If algae cultivation involves the use of wastewater, the amount of contaminated water that is discharged into natural water bodies (rivers or seas) is reduced and the impact on the environment is less. Another advantage of using wastewater is that no other water sources need to be used so these can then be used for (making) drinking water. This will have a direct impact on human health and well-being.

Sewage Sludge

Municipal sewage sludge is an unavoidable by-product of wastewater treatment (Latosińska, Kowalik & Gawdzik, 2021). Sewage sludge is a serious problem for municipalities around the world (Rorat et al., 2019) as it contains hazardous contaminants such as heavy metals, organic pollutants and other pathogens (Latosinska et al., 2021). These pose a risk to the quality of the soil, water and air and therefore the sludge needs to be managed adequately (Raheem et al., 2017).

Municipal wastewater sludge contains a significant amount of influent chemical energy, most of which has not been recovered and is not utilized in current wastewater management practices (Seiple et al., 2020). Seiple et al. (2020) states that HTL is very effective at capturing the latent energy in wastewater and turning it into biofuels. Using sewage sludge to produce SAF can reduce odours from landfills, reduce the risk of groundwater contamination and reduce the risk of health problems caused by the release of harmful pathogens into the air and water.

Food Waste

Food waste is rich in various organic substances such as carbohydrates, fats and proteins derived from fruits, vegetables, meat and other foods (Jinno et al., 2017). According to Scialabba et al. (2014), about a third of all food produced for human consumption (1.3 billion tonnes of edible food) is lost every year and wasted along the entire supply chain.

For HTL, food waste can be used as feedstock, and this can make a significant contribution to the reduction of the amount of waste that ends up in landfills. This is a benefit for both the environment as well as public health (Maddi et all., 2017). Moreover, food waste collection can involve the local communities and raise awareness of the need for reducing waste and creating a sustainable source of bio energy.

Nevertheless, if the use of food waste to produce SAF proves profitable, it could paradoxically encourage increased food production and consequently more waste. This could undermine efforts to reduce waste production and hinder sustainability goals. Truly sustainable and circular societies must prioritise reducing food waste at source, rather than simply improving waste management.

Agricultural Residues

Agricultural residues, including straw, husks and other crop residues, are an important but often overlooked biomass resource (Bharti et al., 2021). These feedstocks can be used for HTL (dos Passos et al., 2023). Bharti et al. (2021) discuss the issue in the context of India, noting that large amounts of straw are either left to decompose in waste fields or are burned in several parts of the country. Open burning of agricultural residues contributes to air pollution, releasing harmful pollutants that cause respiratory and other health problems. Conversion of this residue into SAF by HTL reduces the need for open burning and can therefore improve public health. It can also improve the aesthetics of rural areas, creating a better quality of life. Furthermore, by converting agricultural residues into SAF through HTL, farmers and rural communities have more economic opportunities to use residues that would normally be considered waste. This improves social cohesion by strengthening community capacity and promoting empowerment (Schoneveld, 2014; German et al., 2011). In addition, this process does not require the use of land needed for food production and was therefore considered in this analysis to make a positive contribution to food security.

FP

FP can convert a wide range of feedstocks into SAF, including agricultural and forestry residues and non-recyclable plastics.

Agricultural Residues

Almost all agricultural residues that can be used for HTL can also be used for FP. Consequently, the social impacts of using agricultural residues to produce SAF via FP were considered to be the same as those discussed for HTL.

Forestry Residues

FP predominantly uses wood chips, sawdust and other residues from logging and wood processing as a feedstock. Forest residues are by-products of existing forestry activities and therefore no extra land is required for the production. This reduces the risk of conflicts over land use or disruption to existing agricultural activities and has little potential impact on the environment (Steeper, personal communication, 2024).

Non-recyclable Plastics

The amount of plastic being produced continues to grow, even as plastic waste accumulates in the natural environment and in landfills (Cook & Halden, 2020). According to Cook & Halden (2020), current environmental and health impacts related to plastics are still poorly understood but have potentially far-reaching effects on wildlife and human health.

Using non-recyclable plastics as feedstock for FP can reduce plastic pollution, which can contribute to healthier living conditions for communities and a cleaner environment. Furthermore, for communities, it can offer a way to participate in the collection of these non-recyclable plastics. Additionally, it does not require land needed for food production, thereby preserving food security. However, it may paradoxically, intentionally, or unintentionally, encourage the production of more plastic materials, thereby increasing overall plastic waste. This dual effect can complicate efforts towards a sustainable, waste-free society. In addition, plastics are mainly derived from non-renewable fossil sources such as oil and natural gas (Rhodes, 2018), which contain ancient carbon that has been sequestered for millions of years. Using plastics for SAF releases this carbon into the atmosphere, contradicting the goal of SAF to reduce GHG emissions and dependence on fossil fuels.

HEFA

The HEFA technology can process various oil- and fat-rich feedstocks. These feedstocks can be of either vegetable origin or animal origin (Starck et al., 2016). Oil-based wastes and residues can also be feedstocks for HEFA (Seber et al., 2014).

Food-based Feedstocks

The major food-based feedstocks for HEFA are soybean, rapeseed, sunflower seed, corn, palm and coconut oil (de Souza et al., 2020). If agricultural land is used for growing crops meant for SAF production, this raises debate about whether the limited agricultural land should be used for growing food for people, feed for animals, or crops for energy production. This is especially relevant in regions where food security is a challenge. Hasegawa et al. (2020) found that the large-scale use of bioenergy, if not implemented properly, would raise food prices and increase the number of people at risk of hunger worldwide. Recognizing these concerns, the European Union has implemented restrictions on the use of certain food crops for biofuel production under Renewable Energy Directive (RED) II (European Commission, 2018). By encouraging the use of such feedstocks, RED II aims to relieve pressure on food accessibility while promoting renewable energy production. As mentioned before intensive cultivation of crops for biofuels often leads to significant water use and can cause water pollution from pesticide and fertilizer runoff, reducing the availability of clean drinking water and causing disease among local populations (De Vries et al., 2010); (German, Schoneveld, & Pacheco, 2011). It can also negatively affect food security when using land needed for food production. In addition, biofuel crops can change the visual characteristics of agricultural landscapes by promoting monocultures resulting in less diverse landscapes.

Non-food Crop-Based Feedstocks

The main non-food crop-based feedstocks used for HEFA are jatropha, pennycress and camelina (Tao et al., 2017). These feedstocks are an attractive option because they do not compete with food crops, minimizing food security concerns. Jatropha, touted for its ability to grow on marginal lands with minimal water and fertilizer requirements (Tao et al., (2017), initially seemed like a solution to alleviate pressure on food production and valuable water resources (Seber, 2022). However, the actual seed yields have proven disappointing (Singh et al., 2014), while expectations were high (Singh et al., 2014). The challenges must be addressed before the successful commercialization of Jatropha is possible (Agrawal et al., 2023).

Pennycress is a winter plant and therefore does not compete with existing food crops which grow in the summer (Seber et al., 2022). These crops transform the landscape into a continuously green cover. According to Markel et al. (2018), Pennycress absorbs residual nutrients from the soil, reducing the potential for harmful chemical runoff and pollution. Furthermore, this process improves water quality and reduces health risks associated with exposure to these chemicals. In addition, as a ground cover it suppresses weeds, pests and pathogens, helping to improve soil fertility and structure (Markel et al., 2018). A fertile soil can increase yields, and this directly contributes to food security. However, challenges such as heat tolerance and specific growing conditions may limit its productivity in certain regions.

Camelina shares similarities in opportunities and challenges with pennycress in terms of being winter crops and their shared growth conditions (Moser, 2012).

Waste and Residual Feedstocks

The most common waste and residue feedstocks are used cooking oil (UCO), animal fats, like tallow, and Palm Fatty Acid Distillate (PFAD). PFAD is a by-product of palm oil refining and is therefore considered a residual stream (Wolff & Riefer, 2020). The illegal reprocessing of UCO for human consumption poses a serious health risk worldwide. By converting this oil into SAF, this risk can be significantly reduced (Yang & Shan, 2021), thereby improving public health and food safety. According to Moecke et al. (2016), collecting UCO from the community or through subsidized programmes can generate additional income for households. This approach also encourages community engagement in the collection process and offers economic benefits.

The use of animal fats in SAF production raises ethical concerns in relation to animal welfare and meat consumption, as it may indirectly support practices within the meat industry that are often criticised for causing animal suffering and environmental problems. Furthermore, if biofuel production becomes a significant source of income for meat producers, it could provide an incentive for increased meat production, which could conflict with those who oppose meat consumption on ethical, environmental or health grounds. In addition, using land to raise animals rather than to grow diverse food crops can reduce the diversity and accessibility of local food supplies, particularly affecting vulnerable communities.

Using PFAD for SAF production may lead to the expansion of palm oil plantations which can lead to land conflicts, displacement of local communities, and loss of traditional agricultural lands. This can exacerbate social tensions and put pressure on social cohesion (Qaim et al., 2020). Palm oil has relatively high-water requirements, and intensified production of these crops can significantly impact local water resource balances, especially in regions where they are grown under irrigated conditions (Ale et al., 2019). The expansion of palm oil plantations can also to large-scale deforestation (Austin et al., 2017) and land use competition. This competition mainly occurs between farmers and local communities that depend on the same land for their livelihoods and between the preservation of natural wildlife habitats (Andrianto et al., 2019). In addition, it can change the visual landscape from diverse forests into monoculture plantations.

6.6.2.3 Expert Opinion on Social Impact Related to Feedstock Use Performance

A table summarising the findings from the literature review on the social impacts of using various feedstocks for the SAF pathway, which can be found in appendix L, was presented to the experts. The following scale was used to systematically assign performance scores for social impact related to feedstock use:

- Score 1 (significant negative impact) refers to situations where the use of most feedstocks for the SAF technology causes a very negative social impact.
- Score 2 (negative Impact) refers to situations where the use of most feedstocks for the SAF technology results in a considerable negative social impact.
- Score 3 (mixed impact) refers to situations where the social impact related to feedstocks used for the SAF technology are a combination of positive and negative effects.
- Score 4 (positive Impact) refers to situations where the use of most feedstocks for the SAF technology leads to a beneficial social impact.
- Score 5 (very positive Impact) refers to situations where the use of all feedstocks for the SAF technology results in a substantial social impact.

The table below shows the performance scores assigned by the experts, with further details in the accompanying discussion.

Table 20: Performance scores social impact related to feedstock use.

	FP	HTL	HEFA
Performance score	3	4	1

The experts emphasised the importance of social cohesion and land use in the social impact related to feedstock use performance scores.

HEFA received a performance score of 1. On the one hand, HEFA can provide a sustainable pathway when using non-food oil sources and waste oils. This is the case, for example, with UCO, which reduces waste and can reduce clogging in sewage systems, using these feedstocks would justify a significant higher score. On the other hand, the industry in some regions also includes the use of food-related oils such as palm oil, which has led to deforestation and negative impacts on social cohesion in regions such as rainforests. These activities pose risks that are not fully addressed by existing sustainability policies and can lead to significant social disruption.

FP was rated with a 3 because it primarily uses biomass, which can compete with agricultural land and sometimes lead to conflicts about land use. However, the other feedstocks can have positive impacts, so 3 was considered to be a reasonable performance score for this technology.

HTL was awarded a higher score of 4 due to its ability to process a wider range of waste feedstocks, including food waste and sewage sludge. This additional flexibility provides solutions to waste problems that are particularly prevalent in less developed societies. It may also have the potential to address waste management issues in urban areas, helping to improve urban sanitation and public health.

6.7 Technical Criteria Assessments

6.7.1 TRL

This chapter analyses the three technologies using NASA's TRL framework, which assesses and communicates technology readiness from design to implementation. TRL levels provide a common language for understanding technology readiness, facilitating communication within and across organisations. Furthermore, TRL's systematic approach helps manage technology risk and supports informed decisions about development and implementation (Olechowski, 2015).

The definitions of the TRL levels from Beims (2019) were used in this study and are shown in schematic form below.

Table 21: TRL definitions Beims et al. (2019).

TRL	Scale	Description
9	Industrial operation	Production process proved to be technically and economically viable.
8	Industrial operation	Production process established and qualified as technically feasible.
7	Industrial operation	System prototype demonstration with higher production rates.
6	Pilot	Products validated, and kinetic mechanism demonstrated in a pilot plant environment, with low production rates. Continuous operation. Bio-oil upgrading steps considered in the pilot plant.
5	Lab (bench reactor)	Products validated in a laboratory environment. Upgrading techniques. Data regression for the proposal of kinetic mechanisms.
4	Lab (bench reactor)	Products validated in a laboratory environment. Reaction pathways pro-
3	Lab/ Analytical In-	Analytical and experimental tests performed.
2	Theoretical	Technology concept and/or application formulated.
1	Theoretical	Basic principles observed and reported.

Drawing on the findings of the analysis and their expertise, the SAF experts assigned performance scores as detailed in chapter 3.

6.7.1.1 Research Findings on TRL Assessment

A literature review was conducted to identify TRLs for the SAF pathways. Collard et al. (2023) provided TRL assessments for BTG's Empyro plant and Steeper's Silva Green Fuel, focusing specifically on bio-oil production, one of many sub-processes in the HTL and FP pathways, each with different TRLs. Collard et al. (2023) does not address other sub-processes that affect the overall TRLs of these pathways. In contrast, Watson et al. (2024) assessed the overall TRL for HEFA technology, which includes all sub-processes. This distinction needs to be made to understand the scope and limitations of the TRL analysis within this study. The findings are summarised in the table below.

Table 22: TRL research findings

Technology	TRL
HTL (Steeper’s Silva Green Fuel	7-8
FP (BTG’s Empyro plant)	9
HEFA	9

The results show that the bio-oil production technology of BTG's Empyro plant is fully developed with a TRL of 9, indicating that it is economically and technically feasible and ready for commercial use under various conditions (Beims et al., 2019). However, despite this maturity, other sub-processes of the SAF FP pathway may still have lower TRL levels. This indicates that while the bio-oil technology is mature, BTG's overall SAF production pathway may not be fully developed yet.

With a TRL of 7-8, Steeper's Silva Green Fuel is transitioning from system prototype demonstration at a higher production rate to qualification as technically feasible. This indicates that the prototype has been effectively tested in an operational environment and is close to its final state, requiring only minor improvements and enhancements to ensure reliability in various scenarios before commercial deployment. However, although the bio-oil production technology has reached a TRL of 7-8, other sub-processes of the SAF HTL pathway may still be at lower TRL levels, highlighting that the overall readiness of the SAF production pathway may not yet be at TRL 7-8.

For HEFA, the findings demonstrate that the entire SAF pathway is in place and operational. The HEFA pathway has the highest TRL of all ASTM-certified pathways because a large number of production facilities are already in place, operating and delivering fuel to aircrafts (Prussi et al., 2019).

6.7.1.2 Expert Opinion on TRL Performance

The following scale was used to systematically assign the performance scores for the TRL:

- Score 1 (very low Level of development) denotes technologies at the conceptual or experimental stage (TRL 1-3).
- Score 2 (low level of development) indicates a technology that is at an early stage of development (TRL 4-5). This score can also be assigned to technologies where only certain steps in the production pathway have reached a higher TRL, with other key steps still under development.
- Score 3 (intermediate) indicates that the technology is at the pilot or demonstration stage (TRL 6-7). This score can also be assigned to technologies where only certain steps in the production pathway have reached a higher TRL, meaning that full integration and commercial applicability have not yet been achieved.
- Score 4 (high level of development) refers to technologies that are almost ready for commercial implementation (TRL 8), with most components operationally tested and validated.
- Score 5 (very high level of development) refers to technologies that are fully commercially developed and implemented (TRL 9) across the full range of their production processes.

The table below shows the performance scores assigned by the experts, with further details in the accompanying discussion.

Table 23: Performance scores TRL.

	FP	HTL	HEFA
Performance score	3	2	5

HEFA received the highest score, of 5, because this technology has reached a TRL of 9. This is the highest possible score on the TRL scale, indicating that HEFA is fully commercially developed and widely used in industry.

Although FP has also reached a TRL of 9 for the biocrude production step, this score only applies to that step of the process. Since the entire pathway to SAF is not yet fully developed or proven on scale, FP received a lower score of 3.

HTL received an even lower score of 2, as this technology has a TRL of 7-8, indicating that it is still under development.

6.7.2 Efficiency

The efficiency analysis included carbon conversion efficiency, which measures the effectiveness of converting the carbon in the feedstock into fuel, and energy efficiency, which assesses the usable energy in the fuel relative to the energy input required for the pathway. High values for both indicate more sustainable biomass use and less energy waste. In this study, the energy and carbon content of the off-gasses and char from HTL and FP were considered to be waste. However, if re-used, these by-products could improve both energy and carbon conversion efficiencies.

The carbon conversion efficiency can be expressed by the following formula:

$$\eta_{carbon} = \frac{Carbon\ content\ end\_products}{Carbon\ content\_biomass}$$

Where,

- $Carbon\ content\ end\_products$, represents the carbon content of naphtha, SAF and diesel/marine produced
- $Carbon\ content\_biomass$, represents the carbon content of the initial feedstock

The energy efficiency can be expressed by the following formula:

$$\eta_{energy} = \frac{Energy\ content\ end\_products}{Energy\ required}$$

Where,

- $Energy\ content\ end\_products$, represents the energy content of the biomass, energy content of hydrogen, heat required, and electricity required
- $Energy\ content\ end\_products$, represents the energy content of the naphtha, SAF and diesel/marine produced

It is important to note that this energy efficiency calculation method does not reflect how much of the biomass energy is retained in the fuel and how much additional energy is required. For a better illustration of this, reference is made to the Sankey diagrams in chapter 6.2.2. This gives an overview of the exact energy flows for these technologies. In addition, chapter 6.3 describes the utilities required for HTL and FP as derived from the process model. For HEFA, no detailed process model was developed for this study and therefore it was not possible to construct a Sankey diagram. However, the required utilities are shown in 6.3, adopted from De Jong (2018).

Drawing on the findings of the analysis and their expertise, the SAF experts evaluated an overall performance score for the two efficiency factors simultaneously as detailed in chapter 3.

Drawing on the findings of the analysis and their expertise, the SAF experts assessed the overall efficiency performance, considering the two efficiency factors simultaneously. The assessment was carried out by assigning performance scores as described in chapter 3.

6.7.2.1 Research Findings on Efficiency Assessment

The carbon conversion and energy efficiency findings for HTL and FP were derived using the process model and are shown in the table below. For HEFA the carbon conversion and energy efficiency were calculated using data from Tao et al. (2017).

Table 24: Research findings carbon conversion efficiencies.

Technology	η_{carbon}
FP	~ 6[redacted]%
HTL	~ 7[redacted]%
HEFA	~ 9[redacted]%

From this, it can be concluded that HEFA has the highest carbon conversion efficiency, followed by HTL and then FP. This implies that HEFA has the least carbon loss to other by-products during the conversion process, which suggests that HEFA has the most sustainable use of carbon content of the feedstock, followed by HTL and then FP.

Table 25: Research findings energy efficiencies.

Technology	η_{energy}
FP	~ 6[redacted]%
HTL	~ 7[redacted]%
HEFA	~ 9[redacted]%

From this, it can be concluded that HEFA has the highest energy efficiency, followed by HTL and then FP. This implies that HEFA has the least energy wasted during the conversion process, which suggests that HEFA requires the least overall energy, followed by HTL and then FP.

Due to the approximate nature of the energy consumption estimates derived from the process model, it is important to note that it is not possible to make a definitive distinction between HTL, FP and HEFA in terms of efficiency from this analysis. The results should be considered primarily as preliminary indications. For more in-depth decision making or for a comprehensive benchmarking of the technologies in a commercial setting, additional research is required. Further detailed studies are needed to get a more accurate picture of the energy efficiency of these processes.

6.7.2.2 Expert Opinion on Efficiency Performance

The following scale was used to systematically assign the performance scores for the efficiency:

- Score 1 (very inefficient) indicates that the technology is very inefficient.
- Score 2 (inefficient) indicates technologies that are below standard in terms of efficiency. Although some production takes place, the relationship between inputs and outputs is suboptimal.
- Score 3 (average efficiency) refers to technologies that show reasonable efficiency, with reasonable input-output ratios. There are opportunities for improvement through technological improvements that could further increase efficiency.
- Score 4 (efficient) refers to technologies that are effective in converting inputs to desired outputs with minimal losses. These technologies operate close to their theoretical maximum efficiency, but minor improvements may be possible.
- Score 5 (very efficient) refers to technologies that are optimised and perform well with near-optimal input-output ratios.

The table below shows the performance scores assigned by the experts, with further details in the accompanying discussion.

Table 26: Performance scores efficiency.

	FP	HTL	HEFA
Performance score	3	4	5

HEFA received the highest efficiency score, 5, because the feedstock is already in oil form, making processing more efficient. The feedstock requires less complex conversion processes, resulting in higher efficiencies and lower energy consumption per unit of SAF produced.

HTL received an efficiency score of 4. This score was based on HTL's relatively high carbon conversion efficiency, which converts much of the carbon from the biomass feedstock into usable fuel products. This technology converts the carbon properly into end-products, but its energy efficiency still has room for optimisation.

FP received a score of 3 for efficiency. Although FP is effective in converting biomass feedstock to biocrude, the overall carbon and energy conversion efficiencies are lower compared to HTL.

CHAPTER 7

Final MCA Scores

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7. Final MCA Scores

This chapter presents the final MCA scores for three SAF pathways, segmented by stakeholder group. These scores were obtained by combining the performance scores assigned by the SAF experts with the stakeholder weightings, as detailed in chapter 3. The bar chart below visualises the aggregated final MCA scores of each technology for the different stakeholders.

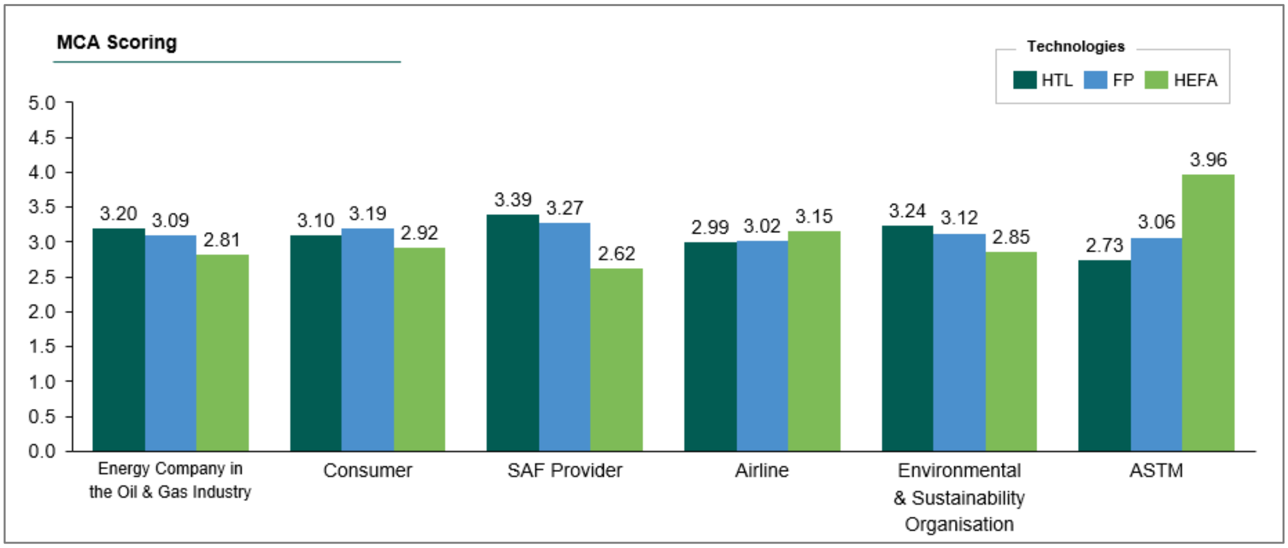

Figure 21: Bar Chart Final MCA scores.

This bar chart shows that no single technology consistently obtained the highest final MCA scores from all stakeholders. Preferences for technologies vary between different groups, suggesting that stakeholders assess the strengths and weaknesses of each technology differently. For example, ASTM stakeholders prefer HEFA because of its focus on TRL. The final MCA scores imply that industry-specific interests influence the evaluation of technologies. Moreover, the bar chart indicates that HTL most often obtained the highest final MCA scores among the stakeholders, ranking first three times among the energy company in the oil and gas industry, the SAF provider and the environmental & sustainability organisation. This pattern may suggest a broader acceptance of HTL compared to FP and HEFA among these stakeholder groups. Furthermore, although the final MCA scores allow for a ranking of the SAF technologies by stakeholder, the scores are very close. This implies that no single technology stands out as the clear 'best' or 'worst' for any stakeholder, and such conclusions should not be drawn from these rankings.

7.1 Ranking Energy Company in the Oil & Gas Industry

For the energy company in the oil and gas industry, the final MCA scores and rankings were as follows: HTL (3.20) > FP (3.09) > HEFA (2.81). HTL achieved the highest final MCA score because this stakeholder gave considerable weightings to several criteria where HTL performed strongly, as indicated by the performance scores assigned by the SAF experts.

Although GWP was the most important criterion for this stakeholder, the equal performance score of 3 for all technologies meant that it did not differentiate the technologies in the ranking. Instead, other key criteria, feedstock cost and social impacts related to feedstock use, were the main determinants. Both HTL and FP scored 4 for feedstock costs, but HTL excelled in social impacts related to feedstock use with a performance score of 4 compared to FP's 3. Despite HEFA's relatively high performance score of 4 for CAPEX, another criterion considered critical by this stakeholder, its relatively lower scores of 1 for both feedstock costs and social impacts related to feedstock use were the primary reasons for its lower overall ranking.

7.2 Ranking Consumers

For the consumer, the final MCA scores and rankings were as follows: FP (3.19) > HTL (3.10) > HEFA (2.92). FP achieved the highest final MCA score because this stakeholder valued several criteria where FP excelled according to the SAF experts' performance scores.

Although GWP was again considered the most important criterion for this stakeholder, the uniform performance score of 3 for all technologies meant that it did not influence the ranking. Instead, the use of by-products and feedstock costs were the main determinants. Both FP and HTL scored relatively high for the use of by-products, with scores of 4 and 3 respectively, which improved their rankings. Similarly, FP and HTL both scored a relatively high 4 for feedstock costs, further improving their rankings. Conversely, HEFA scored 2 for the use of by-products and 1 for feedstock costs, which negatively affected its overall ranking. Despite HEFA's relatively better performance on OPEX and CAPEX, these criteria were considered less critical to this stakeholder, minimising their impact on the final MCA scores.

7.3 Ranking Airline

For the airline, the final MCA scores and rankings were as follows HEFA (3.15) > FP (3.02) > HTL (2.99). HEFA obtained the top position mainly due to its relatively high performance scores of 4 for both OPEX and CAPEX, which were considered the most critical criteria for this stakeholder. After OPEX and CAPEX, the most important criterion was feedstock costs. Despite HEFA's low score of 1 for feedstock costs, its relatively strong performance on the key cost criteria compensated for this. Both FP and HTL, with a score of 4 for feedstock costs, were unable to compete with HEFA, mainly because their performance on OPEX and CAPEX was not as strong. Although GWP was again also considered important for this stakeholder, the uniform score of 3 for all technologies meant that it did not influence the differentiation in the ranking.

7.4 Ranking Environmental and Sustainability Organization

For the environmental and sustainability organisation, the final MCA scores and rankings for the SAF technologies were as follows HTL (3.24) > FP (3.12) > HEFA (2.85). The ranking was mainly influenced by the social impact related to feedstock use, where HTL's relatively higher score of 4 compared to FP's 3 and HEFA's 1 contributed greatly to its leading position. In addition, GWP was again considered important by this stakeholder, but the uniform score of 3 for all technologies meant that it did not influence the differentiation in the ranking. In addition to these criteria, safety was also considered important by this stakeholder, but had less impact on the final MCA score. Despite HEFA's relatively high safety score, it could not compensate for its low scores on the key social criterion, resulting in the lowest final MCA score.

7.5 Ranking SAF Provider

For the SAF provider, the final MCA scores and rankings were as follows: HTL (3.39) > FP (3.27) > HEFA (2.62). Unlike the stakeholders discussed previously, where the final MCA scores were quite close, HEFA's final MCA score is notably lower than that of HTL and FP for this stakeholder. The most influential criterion was feedstock costs, where both FP and HTL performed well with a score of 4, while HEFA scored lower with a score of 1. This difference contributed to HEFA's lower ranking. The second most important criterion was social impact related to feedstock use, where HTL's score of 4 supported its relatively high ranking. FP, with a score of 3, was competitive but did not outperform HTL. HEFA's lower performance score of 1 created a larger gap, affecting its ranking. GWP was again also considered important, but the uniform score of 3 for all technologies meant that it did not affect the ranking. Also, TRL was considered to be a relatively important criterion for this stakeholder, but it’s weighting was lower than the others and therefore did not have a major impact on the final MCA scores. So, despite HEFA's relatively high TRL performance score, it could not compensate for its lower scores in the key criteria, resulting in its lower final MCA score.

7.6 Ranking ASTM

For ASTM, the final MCA scores and rankings were as follows: HEFA (3.96) > FP (3.06) > HTL (2.73). In contrast to the other stakeholders, where the final MCA scores were quite close, HEFA's score is considerably higher than that of HTL and FP for the ASTM. This was largely determined by the performance of the technologies on the TRL criterion, which was relatively the most heavily weighted for this stakeholder. HEFA scored relatively the highest on this criterion with a 5, compared to FP's 3 and HTL's 2. In addition, HEFA scored high on efficiency, another criterion with significant weighting for the ASTM, achieving a score of 5 compared to HTL's 4 and FP's 3. GWP, again an important criterion for this stakeholder, but with all technologies scoring equally, did not affect the differentiation of the MCA ranking. The final MCA scores indicate that HEFA performs well in the areas most valued by ASTM, resulting in a substantial lead over FP and HTL for this stakeholder.

7.7 Sensitivity Analysis

To assess the robustness and reliability of the MCA results, a sensitivity analysis on the expert performance scores was conducted for this thesis. This analysis examined how changes in the expert performance scores could affect the final MCA scores and rankings of the SAF technologies. By doing so, it gave an indication on to what extent the MCA results depend on the subjective assessments of the experts. The focus was on the criteria that were relatively most heavily weighted by the majority of the stakeholders: feedstock price and social impacts related to feedstock use. GWP was excluded from the sensitivity analysis as its consistent performance score across the technologies would not affect the rankings if varied. Therefore, feedstock costs and social impact related to feedstock use were varied by ±50% to observe their impact on the rankings and final MCA scores.

It was decided not to conduct a sensitivity analysis on the criteria weightings due to the limited time available and because the different weightings given by the stakeholders could already illustrate to some extent how different perspectives influence the results of the MCA.

The sensitivity analysis for the feedstock price showed that the MCA rankings generally remain stable with substantial variations in the feedstock price, apart from the specific case of the airline. Increasing the feedstock price highlights the differences between the TL and HEFA technologies, while decreasing it makes the technologies more comparable in terms of their final MCA scores. This suggests that the feedstock price is an impactful criterion in the comparison of the SAF technologies. Furthermore, for social impacts related to feedstock use The MCA ranking were robust, as the ranking remains almost unchanged when increasing/decreasing by 50%. Although there are small shifts in the final MCA scores, the relative positions of the technologies remain largely stable. When comparing the two sensitivity analyses it can be concluded that changes in the performance scores for social impacts related to feedstock use performances scores have less impact on the final MCA scores than for feedstock price, suggesting that feedstock price is a more influential criterion.

The detailed results of the ±50% social impact related to feedstock use and feedstock costs sensitivity analyses are shown in appendix V.

7.8 Conclusion of MCA Results

This thesis aims to answer the research question: *'How do HTL and FP compare with the HEFA route in the production of SAF from a technical, environmental, economic and social point of view, taking into account the perspectives of multiple stakeholders?*

The final MCA results show that while there are differences in performance between the SAF technologies, they are not so pronounced that definitive conclusions can be drawn about the superiority of any of the technologies. The final MCA scores are close to each other, suggesting that while there are advantages and disadvantages to each option, no single technology can be consistently considered significantly better or worse than the others on all the criteria assessed. This aligns with Shehab et al. (2023) who state that there is no silver bullet on which SAF pathway to implement and that all pathways are needed in parallel to maximise SAF production.

The close range of the final MCA scores often illustrated that what is an advantage for one criterion may be a disadvantage for another. For example, technologies such as FP and HTL are able to process more and rougher feedstocks than HEFA, which can be advantageous in terms of feedstock price and social impacts associated with feedstock use. On the other hand, this also results in more severe process conditions, which is a disadvantage for their performance in areas such as safety in terms of potential risks and OPEX.

While the MCA results do not directly indicate a superior technology, they can provide valuable insights that can potentially be used by policy makers and companies to shape their strategies. Using the outcomes of this thesis, decision-makers can develop a better understanding of how the different SAF technologies compare in terms of performance across a wide range of criteria, helping them to make more informed choices. In the following chapter, this will be further elaborated.

CHAPTER 8

Conclusion and Discussion

The airplane picture is generated using Canva's AI, Magic Studio™

8. Conclusion and Discussion

8.1 Answers to Research Questions

To conclude this study, this section provides answers to all the research questions.

Which stakeholders are involved in the implementation of HTL and FP to produce SAF, and what are their interests and influences?

To answer this question, key stakeholders were categorized into quadrants using a power-interest grid. The quadrants are: Players, Subjects, Context Setters and the Crowd. Players, with great power and interest, include SAF providers, airlines, ASTM, aviation engine manufacturers, and secondary fuel use market players. They are directly involved in the development, adoption, and use of SAF technologies and influence the dynamics of the market. Subjects, with high interest but low power, such as environmental organizations, nearby residents factory sites biomass sites, R&D institutions, and feedstock suppliers. They focus on the environmental and social impacts of SAF but have limited decision-making power. Context Setters, possessing considerable power but little interest, include energy companies, airports, the European Commission, and national governments, impact through financial and regulatory means but show limited interest in specific SAF technologies. Finally, the Crowd, with minimal power and interest, consists of investors, financers and consumers, who are more focused on generally oriented towards market trends and overall sustainability rather than on specific SAF technologies.

Due to time constraints, key stakeholders, defined as key informants, from the quadrants were selected for the detailed analysis in this study. The selected stakeholders are: SAF production companies, airlines and ASTM from the Players. Environmental and sustainability organisations from the Subjects. Consumers from the Crowd and energy companies in the oil and gas industry from the Context Setters. This selection ensured a comprehensive representation of relevant stakeholder perspectives that could be incorporated into the study within the timeframe of the study.

Which criteria and their respective weightings should be considered when evaluating SAF production technologies?

To address sub-question two, a literature review was conducted to identify the relevant criteria for this study. These criteria were categorized into four dimensions: environmental, economic, technical, and social. The environmental criteria included the GWP and use of by-products, and the economic criteria focused on CAPEX, OPEX, and feedstock price. Recognizing a gap in existing literature that often omits the social dimension in the evaluation of TL technologies, this study incorporated social criteria. These included the broader social impacts of feedstock use and safety. The technical criteria included TRL and efficiency.

The weightings of these selected criteria were determined through structured interviews with the selected stakeholders using the BWM. The input-based consistency ratio, as proposed by Liang et al. (2020), was used to ensure consistency and reliability of the responses. The selected criteria and their weightings together form the MCA framework for the evaluation of the HTL, FP and HEFA SAF production pathways.

How do HTL, FP and HEFA perform according to the criteria analyses and the performance scores assigned by the experts?

The assessment of HTL, FP, and HEFA technologies for SAF production was conducted through criteria analyses supplemented by expert performance scores.

Environmental Criteria Assessment

The GWP analysis used a simplified 'well to wake' LCA to analyse the emissions (in gCO_2eq per MJ) of the three SAF technologies across three scenarios, conservative, mixed, and progressive, each reflecting different carbon intensities from utilities like electricity, hydrogen, and heat. In this analysis, FP exhibited the highest GWP in the conservative and progressive scenarios mainly due to higher hydrogen production emissions. In the mixed scenario, HTL recorded the highest GWP, influenced by lower hydrogen production emission factors and greater contributions from heat production. HEFA consistently had the lowest GWP across all scenarios, benefiting from efficient use of hydrogen and heat. All technologies received a uniform expert performance score of (3), because of the potential for further GWP reduction through the recovery of off-gases and char for heat generation was noted, particularly for HTL and FP. This consideration suggests that integrating these by-product recovery processes could lead to environmental benefits.

The by-product analysis, derived from an extensive literature review, showed both the potential uses and the challenges associated with these by-products in the context of SAF production. HTL by-products, such as aqueous phases and solid residues, have potential uses in energy and chemical production. However, the environmental impact of processing these by-products, such as the potential for increased pollution, calls for efficient management practices to enhance HTL's sustainability and circularity. FP produces biochar and gases that are beneficial for both energy production and soil enhancement. Despite these environmental benefits, including carbon sequestration and improved soil fertility, the technical and cost challenges of removing impurities like tar from these by-products present challenges. HEFA produces a variety of by-products, including water, CO_2, propane, and other gases, which offer opportunities for reuse or sale. However, the cost and complexity of integrating advanced treatment and separation technologies to fully exploit these by-products require significant investment and often entail modifications to existing facilities.

The experts awarded FP the highest score (4), recognizing the economically viable applications of its biochar. HTL received a neutral score (3) due to its environmental handling challenges, while HEFA was scored the lowest (2) due to the comparatively less profitable by-product valorisation.

Economic Criteria Assessment

The economic criteria analysis expanded beyond the selected metrics, CAPEX, OPEX, and feedstock price to include the revenue of the co-products, diesel and naphtha. This comprehensive approach allows for a more accurate comparison by considering the economic impact of process inefficiencies and the value generated from alternative end-products. In addition, two scenarios, conservative and progressive, were defined for the OPEX assessment associated with process utilities. In terms of CAPEX, HTL required the greatest investment due to its complex equipment needed to handle large volumes of feedstock, reflecting the highest CAPEX. HEFA, due to its scalable and cost-optimized operations, exhibited lower CAPEX, making it an economically attractive option. FP's CAPEX were also on the lower end but likely underestimated.

The OPEX were assessed through conservative and progressive scenarios, with HEFA showing the lowest OPEX due to its minimal hydrogen requirements. In contrast, FP faced the highest OPEX attributed to its intensive operating requirements. HTL's OPEX were mid-range, higher than HEFA but less than FP, influenced by the technology's high pressure and energy requirements.

Feedstock costs are highest for HEFA, which uses expensive used cooking oil, while HTL and FP use cheaper forest residues, with HTL being slightly less efficient in converting feedstock into SAF and therefore having a higher overall feedstock price.

HTL showed the highest market value of co-products, benefiting from favourable process yields that enhance its economic profile. On the other hand, HEFA displayed a lower market value for its co-products, which are less valuable in the market.

The expert scored HEFA high on both CAPEX and OPEX (4 each) because of its efficient operations. HTL received a (2) for CAPEX and a (3) for OPEX; FP received a (3) for CAPEX and a (2) for OPEX. HEFA's low feedstock score of (1) emphasized the cost challenges posed by high-priced feedstocks, while HTL and FP were viewed as more economically viable in terms of feedstock prices with a (4).

Social Criteria Assessments

The safety analysis was carried out through a detailed literature review using the methodology of Pokoo-Aikins et al. (2010), which assesses safety based on operating conditions and chemical properties. Key findings highlighted that HTL, operating at high pressures (300-340 bar), presents significant safety risks related to facility stability. FP, although operating at lower pressures, poses corrosion risks due to the unstabilised pyrolysis crude oil. HEFA, being more established, has lower safety risks due to controlled processes within the industry. The expert scores indicated that HEFA has a relatively low risk with a score of (4), while FP and HTL, with manageable risks, both received a score of (3).

The "social impact related to feedstock use" analysis was conducted through a comprehensive literature review highlighting how each technology is influenced by factors like social cohesion, public health, quality of life and food security.

Key findings showed that HTL excels at processing wet biomass such as algae and sewage sludge, which contributes to waste reduction and minimises environmental risks. This capability not only contributes to a cleaner environment but also enhances public health by reducing landfill usage and mitigating potential pollution sources. The conversion of such waste materials into valuable energy resources aligns with sustainable waste management practices and circularity.

FP technology processes diverse feedstocks, including agricultural and forestry residues as well as non-recyclable plastics, improving soil and public health and reducing landfill waste. However, the use of non-recyclable plastics can unintentionally encourage increased plastic production, complicating efforts to achieve a sustainable society.

Whereas HEFA, which uses oil-rich feedstocks like palm oil, has been criticized for potential deforestation and impacts on food security, it also contributes to waste reduction and promoting recycling practices.by processing used cooking oils as a feedstock. The dual nature of HEFA's feedstock use presents both challenges and opportunities for sustainable development.

The expert scores reflected these dynamics, with HTL receiving a high score (4) for its beneficial environmental and public health impacts, FP getting a moderate score (3) for its balanced positive social impacts, and HEFA scoring lower (1) due to concerns related to the use of food-based oils. This assessment highlights the intricate relationship between the technologies and their broader social impacts. It stressed the importance of a holistic approach that balances the technological advancements with their social and environmental consequences, aiming to enhance overall sustainability in SAF production.

Technical Criteria Assessments

The TRL analysis, based on the definitions of Beims (2019), assessed the level of maturity of the technologies from conceptualization to commercial deployment. A comprehensive literature review identified TRLs for each technology, providing insights into their operational readiness and potential for full-scale implementation.

The assessment highlighted that HTL, and FP's maturity was analysed primarily at the biocrude production plant level, whereas HEFA's maturity encompassed the entire SAF production pathway. Research findings revealed that BTG's Empyro FP plant has achieved full Steeper's Silva Green Fuel HTL plant is in late development approaching commercial readiness with a TRL of 7-8, specifically at prototype validation. Meanwhile, HEFA stands out with a TRL of 9 for its complete production pathway, signifying it is fully commercialized and widely implemented across the industry.

Expert assessments confirmed these findings, with performance scores reflecting the differing stages of technology maturity. HEFA received the highest score of (5). Despite FP's biocrude plant achieving a TRL of 9, it scored a (3) due to the overall SAF production pathway not yet being fully developed or proven at scale. HTL received a score of (2), reflecting its earlier development stage and the unproven nature of its complete production pathway to SAF.

The efficiency analysis focused on calculating carbon and energy conversion efficiencies. This assessment evaluated how effectively each technology converts the carbon in the feedstock into usable fuel and how much usable energy is extracted from a given amount of feedstock, taking into account both the energy input from process utilities and the initial energy content of the feedstock.

Research findings highlighted that HEFA leads in both carbon and energy efficiency metrics. With a carbon conversion efficiency of 9[redacted]% and an energy efficiency of 9[redacted]%, HEFA showcased the lowest energy losses and the most effective utilization of carbon from UCO. HTL followed, achieving a carbon conversion efficiency of 7[redacted]% and an energy efficiency of 7[redacted]%, reflecting its capability to effectively transform biomass into valuable fuel products, though with some energy loss. FP, with carbon and energy efficiencies of 6[redacted]% and 6[redacted]% respectively, demonstrated lower performance in these areas compared to HEFA and HTL.

The expert performance scores confirmed these findings. HEFA received the highest score of (5), reflecting its high efficiency levels in converting UCO into biofuel. HTL was awarded a score of (4), acknowledging its high carbon efficiency due to its relatively high carbon conversion efficiency, though it falls short of perfect due to energy losses. FP received a score of (3), indicating that while it is effective at converting biomass to biofuel, it does so with less efficiency in carbon and energy terms compared to the other technologies.

How do HTL and FP compare to the HEFA pathway when the performance scores assigned by experts are combined with the criteria weightings established by stakeholders to calculate a final score?

When analysing HTL, FP, and HEFA pathways using an MCA that incorporates expert performance scores and stakeholder criteria weightings, the findings indicated that no single SAF technology consistently emerges as the top choice across all stakeholder groups. Each technology has different strengths and weaknesses, which are valued differently by various stakeholders, underscoring the need for a balanced perspective in SAF implementation decisions.

HTL is preferred by the SAF provider, energy company and the environmental organization for its lower feedstock costs and positive social impacts. Conversely, FP is favoured by the consumer for its efficient by-product. The airline and ASTM preferred HEFA due to its lower OPEX and CAPEX and higher TRL, illustrating its appeal in terms of economic and technical viability.

The sensitivity analysis within the MCA highlighted the influence of feedstock price on the final scores, emphasizing its importance in evaluating SAF technologies. This variation demonstrates that preferences among stakeholders can shift based on the cost of the feedstock.

Overall, while HTL frequently received the highest scores for its favourable economic and social impacts, the choice between HTL, FP, and HEFA ultimately depends on the specific priorities of each stakeholder group. This variability suggests that a comprehensive approach, considering multiple viewpoints and criteria, is important in selecting the most suitable technology for SAF production.

Answer to Main Research Question

In addressing the main research question: *"How do HTL and FP compare to the HEFA pathway in producing SAF across technical, environmental, economic, and social aspects, while considering the perspectives of multiple stakeholders?"* the analysis reveals diverse preferences among stakeholders based on multiple criteria. HTL and FP emerge as potential alternatives to HEFA, each presenting different advantages. Technically and economically, HEFA is currently more advantageous across most of the stakeholders due to its maturity and lower associated costs. However, HTL and FP are particularly notable for their environmental and social benefits, which stem from their use of varied feedstocks and the potential for by-product valorisation. This diverse assessment highlighted the necessity of a multifaceted approach in SAF technology selection, which considers the varied priorities and values of different stakeholder groups. Furthermore, it underscored the importance of incorporating comprehensive, balanced evaluations that consider both technical performance and broader impacts to ensure the chosen technology aligns with industry standards as well as sustainability goals.

8.2 Discussion

8.2.1 Limitations and Possibilities for Future Research

For this thesis were a number of potential limitations. A first general limitation could be seen in the collaboration with SkyNRG. The cooperation with SkyNRG undoubtedly provided valuable insights and access to expertise crucial to this study. Nevertheless, the involvement of a commercial organisation introduced the risk of unintentional bias that may have affected the presentation and interpretation of the findings. Through regular consultation and review with academic supervisors, a rigorous review of all aspects of this thesis was ensured. This minimised the influence of any possible subjectivity from the collaboration with SkyNRG.

A fundamental limitation of this study was that the SAF technologies assessed were at different levels of technological maturity. Since HEFA is a more advanced technology it often has better documented records of its performances and more established methods of evaluation than the more novel technologies, HTL and FP, that are still in development. This difference in maturity could have led to distorted results and affected the comparative analysis. The situation could have raised that the established technology, HEFA, could have potentially been evaluated disproportionately positively or negatively compared to the less mature alternatives, HTL and FP.

Several measures were taken to reduce this limitation's impact and provide a more balanced basis for the comparison. Firstly, in-depth interviews were conducted with experts to gain a thorough understanding of the current state of each technology. These interviews helped to better understand and interpret each technology's capabilities and potential future developments. Secondly, the study's time-agnostic nature was explicitly considered when experts assigned the performance scores. For this purpose, potential future improvements, such as advances in heat integration for FP and HTL, were included in their evaluation to ensure a broader and deeper understanding of the future potential of each technology. Except for the TRL criterion assessment, here future improvements were intentionally not considered in order to provide a clear picture of where each technology currently stands in its development.

The following sections discuss the specific limitations of the process model, criteria, assessments and methodology.

8.2.1.1 Limitations Methodology

Experts Assigning Performance Scores

Using the restricted Likert scale 1-5 for performance scores may result in less detailed differentiation between the performance of the technologies. This may have led in a less accurate or representative scores, especially if the actual performance differences are subtle. The used scale may have affected the final MCA score through a ‘capping effect’ where high performance is not adequately distinguished, which may have led to the homogenisation of the final MCA scores. Future research could consider using a broader scale or additional quantitative measures to provide a more nuanced picture. The current study did not use this approach, suggesting an area for improvement in future studies.

The allocation of performance scores solely by experts may have led to an imbalance, as the weighting of the criteria was determined by more stakeholders. This could have provided a distorted picture, especially if the perceptions and interests of experts differ from those of other stakeholders. For future studies, a wider range of stakeholders can be involved in the performance scoring process. This can be accomplished through workshops, surveys, or mixed focus groups that include both experts and non-experts stakeholders.

Stakeholder Selection

The selection of stakeholders for the weighting process of criteria in this thesis did not include all of the stakeholders defined in chapter 4.1. This may have led to an incomplete or biased representation of the interests. The study clearly stated why certain stakeholders were excluded, which provides some transparency, but it does not solve the fundamental problem of under-representation. In addition, only one person per selected stakeholder group was included. This may not have fully captured the complete range of opinions and perspectives within that group and may have reduced the accuracy of reflecting the actual consensus, or lack of it, within each stakeholder group.

Future studies could aim for a more inclusive approach by including more stakeholder groups and more members from each stakeholder group. This would help to provide a more balanced and representative picture of common and diverse interests. This might be achieved, for example, through the use of workshops, focus groups and extensive surveys.

BWM Criteria Weighting
When assigning weightings to the criteria using the BWM in this thesis, some stakeholders may have been more familiar with SAF technologies than others. This may result in a biased weightings of the criteria for some stakeholders. This could have affected the final MCA score and ranking of the SAF technologies. In order to address this issue, future studies could include educational sessions prior to the BWM weighting process to ensure a basic level of understanding among all stakeholders.

Furthermore, only the input-based consistency ratio was used to test whether the stakeholder responses were consistent. By using only this ratio, the consistency of stakeholder responses may be less accurately assessed. For future research, the output-based consistency ratios from Rezaei (2015) could also be used to measure the degree of consistency.

Temporal Scale
The study used a multi-temporal timescale, which was considered suitable for this preliminary exploratory MCA. For future policy decisions, it is recommended that a single time scale is used for all analyses to improve accuracy and comparability.

8.2.1.2 Limitations Process Model

A limitation of the process model in this study was the selection of BTG and Steeper as technology providers. This choice may have had an impact on the results of the study, as the selection of other technology providers may have led to different results. This underlines the limited representativity of the study results for the industry as a whole. The choice of these specific technology providers was well thought out and is clearly documented and justified in the thesis. Nevertheless, the possibility remains that the choice of technology providers may have influenced the research findings. It is therefore suggested that future research could benefit from a wider choice of technology providers to increase the generalisability of the findings.

Another limitation of the process model was the simplification of certain aspects of the FP and HTL processes, as described in 6.2.1. This was deemed necessary due to the lack of detailed information from the technology providers. These simplifications may have resulted in less accurate estimates which do not fully reflect the reality. This limitation is well documented and justified in the thesis, where it is explained that the available data was insufficient to support fully detailed modelling. For future work, it is recommended to engage in closer collaborations with technology providers without confidentiality restrictions. This could lead to better access to detailed data and would allow for more accurate estimation of mass and energy flows and the resulting process utilities of the TL technologies. Such collaboration could significantly improve the depth and reliability of the process model, thereby improving the refinement of the SAF technology criteria assessments.

8.2.1.3 Limitations Criteria Assessments

Limitations Environmental Criteria Assessments
The assumptions made for the GWP assessment may have over- or underestimated the environmental impact of SAF production pathway systems, depending on the circumstances. This may have distorted the actual GHG reduction potential of the technologies. For example, not including indirect environmental impacts, such as land-use change, may have led to an under or over-estimation of the overall environmental impact of the technologies. This has implications for the completeness and accuracy of GWP calculations, as land-use changes can be important sources or sinks of GHGs. In addition, the exclusion of certain life cycle emissions,

such as those associated with the construction and maintenance of production facilities, may have led to an underestimation of the overall environmental impact of the technologies.

Future studies undertaking an LCA for these SAF technologies should aim for a comprehensive and detailed approach to improve the accuracy of the assessment. For example, this could include the development of detailed models that explicitly include logistical factors such as storage and transport, as well as indirect impacts such as land use change. A full LCA covering all stages of production, use and disposal of technologies is also recommended.

For the by-product criterion assessment, this thesis has been limited to the by-products directly resulting from the HTL, FP and HEFA processes. This excluded the by-products generated during the pre-treatment or the upgrading processes. The exclusion of these by-products may have resulted in an incomplete picture of the overall environmental impact and re-use for the SAF technologies. In order to avoid misunderstandings, it is clearly defined in this thesis what is meant by by-products and why some are excluded. For future studies, a more comprehensive inclusion of by-products, including those generated during pre-treatment and upgrading, could be explored. This would provide a more complete picture of the impact of SAF production processes.

Furthermore, the detailed literature review provides a useful starting point for exploring the by-product valorisation of the SAF production technologies. However, future studies could aim at a deeper exploration to identify potential technological innovations that could increase the circularity of within the SAF technologies.

Limitations Economic Criteria Assessments

For the economic criteria assessments, academic data were used for the CAPEX of HTL and FP. This may differ from actual industry data and therefore affect the economic analysis, which may have affected the comparison of the different SAF technologies. The sources of the information are clearly cited, and it is recommended that future studies use more recent and realistic industry data to substitute this data. The industry data can for example be made available through collaboration with industry partners.

In addition, these sources of CAPEX estimates for HTL and FP processes are relatively outdated, and a future study will benefit from incorporating the latest market data and technological developments.

Furthermore, the process yields employed for the SAF technologies have a significant impact on the research findings for the economic criteria assessments. It can be concluded from this thesis that the research findings were sensitive to the process yields input data and variability in this data can lead to substantial variations in the reported economic performance of the different SAF technologies. Future studies could investigate the factors influencing the process yields and integrate a risk analysis into the economic assessment.

Limitations Social Criteria Assessments

The safety criterion assessment considered a limited number of safety factors because of the lack of data for other key safety factors. This allowed the analysis to be based on proven data and avoided making assumptions. Nevertheless, the absence of complete data for all relevant safety factors may lead to an underestimation of potential risks, which may distort the comparative safety assessment for the different SAF technologies. Future studies could aim to collect more complete data on all relevant safety factors. This could be achieved through industry surveys, collaboration with technology providers and the integration of practical field research.

Although the social impact related to feedstock use criterion assessment is already very comprehensive and thereby filled a knowledge gap, it has limitations. The factors examined are social cohesion, public health, food safety and quality of life. However, there are other relevant social impact factors that were not included due to missing data. It is clearly documented that the focus of this analysis has been on the most directly observable and influential social impact factors, and it is acknowledged that the analysis is not complete. The lack of full consideration of all potential social impact factors may mean that an incomplete assessment of the true social impacts of SAF production technologies is being carried out, thereby affecting the comparative analysis. In addition, data were only collected from a literature review. Future studies could aim to collect and integrate more comprehensive data on social impact factors. This could be achieved by working with local communities, governments and non-profit organisations to collect a wider range of data. In addition, longitudinal studies could be conducted to monitor the long-term effects of SAF production technologies on communities.

Limitations Technical Criteria Assessments

For the TRL criterion assessment, for HTL and FP only the TRL for bio-crude production is considered, whereas for HEFA the whole SAF production pathway is considered. The thesis clearly explains why this choice was made and how the results should be interpreted. This inconsistency in the criterion assessment may have resulted in an unbalanced or comparisons between the SAF technologies. Future studies could consider adopting a consistent approach to assessing TRL across the SAF technologies. The approach should include all stages of the production pathway to ensure a balanced and comparative foundation for all the SAF technologies.

The efficiency criterion assessment excludes losses to the environment. This potentially led to an overestimation of the true energy and carbon conversion efficiency of the SAF technologies. This has been explicitly addressed and must be recognised in interpretations. Nonetheless, not taking losses into consideration may have resulted in a distorted picture, with certain SAF technologies appearing more efficient than others. Future studies could construct a comprehensive energy and mass balance where all energy and mass flows, also the losses to the environment, are accurately quantified.

8.2.2 Relevance to CoSEM Program

This study aligns with the CoSEM program's main aims. Firstly, it consists of a design component, particularly in the development of an MCA framework. Given that it explores the complexities of SAF, the topic is fundamentally technical. Choosing the proper criteria for the MCA is dealt with systematically and creatively by combining interviews and literature reviews to determine the best criteria.

In addition, the CoSEM methods and tools in this study, such as multi-criteria analysis, the IDEFO-diagram and the PI-grid, are used to determine public as well as private interests because public as well as private stakeholders are included in the weighting of criteria. Finally, this study makes a convincing link with the energy track by focusing on SAF, which is a crucial part of the comprehensive sustainable energy system.

8.2.3 Scientific Relevance and Implications

The scientific relevance of this thesis lies in its comprehensive and multidisciplinary approach to address three knowledge gaps in the literature discussing TL technologies to produce SAF, consisting of the 12 papers detailed in appendix A. The scientific relevance of this study is underscored below by illustrating its alignment with other research in the field.

Previous research on TL technologies has primarily focused on technical and economic evaluations, specifically examining the performance of FP and HTL in studies by Wang & Wu (2023), Emmanouilidou et al. (2023), Krylova et al. (2023) and Tanzil et al. (2021a). Emmanouilidou et al. (2023) conducted a thorough literature review of the technical characteristics of bio-oil and found mostly consistency with the findings of this study. Krylova et al. (2023) highlight that hydrotreating the bio-oil from FP requires significant amounts of hydrogen and is uneconomical due to strict technological conditions. This contrasts with the findings of this study which, while acknowledging that FP has not yet reached economic excellence according to performance scores assigned by SAF experts, were not considered be completely uneconomic. Tanzil et al. (2021a) notes that pyrolysis derived bio-oil has a high oxygen and solids content, high viscosity, chemical instability and corrosive properties, which are consistent with the findings of the safety analyses in this thesis. Wang & Wu (2023) note that HTL requires complex, high-pressure equipment, which is consistent with the findings of this thesis regarding the relatively high costs.

Okolie et al. (2023) have found in their MCA that HEFA performs relatively better than FP, which is consistent with the findings of this research for almost all stakeholder final MCA rankings. With exception of the consumer MCA ranking where FP outperformed HEFA. The criteria set of Okolie et al. (2023) and the set of this study share some criteria, OPEX, CAPEX, GWP and energy efficiency, but the rest is different.

Björnsson & Ericsson (2024) concluded in their LCA that for FP, the GHG emissions range from 30 to 33 g CO_2eq/MJ when hydrogen is sourced from fossil natural gas. This figure is higher than the GHG emissions of 25 g CO_2eq/MJ calculated in this study for FP in the conservative scenario. Although this represents a difference, it is not substantial.

Van Dyk et al. (2019) observed significant differences in their LCA between two different upgrading techniques for FP and HTL. One of the techniques for FP aligns closely with the LCA results of this study. However, for HTL, both techniques showed substantial differences. This may be because different emission factors have been chosen and these have a big impact on the LCA results.

This study added new insights to the existing literature by uniquely evaluating TL pathways against HEFA. Firstly, this was done by incorporating social aspects related to feedstock use and safety. Previous research had mainly focused on economic, technical and environmental aspects, but still overlooked social dimensions. Incorporating these social criteria provided a more holistic and inclusive assessment of the SAF pathways, thereby addressing a knowledge gap in the literature.

Secondly, the MCA involved a broad selection of stakeholders, bringing to the forefront different perspectives within SAF's value chain. Stakeholders from different quadrants of the PI grid were selected, reflecting the different level of influence and interest of different stakeholders. This multi-perspective approach thereby added new insights to the existing literature by highlighting the influence of stakeholder opinions on SAF technology preferences, an aspect not previously explored.

Thirdly, this study incorporated more recent data by establishing contact with two TL technology providers and conducting interviews to gain a deeper insight into their technologies. These findings were then incorporated into the MCA, enriching the existing literature with updated and practical information on TL technologies.

The multi-perspective MCA framework has been applied exclusively to three SAF pathways in this study, but also offers adaptability for the assessment of other sustainable energy sources. This adaptability makes it a valuable starting point for research implementation in the energy sector. Unfortunately, due to time constraints, this study could only involve a limited number of stakeholders and experts and used a relatively simple method for selecting criteria. However, this framework can serve as a starting point for a more comprehensive MCA. It has demonstrated how multiple stakeholders and criteria dimensions can be included in an MCA. When using this MCA as a starting point, it is recommended to include more stakeholder groups and more participants per stakeholder group. This could be done by holding interactive workshops that allow stakeholders to engage directly with the MCA process. These sessions can include live demonstrations, Q&A sessions and group discussions that encourage active participation from the stakeholders. In addition, a wider selection of SAF experts for the performance scoring would ensure more robust results. Expanding the network of SAF experts can be achieved by joining relevant industry associations such as IATA. Additionally, partnering with universities that have strong expertise in TL technologies can also be effective. Furthermore, it would be interesting not to pre-determine a set of criteria prior to stakeholder discussions, but rather to select them based on stakeholder input on what they consider relevant to include in an SAF technology evaluation. A suitable method for this would be the Multi-Actor Multi-Criteria Analysis (MAMCA) methodology.

8.2.4 Practical Implications

This master thesis research has compared HTL and FP to HEFA as pathways for SAF production. The results presented actionable insights that can guide decision-makers and policymakers within the aviation industry in adopting these technologies to enhance sustainability.

The study highlighted that although HEFA currently outperforms HTL and FP in terms of technological maturity and cost, HTL and FP offer considerable environmental and social benefits. For SAF providers considering HTL and FP technologies, a phased implementation is recommended. This approach allows for a gradual increase in production capacity, helping to deliver environmental and social benefits while gradually helping in meeting the growing demand for SAF. The strategy offers multiple benefits: early adopters can test and refine the technology, addressing any technical and operational challenges. It can also help build market confidence and generate data that supports further investment. As these technologies mature, the focus shift to optimizing processes to increase efficiency and production thereby reduce costs.

Based on the findings of the analysis and the performance scoring of by-product use detailed in this study, SAF providers are also advised to integrate or expand facilities with dedicated by-product processing units. This strategy will not only improve resource efficiency but also benefit from the environmental advantages identified in the research. Further detailed research into the applications and improvements of by-product processing is recommended.

Additionally, although not included in the initial MCA framework, several criteria beyond the established set proved to be important to the stakeholders. To meet the priorities of different stakeholders, SAF providers should focus on several key areas. The environmental and sustainability organization particularly valued transparency and a true commitment to sustainability. To address these priorities, SAF providers could increase transparency in their communications about environmental impacts, such as their contribution to emissions reductions, waste management, and publicly disclosing the environmental footprint of their operations.

To gain support from the airline and the energy company in the oil and gas industry, SAF providers could focus on optimizing supply chains and improving production efficiencies. These stakeholders prioritized cost-effectiveness and reliable supply chains. By optimizing these areas, SAF providers can enhance economic viability and build stakeholder confidence in SAF as a sustainable, long-term solution. This can be achieved through investing in advanced logistics, establishing robust partnerships with feedstock suppliers, and adopting innovative technologies that streamline production processes.

Given the airline's emphasis on stable feedstock prices, it is advisable for SAF providers to develop strategies to manage these costs effectively. Approaches to consider include diversifying feedstock sources and forming strategic partnerships with suppliers. These measures can contribute to a stable and cost-effective supply of feedstocks. Additionally, stability in feedstock prices is vital for ensuring the reliability and predictability of SAF production. Through consistent feedstock prices, disruptions can be prevented, leading to stable production levels. This enables that airlines can depend on a steady availability of SAF, facilitating long-term planning and encouraging further investment in SAF technologies.

Moreover, selecting an appropriate location for the TL SAF production facilities is important for maximizing environmental and social benefits. While the primary focus of this thesis has been on the potential for SAF production facilities in Europe, the research findings indicate that establishing these technologies in economically disadvantaged areas, especially in developing countries, could provide substantial benefits. This is because these regions often have less effective waste management systems due to limited financial resources. This leads to higher levels of waste such as agricultural and forestry residues and non-recyclable plastics, which can be effectively utilised by HTL and FP technologies. This not only helps in improving waste management practices but also creates economic opportunities for the community. Moreover, deploying SAF technologies in these areas can strengthen social cohesion by fostering community engagement and enhance public health by reducing environmental hazards associated with waste. Although this insight extends beyond the original geographic focus of the thesis on Europe, it highlights a potential global application that could inform future strategies.

In addition, SAF providers could collectively consider lobbying for subsidies, tax incentives and other forms of government financial support to address the higher CAPEX and OPEX associated with HTL and FP compared to HEFA. By emphasising the long-term environmental and social benefits of these technologies, the industry can also attract investment from sustainability-focused funds and organisations.

Significant public sector subsidies and aggressive government policies are essential to promote SAF (Beck-en et al., 2023). Therefore, policymakers are advised to provide substantial subsidies that can lower production costs and make SAF competitive with conventional jet fuels. In addition, aggressive policies such as higher blending mandates and stricter emissions targets can drive advancements. Finally, continued investment in research and pilot projects can further support the development of SAF.

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APPENDICES

The airplane picture is generated using Canva's AI, Magic Studio™

A. Papers Analysed for Knowledge Gaps

Table 27: Papers analysed for knowledge gaps.

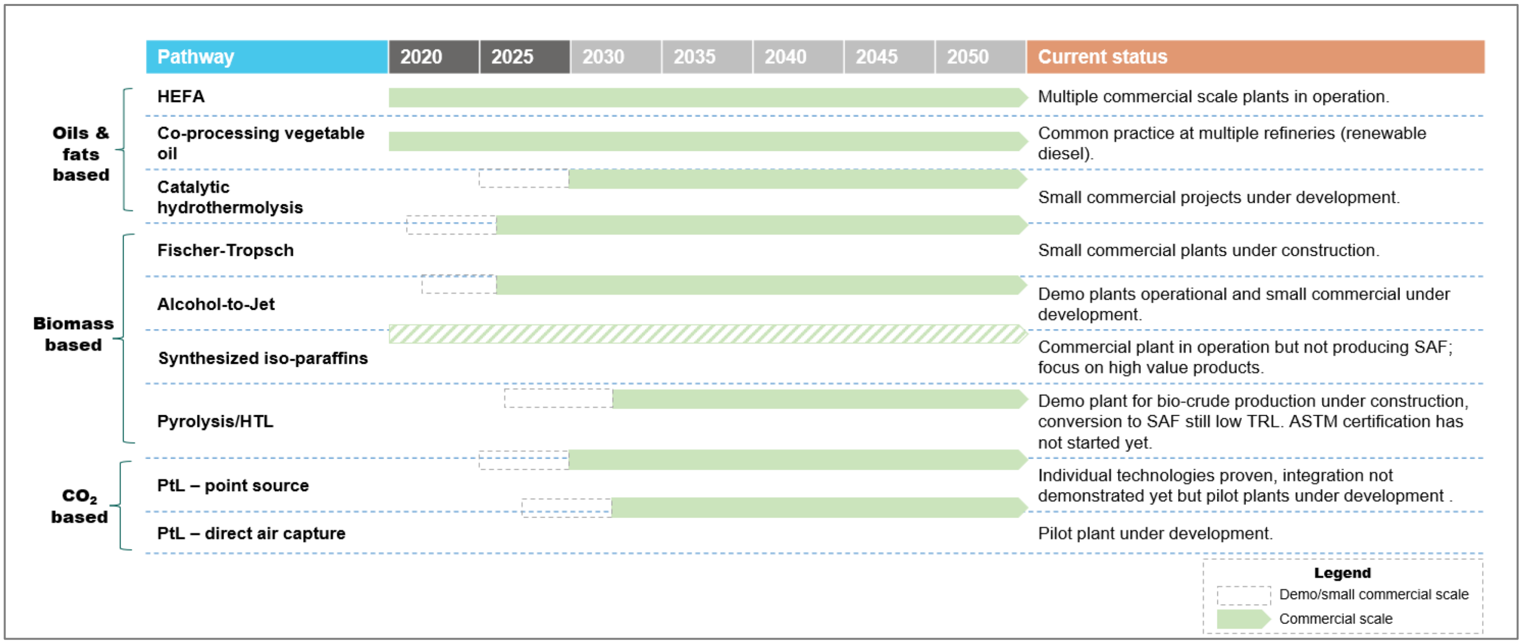
Nr.	Title	Author(s)	Summary of Research	Relevance	Eco.	Env.	Soc.	Tech.
1	Thermochemical conversion of biomass: Potential future prospects	Wang & Wu (2023)	The paper presents various thermochemical conversion processes of biomass, including combustion, torrefaction, liquefaction, pyrolysis and gasification. It evaluates the advantages and disadvantages of these processes and gives examples of industrial applications.	Understanding the broader context of thermochemical conversion helps place pyrolysis in the broader context of biomass conversion technologies. Provides insight into the challenges and opportunities in the production of SAF by pyrolysis. Also provides examples of industrial applications of thermochemical processes.				x
2	An incorporating innovation and new interactive technology into obtaining sustainable aviation fuels	Ershov et al. (2023)	The paper explores how aviation biofuels can be extracted from agricultural and food waste. Different techniques for producing SAF are discussed, with an emphasis on processing oil-and fat-based materials.	The overview of different technologies and feedstocks used in the production of SAF gives an impression of pyrolysis as a specific method within this broader context. The paper discusses the potential of different feedstocks and understanding the feedstocks that can be used for pyrolysis can be crucial.	x			x
3	Multi-criteria decision analysis for the evaluation and screening of sustainable aviation fuel production pathways	Okolie et al. (2023)	The paper evaluates different technologies (HEFA, GFT, ATJ, DSHC and FP) with a multicriteria decision analysis on the benefits, constraints, cost-effectiveness and environmental impacts of each route.	By describing in detail, the advantages, limitations, cost-effectiveness and environmental impacts of fast pyrolysis, the study provides valuable insights into the feasibility and efficiency of a specific pyrolysis method. In addition, the multi-criteria decision framework used in the paper provides insight into important criteria to consider when evaluating aviation fuel performance.	x	x		x
4	Solid waste biomass as a potential feedstock for producing sustainable aviation fuel: A systematic review	Emmanouilidou et al. (2023)	Based on recent literature, the study aims to provide insights into the possibilities of producing sustainable aviation fuel (SAF) from various waste materials through a systematic literature review.	The review on conversion technologies shows where pyrolysis stands in relation to other methods such as hydro processing and gasification. The paper discusses a specific form of pyrolysis. Namely, catalytic pyrolysis of waste plastics and co-pyrolysis with solid biomass residues. This information can be used to better understand the technology and its various forms.	x			x
5	On the Viability of Implementing the Industrial	Krylova et al. (2023)	This study gives an overview of different biofuels and their production technologies.	Pyrolysis is one of the technologies discussed in this paper. The information can be used to better understand the technology in detail.				x

Nr.	Title	Author(s)	Summary of Research	Relevance	Eco.	Env.	Soc.	Tech.
	Production of Liquid Biofuels in Russia							
6	Decentralization of sustainable aviation fuel production in Brazil through Biomass-to-Liquids routes: A techno-economic and environmental evaluation	Guimarães et al. (2023)	This study evaluates three strategies to improve the economic feasibility of producing SAF by gasification and Fischer-Tropsch synthesis (GFT) of lignocellulosic biomass as feedstock in Biomass-to-Liquids (BtL) plants.	One of the strategies the paper evaluates is the decentralization of the SAF production chain using fast pyrolysis (FP) units to convert biomass into bio-oil. This provides information on the application of pyrolysis in SAF production. The paper also conducts a techno-economic assessment and life cycle analysis of SAF production processes. This can provide valuable data and methodologies for the thesis.	x	x		x
7	European Union's biomass availability for Sustainable Aviation Fuel production and potential GHG emissions reduction in the aviation sector: An analysis using GIS tools for 2030	Chandrasekaran et al. (2023)	This study examines four different technologies to produce SAF. On a country specific basis, the technology that produces the least GHG emissions while meeting the fuel requirements for each country is identified. Also, an assessment on feedstock availability is done	Fast pyrolysis is one of the technologies discussed in this paper. The information can be used for this thesis.				x
8	Catalytic pyrolysis of coconut oil with Ni/SBA-15 for the production of bio jet fuel	De Medeiros et al. (2022)	The study examines the catalytic pyrolysis of coconut oil using a Ni/SBA-15 catalyst to produce SAF.	The research discusses catalytic pyrolysis, a specific form of pyrolysis. The paper makes a comparison by highlighting the differences in the composition of hydrocarbons obtained from pyrolysis with and without the use of catalysts. The information can be used to better understand the technology in detail.				x
9	Aviation Biofuels: Conversion Routes and Challenges	Chong et al. (2022)	This study discusses the challenges and opportunities of several SAF production technologies (hydroprocessing, Fischer–Tropsch synthesis, alcohol-to-jet fuel, pyrolysis process, HTL and	Pyrolysis is one of the technologies discussed in this paper. The information can be used for this thesis.	x			x

Nr.	Title	Author(s)	Summary of Research	Relevance	Eco.	Env.	Soc.	Tech.
			blending of fatty acid methyl ester) from a perspective of sustainable development.					
10	Emerging technologies for the production of bio jet fuels from wood—can greenhouse gas emission reductions meet policy requirements?	Björnsson & Ericsson (2024)	This study assesses whether different SAF production technologies (production of hydrocarbon intermediates via (I) fast pyrolysis, (ii) HTL, (iii) thermal gasification followed by Fischer-Tropsch synthesis, and (iv) cellulosic ethanol fermentation) can meet the Swedish projection of 90% reduction in GHG emissions by 2025 and the requirements of the EU Renewable Energy Directive.	The research provides data on the potential GHG emission reductions of aviation fuels produced via fast pyrolysis, which may be key to understanding the environmental benefits of this technology.		x		x
11	Evaluation of dry corn ethanol bio-refinery concepts for the production of sustainable aviation fuel	Tanzil et al. (2021a)	This study examines the feasibility and benefits of producing SAF by integrating them with an existing Dry Grind Corn Ethanol Mill (DGCEM). Twelve co-location and re-use scenarios are examined, and the study aims to determine which SAF production technologies can best integrate with a corn ethanol mill.	One of these technologies is fast pyrolysis. The research provides insight into the efficiency, cost effectiveness and environmental impacts of integration.	x			x
12	Potential yields and emission reductions of biojet fuels produced via hydrotreatment of biocrudes produced through direct thermochemical liquefaction	Van Dyk et al. (2019)	Three direct thermochemical liquefaction methods—fast pyrolysis, catalytic fast pyrolysis, and HTL—were evaluated for their capacity to produce "biocrudes." These biocrudes were then refined into drop-in biofuels through either dedicated hydrotreatment or co-processing hydrotreatment.	Pyrolysis is one of the technologies discussed in this paper. The information can be used for this thesis.	x	x		x

B. Existing and ASTM Certified SAF Pathways

The figure below from SkyNRG (2023) provides an overview of the SAF pathways currently available and their status.



	Pathway	Current status
Oils & fats based	HEFA	Multiple commercial scale plants in operation.
	Co-processing vegetable oil	Common practice at multiple refineries (renewable diesel).
	Catalytic hydrothermolysis	Small commercial projects under development.
Biomass based	Fischer-Tropsch	Small commercial plants under construction.
	Alcohol-to-Jet	Demo plants operational and small commercial under development.
	Synthesized iso-paraffins	Commercial plant in operation but not producing SAF; focus on high value products.
	Pyrolysis/HTL	Demo plant for bio-crude production under construction, conversion to SAF still low TRL. ASTM certification has not started yet.
CO_2 based	PtL – point source	Individual technologies proven, integration not demonstrated yet but pilot plants under development .
	PtL – direct air capture	Pilot plant under development.

Figure 22: SAF pathways. Source: SkyNRG (2023)

By October 2021, the following of the existing SAF production pathways were certified under the ASTM D7566: Fischer-Tropsch Synthetic Paraffin Kerosene, Hydro-processed Ester and Fatty Acid, Synthesized Iso-paraffin, Fischer-Tropsch Synthetic Paraffin kerosene with Aromatics, Alcohol-To-Jet synthetic paraffin kerosene, Catalytic Hydrothermolysis jet fuel, Hydro-processed Hydrocarbons, Esters, & Fatty acids, Fischer-Tropsch Co-processing and Fats, Oils, and Grease Co-processing (Shahriar & Khanal, 2022)

C. Types of Thermochemical Liquefaction Technologies

The table below presents six different TL technologies that were found through the literature review.

Table 28: Types of thermochemical liquefaction.

Fast Pyrolysis	The FP of biomass is conducted at a higher heating rate and a shorter hot vapor residence time than typical pyrolysis under moderate temperature conditions. This approach maximizes the yield of liquid products (Li et al., 2021). Biomass is converted to bio-oil at temperatures around 450–650 °C (Park et al., 2019).
Slow pyrolysis	With slow pyrolysis the biomass is heated at relatively low temperatures (usually 300-500°C) in the absence of oxygen. With slow pyrolysis, the biomass is heated more slowly, and the residence time is longer, resulting mostly in biochar. The slow heating distinguishes this from FP (Vuppaladadiyam, 2022).
Catalytic Pyrolysis	Catalytic pyrolysis is the type of pyrolysis in which a catalyst is used to improve the yield and quality and reduce the oxygen content of the bio-oil produced. The use of a catalyst in this process lowers the level of unwanted compounds, such as acids and aldehydes. Catalytic Pyrolysis is split into two different types: in-situ and ex-situ. During the in-situ catalytic pyrolysis process, the catalyst resides in the reaction zone, whereas for ex-situ catalytic pyrolysis, the biomass is pyrolyzed prior to the bio-oil being enhanced through contact with the catalyst separately (Jenkins et al., 2016).
Co-pyrolysis	With co-pyrolysis, various raw materials (which are not necessarily renewable) such as coal, plastics, tires, and sludge are introduced and decomposed together with the biomass. The main factor influencing the effectiveness of this process is the synergetic interaction of free radicals that are released from the various feedstocks (Wang & Wu, 2023).
HTL	In HTL biomass is heated in the presence of water. HTL contains water which helps break down the biomass' complex organic molecules into simpler components, which in turn can be condensed into a liquid oil. Moreover, compared to bio-oil produced by pyrolysis, HTL usually produces a biocrude oil with a higher carbon content and less oxygen (Van Dyk et al., 2019).
Hydropyrolysis	Hydropyrolysis uses pressurized hydrogen (>10 MPa) to convert biomass into a high-quality pyrolytic oil. Advantages include the inhibition of char formation and bio-oil with a low oxygen content. In addition, the hydrocarbons show better stability (Vuppaladadiyam, 2022).

Due to time constraints, it was not possible to fully investigate all six technologies. As a result, four technologies were excluded from further consideration in this thesis. Hydrogen is currently still costly and not readily available (IEA, 2019), and as such hydropyrolysis has been eliminated from further investigation. Co-pyrolysis is generally considered to be unsustainable because of its co-feedstock, such as plastics, tires, and sludge (Wang & Wu, 2023) and has therefore also been excluded. Slow pyrolysis is excluded for further investigation because its primary product is charcoal rather than the bio-oil, which is required for SAF (Vuppaladadiyam, 2022).

The exclusion of the three technologies, hydro pyrolysis, co-pyrolysis and slow pyrolysis leaves catalytic pyrolysis, FP and HTL.

Furthermore, research on the different TL technologies has revealed that there are inconsistencies in the definitions of thermochemical liquefaction technologies, for example, in terms of operating temperatures and residence times. To streamline the research, a single industry supplier was selected for each technology for in-depth analysis.

In the search for suitable industrial suppliers, several interviews were conducted with technology providers to assess their willingness to share data. Unfortunately, a practical example for catalytic pyrolysis could not be selected because suppliers were unwilling to share data, citing confidentiality concerns. Therefore, catalytic pyrolysis has also been excluded for in-depth investigation.

The focus of this study is therefore on a multi-perspective analysis of HTL and FP, selected based on data availability and the relevance of these technologies to SAF production at the time of writing.

D. BTG FP

The FP process of BTG first reduces the biomass to less than 6 millimetres in a hammer mill in order to augment heat penetration before it enters into the FP reactor, after which it is dried to a moisture content of approximately 3-4% (Interview BTG, 2024). The pre-treated feedstock can subsequently be entered into the FP reactor, where it is heated rapidly to 450-600°C in the absence of oxygen. This causes it to release organic vapours and gases that are condensed into Fast Pyrolysis Bio-Oil (FPBO). This FPBO has a higher energy density than the original feedstock but cannot be used directly as a transportation fuel (BTG Bioliquids, 2022).

Apart from FPBO, FP also produces gas and char as by-products. These by-products can both play an important role in the energy dynamics of the system. The char is moved from the reactor to a combustor where sand is added, which is then heated by the combustion of the char. The heated sand is returned to the reactor, thereby creating a loop of thermal energy that is self-sustaining. Char and non-condensable gases are burnt in the combustor in some plants, which generates considerable heat. This heat is subsequently used to produce steam, which can be used to dry the biomass and drive the steam turbine and as such this technology is completely self-sufficient for heat and electricity (interview BTG, 2024).

FPBO stabilization is carried out at high pressure in a hydrogen atmosphere using BTG's Picula™ catalyst. This step improves the quality of the oil by converting reactive oxygenated compounds (such as aldehydes and ketones) to less reactive types, such as alcohol, making the oil more stable. After this step, the FPBO is called stabilized pyrolysis oil (SPO) (BTG Bioliquids, 2022).

After stabilization, the oil can be further treated by hydrotreating, a process in which the SPO is combined with hydrogen in the presence of a catalyst. The result is hydrodeoxygenation, a process in which oxygen is removed from the SPO by forming water and saturating the hydrocarbons and creating Hydrotreated Pyrolysis Oil (HPO). The properties of HPO are similar to that of fossil fuels and can therefore serve as a drop-in replacement for existing vehicles and distribution systems. This includes use in aviation, marine, and long-haul road transport (BTG Bioliquids, 2022).

These steps are visualized in the IDEF0 diagram below. IDEF0 is a functional modelling method for the representation of functions, activities, and processes within a system. Each box in the EDEFO diagram represents a single function. To represent the connections between functions, arrows are used in an IDEF0 diagram. There are four types of arrows in an IDEF0 diagram. Firstly, input (I): these arrows enter on the left side of a box and refer to the resources required by a function. Secondly, output (O): these arrows leave the right-hand side of a box and refer to the output that is produced by a function. Thirdly, Controls (C): these are the arrows that enter the top of a box and refer to the constraints, conditions or guidelines under which the function operates. Finally, Mechanisms (M), these arrows enter the bottom of a box, refer to the tools, systems or resources that support the performance of function (Jørgensen, 2005). An overview is given below.

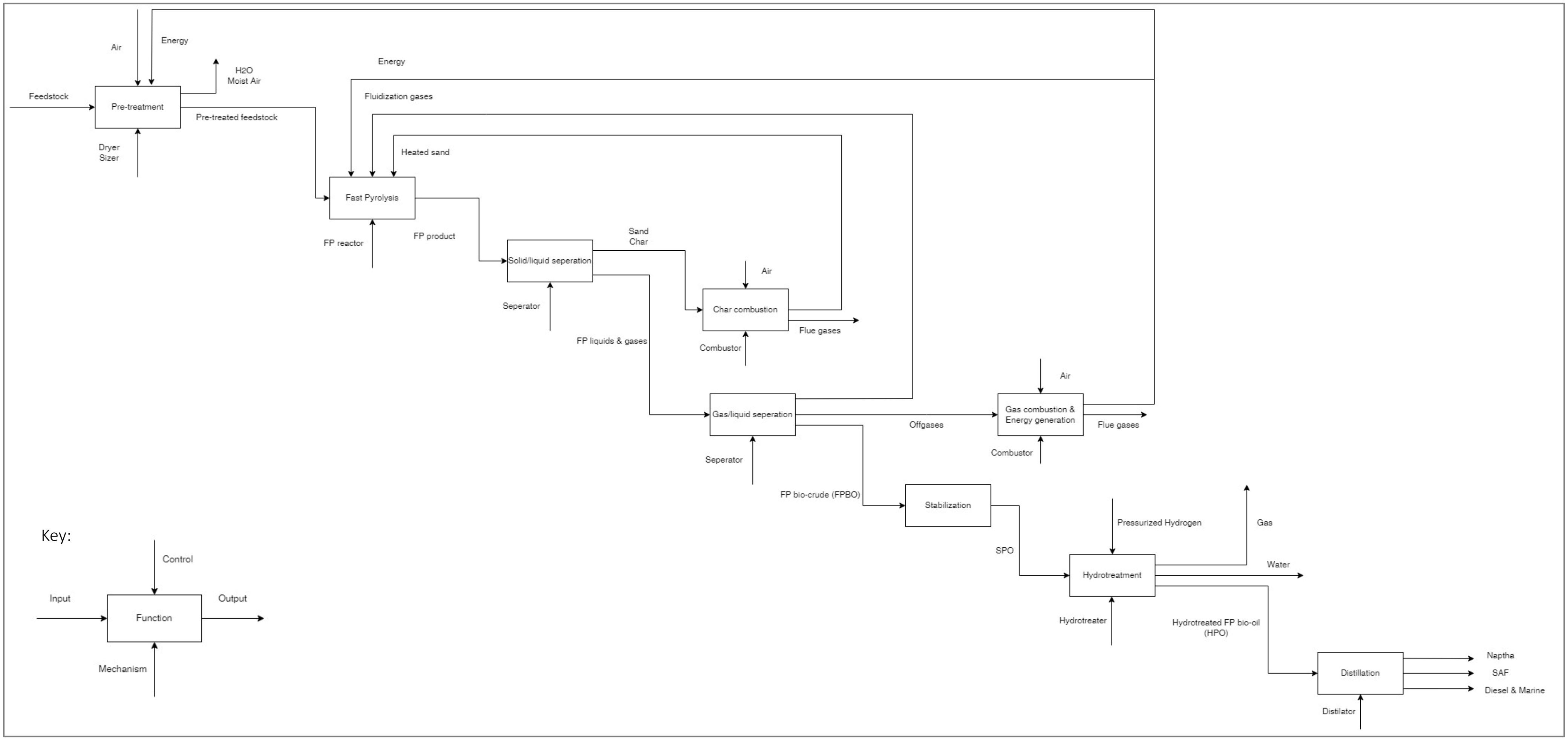


Figure 23: IDEF0 FP BTG

E. HTL Steeper

The Steeper Energy Hydrofaction™ process is involves reducing the feedstock to a size that can be processed, after which it is mixed with water and a homogenous catalyst, such as potassium carbonate and sodium hydroxide, and a water-soluble organic compound, that could be recycled, as well as some Hydrofaction™ oil from an earlier processing cycle. The recirculation in this process encourages chemical reactions and increases efficiency as well as yield (Jensen et al., 2018).

The HTL reactor then turns the pre-treated feedstock into biocrude under supercritical water conditions with pressures between 300-350 bar and temperatures between 390-420°C. During the HTL process, two by-products are produced: gases and water-soluble organic substances, also called the aqueous product. After HTL, the products are separated. A part of the Hydrofaction™, oil is sent for further upgrading. The aqueous product and the other part of the Hydrofaction™ oil are fed back to the beginning of the process for re-use (Jensen et al., 2018).

The non-condensable gases from this process can be burnt to generate heat, which in turn can produce steam that can be used to dry the biomass or to power a steam turbine that generates electricity. This electricity can power the process or the plant (Interview Steeper, 2024).

Via hydrotreating, oxygen is removed from the Hydrofaction™ oil and the oil is stabilised, resulting in renewable fuels that meet the requirements of the existing fossil fuel infrastructure (Jensen et al., 2018).

The various stages of the process are set out in the IDEFO diagram below.

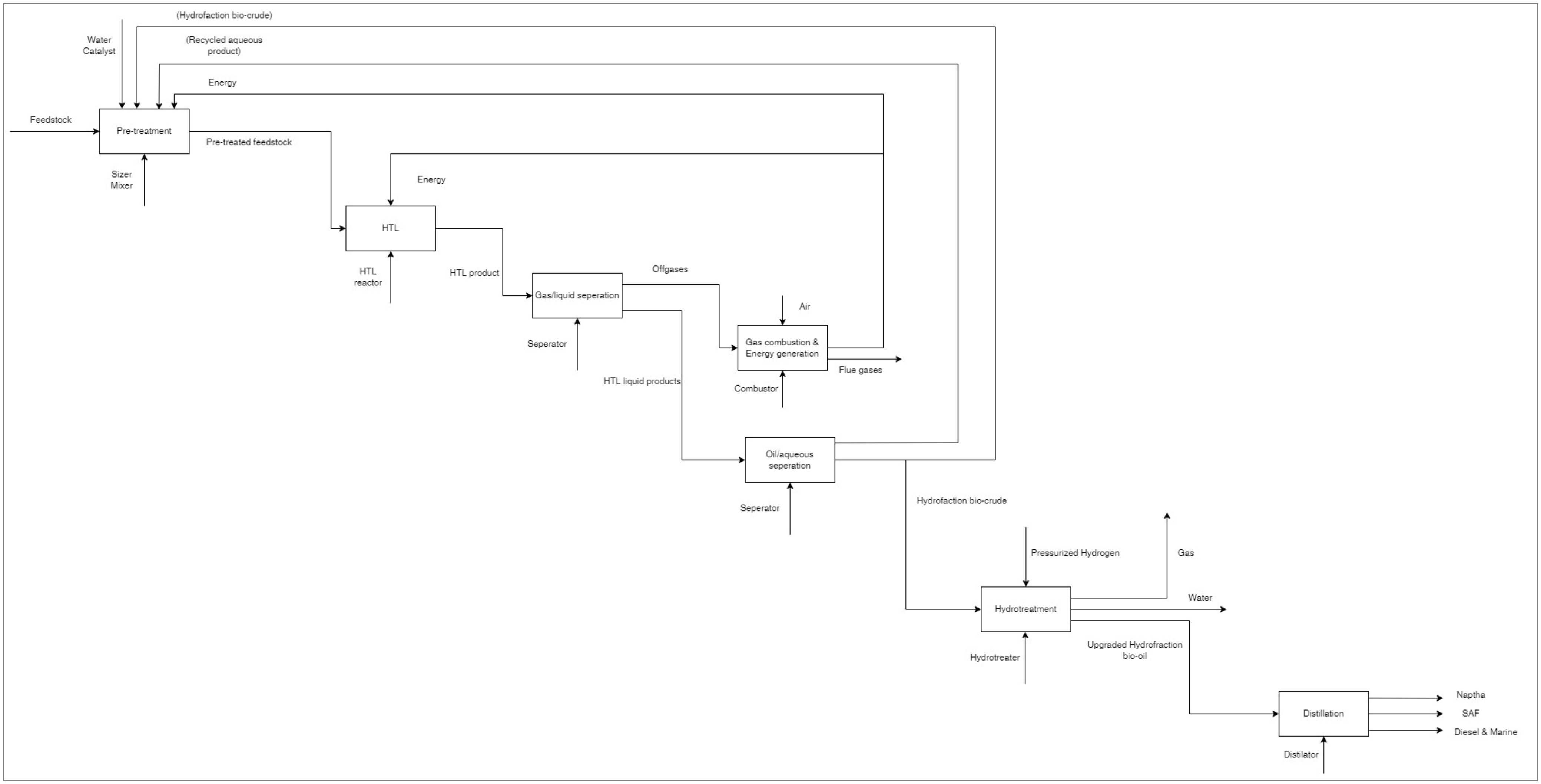


Figure 24: IDEF0 HTL Steeper

F. HEFA IDEF0 Diagram

The IDEF0 diagram below presents the HEFA production pathway again, specifying the inputs, control, mechanisms, and outputs of every stage in the process.

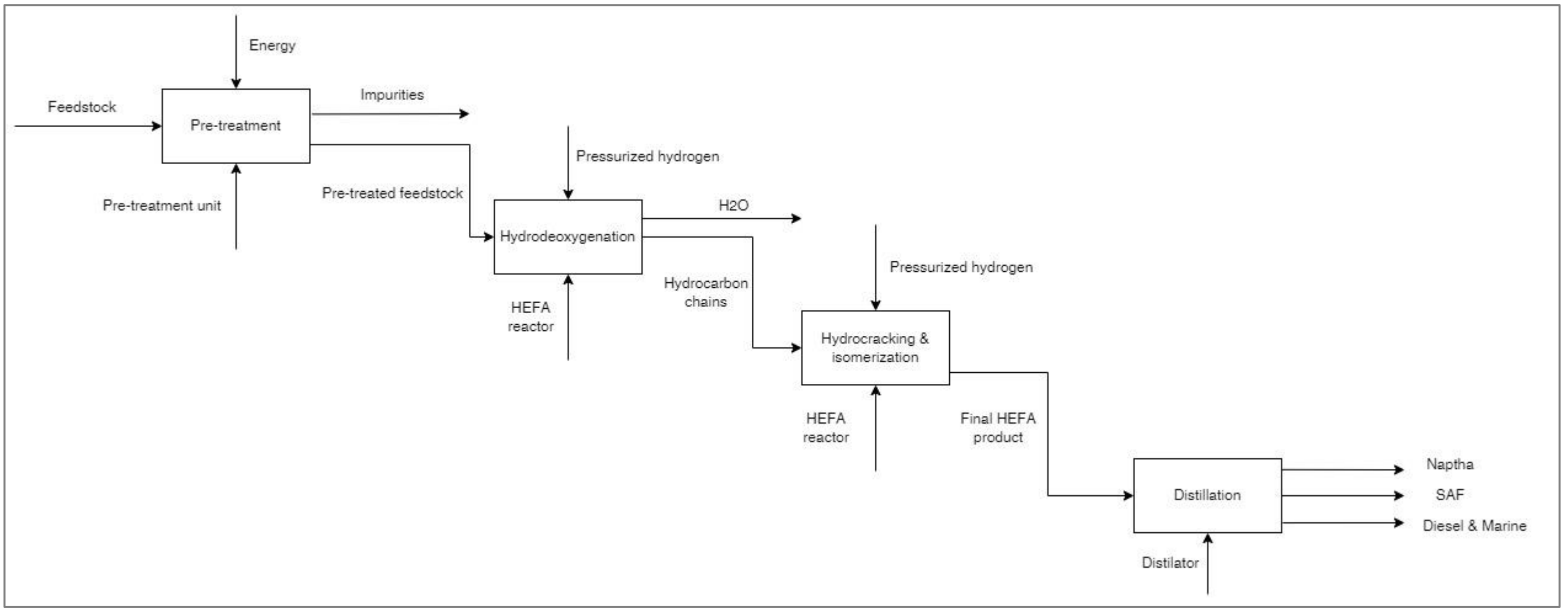


Figure 25: IDEF0 HEFA

G. Criteria

Table 29: Papers analysed for criteria selection.

Nr.	Title	APA	Criteria Used			
			Environmental	Economic	Social	Technical
1	Assessment of alternative nuclear fuel cycles for the Brazilian nuclear energy system	Estanislau, F. B., Velasquez, C. E., Costa, A. L., & Pereira, C. (2023). Assessment of alternative nuclear fuel cycles for the Brazilian nuclear energy system. *Nuclear Engineering and Design*, *415*, 112692.	> Use of natural resources > Amount of generated waste > GHG emissions	> Normalized unit costs of the fuel cycle (LUFC)		> Requirements or avoidances for each phase of the fuel cycle
2	A multi-criteria approach for comparing alternative fuels and energy systems onboard ships	Rivarolo, M., Piccardo, S., Montagna, G. N., & Bellotti, D. (2023). A multi-criteria approach for comparing alternative fuels and energy systems onboard ships. *Energy Conversion and Management: X*, *20*, 100460.	> Environmental hazards >Emissions (both CO_2 and NOx) > GHG emissions	> Costs		> Volume > Weight
3	Multi-Criteria Analysis to Determine the Most Appropriate Fuel Composition in an Ammonia/Diesel Oil Dual Fuel Engine	Rodríguez, C. G., Lamas, M. I., Rodríguez, J. D. D., & Abbas, A. (2023). Multi-Criteria Analysis to Determine the Most Appropriate Fuel Composition in an Ammonia/Diesel Oil Dual Fuel Engine. *Journal of Marine Science and Engineering*, *11*(4), 689.	> Emissions of CO_2, NOx, NH3, and N2O			

Nr.	**Title**	**APA**	**Criteria Used**			
			Environmental	Economic	Social	Technical
4	Alternative Fuel Selection Framework toward Decarbonizing Maritime Deep-Sea Shipping	Moshiul, A. M., Mohammad, R., & Hira, F. A. (2023). Alternative fuel selection framework toward decarbonizing maritime deep-sea shipping. *Sustainability*, *15*(6), 5571.	> Life cycle emissions from production to consumption > Air pollution and ecosystem impact	> Government and organizational policies promoting technological advancement > Infrastructure costs > Fuel costs incl production, transportation and storage costs > Opportunity cost: logistics and the impact on cargo capacity	> Health & Safety > Public acceptance > Ethical Considerations	> Fuel properties > pre-treatment requirements > Engine compatibility > Maturity > Reliability > Global availability of technology
5	In Search of the Best Technological Solutions for Optimal Biobutanol Production: A Multi-Criteria Analysis Approach	Berzina, I., Mika, T., & Spalvins, K. (2023). In Search of the Best Technological Solutions for Optimal Biobutanol Production: A Multi-Criteria Analysis Approach. *Environmental and Climate Technologies*, *27*(1), 864-877.		> Pre-treatment and transportation costs > Storage costs	> Shelf life > By-product seasonality	> Biobutanol concentration and yield > ABE/IBE yield > Process time > Productivity > Strain tolerance to oxygen > Optimal cultivation temperature > Substrate availability

Nr.	Title	APA	Criteria Used			
			Environmental	Economic	Social	Technical
6	Transportation Biofuels in Latvia: A Life Cycle Thinking Approach	Kirsanovs, V., Romagnoli, F., Piščika, A., Safronova, A., & Feofilovs, M. (2023). Transportation Biofuels in Latvia: A Life Cycle Thinking Approach. *Environmental and Climate Technologies*, *27*(1), 40-55.	> Climate change impact > Ecosystem quality > Resource usage	> Feedstock price > Production cost > Market price of biofuel > Distance cost efficiency	> Job creation > Awareness raising > Inclusion of small-scale producers > Development of rural areas > Human health impact	> Technical development status > Feedstock type > Average energy consumption > Calorific value
7	Novel Methodology to Assess Advanced Biofuel Production at Regional Level: Case Study for Cereal Straw Supply Chains	Ugolini, M., Recchia, L., Guandalini, G., & Manzolini, G. (2022). Novel methodology to assess advanced biofuel production at regional level: Case study for cereal straw supply chains. *Energies*, *15*(19), 7197.	> GHG emissions	> Transport distance		> Second level availability > Number of regions > Transport complexity > Production seasonality > Storage complexity > Standardization of supply chain > Nominal plant capacity > Pre-treatment necessity > Calorific value

Nr.	Title	APA	Criteria Used			
			Environmental	Economic	Social	Technical
8	Towards just transition of coal regions - Cultivation of short rotation copies and dedicated energy crops for biomass co-firing vs photo voltaic power plants	Merzic, A., Turkovic, N., Ikanovic, N., Lapandic, E., Kazagic, A., & Music, M. (2022). Towards just transition of coal regions-Cultivation of short rotation copies and dedicated energy crops for biomass co-firing vs photo voltaic power plants. *Energy Conversion and Management: X*, *15*, 100267.	> CO_2 emissions saved	> Capital Expenditures (CAPEX) > Operating Expenses (OPEX) > Yearly balancing power costs > Annual revenue, > Cost of retraining, > Severance package/employees' wage	> Number of employees	
9	STEAM-ENHANCED GASIFICATION OF A HYBRID BLEND COMPOSED OF MUNICIPAL SOLID WASTE AND TORREFIED BIOMASS	Lamas, G. C., Costa, F. C., Santanna, M. S. S., Chaves, B., Galvão, L. G. O., Macedo, L., & Silveira, E. A. (2022). Steam-enhanced gasification of a hybrid blend composed of municipal solid waste and torrefied biomass. In *30th European Biomass Conference and Exhibition* (pp. 9-12).				> Hydrogen to Carbon Monoxide Ratio (H_2/CO) > Cold Gas Efficiency (CGE) > Lower Heating Value (LHV)

Nr.	**Title**	**APA**	**Criteria Used**			
			Environmental	Economic	Social	Technical
10	Multi-criteria analysis of detoxification alternatives: Techno-economic and socio-environmental assessment	Llano, T., Rueda, C., Dosal, E., Andrés, A., & Coz, A. (2021). Multi-criteria analysis of detoxification alternatives: Techno-economic and socio-environmental assessment. *Biomass and Bioenergy*, *154*, 106274.	> Waste Toxicity	> Fixed Capital Invested > Manufacturing Costs	> Social Acceptance > Employment	> Total Inhibitors Removal > Total Sugar Losses > Acetic Acid Removal - Phenolics Removal - Lignosulfonates Removal
11	Multi-Criteria Analysis of Lignocellulose Substrate Pre-Treatment	Vamza, I., Valters, K., & Blumberga, D. (2020). Multi-Criteria Analysis of Lignocellulose Substrate Pre-Treatment. Rigas Tehniskas Universitates Zinatniskie Raksti, 24(3), 483-492.		> Operational cost		> retention time > operational temperatures > glucose recovery

Nr.	**Title**	**APA**	**Criteria Used**			
			Environmental	Economic	Social	Technical
12	Blended Lifecycle Integrated Social System Method	Tavakoli, H., & Barkdoll, B. D. (2020). Blended lifecycle integrated social system method. *International Journal of Environmental Research*, *14*, 727-749.			> employment > income levels > safety at work > food security > conservation of resources > social acceptance > transparency > stakeholder participation > risk of catastrophic events > visual impacts of production facilities	
13	Probabilistic multi-criteria analysis for evaluation of biodiesel production technologies from used cooking oil	Mendecka, B., Lombardi, L., & Kozioł, J. (2020). Probabilistic multi-criteria analysis for evaluation of biodiesel production technologies from used cooking oil. *Renewable Energy*, *147*, 2542-2553.	> Global Warming Potential (GWP)	> Investment costs > Operating Costs	> The Human Health indicator (HH) expressed by Disability-Adjusted Life Years (DALY)	> Cumulative Exergy Consumption (CExC)
14	Multi-scale integrated assessment of second generation bioethanol for transport sector in the Campania Region	Fierro, A., Forte, A., Zucaro, A., Micera, R., & Giampietro, M. (2019). Multi-scale integrated assessment of second generation bioethanol for transport sector in the Campania Region. *Journal of cleaner production*, *217*, 409-422.	> waste production	> the costs and profitability of the bioethanol		> Material flows > Energy inputs

Nr.	Title	APA	Criteria Used			
			Environmental	Economic	Social	Technical
15	Assessing the current scenario of the Brazilian biojet market	de Souza, L. M., Mendes, P. A., & Aranda, D. A. (2018). Assessing the current scenario of the Brazilian biojet market. *Renewable and Sustainable Energy Reviews*, *98*, 426-438.	> Infrastructural issues	> High costs of feedstocks and final products > Lack of public-private investment	> Food security risks	> Reduced technical dominance of alternative feedstocks > The developmental status of refining technologies
16	Jet fuel production in eucalyptus pulp mills: Economics and carbon footprint of ethanol vs. butanol pathway	Braz, D. S., & Mariano, A. P. (2018). Jet fuel production in eucalyptus pulp mills: Economics and carbon footprint of ethanol vs. butanol pathway. *Bioresource technology*, *268*, 9-19.	> The carbon footprint abatement (ΔGWP)	> Net Present Value (NPV) > Return on Capital Employed (ROCE) > Internal Rate of Return for Phase 1 (IRR-1)		
17	Decision support systems for assessment of biorefinery transformation strategies	Benali, M., Jeaidi, J., Mansoornejad, B., Ajao, O., Gilani, B., & Ghavidel Mehr, N. (2018). Decision support systems for assessment of biorefinery transformation strategies. *The Canadian Journal of Chemical Engineering*, *96*(10), 2155-2175.	> GHG emission > Non-renewable energy usage > Water scarcity > Land occupation > Human health	> CAPEX > OPEX > Internal Rate of Return (IRR) > Return on Capital Employed (ROCE) > Earnings Before Interest, Taxes, Depreciation and Amortization/tonne of biomass (EBITDA/biomass) > Payback Period		> Pulp Production Increase > Maximum Pulp Production Increase > Incremental Steam Production > Evaprator system impact > Recovery Boiler Impact > Wastewater treatment

Nr.	Title	APA	Criteria Used			
			Environmental	Economic	Social	Technical
18	Assessing the stakeholder support for different biofuel options in France by 2030 using the range-based Multi Actor Multi Criteria Analysis framework	Baudry, G., & Vallée, T. (2018). 10. Assessing the stakeholder support for different biofuel options in France by 2030 using the range-based Multi Actor Multi Criteria Analysis. *Decision-Making for Sustainable Transport and Mobility: Multi Actor Multi Criteria Analysis*, 183.	> Water footprint > GHG emissions	> Producer income > Rural jobs	> Market diversification > Market policy support	
19	Can microalgae biodiesel contribute to achieve the sustainability objectives in the transport sector in France by 2030? A comparison between first, second and third generation biofuels though a range-based Multi-Actor Multi-Criteria Analysis	Baudry, G., Macharis, C., & Vallée, T. (2018). Can microalgae biodiesel contribute to achieve the sustainability objectives in the transport sector in France by 2030? A comparison between first, second and third generation biofuels though a range-based Multi-Actor Multi-Criteria Analysis. *Energy*, *155*, 1032-1046.	> Water footprint > GHG emissions	> Producer income> Rural jobs	> Market diversification > Market policy support	
20	Renewable methane – A technology evaluation by multi-criteria decision making from a European perspective	Billig, E., & Thraen, D. (2017). Renewable methane–A technology evaluation by multi-criteria decision making from a European perspective. *Energy*, *139*, 468-484.	> By-product CO_2	> Production Costs		> Type of Substrate > Energy Efficiency > Resulting Gas Pressure
21	Evaluation of biomethane technologies in Europe – Technical concepts under the scope of a Delphi-Survey embedded in a multi-criteria analysis	Billig, E., & Thrän, D. (2016). Evaluation of biomethane technologies in Europe–Technical concepts under the scope of a Delphi-Survey embedded in a multi-criteria analysis. *Energy*, *114*, 1176-1186.	> By product C02			> Gas pressure > Type of subtrate > Energy efficiency

Nr.	Title	APA	Criteria Used			
			Environmental	Economic	Social	Technical
22	Assessing Jatropha Crop Production Alternatives in Abandoned Agricultural Arid Soils Using MCA and GIS	Corral, S., Romero Manrique de Lara, D., Tejedor Salguero, M., Jimenez Mendoza, C. C., Legna-de la Nuez, D., Dorta Santos, M., & Díaz Peña, F. (2016). Assessing Jatropha crop production alternatives in abandoned agricultural arid soils using MCA and GIS. *Sustainability*, *8*(6), 505.	> Water consumption > Energy consumption	> Purchase cost > Initial investment > Water cost > Direct & indirect labor cost > Energy cost > Fertilizer cost		> Seeds prodcution
23	Multi-level multi-criteria analysis of alternative fuels for waste collection vehicles in the United States	Maimoun, M., Madani, K., & Reinhart, D. (2016). Multi-level multi-criteria analysis of alternative fuels for waste collection vehicles in the United States. *Science of the Total Environment*, *550*, 349-361.	> Life cycle emissions > Tailpipe emissions > Water footprint (WFP) > Power density	> Vehicle cost > Fuel price > Fuel price stability > Fuelling station availability		
24	Environmental and technical evaluation of the use of alternative fuels through multi-criteria analysis model	Zorpas, A. A., Pociovălişteanu, D. M., Georgiadou, L., & Voukkali, I. (2016). Environmental and technical evaluation of the use of alternative fuels through multi-criteria analysis model. *Progress in Industrial Ecology, an International Journal*, *10*(1), 3-15.	> Sustainability of production methods > Emissions of carbon dioxide (complete combustion) > Main by-products (complete combustion) > Impacts on ecosystems	> Production costs > Labour force > Resource availability	> Job creation > Public acceptance > Safety	> Calorific value > Octane number > Density

Nr.	**Title**	**APA**	**Criteria Used**			
			Environmental	Economic	Social	Technical
25	Social, economic, and environmental impacts of biomass and biofuel supply chains	Sacchelli, S. (2016). Social, economic, and environmental impacts of biomass and biofuel supply chains. In *Biomass supply chains for bioenergy and biorefining* (pp. 191-213). Woodhead Publishing.	> Biodiversity > Water use efficiency > Soil quality > Climate change impacts	> Cost-benefit analyses > Employment effects > Potential impacts on local and global markets	> Effects on local communities: including health, food security, landscape changes, and social justice.	
26	Microalgae-based biodiesel: A multicriteria analysis of the production process using realistic scenarios	Torres, C. M., Ríos, S. D., Torras, C., Salvadó, J., Mateo-Sanz, J. M., & Jiménez, L. (2013). Microalgae-based biodiesel: a multicriteria analysis of the production process using realistic scenarios. *Bioresource technology*, *147*, 7-16.	> Potential environmental impact: including energy consumption, GHG emissions, water usage, and land usage.	> Capital cost > Production cost > Profitability indicators: Break-Even Price (BEP)		
27	Integrated evaluation of biofuel production options in agriculture: An exploration of sustainable policy scenarios	Finco, A., Bentivoglio, D., & Nijkamp, P. (2012). Integrated evaluation of biofuel production options in agriculture: an exploration of sustainable policy scenarios. *International Journal of Foresight and Innovation Policy*, *8*(2-3), 173-188.	> Emissions of GHGs in the production of biodiesel versus fossil fuels > Energy balance of biodiesel production, processing and distribution > Land-use change (direct and indirect)			

Nr.	Title	APA	Criteria Used			
			Environmental	Economic	Social	Technical
28	Development of a decision support tool for the assessment of biofuels	Perimenis, A., Walimwipi, H., Zinoviev, S., Müller-Langer, F., & Miertus, S. (2011). Development of a decision support tool for the assessment of biofuels. *Energy Policy*, *39*(3), 1782-1793.	> Simplified Life Cycle Assessment (LCA): focusing on global warming (GHG emissions) and primary energy demand (PED).	> Capital-related costs > Consumption-related costs > Operation-related costs > Other costs & revenues	> Employment creation along the biofuel pathway	> Energy efficiency > Feedstock conversion ratio > Complexity & development status of the technology
29	A multi-actor multi-criteria framework to assess the stakeholder support for different biofuel options: The case of Belgium	Turcksin, L., Macharis, C., Lebeau, K., Boureima, F., Van Mierlo, J., Bram, S., ... & Pelkmans, L. (2011). A multi-actor multi-criteria framework to assess the stakeholder support for different biofuel options: The case of Belgium. *Energy Policy*, *39*(1), 200-214.	> Air quality > GHG balance	> Impact on economic growth > Investment costs	> Food prices	
30	A multi-criteria approach to screening alternatives for converting sewage sludge to biodiesel	Pokoo-Aikins, G., Heath, A., Mentzer, R. A., Mannan, M. S., Rogers, W. J., & El-Halwagi, M. M. (2010). A multi-criteria approach to screening alternatives for converting sewage sludge to biodiesel. *Journal of Loss Prevention in the Process Industries*, *23*(3), 412-420.		> simulation tools for total cost estimation		> Safety Index (SI) based on solvent criteria and process conditions
31	Multicriteria analysis to evaluate the energetic re-use of riparian vegetation	Recchia, L., Cini, E., & Corsi, S. (2010). Multicriteria analysis to evaluate the energetic re-use of riparian vegetation. *Applied Energy*, *87*(1), 310-319.	> Distance > Number of machines > Efficiency	> Cost difference > Storage > Investment	> Logistic aspects: number of machines, number of transport & plant	

H. Additional Key Criteria Identified by Stakeholders

Although the criteria for this study were established through the literature review, further criteria were considered important when evaluating SAF technology from the interviewed stakeholder's point of view.

For the airline, several other key criteria play a role in the evaluation of the performance of SAF technologies. Firstly, feedstock availability and the location of the SAF production facilities are considered critical because the geographical location affects both logistics and feedstock accessibility. The airline has a vested interest in making sure that certification and compliance with regulations and standards, such as the Renewable Energy Directive (RED) and the Roundtable on Sustainable Biomaterials (RSB) are taken into account. Moreover, the feedstocks used need to meet specific airline requirements. Only limited use of palm oil or its by-products are allowed, for example. Feedstocks must also be in line with the RED II criteria, which place emphasis on sustainability and responsible use of feedstocks. Furthermore, Indirect land use change (ILUC) is also important to them. The airline aims to minimise ILUC impact, such as deforestation and biodiversity loss. Finally, it is a priority to use renewable energy sources in the production process of SAF, indicating the aviation industry's aims to become more sustainable and to contribute towards the reduction of the carbon footprint within the aviation industry.

The Environmental and Sustainability Organisation prioritized the assessment of GWP of an SAF production pathway. They stressed that assessing this potential exceeds looking at emissions. To assess the full spectrum of sustainability issues related to different feedstocks, sustainability assessment must be individualised or assessed on a case-by-case basis to determine whether a feedstock is sustainable. An example is given of a life cycle assessment for used cooking oil, which can result in an 85% emission reduction. However, such accounting methods can overlook other sustainability issues by adopting a purely emissions-oriented perspective. Another important criterion according to the environmental and sustainability organisation is the feedstock availability. It is important to evaluate the availability of feedstock supply so that sustainability can be ensured. This raised the question of alternative uses of feedstocks. Animal fats, for example, are also often used in the cosmetics and other industries, so using these same fats for biofuel production can lead to an increase in demand for palm oil, which contradicts the sustainability goal. The third criterion considered important in assessing an SAF production pathway is the potential for fraud. The environmental and sustainability organisation elaborated on the challenges of detecting fraud, for example with used cooking oils, where virgin oil can pass for waste. It is being stated that certification systems are flawed, often not providing adequate controls.

From the consumer's point of view, an important criterion is the ability of an SAF production pathway to manage waste properly and the potential for SAF to be blended with traditional fuels without degrading performance. In addition to this, the demand for transparency and involvement in the introduction of SAF technologies is increasing, making this an important factor if not a separate criterion. As part of the ongoing trend for the consumer to get informed, there is an ever growing interest in the origins and production pathways of SAF and there is a growing demand for a thorough analysis of SAF and how it compares to other fuel technologies.

An important consideration in the evaluation of new SAF technologies according to the SAF production company's point of view is the CO_2 abatement costs. This represents the costs associated the reduction of CO_2 emissions. It is an important criterion in the assessment of the commercial viability of SAF technology. The long-term competitiveness of the feedstock is also considered very important. Finally, it is noteworthy that all the parties involved in the development and application of SAF production technologies are all known.

For the ASTM, competition between different companies using the same technologies is important. Additionally, plant capacity is an important consideration. Environmental concerns including non-GWP emissions are an important criterion from the ASTM's point of view. This means that as well as focusing on reducing greenhouse gas emissions, it is important to look at other environmental impacts, such as air pollution, water use and the effects on biodiversity. Finally, it is crucial to bear in mind the robustness of the process and the reliability and stability of the production process in different circumstances.

Finally, in the interview with the energy company in the oil and gas industry, several criteria were dis-cussed that are critical to the success of a production route for SAF. The following factors were mentioned: emissions, technology, market, politics, unit economics, storage, infrastructure required and scalability.

I. Thresholds

The thresholds defined for the CR^I by Liang et al. (2020) are shown below.

Table 30: Thresholds.

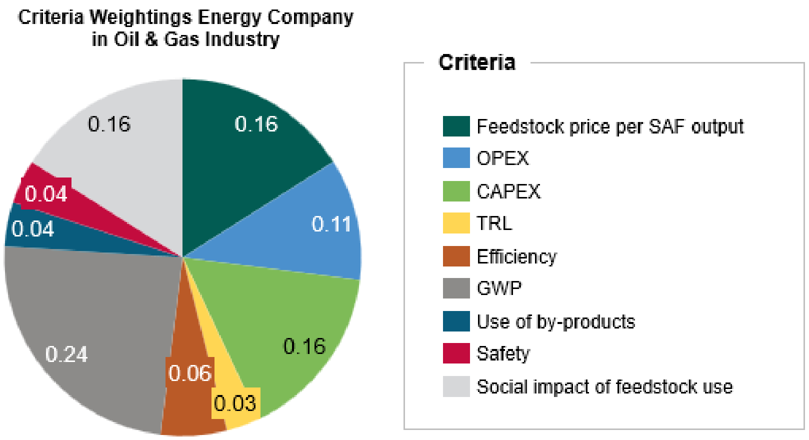
	Criteria						
Scales	**3**	**4**	**5**	**6**	**7**	**8**	**9**
3	0.1667	0.1667	0.1667	0.1667	0.1667	0.1667	0.1667
4	0.1121	0.1529	0.1898	0.2206	0.2527	0.2527	0.2683
5	0.1354	0.1994	0.2306	0.2546	0.2716	0.2844	0.2960
6	0.1330	0.1990	0.2643	0.3044	0.3144	0.3221	0.3262
7	0.1294	0.2457	0.2819	0.3029	0.3144	0.3251	0.3403
8	0.1309	0.2521	0.2958	0.3154	0.3408	0.3620	0.3657
9	0.1359	0.2681	0.3062	0.3337	0.3517	0.3620	0.3662

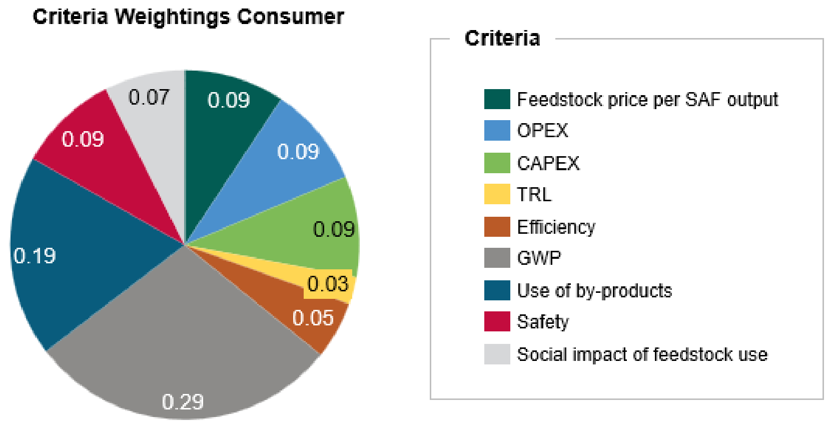
J. MCA framework and Detailed Criteria Weightings

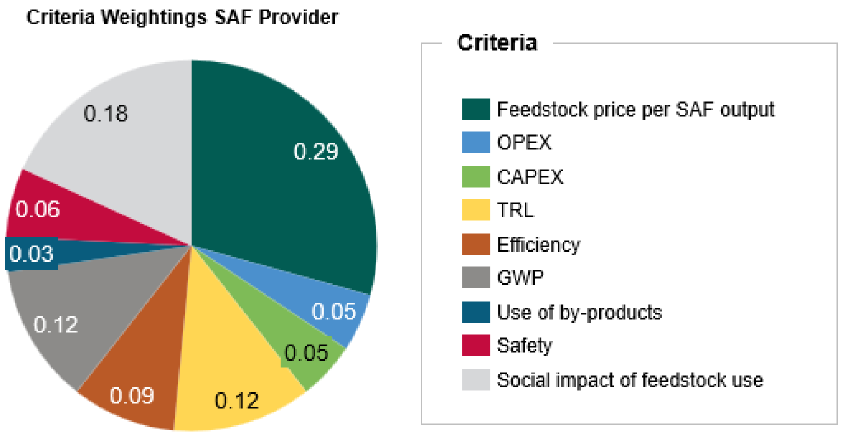
The criteria and their rounded respective weightings were integrated into the MCA framework in the form of a table, as shown below.

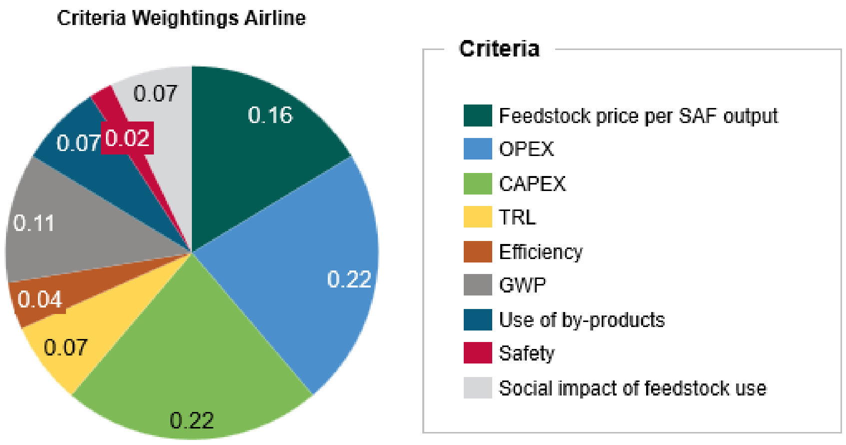
Table 31: MCA framework.

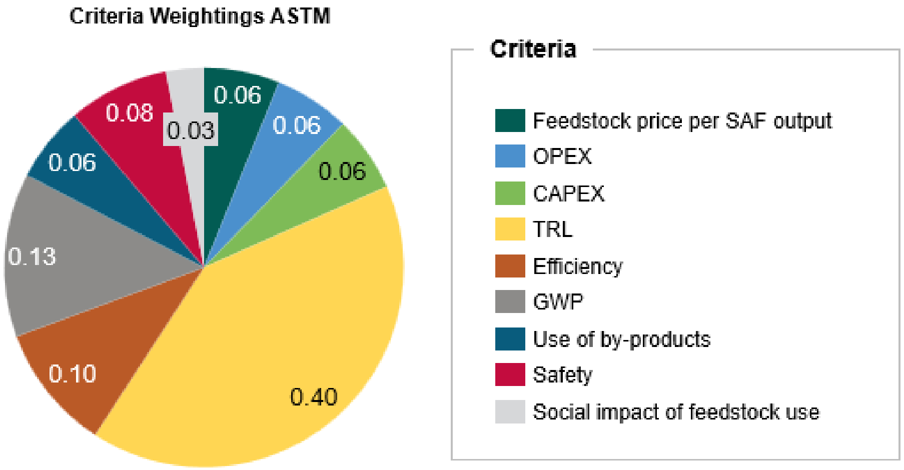
MCA FRAMEWORK		**Stakeholders**					
		Traveler	**Shell**	**SAF production company**	**Airline**	**Environmental & Sustainability organisation**	**ASTM**
Economic criteria	**Feedstock price per SAF output**	0.09	0.16	0.29	0.16	0.07	0.06
	Operational costs	0.09	0.11	0.05	0.22	0.03	0.06
	Capital costs	0.09	0.16	0.05	0.22	0.05	0.06
Technical criteria	**Technological Readiness Level**	0.03	0.03	0.12	0.07	0.07	0.40
	Efficiency	0.05	0.06	0.09	0.04	0.08	0.10
Environmental criteria	**Global Warming Potential**	0.29	0.24	0.12	0.11	0.31	0.13
	Use of by- products	0.19	0.04	0.03	0.07	0.08	0.06
Social criteria	**Safety**	0.09	0.04	0.06	0.02	0.10	0.08
	Social impact of feedstock use	0.07	0.16	0.18	0.07	0.20	0.03

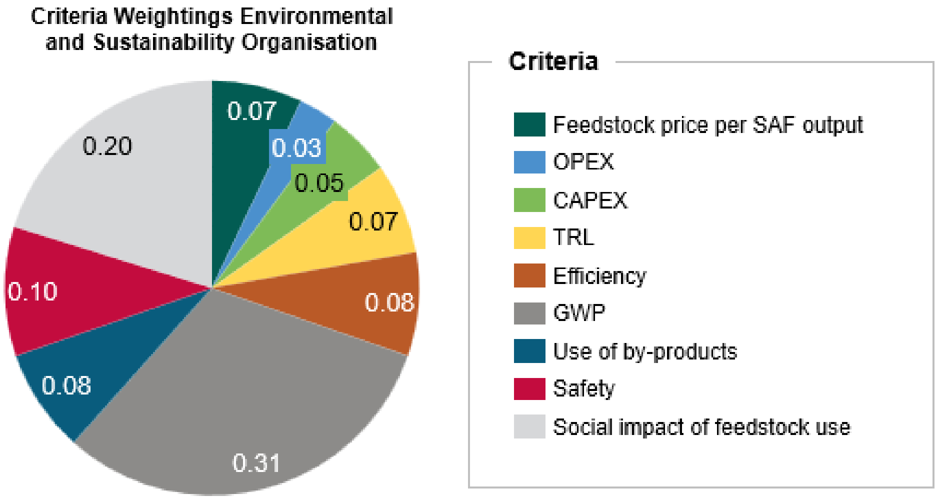

Criteria Weightings Energy Company in Oil & Gas Industry


Criteria Weightings Consumer


Criteria Weightings SAF Provider


Criteria Weightings Airline


Criteria Weightings ASTM
0.06
0.06
0.06
0.40
0.10
0.13
0.06
0.08
0.03
Criteria
Feedstock price per SAF output
OPEX
CAPEX
TRL
Efficiency
GWP
Use of by-products
Safety
Social impact of feedstock use


Criteria Weightings Environmental and Sustainability Organisation
0.07
0.03
0.05
0.07
0.08
0.31
0.08
0.10
0.20
Criteria
Feedstock price per SAF output
OPEX
CAPEX
TRL
Efficiency
GWP
Use of by-products
Safety
Social impact of feedstock use

K. Comprehensive Research Findings on Use of By-products

This appendix presents the research findings of a comprehensive literature review on the by-products of HTL, FP, and HEFA technologies and their potential uses. The research findings are presented per technology. It is important to note that only by-products resulting from the actual HTL, FP and HEFA step have been included in this analysis. Thus, by-products generated during the pre-treatment step or during upgrading processes are not included in this assessment. Furthermore, for this study, the products obtained after the distillation step, such as naphtha, diesel, and LPG, are considered to be end-products and not by-products. These end-products, are ready for immediate commercial use and can be directly sold on the market, distinguishing them from by-products which may require further processing to realize their value. Consequently, they are not included in this analysis of use of by-products.

HTL by-products

The by-products of HTL are primarily the aqueous phase (HTL AP), followed by gaseous by-product, and, to an even lesser extent, a solid residue (Peterson et al., 2008).

Aqueous phase

HTL AP is a potentially valuable resource for diverse applications (Zhang et al., 2020). In Watson et al (2020) the potential of HTL AP for nutrient recycling as well as electricity production is described. The nutrient-rich HTL AP can be applied in the production of biomass, such as in the cultivation of algae, which can absorb the nutrients from HTL AP. Algae cultivation can then be used for biofuel production or agricultural applications. More importantly, the organic richness of HTL AP can be put to good use in the generation of electricity through the use of Microbial Fuel Cells (MFCs) and Microbial Electrolysis Cells (MECs). These micro-organisms help break down the HTL Ap organic compounds and turn them into electrons. These electrons then travel along an external circuit which culminates in the generation of electricity (Watson et al., 2020).

The potential value of HTL AP can also be understood by its ability to yield chemicals such as acetic acid, phenol, and glycolic acid, which can all be used across a variety of different industries. Swetha et al. (2021) specifically highlight the value of glycolic acid in the cosmetics industry and the application of phenol in the production of dyes, antioxidants, pigments, and resins. According to Swetha et al. (2021) acetic acid can be used to produce chemicals or fuels. Li et al. (2019) also points out the potential to convert the organic content of this by-product into methane through aerobic digestion, which in turn can be used for the generation of energy.

Given that this by-product is rich in essential nutrients, such as nitrogen and phosphorous, it is ideal for recycling and use in fertilizers. This facilitates more sustainable agricultural practices (Wang et al., 2021).

Gaseous by-product

Ranganathan and Savithri (2019) assert in their study that the gaseous by-product is used predominantly for the cultivation of microalgae. H_2-rich gas is recirculated and utilized in the upgrading process to enhance the quality of the biocrude (Mathkander et al., 2021). In order to enhance the biofuel and increase its value, this step is crucial, and it proves that all HTL by-products can be reused, which brings us closer to a more sustainable and circular biofuel production process.

Moreover, an expert on Steeper HTL Technology explained during an interview (Steeper, personal communication, 2024), that the gaseous HTL by-product can potentially be re-used in the process of generating energy and heat.

Solid residues

The future value of the solid residue left after the HTL process lies in the fact that it may have properties that make it suitable for re-use or further valorisation.

Amar et al. (2020) demonstrate that the solid residue, after separation from the HTL-processed slurries, is thermally treated to produce hydrochar. This hydrochar is then thoroughly characterized and can be applied in energy storage technologies, such as in the development of asymmetric supercapacitors. These technologies are used in many different applications, such as portable gadgets that need to store and release energy quickly, emergency power sources, and peak power assistance for electric and hybrid cars (Amar et al., 2020).

Furthermore, the study by Arun et al. (2020) shows that the solid residue, after appropriate treatment and in combination with a suitable catalyst, has the potential for re-use in processes such as hydrogen production.

Challenges

Managing the aqueous by-product from HTL also presents challenges. While this by-product contains valuable organic compounds and nutrients, improper handling can result in environmental issues, such as pollution and eutrophication, highlighting the potential environmental impacts of inadequate treatment (Zhang et al., 2020). Additionally, the presence of phenolics and ammonia not only complicates biological treatment processes but also hinders energy recovery efforts, stressing the need for innovative treatment methods (Wang et al., 2021). Moreover, the complexity and associated costs of effective treatment and disposal pose ongoing challenges, as these factors critically influence the sustainability and economic viability of HTL technology (Hong et al., 2021). This duality of opportunity and difficulty needs a balanced approach, focusing on ongoing research and on developing efficient and ecologically responsible solutions.

The literature review did not specifically identify challenges associated with the gaseous by-products. However, considering the inherent complexities of the HTL process, it is reasonable to assume such challenges exist due to the variability in the composition of gaseous by-products, depending on the feedstock used. This necessitates flexible and adaptable treatment technologies, as standardized systems may not handle all outputs efficiently. Further research is needed to explore the design and efficacy of such systems.

Solid residues also require additional processing to tailor their properties for specific application in energy storage. The complexity of production processes and higher costs associated with this might limit their application (Amar et al., 2020). These challenges must be addressed to realize the potential of hydrochar in energy storage applications, highlighting the need for further research to develop cost-effective and efficient processing techniques. Although these aspects fall outside the scope of this thesis, they are important for future advancements.

FP by-products

Bio char and off-gasesses are considered as valuable by-products of FP (Pattiya, 2018). Below, both the re-use of the off-gasses and bio-char from FP and the challenges that need to be overcome to realise their full potential are discussed.

Off-gasses

The process of FP generates off-gasses that are typically made up of a combination of carbon monoxide (CO), carbon dioxide (CO_2), hydrogen (H_2), methane (CH_4), and other light hydrocarbons (Pattiya, 2018).

In an interview with an expert on the FP BTG technology (BTG, personal communication, 2024), the potential for re-use of pyrolysis gases was reported to be significant, especially for the generation of energy and process heat. Goyal et al. (2008) poses that these gases can be re-used as fuel combustion purposes in industry. As such, they provide an alternative to fossil fuel use and contributes to the reduction of GHG emissions. Furthermore, Bridgewater (2000) also stresses the importance of a particular application of pyrolysis gas as a fluidizing medium or carrier gas in fluidised bed reactors. This can improve the efficiency of chemical processes and these gases also serve as a source of process heat within the production facility. The study by Zhang et al. (2011) continues Bridgewater's work by examining into the potential re-use of pyrolysis gases as carrier gases in the FP process. They argue that a larger amount of bio-oil can be obtained through the optimization of the atmosphere of the carrier gas in the pyrolysis process and the bio-oil thus extracted has enhanced properties. Alternatively, more economical pyrolysis gases are generated that can be re-used or burnt for energy.

Char

Sustainable solutions to environmental problems are growing in importance and in this debate, biochar, a carbon-rich by-product of pyrolysis, has come to the fore as a key player with a multitude of potential applications. The use of biochar in, amongst other things, sustainable agriculture, climate change mitigation, organic waste management, and water treatment looks promising. It plays a fundamental role in the promotion of environmental sustainability and the development of a circular economy. The carbon-rich char is a solid that is produced alongside bio-oil during FP. Its potential applications as soil amendment, for carbon sequestration or as a feedstock for activated carbon production were discussed extensively in the “IATA: What’s Next?’ Conference (IATA, 2024).

Mohan et al. (2018) demonstrate in a recent study that biochar which is extracted from agricultural waste matter, such as rice husks and maize straw, can improve the properties of soil and thus its fertility. The study emphasizes the enriching qualities biochar has for organic carbon in soil and it highlights its capacity to increase the retention of water. The latter is particularly prized in drier climates or during droughts, when efficient water management is essential to ensure crop growth. Organic carbon in biochar provides essential nutrients for soil micro-organisms as it supports the growth and activity level of the microbes, which play a crucial role in maintaining a healthy soil structure and ensure the long-tern fertility of the soil. The porous structure of the biochar improves the permeability of the soil, which facilitates the aeration of the soil and the distribution of water throughout the soil, thus ensuring healthier plants. Moreover, the pores in the biochar are also better able to retain nutrients, ensuring longevity of use by plants. The whole process reduces the need for fertilisers and therefore GHG emissions. It can be classed as a sustainable and efficient way to support the productivity of farmland (Mohan et al., 2018; Leng et al., 2019).

Beesley et al. (2011) also highlights biochar's ability to effectively immobilize heavy metals. These metals can cause serious health problems when people are exposed to them. The large surface area and porous structure of biochar make it effective for adsorbing heavy metals from water and soil, as these metals adhere to the surface of the biochar particles. In addition, biochar contains functional groups that can participate in ion exchange processes. This means that heavy metals in soil or water can exchange with more harmless ions already present in the biochar, resulting in the immobilization of the heavy metals. These properties result in the sequestration of these metals in a state that inhibits the absorption by organisms and reduces the likelihood of them entering the food chain. It also minimizes the environmental impact. Biochar is therefore particularly suitable to remediate contaminated sites and to improve the safety of drinking water and the quality of soil (Beesley et al., 2011).

Research by Sanchez-Mondero et al. (2018) focusing on the potential of biochar to improve the process of composting organic waste, credits its high porosity and ability to hold nutrients. This means that biochar is particularly good at absorbing unwanted odours, aiding the management of the composting process. Moreover, it increases the nutritional content of the compost and because of its capacity for cation exchange, biochar can retain these essential nutrients. Consequently, when this nutrient-rich compost is mixed with soil, plants can absorb them, which results in optimized metabolic processes and in turn an improvement in growth (Sanchez-Monedero et al., 2018).

Biochar also plays a crucial role in sustainable and circular wastewater treatment. Research by Inyang et al. (2016) stresses the biochar's adsorption qualities, which can be used as a filtration medium in wastewater treatment facilities. Applying biochar in this way has proven to be particularly efficient at eliminating pollutants and nutrients from the wastewater before it is discharged into water bodies in nature, such as rivers and lakes. The efficiency with which biochar captures contaminants is due to its large surface area and porous structure. This protects aquatic ecosystems and contributes to a consistent water quality. The use of biochar in wastewater treatment is an important step towards the mitigation of the impact of human activities on the environment and it makes an important contribution to the circular economy in that it turns waste products into useful water treatment tools (Inyang et al., 2016).

In addition to this, the potential for re-use of FP char in the generation of energy and process heat is substantial, according to an expert on BTG FP technology (BTG, personal communication, 2024).

Challenges

Another promising use of off-gasses and biochar for energy recovery could result in a significant improvement in efficiency and minimizes the number of discarded by-products. However, managing these by-products effectively and finding a use for them is a serious challenge that requires a comprehensive solution.

One such challenge when re-using FP by-products such as off-gasses and biochar is the presence of tar and other contaminants. They can only be safely re-used when these contaminants are removed through a lengthy and complex purification process (Guo et al., 2020). According to Guo et al. (2020), tar can potentially be removed through catalytic reforming. However, this is likely to incur higher costs because it requires specialized equipment, which need to be maintained, as well as a higher consumption if energy (Guo et al., 2020). Other research shows that, depending on its future use, biochar requires additional preparation or purification processes in order to achieve the desired qualities (Srinivasan et al., 2015). These processes, which may include steps such as washing, activation or chemical modification, are required to increase the surface area of biochar for pollution remediation applications or to remove contaminants for safe agricultural use. Srinivasan et al. (2015) also emphasise that these additional processing steps have potential cost implications, underlining the importance of economic considerations when considering the feasibility of biochar-based projects.

A further challenge is the optimization of process parameters, such as temperature, heating rate, and residence time. Adjustments to these parameters, however small, have significant consequences for the quality as well as the quantity of the biochar produced. Parameters therefore play a significant role in determining the efficiency of biochar production. Tripathi, Sahu, & Ganesan (2016) highlight that precise control and optimization of these pyrolysis parameters is essential to obtain the best results in terms of energy recovery and biochar yield. These challenges are critical because biochar properties, such as porosity, carbon content and chemical composition, are directly influenced by the specific conditions under which pyrolysis takes place. For the further development and application of pyrolysis technologies for the production of biochar as a by-product, optimizing the adjustment of parameters is essential.

The study by Srinivasan et al. (2015) points out other challenges related to the production and utilization of biochar. Firstly, the variability of the composition of biochar depends to a large degree on the biomass feed used and the pyrolysis conditions and this has an immediate effect on the efficiency of the pyrolysis process as well as the applicability of biochar in agronomic and environmental applications. In addition, according to Srinivasan et al. (2015), the economic feasibility of biochar production is an issue. Cost-effectiveness depends on the availability of cheap and reliable biomass sources. According to Srinivasan et al. (2015), the other challenge is the management of heavy metals in biochar. Heavy metals increase the potential risk for the environment, in particular when biochar is produced from waste biomass with high concentration of these metals. Consequently, using biochar as an enhancer of soil needs to be monitored carefully and the negative impact on the environment of these heavy metals needs to be mitigated. Heavy metals increase the potential risk for the environment, in particular when biochar is produced from waste biomass with high concentration of these metals. Consequently, using biochar as an enhancer of soil needs to be monitored carefully and the negative impact on the environment of these heavy metals needs to be mitigated.

In conclusion, the number of potentially useful applications of the by-products of FP are varied, but equally, there are still important technical and economic challenges that need to be addressed so that the opportunities these by-products proved can be fully exploited. Further research and innovation are required so that the technological and economic hurdles can be overcome.

HEFA by-products

The HEFA process primarily produces water, CO_2, and propane as by-products (Neuling & Kaltschmidt, 2018).

Water

After pre-treatment in the production of HEFA fuels, the hydrogenation of triglycerides takes place (Neuling & Kaltschmidt, 2018). According to Neuling & Kaltschmitt (2018) the preferable reaction taking place within the hydrogenation process is hydrodeoxygenation. During hydrodeoxygenation the triglycerides react with hydrogen and a solid catalyst at high temperatures and pressures (Gutiérrez-Antonio, 2017). The hydrogen is attached to the oxygen and forms an aldehyde intermediate, and the hydrogen also removes the oxygen from the triglycerides of the fatty acid chains of the oils and fats (Chu et al., 2017). The oxygen naturally present in the feedstock is removed by forming water as a by-product (Neuling & Kaltschmitt, 2018). After treatment, the water can be re-used within the plant for other processes, such as cooling or cleaning, or can be disposed of.

CO_2 and Propane

Decarboxylation occurs in parallel to the hydrodeoxygenation when hydrogen is only sufficient for the saturation of the double bonds of the organic molecule and for the separation of the propane (Neuling & Kaltschmitt, 2018). In this case the oxygen is then removed as a by-product, carbon dioxide. According to Tao et al. (2017) the CO_2 generated during the decarboxylation pathway can be vented or recycled within the process. Another by-product of the hydrogenation step of vegetable oil is propane which is either removed and sold separately (Tao et al., 2017) or used for energy provision within the biorefinery (Neuling & Kaltschmitt, 2018).

Gaseous products

The subsequent process involves cracking and isomerizing the intermediate product (Neuling & Kaltschmitt, 2018). According to Kalnes et al. (2010) the cracking and isomerization reactions are either concurrent or sequential. These reactions are required to meet the biofuel specifications cold flow and combustion properties (Tao et al., 2017; Neuling & Kaltschmitt, 2018). During the catalyst-controlled isomerization process, straight-chain hydrocarbons are broken down into branched structures which have lower freezing points. Catalytic cracking breaks down the long-chain fatty acids into shorter-chain hydrocarbons to enhance the combustion properties of the fuel (Neuling & Kaltschmitt, 2018). The hydrocarbon products from the hydroisomerization and cracking process are distilled to remove gaseous products (Tao et al., 2017). According to Tao et al. (2017) these gaseous products contain propane, H_2, and CO_2.

These gases are subjected to further separation. The propane is dissolved in hexane and separated from CO_2 and H_2 (Tao et al., 2017). Propane, once conditioned, is conserved and can be sold as a co-product. It can be used as fuel or as an internal energy carrier after a conditioning step (e.g. cleaning via amine wash). CO_2 and H_2 are vented, or the latter can be recycled to the hydrogenation step (Neuling & Kaltschmitt, 2018).

Challenges

Treating water before it can re-used is a costly process which often require advanced treatment methods and monitoring of environmental standards, as well as the removal of contaminants (Tao et al., 2017; Davis et al., 2013).

Moreover, the original design of the existing facilities bore in mind the optimization of HEFA fuel production and did not take account of the valorisation of by-products. For further processing in the refinery, corresponding on-site systems (e.g. gas separation units, and storage capacities) have to be realized (Neuling & Kaltschmitt, 2018). Reusing the CO_2 has similar challenges to the cracking and isomerization process.

Summary of research findings

This table serves as a concise summary of the findings from a comprehensive analysis of the reuse of by-products. It is specially designed to provide experts with a clear and organized overview of key aspects that determine the viability and impact of by-product reuse.

1. Sustainability: This column summarizes contributions to sustainability goals, such as waste reduction, emissions reduction, and more efficient use of resources. It provides direct insight into the environmental benefits of by-product reuse. This information helps experts assess the environmental impact of reuse strategies, focusing on their contribution to sustainable practices and compliance with environmental regulations.
2. Technical feasibility: this column analyses the technological aspects related to the reuse of by-products. It details whether technologies are readily available and suitable for immediate application, as well as whether they require modifications or further development for effective use. The column informs experts about the technical landscape and challenges, aiding in understanding the technical readiness and potential hurdles of a reuse strategy.
3. Economic viability: This column evaluates the economic benefits of reusing by-products, such as cost savings or revenue generation. It helps determine the economic feasibility of reuse strategies, focusing on their potential to be cost-effective and financially beneficial. This evaluation is crucial for understanding the financial implications of reuse practices and guiding investment and operational decisions.
4. Operational feasibility: This column provides insights into how easily by-product reuse strategies can be integrated into existing operations and infrastructures. It examines the compatibility of new reuse practices with existing processes, the need for new equipment or changes to operational workflows, and the potential impact on production efficiency. This assessment is vital for determining whether a reuse strategy can be implemented with minimal disruption and adaptation costs.

Table 32: Comprehensive summary use of by-products analysis.

Technology	Sustainability	Technical feasibility	Economic viability	Operational feasibility
HTL	Utilizing the aqueous phase for energy production or as a food source for algae contributes to sustainability. Gases can help grow microalgae, reducing CO_2 emissions.	Technologies for treating HTL by-products are being developed, especially for aqueous phase valorisation and efficient gas re-use.	The cost of treating and valorising HTL by-products can be high	It requires high-tech systems for separating and treating the various by-products.
FP	Biochar enriches the soil and increases water retention, which is beneficial in arid areas. Off-gasses can be re-used for energy generation, helping to reduce fossil fuel use and GHG emissions.	There are proven technologies for utilising biochar in agriculture and off-gasses as fuel. However, the optimal utilisation of these gases for improved FP processes requires further research.	The re-use of biochar and gases can be cost-effective, depending on the demand for biochar in the local market and the configuration of energy re-use systems.	Integration of biochar use in agriculture and off-gases re-use in energy processes may require logistical and infrastructural adjustments.
HEFA	The re-use of water and gases can reduce the footprint and contribute to sustainability goals.	Technologies for water recycling and CO_2 valorisation are available, but optimisation is needed for specific applications in HEFA production. This can pose specific technological challenges.	Depending on the scale and integration of recycling technologies, costs may vary.	Integration of recycling and re-use within existing HEFA facilities can be complex It requires modifications to existing infrastructure, such as new equipment pipelines, and storage capacities include.

L. Summary of Research Findings on the Social Impacts of Related to Feedstock Use

This summary table categorizes the impact of each feedstock on social cohesion, public health, food security, and quality of life. The summary table shows the results of the analysis for each social factor. The summary table shows the results of the analysis for each social factor expressed as positive (+), negative (-) or mixed (+/-) scores. Below, the logic behind assigning these scores is detailed:

1. **Social Cohesion:** positive (+): feedstocks that ensure communities are actively involved in their collection or processing, or that provide economic opportunities that benefit local communities, are given a positive score. Negative (-): the use of feedstocks that lead to land conflicts or displacement of local communities are given a negative score due to the disruption of existing community structures.
2. **Public health:** positive (+): the use of feedstocks that lead to a cleaner environment or the reduction of health risks score positively. Mixed (+/-): when the feedstock potentially has both positive and negative health impacts
3. **Food security:** positive (+): feedstocks that grow on marginal land that does not compete with food production can contribute positively to food security by keeping agricultural land free for food crops. Negative (-): feedstocks that intensively use land and water that could otherwise be used for food production are given a negative score.
4. **Quality of life:** positive (+): feedstocks that provide improvements in air quality, water quality, and access to renewable energy sources that contribute to a higher standard of living result in a positive score. Negative (-): where the use of feedstocks results in environmental pollution or degradation of landscapes that reduce the quality of life of (nearby) communities.

Table 33: Summary social impact related to feedstock use analysis.

Technology	Feedstock	Social cohesion	Public health	Food security	Quality-of-life
HTL	Algae	+	+	+	
	Sewage sludge		+	+	+
	Food waste	+	+/-	+	+
	Agricultural residues	+	+	+	+
FP	Agricultural Residues	+	+	+	+
	Forestry residues	+		+	+
	Non-recyclable Plastics	+	+/-	+	+
HEFA	Food-based		-	-	-
	Non-food based		+	+	-
	Waste feedstocks (UCO)	+	+	+	
	Residual feedstocks (animal fat)	-		+	
	Residual feedstocks (PFAD)	-	-	-	-

M. Performance Matrix

The performance matrix below shows all the expert performance scores for each technology against the MCA criteria for this thesis.

Table 34: Performance matrix.

	Criteria								
Technology	**GWP**	**Use of by-products**	**CAPEX**	**OPEX**	**Feedstock price**	**Safety**	**Social impact related to feedstock use**	**TRL**	**Efficiency**
FP	3	4	3	2	4	3	3	3	3
HTL	3	3	2	3	4	3	4	2	4
HEFA	3	2	4	4	1	4	1	5	5

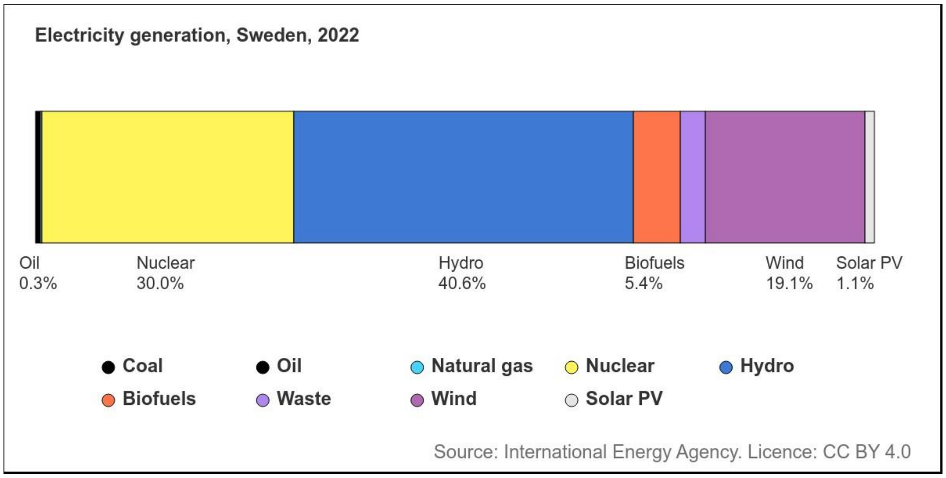
N. Detailed Explanation Scenarios LCA

Electricity

For this study three electricity utility scenarios were constructed to reflect a range of potential carbon intensity levels. Using multiple intensity levels ensures the time-agnostic nature of this thesis. The scenarios are defined as the green, mixed, and fossil based electricity scenarios and are based on the energy mix of a specific country in the EU. This approach provides a basis for the credibility and practical relevance of the scenarios because they are based on actual, realistic data from different countries. It also provides a structured approach to how different energy generation mixes can affect the GWP of SAF production pathways. This analysis will clarify how the choice of electricity source impacts the carbon footprint of SAF production technologies and will illustrate how the environmental performance of different production pathways varies depending on the scenario chosen. The countries selected for the three scenarios are presented below.

Green Electricity Scenario: Sweden

Sweden's extensive use of renewables and nuclear power for the generation of electricity make it a good example of the green electricity scenario (see IEA (n.d.b) figure below). A significant proportion of its electricity is generated by hydro power, followed by nuclear power and then wind power. This diversification has resulted in Sweden having the lowest carbon intensities in Europe for the generation of electricity. Sweden's 2022 electricity energy mix, taken from IEA (n.d.b) is shown in the figure below.



Source: International Energy Agency. Licence: CC BY 4.0

Figure 26: Green electricity scenario.

Mixed Scenario: Spain

Spain's significant investment in wind and solar power (IEA, n.d.) means it can serve as a baseline for the mixed scenario. The renewable energy sources make an important contribution towards the energy mix together with traditional fossil fuels, such as natural gas and oil. This mix of renewables and non-renewables illustrates the phase of Spain's transition towards a more sustainable energy system. Spain's 2022 electricity energy mix, taken from IEA (n.d.) is shown in the figure below.

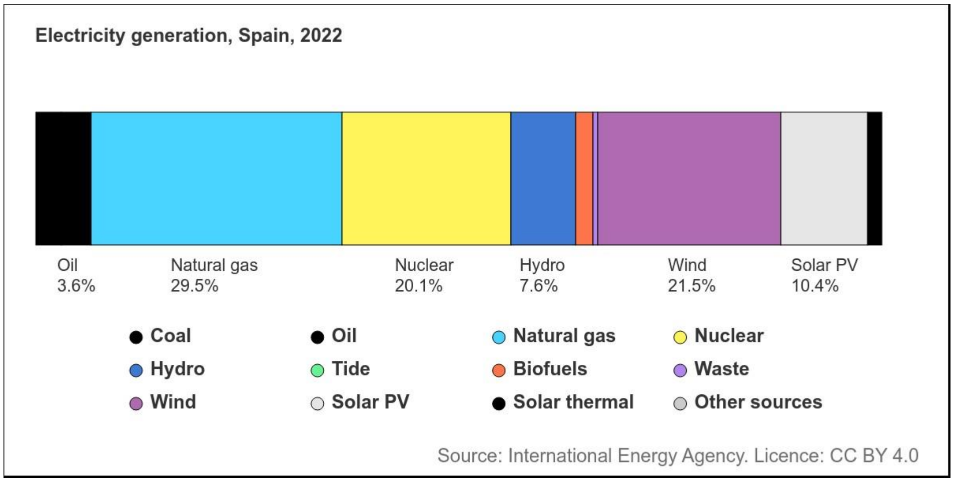


Figure 27: Mixed electricity scenario.

Fossil-based Scenario: Poland

Poland represents the fossil fuel scenario due to its high dependence on coal for electricity generation. Despite growing renewable energy, coal continues to dominate electricity generation (IEA, n.d.a). As a result of this energy mix for electricity generation, Poland has one of the highest carbon intensities in Europe. Poland's 2022 electricity energy mix, taken from IEA (n.d.a) is shown in the figure below.

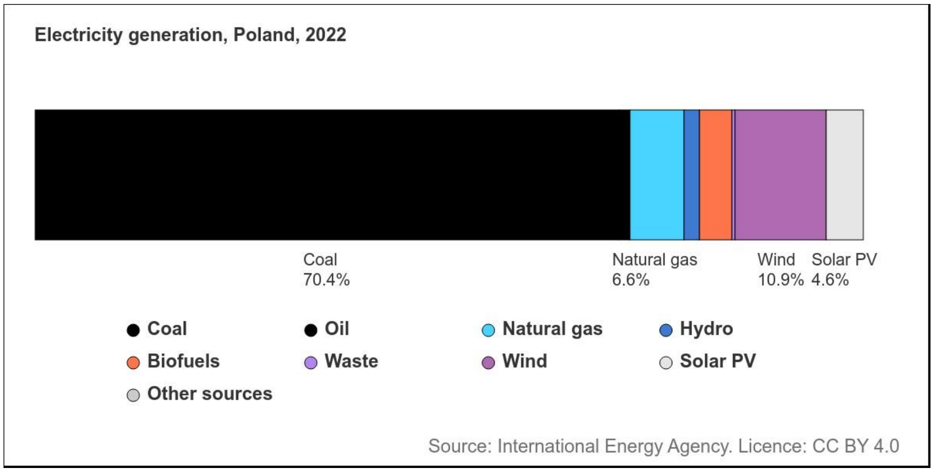


Figure 28: Grey electricity scenario.

Based on this information, the following emission factors for electricity generation were used in the three scenarios, adopted from Commission Delegated Regulation (EU) (2023).

Table 35: Electricity scenarios.

Scenario	GHG emission intensity of generated electricity (gCO$_2$eq/MJ)	Source
Green Electricity Scenario	4.1	Delegated Regulation - 2023/1185 - EN - EUR-Lex (n.d.)
Mixed Electricity Scenario	54.1	
Fossil Based Scenario	196.5	

Hydrogen

This study considers three hydrogen production scenarios for the SAF production technologies: green, blue, and grey. The choice of hydrogen source can have a significant impact on the sustainability of the final product and the impact of this is explored by considering different scenarios. The time-agnostic nature of the study is guaranteed by incorporating various hydrogen production scenarios. Taking different potential developments into account results in robust findings that can be applied regardless of changes in the production of hydrogen. Green hydrogen sets the standard for a sustainable future; grey hydrogen depicts the current and more polluting state; and blue hydrogen represents a practical transition scenario. Green hydrogen is produced by the electrolysis of water using only renewable energy sources such as wind or solar power, resulting in a process with a minimum of CO_2 emissions. Grey hydrogen, the most widely used type, is produced using fossil fuels (natural gas specifically) and by doing so releases carbon dioxide. Although blue hydrogen is also produced using fossil fuels, the CO_2 is captured and stored during the production process, reducing its impact on the environment (Carella, 2024). The Hydrogen Council (2021) provided the carbon equivalent emissions per hydrogen production pathway. The same source also provides hydrogen emission factor predictions for 2030 and 2050.

The emission factors for 2030 were selected because they better align with the short-term values provided for other process utilities. The average of all renewable electrolysis pathways is taken as input for the green hydrogen scenario. For blue hydrogen, the average of fossil with CCS is taken as input. And for grey hydrogen, the average of the fossil fuel pathways without CCS is taken as the input. The values are shown in the table below.

Table 36: Hydrogen scenarios.

Type of hydrogen	GHG emissions, kg/kgH_2	Source
Green	0.60	Hydrogen Council et al. (2021)
Blue	3.86	
Grey	9.83	

Heat

Heat is added in the HTL and FP production processes for SAF, in order to facilitate the endothermic reactions. The energy balance of these processes illustrates a net energy deficit and therefore external heat sources are required. In this study, natural gas (NG) and renewable natural gas (RNG) are chosen for the scenarios to supply this required heat in the form of steam. The two heat scenarios have been chosen to show a range of energy sources, from a more sustainable to a more conventional option, thereby allowing a more nuanced analysis of the environmental impact.

The emission factor for natural gas has been taken from the Delegated Regulation - 2023/1185 and the emission factor for RNG has been taken from Bhattacharjee (2022), who calculated a GWP of 0.61 kg CO_2eq to produce RNG from landfill biogas. The production process of RNG in this study involves the methanation of CO_2, using hydrogen produced via solar-powered electrolysis. It is important to note that the carbon footprint of RNG can vary widely. This value of 0.61 kg CO_2eq to produce RNG using solar electricity serves as a proxy for the evaluation of the environmental impact of the SAF production pathways.

Table 37: Heat scenarios.

Heat Source	Total emissions (gCO$_2$eq/MJ)	Source
Natural Gas	66	Delegated Regulation - 2023/1185 - EN - EUR-Lex (n.d.)
Renewable Natural Gas	0.61	Bhattacharjee (2022)

O. Interview Questions Technology Providers

BTG Expert

Introduction

1. What are the steps you divide your technology process in?
2. What is the production capacity of your plant?
    a. What is the maximum and minimum?
    b. What are the limiting factors of scale up or scale down?
3. What makes your technology better than others?

Feedstock

1. What is the optimal feedstock for your process?
2. How dirty or how clean does the feedstock need to be?
3. What is your vision on where it should come from?

Pretreatment

1. What are the general characteristics of the biomass you want to get into the reactor? In terms of wetness, impurities, size?
2. What kind of feedstock pre-treatment are you using before it enters the pyrolysis reactor?
3. Drying? Chemical treatment? Sorting? Milling?
4. What types of impurities cannot enter the process?
5. How much moisture can be in the feedstock?

Pyrolysis

1. I have read on your website that your FP process consists of “a thermochemical decomposition of biomass through rapid heating, at a temperature of 450-600°C in the absence of oxygen”. Is this the case and what pressure conditions are maintained in your pyrolysis process?
2. What is the residence time of the pyrolysis process?
3. What is the energy input of your pyrolysis process?
4. How easily can the heat be recovered?

Bio-oil

1. Is the oil stable? What types of treatment are needed to stabilize the oil?
2. What are the general characteristics of the bio-oil?
3. How much oxygen is present in the bio-oil? Other compounds in there (i.e. nitrogen)?
4. What percentage of oxygen by mass is present. And nitrogen?
5. What other heteroatomic species that was not mentioned?
6. How much water is present in the bio-oil?
7. How acidic is the bio-oil?
8. What is the carbon conversion efficiency of producing the bio-oil?

Outputs

1. What other products aside from bio-oil are produced? And in what ratio are they produced?
2. The by-products, where do you use them for? Can they be used for heat generation?

SAF production

1. What kind of treatments need to be done after your technology to further upgrade the bio-oil to SAF?
2. What is the product distribution of the hydrocarbons?

3. What is the maximum SAF output?
4. What are advantages and disadvantages for you to use it for SAF?
5. What is the upgrading severity? → low, mid, or high severity upgrading conditions.
6. Approximately how much hydrogen is needed per litre or per kg of the bio-oil to upgrade it?
7. Do you have any idea how much energy this would cost?
   a. What is the product composition of the SAF? Approximately how much aromatics, iso-alkanes, n-alkanes, and cyclo-alkanes are in the product?
   b. Do you produce aromatics?
   c. What are the main types of hydrocarbon types? Which one is the highest?

Economics

1. Can you tell me the costs to build your plant and what do they consist of?
2. Can you tell me the costs to operate your plant and what do they consist of?
3. What are the costs per litre of bio-oil?

Storage and Risks:

1. How is the bio-oil packaged for transport?
2. Is there an expiration date for your bio-oil?
3. What are the risks associated with storing your bio-oil?
4. What is the flammability of your bio-oil?
5. What is the flash point of your bio-oil?
6. What are the risks associated with transporting your bio-oil?

Steeper Expert

Introduction

1. What are the steps you divide your technology process in?
2. What is the production capacity of your plant?
   a. What is the maximum and minimum?
   b. What are the limiting factors of scale up or scale down?
3. What makes your technology better than others?

Feedstock

1. What is the optimal feedstock for your process?
2. How dirty or how clean does the feedstock need to be?
3. What is your vision on where it should come from?

Pretreatment

1. What are the general characteristics of the biomass you want to get into the reactor? In terms of wetness, impurities, size?
2. What kind of feedstock pre-treatment are you using before it enters the HTL reactor?
3. Chemical treatment? Sorting? Milling?
4. What types of impurities cannot enter the process?
5. How much moisture can be in the feedstock?

HTL

1. I have read in Thomas Helmer Pedersen's Ph.D. dissertation that your HTL process has a maximum operating pressure of 350 bar and temperature of 450 ◦C. Is this the case?
2. What is the residence time of the HTL process?
3. What is the energy input of your HTL process?

4. How easily can the heat be recovered?

Bio-Oil

1. Is the oil stable? What types of treatment are needed to stabilize the oil?
2. What are the general characteristics of the bio-oil?
3. How much oxygen is present in the bio-oil? Other compounds in there (i.e. nitrogen)?
4. What percentage of oxygen by mass is present. And nitrogen?
5. What other heteroatomic species that was not mentioned?
6. How much water is present in the bio-oil?
7. How acidic is the bio-oil?
8. What is the carbon conversion efficiency of producing the bio-oil?

Outputs

1. What other products aside from the bio-oil are produced? And in what ratio are they produced?
2. The by-products, where do you use them for? Can they be used for heat generation?

SAF production

1. What kind of treatments need to be done after your technology to further upgrade the bio-oil to SAF?
2. What is the product distribution of the hydrocarbons?
3. What is the maximum SAF output?
4. What are advantages and disadvantages for you to use it for SAF?
5. What is the upgrading severity? → low, mid, or high severity upgrading conditions.
6. Approximately how much hydrogen is needed per litre or per kg of the bio-oil to upgrade it?
7. Do you have any idea how much energy this would cost?
   a. What is the product composition of the SAF? Approximately how much aromatics, iso-alkanes, n-alkanes, and cyclo-alkanes are in the product?
   b. Do you produce aromatics?
   c. What are the main types of hydrocarbon types? Which one is the highest?

Economics

1. Can you tell me the costs to build your plant and what do they consist of?
2. Can you tell me the costs to operate your plant and what do they consist of?
3. What are the costs per litre of bio-oil?

Storage and Risks:

1. How is the bio-oil packaged for transport?
2. Is there an expiration date for your bio-oil?
3. What are the risks associated with storing your bio-oil?
4. What is the flammability of your bio-oil?
5. What is the flash point of your bio-oil?
6. What are the risks associated with transporting your bio-oil?

P. Summary Interview BTG

Interview BTG 05/02/2024

The FP process steps

The SAF production process via the BTG FP technology is outlined as a sequence of closely linked stages, each of which is an integral part of the final product. The first stage of FP, along with the subsequent solid-liquid and gas-liquid separation stages, is a unified, interdependent process. This is followed by hydrogen upgrading and separation, which are seen as a separate phase from the initial stages. Distillation, the concluding stage is critical to making the final product suitable for blending with jet fuel.

Capacity commercial unit

[redacted] ton/hr, [redacted] MW. [redacted] ton bio-oil/hr based on dry biomass

The limiting factors to scale up or down

There was one unit in Malaysia of two tons an hour and there the conclusion was it should be bit little bit bigger. The question with biomass is, how much will you scale up and when do you put units in parallel. The current approach is to have multiple units of 5 tons an hour in parallel. This gives them more flexibility and It's more like a standard unit. It’s a modular construction and appears to be a quite good capacity. At the moment they look at a little bit larger because the current units’ capacity can be a little bit higher than they use at the moment. But, if they want to go to 20 tons an hour, they just have three or four units in parallel. At the moment is not really a driver to scale up. In the past, some studies have been done that it should be technically possible to go to 10 or even 20 tons an hour, but probably at the moment it's not really a driver.

Differences with other technologies

The mixing of biomass and hot sand. The major other FP that is available is, Ensyn, uses a circulating fluid bed in which biomass and hot sand are effectively mixed by a gas stream. What BTG does is a very critical step in the first process: mixing hot sand and biomass, because it has to heat up very quickly. This critical mixing step is followed by vapor condensation, resulting in the formation of pyrolysis oil. This is where the strength lies: the precision and speed of the heating process, which sets their technology apart.

This means that the initial mixing is a critical step. Ensyn is doing it by circulating the gas. What BTG is doing is a kind of mechanical mixing, what's called the rotating cone. So, it is a different way in mixing and they think that's better, but it is noted that, likely Ensyn says that they are better. But the unique difference is in this initial mixing. But the advantage is also that with mixing they don't use gas, it means that the vapours are more concentrated, so the equipment is a little bit smaller.

Comparison with HTL

The comparison between HTL (HTL) and pyrolysis technologies is discussed in the interview. It is recognized that HTL can be advantageous for processing very wet feedstocks, but it requires working under high pressure (around [redacted] bar) from the first step. The importance of simplicity in the first steps of the process is emphasized, noting that the high pressure required makes HTL complex.

Although HTL produces biocrude, which may have a high carbon content, the need to operate at [redacted] bar and high temperatures (near subcritical conditions) makes it energy intensive. The assumption that HTL is more energy efficient because it avoids the drying process is being challenged. It is argued that the energy required to heat the water in HTL is almost comparable to the energy required for drying in other processes. In addition, it is noted that HTL requires heating at reactor conditions [redacted] bar and several hundred degrees Celsius), which requires more energy in comparison to the low-temperature heat used for drying biomass in other processes.

The critical importance of heat exchange in the HTL process is emphasized, stating that an extremely good heat exchanger is necessary to efficiently transfer heat between the feedstock and the product. Achieving effective heat exchange proves to be a common challenge in practice and is critical to making the HTL process energy efficient.

It is also noted that many HTL initiatives nowadays start with solid feedstock, and it is suggested that it would be beneficial if they could use sludge and similar materials. The main challenge in HTL appears to be heat exchange, which is required to operate at relatively high temperatures and pressures, making it a complex process to manage.

Self-sustaining

Another remarkable aspect of FP is its ability to operate without external heat sources, especially when processing raw materials with moderate moisture content, such as [redacted] This means that for materials such as fresh wood, the process can be self-sufficient because it uses internally generated heat. This availability of internal heat is a significant advantage because it reduces the need for additional energy inputs and increases the overall efficiency of the FP process.

Drying

During the discussion of the drying process in FP, it is emphasized that drying is an essential part of the process. The moisture content of the raw materials plays a crucial role in achieving self-sustaining operation. Raw materials with moisture content up to [redacted]% are considered acceptable. After drying, the moisture content before the reactor should be below [redacted]%, preferably < [redacted]%, as the water introduced at this point will end up in the pyrolysis oil

Regarding the energy dynamics of the endothermic pyrolysis process, especially in relation to the drying phase, the internal energy generation and utilization of the process are explained. By depolymerizing the biomass produces liquid, gas, and char. The char and sand are transferred from the reactor to a combustor, where the burning of the char heats the sand. This heated sand is then returned to the reactor, creating a self-sustaining loop for thermal energy.

The combustion of char is essential to power the process. In some facilities, char and non-condensable gases are burned in the combustor, generating considerable heat. This heat is then used to generate steam, which performs two functions: drying the biomass and powering a steam turbine. This system design provides complete self-sufficiency in terms of heat and electricity (Empyro, Hengelo). Although the economic feasibility of using a steam turbine may not be justified due to cost and market price considerations, the system inherently has the potential to operate autonomously.

Comparison catalytic pyrolysis

During the discussion there is being asked about the current status and key players in the field of catalytic pyrolysis. It is acknowledged that there are several initiatives in the field, notably one in the U.S. (Anellotech) focused on producing aromatics and another company (Valmet), from Finland/Sweden, exploring catalytic processes.

Catalytic pyrolysis is highlighted for its potential to produce higher quality oil, characterized mainly by reduced oxygen content. This process breaks down the sugars in biomass, leaving behind mainly lignin, which is relatively easier to upgrade. However, this method means losing the sugars, which make up about half of the biomass depending on the assessment method. Valmet is identified as actively engaged in catalytic pyrolysis.

TRL

The TRL of the FP process is being discussed, emphasizing the importance of distinguishing between the FP itself and the upgrading process, such as hydrotreatment, as these are different elements.

For FP of woody biomass, it is indicated that the TRL is relatively high, at 9, indicating that the process is commercial and operational. However, if residues or other types of biomasses such as straw are involved, the TRL may be lower because they require further demonstration. It is mentioned that experiments and pilot plant operations are taking place for these materials, but there are currently no commercial or demonstration plants using them.

Regarding the upgrading process, specifically hydrotreatment, the TRL is estimated to be about 5-6. This indicates that the process is in the pilot plant phase, indicating an intermediate level of technological maturity. It is recognized that TRL ratings may vary somewhat (plus or minus one) based on specific criteria or the direction of the project. However, it is reiterated that no commercial or demonstration plants are yet in place for the upgrading process, and that activities are being conducted on a pilot scale.

Feedstock

It is confirmed that wood is indeed considered a suitable, if not optimal, feedstock. The discussion then shifts to the purity of the starting material. Most development work and commercial activities have been conducted with clean wood or sawdust, specifically wood scraps, or sawdust. It is noted that commercial units, especially in Sweden and Finland, are often located next to sawmills, which provides easy access to clean sawdust, the easiest material to work with.

However, it is pointed out that other types of starting materials are generally more complicated, especially if they contain a high ash content, which can affect process operations or oil quality. The preference for clean feedstock appears to be a general feature of many thermochemical processes, not just pyrolysis. A high ash content is particularly undesirable because it can have a catalytic effect on the process. Ideally, ash content should be as low as possible, and contaminants such as soil or sand should be avoided. In general, wood chips and similar materials are considered suitable starting materials for the process.

Where the feedstock should come from

The interview also focuses on the location of a pyrolysis process plant in relation to the source of the feedstock. It is suggested that the processing plant should be located close to the feedstock to facilitate operations. The Netherlands is not the ideal location to operate a pyrolysis plant, because there is limited biomass. Countries such as Sweden and Finland are cited as ideal because of their abundant biomass, which allows local processing and subsequent centralized upgrading of the pyrolyzed material.

The model described is the hub-and-spoke model, in which decentralized pyrolysis operations process biomass locally and the resulting pyrolysis oil is then transported to a central location for upgrading, usually a chemical process that benefits from being close to a refinery. The upgrading process requires substantial input of feedstock, possibly from 3/4/5 pyrolysis plants, to be viable and efficient. 5 tons an hour is too small.

Mixing different feedstocks

Regarding the use of mixed feedstocks in one plant, it is noted that while it is possible to use different or mixed feedstocks, this may present challenges. Mixing certain feedstocks, such as woody biomass and straw, is discouraged because of contaminants in one that can affect the quality of the product from the other. The mixing of biomass and plastics is particularly discouraged because their optimal processing temperatures differ significantly, making simultaneous processing ineffective.

The importance of the feeding system when switching from one feedstock to another is noted, as different feedstocks have different bulk densities that significantly affect the feeding process. If the physical behaviour of the feedstock materials is similar, switching can be relatively easy. However, substantial differences in the characteristics of the feedstock can make the transition difficult.

Size of the feedstock

The usual particle size used is smaller than 6 millimetres. It is noted that defining the size of a biomass particle can be somewhat problematic because of the critical size for heat penetration. An example is given of a needle [redacted] millimetres thick and [redacted] meters long that would not be a problem, while a cube [redacted] by [redacted] by [redacted] centimetre would not work. Sawdust is not a problem. It is emphasized that the distance for heat penetration should not be too large to avoid producing charcoal.

So, size reduction is needed. This is done by a hammermill. The energy-intensive nature of reducing the particles is also discussed and it is noted that if the particles remain above a few millimetres, it is not too difficult. However, once the particles must be below [redacted] microns, it becomes extremely energy intensive. It is concluded that it is difficult to define the exact size of the biomass, but that they usually work with particles of a few millimetres and that finer particles are very energy intensive to produce.

Moisture content biomass

It is discussed that regarding moisture content, the guideline for a long time has been that it should be below [redacted]%. However, it is noted that it is difficult to keep the moisture content below [redacted]% when wood is transported, because there is some kind of equilibrium where it always goes back to about [redacted]%. However, the moisture content of the material becomes drier in the process, depending on the type of material being processed. Excess heat is available, so the material is dried to about [redacted]% moisture content just before the reactor, but this is not the moisture content of the material being transported.

Most energy intensive part of pre-treatment

Probably the most energy-intensive part of the process is the drying because significant amounts of water must be removed there. However, the drying is fed with excess heat from the plant, so it does not consume additional energy. As for milling, that is indeed a process that consumes energy, but no chemical treatment is used. There is also no sorting at the biomass delivery site. However, if the plant is located next to a sawmill, the biomass delivered usually already meets specifications, except for moisture content.

Process conditions

The temperature of a FP reactor varies in the range of [redacted] degrees Celsius, usually around [redacted] degrees Celsius. There is no pressure involved, as the process is atmospheric. The residence time of the biomass in the reactor can vary but is usually expressed in tens of seconds. There are no significant temperature fluctuations in the process, as the temperature of the sand entering and circulating the reactor is kept constant. There is no preheating of the feedstock before it enters the reactor. The process uses an abundance of sand, which is intensively mixed mechanically to ensure even temperature distribution. The solid is removed from the reactor and then reheated to the desired temperature before being returned to the reactor. The temperature of the biomass [redacted] degrees C and sand of [redacted] That's mixed intensively by mechanical mixing and the outcome is a mixture of [redacted] degrees. The vapor is removed from the reactor and the sand and char sent to the char combustor. There it is reheated to [redacted] and sent back to the reactor, that's the system.

Energy input for pyrolysis process

The energy required depends on the type of biomass used. If the feedstock is very dry, the process generates more energy than needed, allowing excess steam to be exported. In the case of wetter biomass, with about [redacted]% moisture, the heat produced is just enough to dry the biomass, making the process self-sufficient without the need for external fuel except during the start-up phase. Startup is usually done using propane or natural gas, depending on what is locally available. Once in operation, the process becomes self-sufficient.

In addition, if there is excess heat, it is often used to produce steam in a steam boiler with the flue gases from the incinerator. This steam can be used for various purposes, such as exchange with neighbours or for drying processes. However, after the start-up phase, no external heat is needed for the operation of the process.

Bio-oil characteristics

The discussion raised questions about the stability of bio-oil produced from the pyrolysis process. It was clarified that the stability of bio-oil depends on its intended use and the definition of stability. The bio-oil will change over time, with an increase in viscosity over a one-year period due to the presence of reactive components such as aldehydes and ketones. However, for most applications this is not a problem, despite literature often suggesting that bio-oil is unstable. The bio-oil produced has been used successfully in boilers even when stored for more than six months. Stabilization of the bio-oil is not part of the standard process, but is done when upgrading the oil, with the goal of removing reactive components. If you want to make it a little bit nicer it helps to add a little of ethanol or methanol.

The water content can vary based on the type of biomass used, with woody biomass resulting in about [redacted]% water content and straw increasing it to about [redacted]%. The interview also covered the oxygen content in the products, which is around [redacted]%, including water.

The presence of contaminants such as nitrogen, sulphur and chlorine in the bio-oil depends on their presence in the original biomass. These elements can enter the oil in varying degrees, which presents challenges for certain applications, especially when dealing with agricultural residues known to have higher levels of contaminants.

The pH level of the bio-oil was discussed, with lower pH being common due to organic acids, with typical values around [redacted]. However, the pH can vary with different feedstocks, such as algae, which can result in a higher pH due to nitrogen compounds.

Finally, the carbon conversion efficiency of bio-oil was mentioned, especially for woody biomass, where it is estimated to be around [redacted] to [redacted]%, with some of the carbon ending up in gases and char, the latter being rich in carbon.

Products and ratio's

The typical yield was described as [redacted]% oil, [redacted]% gas and [redacted]% char. It was noted that these ratios can vary significantly when other feedstocks are used. However, for woody biomass, these are the approximate ranges observed for the products.

It was further discussed how the by-products, such as char and gas, are used. The char is generally burned, which contributes to the process by generating heat. The gas, which could potentially be used for other purposes, such as a source of CO_2 due to its rich concentration, is currently burned in the free part of the char combustor in commercial units. This combustion process generates additional heat and therefore produces more steam, which increases the energy efficiency of the entire process.

Upgrading to SAF

The approach described involves a two-step process: catalytic upgrading and hydrotreatment.

The first step is stabilization, performed with a specific catalyst. This process involves the transformation of carbonyls into alcohol groups, effectively converting the C=O (carbonyl) into a C-OH (alcohol), which is more stable and less reactive. This transformation does not necessarily reduce the oxygen content but changes the chemical structure to make it less reactive and more stable. The stabilized oil is less likely to form undesirable compounds such as carbonates.

The second step is hydrotreatment, which is performed with a known commercial catalyst. In this stage, the stabilized oil undergoes further treatment to reduce its oxygen content, which increases its heating value and converts it into a product rich in hydrocarbons. The product of this process is called hydro-treated pyrolysis oil (HPO), which is almost free of oxygen.

If the goal is to produce specific fuel types, additional steps such as distillation may be required to obtain the appropriate fractions of the product.

Product distribution after upgrading

The upgraded product distribution usually includes a light fraction, a middle fraction and a heavier fraction. Quantitatively, the light fraction (=naphtha) makes up about [redacted]% of the product, the middle fraction (=jet) is about [redacted]%, and the rest is the diesel fraction.

It was also noted that these distributions are based on the use of woody biomass as feedstock, and the distribution may vary when using different types of feedstocks.

Maximum SAF output would be [redacted]% from the HPO.

The pros and cons of using bio-oil to produce SAF

The importance of liquid fuels for sustainable aviation was recognized, with bio-oil as a possible option. However, the stringent quality requirements and intensive upgrading process to meet SAF standards were cited as challenges.

Severity of upgrading

The discussion of the severity of upgrading bio-oil to SAF focused on temperature, hydrogen quantity and pressure. The temperature was described as not extremely high, possibly up to [redacted] degrees Celsius. In the table characterized as medium.

However, the focus was more on the aspects of pressure and hydrogen in the process.

The process involves high pressures, significantly higher than typical operations, with a mention of using fluids at [redacted] bar. Comparisons were made to illustrate the relativity of pressure in different substances. It was indicated that for the stabilization phase, not the hydrotreatment, pressures are increased because of the nature of the polar liquids involved. The poor solubility of hydrogen in polar liquids makes this increased pressure necessary to facilitate the reaction. In the table pressure is characterized as high.

The amount of hydrogen used was described as significant, but not completely lost, as it participates in chemical reactions within the process. It was noted that with standard hydrotreatment pressures around [redacted] bars. This indicates that for this particular hydrotreatment process, the pressure is remarkably high. In the table the amount of hydrogen is characterized as high.

Amount of hydrogen

The complete process requires about [redacted] weight percent hydrogen. It was noted that in an actual process this probably rises to [redacted] weight percent, given that not all hydrogen can be used efficiently and thus there is some loss. This is [redacted] to [redacted] grams of hydrogen per kilogram of pyrolysis oil to be processed.

Energy for temperature and pressure upgrading process

No specific value was available here, but it was emphasized that generating pressure with a liquid is relatively easy, mainly using a liquid pump. However, obtaining hydrogen at the required pressure of [redacted] bar was identified as a more important consideration.

Composition of the SAF

The majority are iso-alkanes and cyclo-alkanes, indicating a quality close to SAF-compatible quality. The amount of n-alkanes is usually quite low compared to standard jet fuel. The amount of aromatics can be controlled to some extent by adjusting the severity of treatment. It was noted that it is desirable to move the aromatics to the lower range to keep all properties within proper specifications, ideally closer to [redacted]% than [redacted] %.

Economics

CAPEX is hard to estimate for this process. The main cost drivers for the upgrading are the pyrolysis oil itself and the hydrogen. And for the pyrolysis process itself it's a combination of biomass costs and CAPEX. Labour etc. is minor, for both. It was emphasized that costs can be strongly influenced by the price of the biomass feedstock.

Safety and risks

It was indicated that bio-oil is shipped from the production process by tank trucks, which works well for both large quantities and smaller samples. For international transport, smaller samples are shipped in IBCs or other packaging. It was emphasized that transporting bio-oil is relatively easy because it is not a hazardous substance as defined by transportation regulations, in part because its flammability is low. It's not easy to ignite the pyrolysis oil.

Not checked for an expiration date but normally the bio-oil is used within a couple of months after producing it, so this not a problem.

Certain precautions in bio-oil storage were noted, such as the importance of constant mixing or circulation to manage internal heat generation and dissipation. Unmixed storage can lead to self-accelerating chemical reactions and eventually hardening of the bio-oil, which is problematic in large storage tanks. This should be considered.

Furthermore, you should not have an open connection to the surroundings because you will get the smell.

Transportation of upgraded products, such as HPO, presents other considerations because of the lower flash points, like gasoline transportation. For the bio-oil, you cannot measure the flash point. But there is another way to do this, called sustained combustion. The pyrolysis-oil is not considered flammable due to the impossibility of sustained combustion at temperatures around [redacted] °C.

If you do the upgrading the flash point of the HDO is below [redacted]/ [redacted] or even below zero.

After further processing like distillation, the end-products can resemble conventional fuel types like jet fuel, marine fuel, or naphtha, each with its specific flashpoint. Jet fuel typically has a minimum flashpoint around [redacted] degrees Celsius, diesel is above [redacted] degrees Celsius, and naphtha can have a very low flashpoint, even below degrees Celsius, making it highly flammable. These characteristics are crucial for handling, storage, and transportation, as they dictate the safety measures needed to prevent accidental ignition.

Q. Summary Interview Steeper

Interview Steeper 06/02/2024

Economies of Scale & managing biomass logistic costs

During the interview the challenge of scaling biomass processing HTL plants is being discussed, focusing on finding a balance between achieving economies of scale and managing biomass logistics costs. It is explained that plants should not be too large to keep logistical costs manageable, but also not too small to achieve economic benefits. A daily processing of [redacted] barrels is given as an example, with capacity expressed in about [redacted] tons per year.

Discussion continues the use of modular plant design, where capacity is adjusted by increasing the number of pipes in the reactor design. The modular design provides flexibility and scalability. This is compared to other approaches where the size of the reactor is adjusted. The modular approach includes plug flow reactors that heat and depolymerize the biomass mix, with chemical reactions taking place within the tubes under high pressure and temperature. This process breaks down cellulose and hemicellulose into sugars and lignin into smaller components, which are then recombined, and the oxygen is removed as carbon dioxide and water.

TRL

The plant in Norway is mentioned as an example, noting that it does not operate as a pilot but with commercial sized reactors. The conversation clarifies that many of the process steps, such as biomass drying and size reduction, are already operating at commercial scale. Also, the back-end phase of separators is commercial. What is not commercial is the reactions that are used. The TRL (Technology Readiness Level) of the whole process is discussed, suggesting that it is around 5 or 6, depending on how one looks at the entire process.

The collaboration with Topsoe is then mentioned, aimed at improving the upgrading of the oil produced. It is noted that Topsoe is waiting for a demonstration of the plant's capacity to make quality products. The discussion also addresses the challenges of demonstrating the reliability, quality, and operational feasibility of the process on a larger scale.

Feedstock

During the interview it is clarified that the focus so far has mainly been on woody biomass because of its composition and low ash content, which makes it attractive for processing. It is explained that agrobiomass can contain higher percentages of silicates and ash, sometimes up to [redacted] or [redacted] %, which presents challenges for processing. The approach is to first optimize the process for low ash biomass before exploring other types of feedstocks with higher ash contents.

It is further mentioned that other types of feedstocks, such as sludge with very high ash contents, may be economically advantageous to process because you get paid to process them. These have already been tested in pilot projects, but the current focus is on using forest residues in the new plant, seen as the first application. (The Norwegian plant Silva Green Fuel (statkraft.com) is owned by Statkraft)

The discussion also highlights the importance of finding an optimal type of feedstock, not only from a technical standpoint because of ash content, but also from an economic perspective, weighing the cost of processing different types of feedstocks against the potential revenues or savings.

Where the feedstock should come from

During the discussion, the view on the origin of feedstock is discussed. The importance of plant location and sitting is emphasized, with attention to indirect land use change and indirect impacts. It is explained that indirect impacts are also considered when determining sustainability and calculating GHG emissions. These indirect impacts would occur if the forestry residues to be process had an existing use and that using them to produce HTL would cause an increase in fossil fuel.

Site selection is crucial to ensure that there is no direct competition with combined heat and power plants, especially in regions such as Scandinavia where biomass is widely used to produce district heat and electricity.

It is indicated that if the plants are placed too close to these power plants, it could lead to the accusation of taking away their feedstock, which could force them to use fossil fuels. Therefore, there should be close co-operation with feedstock suppliers and the location should be chosen so that there is sufficient availability of feedstock, such as forestry residues, without competing with the combined heat and power plants.

There is also speculation that in the future the demand for these feedstocks could decrease due to the increased use of heat pumps and renewable energy, which would make more feedstock available. The focus is currently on utilizing forest industry residues left in the forest to use without competing with combined heat and power plants.

Finally, it is noted that the technology used is very similar to other pyrolysis technologies, the main difference being that less drying is required; however, the material must be reduced to chips. This suggests that the technical requirements for the feedstock between different pyrolysis technologies are largely similar.

Pre-treatment and feedstock characteristics

The conversation discusses the importance of feedstock sourcing and how it affects commercial plans. It is emphasized that the location and availability of feedstock are essential, especially in areas with high forest residues and without direct competition with combined heat and power plants. The discussion highlights the importance of biomass particle size for the pretreatment process. It is explained that larger chips can be used, as long as they are pretreated in a certain way so that the viscosity of the slurry remains low enough for the pumps. The focus is on adjusting the size so that when the biomass is introduced into the reactor, the distance from the outside to the inside of the particles is not too large. This optimizes reaction efficiency within the reactor. The specific dimensions mentioned are a thickness of two millimetres for the particles, which can be longer, with thickness being the critical dimension for processing. This emphasizes the importance of the specific dimensions of the particles for the success of the process.

the optimum particle size thickness will be tested and validated at Tofte; the pilot plant has used very small particles which are not commercially viable; different technologies are being evaluated to get particles to a size that after pretreatment will be liquefied in a short period of time; the HTL process heats up the biomass in a slurry with added chemicals to first depolymerize the biomass constituents and then recombine the fragments while removing oxygen, the lower the oxygen in the biocrude the easier it will be to upgrade and mix with fossil hydrocarbons

There is further discussion of biomass moisture content, with a range of [redacted] to [redacted] percent by weight cited as ideal, although slightly higher moisture contents are also useful. Better to say [redacted] - [redacted] percent because otherwise it sounds so specific, while it is not.

there is no ideal moisture content; the HTL process takes place in water, so the biomass moisture content is important to allow for economic size reduction

It is stated that various pretreatment methods have been tested to determine which is most optimal for the process. The goal is to use the minimum necessary pretreatment without adding unnecessary extra steps. In the pilot project, the pipes (heating tubes) were narrower, which required finer materials to prevent clogging. For commercial plans, attempts are being made to use larger materials and the simplest method of preparing these materials is still being explored. Reducing the size of the biomass and adjusting the moisture content is called comminution. This is followed by pre-treatment, mixing the slurry and dosing chemicals to make the slurry pumpable.

It is discussed that the most energy-intensive step of pretreatment is size reduction, especially if the biomass is to be processed into very fine materials. The conversation also highlights that the energy integration of the system is primarily within the process itself, with heat exchangers recovering energy, and that pretreatment is not the primary focus for energy efficiency. The bio-crude coming from the reactors is at approximately [redacted] - [redacted] C and heat is recovered during cooling down the biocrude to room temperature.

It is also indicated that the technology can process wet material without concern for water content, which is an advantage over pyrolysis technologies that require drier material. This makes it possible to use wet biomass directly from the forest, utilizing the natural drying process in the forest to bring the material to an appropriate moisture content ([redacted]wt%).

Temperature and Pressure

It was asked in the discussion whether the temperatures and pressures used during tests for the HTL process will be applicable to commercial plants. It is explained that temperatures above [redacted] degrees Celsius are not used because it is not necessary and that the optimal temperature range is around [redacted] to [redacted] degrees Celsius, just above the supercritical temperature of water ([redacted] degrees Celsius).

The high temperatures used will speed up the reactions for removal of oxygen as CO_2 but if the biocrude is kept at high temperatures for too long a time char will begin to form so the process is optimized to remove oxygen as effectively as possible while minimizing char formation

As for the pressure, it is stressed how important it is to keep it high enough, specifically between [redacted] and [redacted] bar, to keep the reactions in the condensed phase and prevent gas formation. This is crucial to ensure that the gas molecules formed remain in the liquid phase and can continue to react there, rather than escape. The molecules can't escape; the goal is to carry out the reactions in the condensed phase.

This management of temperature and pressure is essential for the desired chemical reactions to proceed efficiently in the HTL process.

Residence time

The interview discusses the residence time in the HTL process. It is mentioned that HTL has a slower residence time than FP, but the exact residence time is not disclosed. Importantly, the high-temperature residence time is limited. Total residence time will be less than [redacted] minutes which means high temperature residence time much less than that.

It would be below [redacted] minutes because higher temperatures are used in HTL than in subcritical processes, so less time is needed.

A comparison is also made with FP, where temperatures are normally between [redacted] and [redacted] degrees Celsius. This is considered a significant difference, so FP has much faster reactions at these higher temperatures. The importance of temperature control is emphasized, especially since HTL gradually heats up to [redacted] degrees Celsius, which is different from the direct exposure to higher temperatures in FP. In FP the residence time is on the order of a few seconds; the temperature was determined by the cracking of the lignin.

Energy input HTL process

The conversation asks about the energy input required for the HTL process. It is explained that both electrical energy and heat energy are required. Heat energy is obtained from the process itself, by first heating up the biomass and then recovering heat during cooling the materials, additional energy is obtained by burning the gases that are released and are not condensable (such as hydrogen, methane and ethane). This makes it possible to heat the process without using fossil fuels.

The electrical energy is mainly used for the high-pressure pumps, facilities such as lighting, pumping liquids around, and for equipment such as woodchippers.

It is also discussed that the GHG balance of the HTL process depends on location because of differences in emissions from the power grid. In countries such as Scandinavia, where electricity grid emissions are low, most emissions from the HTL process come from the production of the chemicals used.

Bio-oil stability

It is mentioned that the total acid number (TAN) of the oil, indicated in milligrams of potassium hydroxide per gram of product, is an indicator of the stability of the oil. A value > [redacted] suggests some instability due to the presence of organic acids that may react over time. A demineralization step is discussed as a way to remove the metal contaminants as well as a chemical treatment method of reducing acidity, but there remains a struggle with very low levels of some acids.

The viscosity of the oil at [redacted] degrees Celsius is very high, indicating that heating is needed to reduce the viscosity before use in a diesel engine or combusted in order to allow the formation of a small droplet spray. This heating can accelerate the reaction of the acids present, which can cause problems in some applications. It is much more stable than the FP bio-oil, but it is not [redacted] % stable.

There is discussion of the possibility of chemical treatment of the oil to reduce acidity, such as by reaction with alcohol to form esters. Hydrotreatment is mentioned as the best method for stabilization, although it is more technically demanding complex because of the need for a catalyst, a hydrogen source, and systems for recycling hydrogen.

The complexities and costs of hydrotreating are discussed further, focusing on the challenges of catalyst life, metal levels, and recycling hydrogen from the gases coming out of the reactor. The idea of a hub-and-spoke model for SAF production is proposed, with regional HTL facilities supplying the oil to a larger facility for upgrading.

Carbon conversion efficiency

It is confirmed that the carbon conversion efficiency before upgrading is about [redacted] %. This efficiency can vary, so a general percentage is given rather than an overly specific value. The goal of the HTL process is to convert as much carbon as possible from the biomass into the final product, with a reduction of char and coke production to a very low level. This results in a relatively high carbon conversion efficiency, with most of the carbon loss occurring in the form of carbon dioxide due to the removal of oxygen from the biomass.

Product distribution

It is verified that oil is the main product of the HTL process, making up about [redacted] – [redacted] % of the output. Gas follows as the next product, and char is the smallest part, about [redacted] - [redacted] %. The gas produced during the process is used to generate heat needed for the process, while the destination of the char has not yet been determined.

Various uses for the char are being considered, such as using it as a soil conditioner or for combustion for heat production, but the focus is not currently on char. In addition, water is also produced during the process, which contains some organic matter and chemicals. The exact proportions of the products can vary depending on specific conditions and the size of the particles in the biomass.

The degree of upgrading required

The upgrading conditions of HTL for SAF are discussed, in terms of temperature, pressure and hydrogen consumption, compared to FP. For HTL the conditions for pressure and temperature would be medium. The discussion highlights that HTL requires a less severe approach in terms of pressure and temperature and requires significantly less hydrogen compared to FP, which is estimated to require [redacted] to [redacted] times more hydrogen. The degree of upgrading to achieve the technical specification of SAF is still being evaluated.

This number is based on an analysis that assesses the hydrogen to carbon ratio of the bio-oil produced by each method and the additional hydrogen needed to upgrade this oil to meet SAF specifications. FP typically generates bio-oil with a lower hydrogen to carbon ratio and a higher oxygen content, necessitating a more substantial addition of hydrogen to achieve the desired fuel characteristics. The calculation involves estimating the amount of hydrogen required for hydrodeoxygenation and for adjusting the hydrogen to carbon ratio to align with that of conventional aviation fuels.

It is stressed that SAF production through HTL with low high hydrogen to carbon ratios may not be economically feasible unless the SAF market grows significantly and becomes the main market. A preference is expressed for producing biofuels for both the aviation and maritime sectors, noting that pursuing extremely high production of SAF may lead to lower overall product and higher costs.

Furthermore, it is suggested that government mandates enforcing the use of renewable fuels may drive up the price of SAF, which would make the use of biomass thermochemical processes more economically feasible. The discussion also recognizes the challenges in the supply and demand dynamics of SAF, particularly the large gap between current production capacity and potential demand. The production of HEFA SAF from residual and waste streams will not be enough, it will get [redacted] - [redacted] million tons, but you want something like [redacted] million times. It's a big gap there and that is where technologies like HTL could come in.

R. IATA Conference Notes

Feedstock and Technology Matching

- Focus on expanding feedstock portfolios and identifying technologies that improve yields from feedstock and intermediaries.
- Match technologies with regional feedstocks for optimal use and efficiency.

Potential Technologies for Scale-Up by 2030

- Consider MtJ, HTL, and POtJ for their potential to contribute to production scale-up before 2030.
- Explore solutions that can process feedstocks typically incompatible with certain production pathways through a two-step conversion process.

Existing Facilities and Cost Implications

- Utilize existing HEFA facilities to avoid the high costs associated with building new facilities, which can amount to 1 billion dollars and take 10-15 years to achieve a return on investment.

Pyrolysis Technology

- Pyrolysis can process woody/solid biomass and municipal solid waste, including plastics and rubber, converting them into pyrolysis oil.
- Pyrolysis oil can be compatible with existing HEFA plants, extending feedstock profiles and prolonging the lifespan of HEFA facilities.
- Pyrolysis produces valuable by-products like biochar, which enhances soil productivity and acts as a permanent carbon capture solution.

HTL (HTL)

- HTL is notable for converting both solid and wet waste, addressing environmental and socio-economic challenges associated with waste management.
- By-products include clean drinking water, showcasing HTL's additional environmental benefits.

Environmental and Socio-Economic Benefits

- HTL addresses overrun sewage infrastructure and mismanagement of wet waste systems, which can cause significant disease and environmental degradation.
- Projects align with Sustainable Development Goals (SDGs) and aim at poverty alleviation by targeting areas with local governmental challenges.

Strategic Expansion and Industry Impact

- Both HTL and pyrolysis technologies offer significant potential to expand the feedstock base and optimize the value chain around local environmental challenges and value chains.
- The focus extends beyond fuel production to include nature restoration and industry creation, enhancing local wealth and environmental quality.

Market Dynamics for Renewable Diesel and SAF

- Renewable diesel demand is expected to peak before the end of the decade due to electrification of two-thirds of road transport.
- As demand for traditional fuels falls, there is an increased push to boost SAF production, where the airline industry becomes a crucial customer because aviation fuel cannot be easily replaced.

Regional Application of Technologies

- Pyrolysis targets regions with strong agricultural activities, enhancing soil quality and productivity through biochar production, making it particularly beneficial for farming-intensive areas.

S. Interview Stakeholders

Airline

For the airline perspective, an employee of KLM was interviewed. During this interview it was stated that the most important perspective from a KLM perspective is environmental. When asked about the mutual relevance of the other perspectives in relation to the most relevant perspective, the following ratings were given:

Most relevant to others	Economic	Technical	Environmental	Social
Environmental	3	8	1	5

The least relevant perspective from KLM's point of view is the technical perspective. When asked about the mutual relevance of the other perspectives in relation to the least relevant perspective, the following ratings were given:

Others to least relevant	Technical
Economic	3
Technical	1
Environmental	9
Social	5

When asked about the relevance of the selected criteria. From a KLM perspective, the most important criterion in an evaluation is feedstock price per SAF output. When asked about the mutual relevance of the other criteria in relation to the most relevant criteria, the following ratings were given:

Most relevant to others	Feedstock price per SAF output	Operational costs	Capital costs	Technological Readiness Level	Efficiency	Global Warming Potential	Use of by-products	Safety	Social impact of feedstock used
Feedstock price per SAF output	1	1	1	3	5	2	3	5	3

The least relevant criteria from KLM's point of view is safety. When asked about the mutual relevance of the other criteria in relation to the least relevant criteria, the following ratings were given:

Others to least relevant	Safety
Feedstock price per SAF output	9
Operational costs	8
Capital costs	8
Technological Readiness Level	6
Efficiency	3
Global Warming Potential	8

Use of by-products	6
Safety	1
Social impact of feedstock used	6

Although the criteria for this study had already been established, KLM was also asked what other criteria were important to them when evaluating a new SAF technology. For KLM, several other key criteria play a role in the selection and implementation of new SAF technologies. Firstly, feedstock and geographical location were identified as important. Feedstock availability and the location of production facilities are critical. Geographical location affects both logistics and feedstock accessibility, which is essential for producing SAF. Certification was also identified as important. Compliance with regulations and standards such as the Renewable Energy Directive (RED) and the Roundtable on Sustainable Biomaterials (RSB) is essential for KLM. Certifications that demonstrate that SAF meets strict sustainability criteria and regulatory requirements are key. In addition, KLM has specific requirements for the raw materials used. For example, the use of palm oil or its by-products is restricted. Feedstocks must also be in line with the RED II criteria, which place emphasis on sustainability and responsible use of raw materials. Indirect land use change (ILUC) is also important to them. The impact of ILUC is an important consideration. KLM aims to minimise indirect land use impacts such as deforestation and biodiversity loss. Finally, the use of renewable energy sources in the production process of SAF is also a priority. This supports the aviation industry's sustainability goals and helps reduce the carbon footprint.

Environmental and sustainability Organization

For the environmental and sustainability organizations perspective, an employee of Transport and Environment was interviewed. During this interview it was stated that the most important perspective from an Environment and Transport perspective is environmental. When asked about the mutual relevance of the other perspectives in relation to the most relevant perspective, the following ratings were given:

Most relevant to others	Economic	Technical	Environmental	Social
Environmental	9	7	1	5

The least relevant perspective from Transport and Environment’s point of view is the economic perspective. When asked about the mutual relevance of the other perspectives in relation to the least relevant perspective, the following ratings were given:

Others to least relevant	Economic
Economic	1
Technical	5
Environmental	8
Social	4

When asked about the relevance of the selected criteria. From a Transport and Environment perspective, the most important criterion in an evaluation is Global Warming Potential. When asked about the mutual relevance of the other criteria in relation to the most relevant criteria, the following ratings were given:

Most relevant to others	Feedstock price per SAF output	Operational costs	Capital costs	Technological Readiness Level	Efficiency	Global Warming Potential	Use of by-products	Safety	Social impact of feedstock used
Global Warming Potential	6	8	8	6	5	1	5	4	2

The least relevant criteria from Transport and Environment 's point of view is safety. When asked about the mutual relevance of the other criteria in relation to the least relevant criteria, the following ratings were given:

Others to least relevant	Operational costs
Feedstock price per SAF output	6
Operational costs	1
Capital costs	2
Technological Readiness Level	5
Efficiency	6
Global Warming Potential	9
Use of by-products	6
Safety	5
Social impact of feedstock used	8

Although the criteria for this study had already been established, Transport and Environment was also asked what other criteria were important to them when evaluating a new SAF technology. Firstly, the emphasis was placed on how to assess global warming potential. It was stressed that assessing this potential goes beyond just looking at emissions. Because the full spectrum of sustainability issues related to different feedstocks is not reflected in this way, sustainability assessment must be individualised or assessed on a case-by-case basis to determine whether a feedstock is sustainable.

An example is given of a life cycle assessment for used cooking oil. This can result in an 85% emission reduction. However, such accounting methods can overlook other sustainability issues by adopting a purely emissions-oriented perspective.

Another important issue to consider is feedstock availability. The importance of evaluating the supply potential of the feedstock to ensure sustainability is stressed. This led to a discussion on alternative uses of raw materials. For example, animal fats can be used in cosmetics and other industries. The use of these fats for biofuel production leads to increased demand for palm oil, which may raise sustainability concerns.

The third criterion considered important in assessing an SAF production pathway is the potential for fraud. It elaborated on the challenges of detecting fraud, for example with used cooking oils, where virgin oil can pass for waste. Certification systems are flawed, often not providing adequate controls.

Consumer

For the traveller perspective, someone who travels a lot for work was interviewed. During this interview it was stated that the most important perspective from a traveller perspective is environmental. When asked about the mutual relevance of the other perspectives in relation to the most relevant perspective, the following ratings were given:

Most relevant to others	Economic	Technical	Environmental	Social
Environmental	3	8	1	6

The least relevant perspective from the traveller point of view is the technical perspective. When asked about the mutual relevance of the other perspectives in relation to the least relevant perspective, the following ratings were given:

Others to least relevant	Technical
Economic	7
Technical	1
Environmental	9
Social	6

When asked about the relevance of the selected criteria. From a traveller perspective, the most important criterion in an evaluation is Global Warming Potential. When asked about the mutual relevance of the other criteria in relation to the most relevant criteria, the following ratings were given:

Most relevant to others	Feedstock price per SAF output	Operational costs	Capital costs	Technological Readiness Level	Efficiency	Global Warming Potential	Use of by-products	Safety	Social impact of feedstock used
Global Warming Potential	4	4	4	8	7	1	2	4	5

The least relevant criteria from travellers' point of view is safety. When asked about the mutual relevance of the other criteria in relation to the least relevant criteria, the following ratings were given:

Others to least relevant	Technological Readiness Level
Feedstock price per SAF output	6
Operational costs	6
Capital costs	6
Technological Readiness Level	1
Efficiency	3

Global Warming Potential	9
Use of by-products	8
Safety	7
Social impact of feedstock used	5

Although the criteria for this study had already been established, the traveller was also asked what other criteria were important when evaluating a new SAF technology. From the traveller's point of view, it was stressed how important it is to have access to a thorough comparison of SAF with other fuel technologies. This will enable them to educate themselves properly. It was also emphasized how crucial it is to manage waste properly and how SAF may be blended with traditional fuels without degrading performance. A strong demand for increased transparency and involvement in the introduction of new SAF technologies is also visible. Travellers are intrigued about the origins and production pathways of SAF.

SAF Provider

For the SAF provider perspective, someone in the commercial team of SkyNRG was interviewed. During this interview it was stated that the most important perspective from a SkyNRG's commercial perspective is economic. When asked about the mutual relevance of the other perspectives in relation to the most relevant perspective, the following ratings were given:

Most relevant to others	Economic	Technical	Environmental	Social
Economic	1	6	4	4

The least relevant perspective from the SkyNRG's commercial point of view is the technical perspective. When asked about the mutual relevance of the other perspectives in relation to the least relevant perspective, the following ratings were given:

Others to least relevant	Technical
Economic	6
Technical	1
Environmental	3
Social	3

When asked about the relevance of the selected criteria. From a SkyNRG's commercial perspective, the most important criterion in an evaluation is feedstock price per SAF output. When asked about the mutual relevance of the other criteria in relation to the most relevant criteria, the following ratings were given:

Most relevant to others	Feedstock price per SAF output	Operational costs	Capital costs	Technological Readiness Level	Efficiency	Global Warming Potential	Use of by-products	Safety	Social impact of feedstock used
Feedstock price per SAF output	1	7	7	3	4	3	8	6	2

The least relevant criteria from a SkyNRG's commercial point of view is safety. When asked about the mutual relevance of the other criteria in relation to the least relevant criteria, the following ratings were given:

Others to least relevant	Use of by-products
Feedstock price per SAF output	8
Operational costs	3
Capital costs	3
Technological Readiness Level	7
Efficiency	6
Global Warming Potential	7
Use of by-products	1
Safety	4
Social impact of feedstock used	8

Although the criteria for this study had already been established, there was also asked what other criteria were important when evaluating a new SAF technology from SkyNRG's commercial point of view. An important consideration in the evaluation of new SAF technologies according to SkyNRG's commercial point of view is the CO_2 abatement costs. This represents the costs associated with reducing the CO_2 emissions. It is an important factor in the assessment of the commercial viability of the SAF technology. It was also stressed that the long-term competitiveness of the feedstock is very important. Finally, it was noted that it is crucial to know who is involved in the development and application of SAF production technologies.

Energy Company in the Oil & Gas Industry

For the energy companies in the oil and gas industry perspective, someone from Shell was interviewed. During this interview it was stated that the most important perspective from a Shell perspective is environmental. When asked about the mutual relevance of the other perspectives in relation to the most relevant perspective, the following ratings were given:

Most relevant to others	Economic	Technical	Environmental	Social
Environmental	6	7	1	8

The least relevant perspective from the Shell's point of view is the social perspective. When asked about the mutual relevance of the other perspectives in relation to the least relevant perspective, the following ratings were given:

Others to least relevant	Social
Economic	7
Technical	6

Environmental	8
Social	1

When asked about the relevance of the selected criteria. From a Shell perspective, the most important criterion in an evaluation is Global Warming Potential. When asked about the mutual relevance of the other criteria in relation to the most relevant criteria, the following ratings were given:

Most relevant to others	Feedstock price per SAF output	Operational costs	Capital costs	Technological Readiness Level	Efficiency	Global Warming Potential	Use of by-products	Safety	Social impact of feedstock used
Global Warming Potential	2	3	2	6	5	1	8	8	2

The least relevant criteria from a Shell point of view is TRL. When asked about the mutual relevance of the other criteria in relation to the least relevant criteria, the following ratings were given:

Others to least relevant	Technological Readiness Level
Feedstock price per SAF output	8
Operational costs	7
Capital costs	8
Technological Readiness Level	1
Efficiency	5
Global Warming Potential	9
Use of by-products	2
Safety	3
Social impact of feedstock used	8

Although the criteria for this study had already been established, there was also asked what other criteria were important when evaluating a new SAF technology from Shell's point of view. In the interview with a Shell representative, several criteria were discussed that are critical to the success of a production route for (SAF). The following points were mentioned: emissions, technology, market, politics, unit economics, storage, infrastructure required and scalability.

ASTM

For the ASTM perspective, someone from SkyNRG who works with ASTM on a weekly basis was interviewed. During this interview it was stated that the most important perspective from an ASTM perspective is technical. When asked about the mutual relevance of the other perspectives in relation to the most relevant perspective, the following ratings were given:

Most relevant to others	Economic	Technical	Environmental	Social
Technical	8	1	4	9

The least relevant perspective from the ASTM's point of view is the social perspective. When asked about the mutual relevance of the other perspectives in relation to the least relevant perspective, the following ratings were given:

Others to least relevant	Social
Economic	3
Technical	9
Environmental	8
Social	1

When asked about the relevance of the selected criteria. From an ASTM perspective, the most important criterion in an evaluation is TRL. When asked about the mutual relevance of the other criteria in relation to the most relevant criteria, the following ratings were given:

Most relevant to others	Feedstock price per SAF output	Operational costs	Capital costs	Technological Readiness Level	Efficiency	Global Warming Potential	Use of by-products	Safety	Social impact of feedstock used
Technological Readiness Level	8	8	8	1	5	4	8	6	9

The least relevant criteria from an ASTM point of view is Social impact of feedstock used. When asked about the mutual relevance of the other criteria in relation to the least relevant criteria, the following ratings were given:

Others to least relevant	Social impact of feedstock used
Feedstock price per SAF output	3
Operational costs	5
Capital costs	5
Technological Readiness Level	9
Efficiency	6
Global Warming Potential	7
Use of by-products	3
Safety	4

Social impact of feedstock used	1

Although the criteria for this study had already been established, there was also asked what other criteria were important when evaluating a new SAF technology from ASTM's point of view. Competition between different companies using the same technologies is important to them. Additionally, plant capacity is an important consideration. Environmental concerns and then also looking at non-GWP emissions. This means that as well as focusing on reducing greenhouse gas emissions, it is important according to ASTM to look at other environmental impacts such as air pollution, water use and impact on biodiversity. Finally, process robustness, the reliability and stability of the production process under different conditions is essential.

Interview KLM - rationale behind criteria scoring

Perspectives

Technische Aspecten

Technische aspecten worden als minder relevant gezien voor een airline als KLM omdat zij simpelweg vertrouwen op bestaande certificeringsprotocollen, ASTM etc.

Sociale aspecten

Sociale aspecten worden erkend maar zijn niet de drijvende kracht achter hun SAF-initiatieven, voornamelijk vanwege de complexiteit van het uitleggen van deze initiatieven aan het publiek.

Milieu & economische aspecten

Deze aspecten worden gezien als relatief de belangrijkste. Er wordt een sterke nadruk gelegd op milieuoverwegingen, ondanks de hoge kosten geassocieerd met SAF. Dit wordt aangedreven door de noodzaak om te voldoen aan duurzaamheidsdoelstellingen.

Andere belangrijke aspecten die als belangrijk worden erkend

Praktische aspecten worden erkend als een belangrijk aspect voor de implementatie van SAF voor KLM. Hiermee waar wordt bijvoorbeeld bedoelt: waar vindt een project plaats? Waar kunnen wij het in ons systeem krijgen? Waar kunnen wij het tanken? Maar ook bijvoorbeeld blending limits. Dit wordt ook wel omschreven als de logistieke angle.

Toelichtingen voor criteria scoring

Feedstock prijs per ton SAF

De prijs en stabiliteit van de feedstock worden als cruciaal beschouwd voor het beoordelen van een SAF technologie, vooral vanwege de langetermijncontracten en de wens om onvoorspelbare kosten te vermijden.

Global Warming Potential (GWP) en gebruik van bijproducten

GWP is een doorslaggevend criterium, waarbij een minimale reductie van 75% in broeikasgasemissies vereist is. Het gebruik en de waarde van bijproducten in het productieproces worden ook beoordeeld, maar zijn ondergeschikt aan de milieu-impact van de brandstof.

Veiligheid

Hoewel veiligheid van cruciaal belang is voor KLM, vertrouwen zij op de bestaande certificeringsnormen (zoals ASTM) voor de veiligheid van de productie van SAF en wordt dit dus daarom gezien als een minder relevante criteria.

TRL

Er wordt erkend dat KLM redelijk vrij is in het selecteren van technologieën op basis van hun TRL. Deze hoeft niet per se heel hoog te zijn maar er wordt wel benadrukt dat zij natuurlijk ook niet ergens in stappen met een hele lage TRL.

Efficiëntie

Wordt als minder relevant gezien omdat als er hele high quality bijproducten worden geproduceerd in het proces die je als fabrikant gewoon kan verkopen, dan is het voor hen niet erg als de efficiëntie wat lager is.

Andere belangrijke criteria

- Feedstock en geografische locatie: de locatie van productiefaciliteiten en de beschikbaarheid van feedstock zijn belangrijk voor de implementatie van een nieuwe SAF technologie
- Certificatie: Compliance met regelgeving zoals RED en RSB is essentieel voor KLM. Het belang wordt benadrukt van certificeringen die aantonen dat een bepaalde vorm van SAF voldoet aan duurzaamheidscriteria en regelgevende vereisten.
- Feedstock eisen: bijvoorbeeld geen palmolie, geen bijproducten van palm, etc... Het moet RED II compliant zijn.
- Indirect land use change
- Gebruik van hernieuwbare energie in het productieproces

Interview Transport and Environment - rationale behind scoring

Perspectives

When weightings were assigned to the perspectives, the priority for environmental over economic factors was explained. Although economic viability is necessary, it should not compromise environmental sustainability.

During the interview, it was emphasized that the sustainability of SAF largely depends on the feedstocks used. It is highlighted that first-generation biofuel, derived from food, and feed crops, is seen as unsustainable. This is because they compete with land for food production and have the potential to cause indirect land use change effects, such as deforestation.

Criteria

Global warming potential and social use of resources emerged as particularly important in assigning weightings.

It is highlighted that the methodology used to calculate the emissions is very important. Even internationally, it tends to underestimate some emissions because it accounts for only direct emissions. Although there is some consideration for indirect emissions, the effects of indirect land-use change need to be adequately represented in these accounting methodologies.

The feedstock price per unit of produced SAF is critically important because it influences the product developers' selection of feedstocks. Often, developers opt for the most economically viable options, which may only sometimes be the most sustainable. Therefore, pursuing lower-cost feedstocks can lead to choices that do not align with the long-term sustainability goals of SAF production.

Other important criteria

When asked about other criteria essential for T & E, the focus was placed on how the global warming potential should be evaluated. It was emphasized that assessing this potential goes beyond merely considering emissions. Because this will fail to capture the full spectrum of sustainability issues related to various feedstocks, the sustainability assessment should be individualized or assessed on a case-by-case basis to determine if a feedstock is sustainable.

An example of life cycle assessments for used cooking oil is given. This can result in an 85% emission reduction. However, such accounting methodologies might overlook other sustainability issues by adopting a purely emission-centric perspective.

Another important topic to consider is the availability of the feedstock. The importance of evaluating the supply potential of the feedstock to ensure sustainability is stressed. This led to a discussion on the alternative uses of feedstocks. For example, animal fats can be used in cosmetics and other industries. The diversion of these fats to biofuel production leads to increased demand for palm oil, which can cause sustainability concerns.

The third criterion identified as important in the assessment of an SAF production pathway is the potential for fraud. There was an elaboration on the challenges of detecting fraud, for example, with used cooking oils, where virgin oil could be passed off as waste. There are flaws in the certification schemes, so they often fail to provide adequate checks.

Interview Shell – rationale behind scoring

Perspectives

[redacted]

Andere belangrijke criteria

In het interview worden een aantal criteria genoemd die het succes van een SAF productie route kan bepalen volgens Shell:

A. Emissions
B. Technology
C. Market
D. Politics
E. Unit Economics
F. Storage

G. Infrastructure Required
H. Scalability

T. Process Model Description

The process model for HTL and FP is developed to estimate the three inputs for the criteria assessment: the required amount of hydrogen, heat and electricity. First, the required hydrogen was determined from the mass balance of the process. Then, the required heat was determined by assigning energy quantities to the mass flows, calculating the difference in energy going into and out of the process. Finally, the electricity required was estimated by considering the main pumps and compressors and determining how much electricity is needed to run them.

The model for the HTL and FP process has been constructed as shown in the figures below

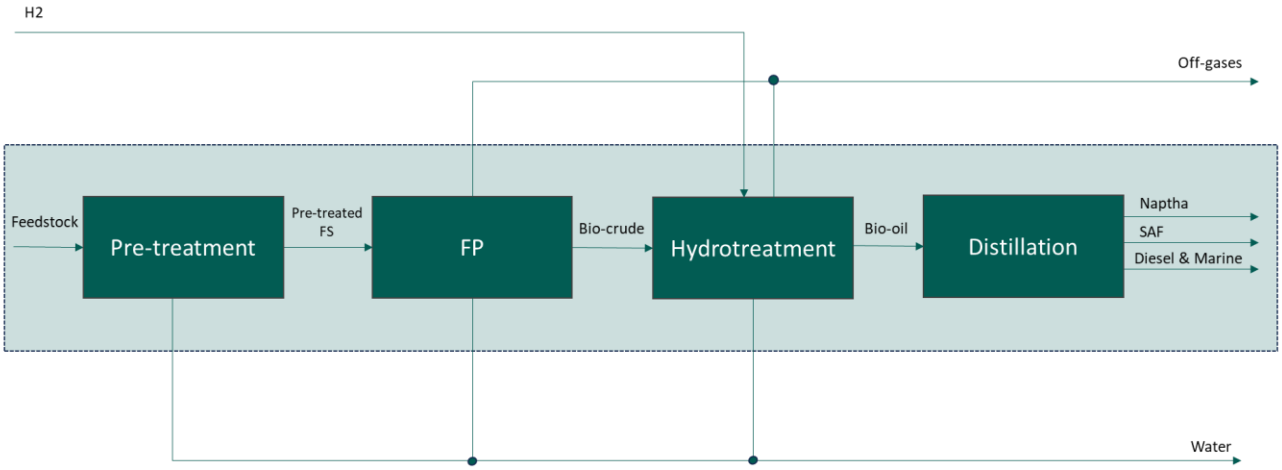


Figure 29: FP process model visualisation.

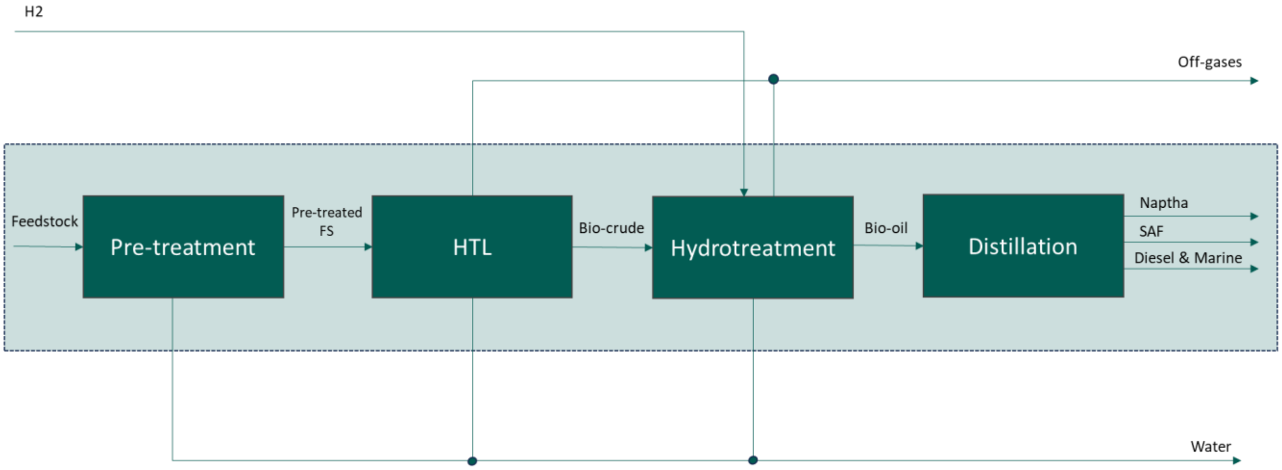


Figure 30: HTL process model visualisation.

Mass Balance HTL and FP

1. Pre-treatment Step

For the pre-treatment of the feedstock, only the drying operation was modelled. This was chosen because this operation is the most energy intensive and is the most critical step within the pre-treatment, as indicated by the interview with BTG. Other pretreatment operations were therefore not included in the model, although they have been discussed previously.

The interview with BTG revealed that the forest residues are dried to a moisture content of up to [redacted] % by weight and the interview with Steeper revealed that for HTL the forest residues are dried up to [redacted] % by weight. The drying is needed because the forest residues contain more water (~ [redacted] wt%) than is compatible in the HTL and FP reactors.

The mass flows of this process step are:

- Mass flow in:
  - The raw feedstock, of which [redacted] wt% is water and [redacted] wt% is biomass (BTG interview).
- Mass flow out:
  - The mass flow of water leaving the system. This is the difference between the initial amount of water in the feedstock and the amount of water allowed in the feedstock after the drying process.
  - The mass flow of pre-treated feedstock for FP with a water content of [redacted] wt%. And for HTL with water content of [redacted] wt%.

2. FP/HTL Step

In the FP step, the pre-treated feedstock is rapidly heated to [redacted] °C in an oxygen-free environment and subsequently decomposed into bio-crude, char and off-gasses. And for the HTL step the pre-treated feedstock is pressurized under [redacted] bar and heated to [redacted] °C in an oxygen-free environment and subsequently decomposed into bio-crude, water and off-gasses.

The mass flows of this process step are:

- Mass flow in:
  - Pre-treated feedstock
- Mass flow out for FP:
  - Char which represents [redacted] % of the mass flow in.
  - Bio-crude which represents [redacted] % of the mass flow in. The bio-oil is directed to the hydrotreatment step for further processing.
  - Off-gasses which represents [redacted] % of the mass flow in.
- Mass flow out for HTL:
  - Water which represents [redacted] % of the mass flow in.
  - Bio-crude which represents [redacted] % of the mass flow in. The bio-oil is directed to the hydrotreatment step for further processing.
  - Off-gasses which represents [redacted] % of the mass flow in.

The mass flow out percentages for FP are based on information obtained during the interview with BTG and for HTL the percentages are based on information obtained from Steeper Energy Aps. (2018). Although the off-gasses and solid carbon could potentially be re-used within the process, as indicated in previous discussions, this is not incorporated in this process model.

3. Hydrotreatment Step

The bio-crude from the HTL and FP is unstable and requires further upgrading. The upgrading is done by removing the oxygen in the bio-crude with hydrogen. For this model, it is assumed that only oxygen needs to be removed from the bio-oil by hydrogen and that the presence of other heteroaromatics is negligible. In the FP model, stabilisation and hydrotreatment as shown in Figure XX, are combined into one hydrotreatment step.

- Mass flow in:
    - The bio-crude which contains water. For FP the composition was taken from the presentation slides of Bert van de Beld's seminar (2022). And for HTL the composition was taken from Steeper Energy Aps. (2018). [1]
    - The hydrogen required for the hydrotreatment [2]
- Mass flow out:
    - The bio-oil consisting of hydrocarbons [3]
    - The water extracted from the bio-crude [4]
    - The water produced by the reaction of hydrogen with oxygen from the bio-oil [5]
    - The off-gasses, which contains some of the oxygen from the initial bio-crude [6]

To determine the values of the mass flows above, the following back calculating procedure was followed.

First for FP, it was taken from Miguel Mercader (2010) that 5% of the carbon content of the bio-crude of FP ends up in the off-gasses after hydrotreatment. Because the carbon content of the bio-crude is known the carbon content of the off-gasses could be calculated. Also, the off-gases composition was adopted from Miguel Mercader (2010). Based on the off-gases composition it could be calculated that the carbon content makes up 41% of the total weight of the off-gases. By knowing that 5% of the carbon content of the bio-oil is ending up in the off-gases and that this makes up 41% of the total mass flow of off-gasses [6] the total mass flow could be calculated.

For HTL the percentage of C from the bio-crude that ends up in the off-gasses was not known, therefore it was assumed that the amount of oxygen leaving with the off-gasses is equal to the amount of oxygen leaving with the off-gasses of FP, which is calculated at 6%. From here on, the mass flow of the off-gasses [6] could also be calculated for HTL.

The rest of the carbon that was initially in the bio-crude ends up in the bio-oil. Out of the C/H ratio in SAF taken from Steeper Energy Aps. (2018), the H content could be calculated. The total mass flow for the bio-oil of HTL and FP [3] would then be the sum of the H content and the C content.

It was assumed that the bio-oil contains 0% of oxygen after the hydrotreatment. The oxygen is removed by hydrogen and forms into water. The amount of O removed is equal to the O in the initial bio-crude minus the O in the off-gasses. The O in the off-gasses could be determined by the off-gasses composition adopted from Miguel Mercader (2010). Thus, the mass flow of the water produced of HTL and FP [5] is equal to the oxygen that needs to be removed plus the hydrogen required for this.

The amount of hydrogen required for the hydrotreatment for HTL and FP can be calculated using the following equation:

$$H\_required = H\_out - H\_in$$

Where,

- H_in represents the hydrogen present in the bio-oil (liquid organics + water) entering the hydrotreatment unit
- H_out represents the hydrogen that flows out of the hydrotreatment step
- $H\_required$ represents the hydrogen that is needed to upgrade the bio-oil

4. Distillation Step

In the distillation step the bio-oil is distilled into the end-products: diesel/marine, SAF and Naptha. The mass flows of this process step are:

- Mass flow in:
    - The bio-oil, consisting of hydrocarbons
- Mass flow out for FP:
    - Naptha which represents [redacted] % of the mass flow in.
    - SAF which represents [redacted] % of the mass flow in.
    - Diesel/Marine which represents [redacted] % of the mass flow in.
- Mass flow out for HTL:
    - Naptha which represents [redacted] % of the mass flow in.
    - SAF which represents [redacted] % of the mass flow in.
    - Diesel/Marine which represents [redacted] % of the mass flow in.

These distributions are based on information obtained during the interview with BTG and Steeper.

The mass balance for the FP process and HTL process are schematically presented at the top in the M&E FP Balance tab and M&E FP Balance tab.

Energy Balance HTL and FP

The energy balance of the HTL and FP process are outlined under the mass balance in the M&E FP Balance tab and M&E FP Balance tab. The energy flows within the energy balance are determined by multiplying the mass flow of each stream by its Higher Heating Value (HHV). The HHV is a measure of the total amount of energy released when a fuel burns completely. It includes both the energy released as heat during combustion and the heat released when the water produced during combustion condenses. The HHV represents the maximum amount of heat energy available from a fuel and is usually expressed in megajoules per kilogram (MJ/kg) (Editor Engineeringtoolbox, 2023c).

1. Thermal Heat Requirements

To calculate how much energy the HTL and FP process requires, the difference between the energy leaving the entire process and the energy entering the FP/HTL step is calculated. In this model, it is assumed that this energy difference is compensated by steam, which is generated from natural gas.

The energy required for drying in the pre-treatment step is calculated by accounting for the energy required to heat and then evaporate water. This consists of two elements:

1. The specific heat capacity, C_p, and the temperature difference, Δt, for heating the water to the boiling point (Editor Engineeringtoolbox, 2023a)
2. The latent heat of evaporation, L, for converting the water from liquid to gaseous phase (Editor Engineeringtoolbox, 2023b).

To obtain an accurate estimate of the energy required for drying, these two components are combined and adjusted for the efficiency of the system. The total energy input for heating and evaporating water is then calculated by the following equation:

$$Total\ E_{required} = (Q_s + Q_L) \times \eta_{boiler}$$

- Q_s, represents the sensible heat energy, which is the energy required to raise the temperature of the water mass flow
- Q_L, represents the total amount of latent heat energy, which is the amount of energy required to convert the water mass flow into vapor
- η_{boiler}, the boiler efficiency, which is assumed to be 80% for this study

The following formula for Q_s can be used to calculate the energy required to raise the temperature of a given quantity of water:

$$Q_s = m \times C_p \times \ \Delta t$$

- m, represents the mass flow of water in kilograms per second (kg/sec)
- C_p, represents the specific heat capacity, which is approximately 4.18 kJ/kg-K for liquid water (Editor Engineeringtoolbox, 2023c)
- Δt, represents the temperature difference in K. The inlet temperature of the water is assumed to be 25 °C (298.15 K) and the outlet is 100 °C (373.15 K).
- Q_s , represents the energy that is required to heat the water in kW

When the mass flow of water reaches its boiling point, the energy required for its transition from liquid to vapour can be calculated using the following formula:

$$Q_L = m \times L$$

- m, represents the mass flow of water in kilograms per second (kg/sec),
- L, represents the latent heat of evaporation which is 2256 kJ/kg at 100 °C C (373.15 K) (Editor Engineeringtoolbox, 2023c)
- Q_L, represents the energy that is required to convert the water into water vapor in kW

2. Electricity required for pump and compressors

Apart from heat, the HTL and FP processes also require electricity for maintaining the desired pressure within the various process units. The electricity is used to drive the main pumps and compressors. To estimate the electricity required, the main pumps in the process were considered. For the FP process, these include the pumps from FP to stabilization and hydrotreatment. For the HTL process, these include the pumps from HTL and hydrotreatment. The hydraulic pump power formula (Engineering Toolbox in 2023d) was used for this estimation and adjusted for pump and motor efficiency, which was assumed to be 70%.

The estimation is done according to the following equation:

$$P_{pump} = \frac{\Delta p \times Q}{3.6 \times 10^6} \times \ \eta_{pump}$$

and,

$$Q = \frac{m}{\rho}$$

- P_{pump}, represents the hydraulic power in kilowatts (kW)
- m , represents the mass flow in kilograms per second (kg/sec)
- ρ , represents the density of the fluid in kilograms per cubic metre (kg/m³)
- Δp , represents the pressure difference in pascals (Pa)
- η_{pump}, represents the pump efficiency, which is assumed to be 70%
- Q, represents the volumetric flow rate (m³/sec)

Another unit that consumes electricity in the HTL and FP process is the compressor. The compressor unit is responsible for compressing the incoming hydrogen, which is at low pressure, to the desired pressure of ~130 bar, which is required to process the hydrogen (BTG Bioliquids, 2022). An initial pressure of 1 bar is assumed for this model.

In the HTL and FP model, the energy consumption of the compressor, $P\_compressor$, is not calculated using a specific formula, but the analysis is based on the findings of Zaimes et al. (2015). This study is relevant because it examines the energy required for the compression of hydrogen to a pressure that is equivalent to the pressure required for the HTL and FP processes (~130 bar). For this research, it is assumed that the energy consumption of the compressor increases linearly with the increase in hydrogen mass flow rate. With this assumption, the energy consumption per kilogram of hydrogen in megajoules (MJ) was calculated using the data from Zaimes et al. (2015). This calculation is then adjusted to consider compressor efficiency, which is assumed to be 85%. This adjusted energy consumption per kilogram of hydrogen could then be multiplied by the total hydrogen flow rate determined by the mass balance for the HTL and FP processes to estimate the total energy consumption of the compressor for HTL and FP.

The total electricity required for the main pumps and compressors of HTL and FP is then calculated by:

$$Total\ Electricity\ required = P_{pump} + P_{compressor}$$

- P_{pump}, represents the hydraulic power in kilowatts (kW) of the main pumps
- $P_{compressor}$, the power of the compressors used to compress the hydrogen in kilowatts (kW)

In the table below the inlet pressure, outlet pressure and the mass flow of the pumps and compressors are shown for HTL and FP

Table 38: Pressure pumps and compressors.

Technology	Pump/compressor	Inlet pressure (bar)	Outlet pressure (bar)	Mass flow(kg/hr)
FP	FP unit	1	200	[redacted]
	Hydrotreatment unit	1	137	[redacted]
	Hydrotreatment compressor	1	137	[redacted]
HTL	HTL unit	1	200	[redacted]
	Hydrotreatment unit	1	137	[redacted]
	Hydrotreatment compressor	1	137	[redacted]

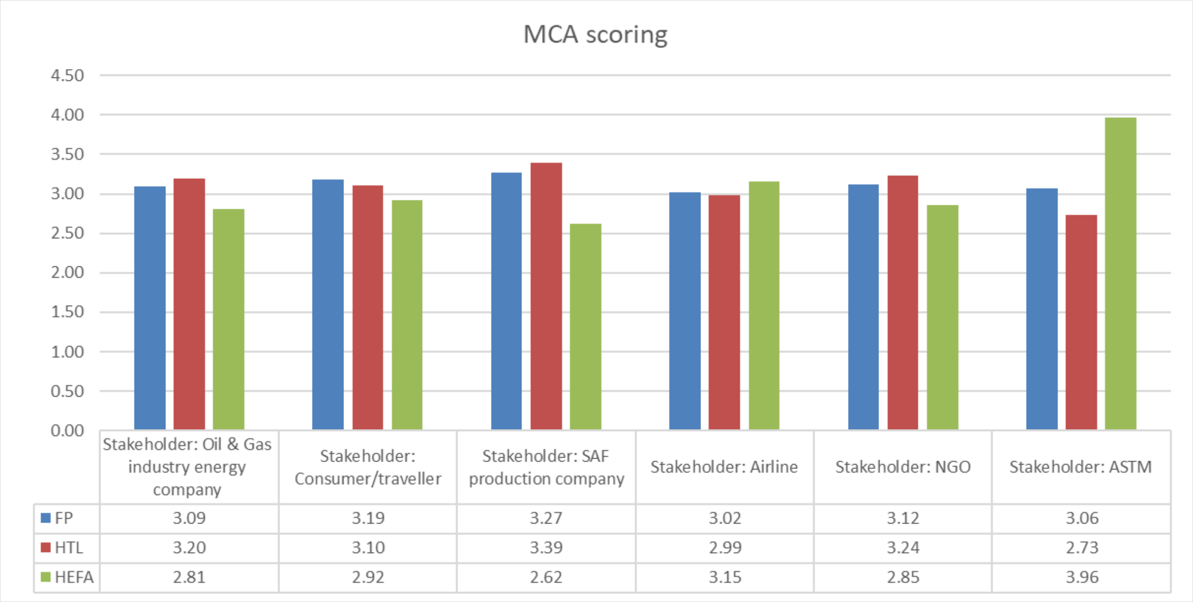
U. Inputs Economic Criteria Analysis

Table 39: Economic inputs.

Input	Value	Source
CAPEX FP	$ 316,900,000	Jones & Zhu (2009)
CAPEX FP	$ 338,910,000	Brown et al. (2013)
CAPEX HTL	$ 274,029,946	Jones & Zhu (2009)
CAPEX HTL	$ 356,300,000	Nie & Bi (2018)
CAPEX HTL	$ 243,900,000	Zhu & Biddy (2014)
Conversion Rate EUR/USD	0.92	European Central Bank (2024)
Bio-oil Production FP - BTG	29.78 kt/yr	BTG (Personal Communication, 2024)
Bio-oil Production HTL-Steeper	121.99 kt/yr	Steeper (Personal Communication, 2024)
Price Forest Residues	€ 150 /t FS	SkyNRG (Personal Communication, 2024)
Price UCO	€ 1,040 /t FS	Argus via SkyNRG (Personal Communication, 2024)
Price H_2 Green	€ 9,850/t H_2	Clean Hydrogen JU. (2023)
Price H_2 Grey	€ 6,230/t H_2	Clean Hydrogen JU. (2023
Price Electricity grey	€ 0.13	“Quarterly Report On European Electricity Markets” (2022)
Price Electricity green	€ 0.10	“Quarterly Report On European Electricity Markets” (2022)
Price Heat natural gas	€ 14.00 EUR/GJ	“Quarterly Report On European Electricity Markets” (2022)
Price Heat RNG	€ 21.75 EUR/GJ	IEA (2020)
Costs of production diesel	€ 700/ton	SkyNRG (Personal Communication, 2024)
Costs of production naphtha	€ 500/ton	SkyNRG (Personal Communication, 2024)

V. Detailed Results Sensitivity Analyses

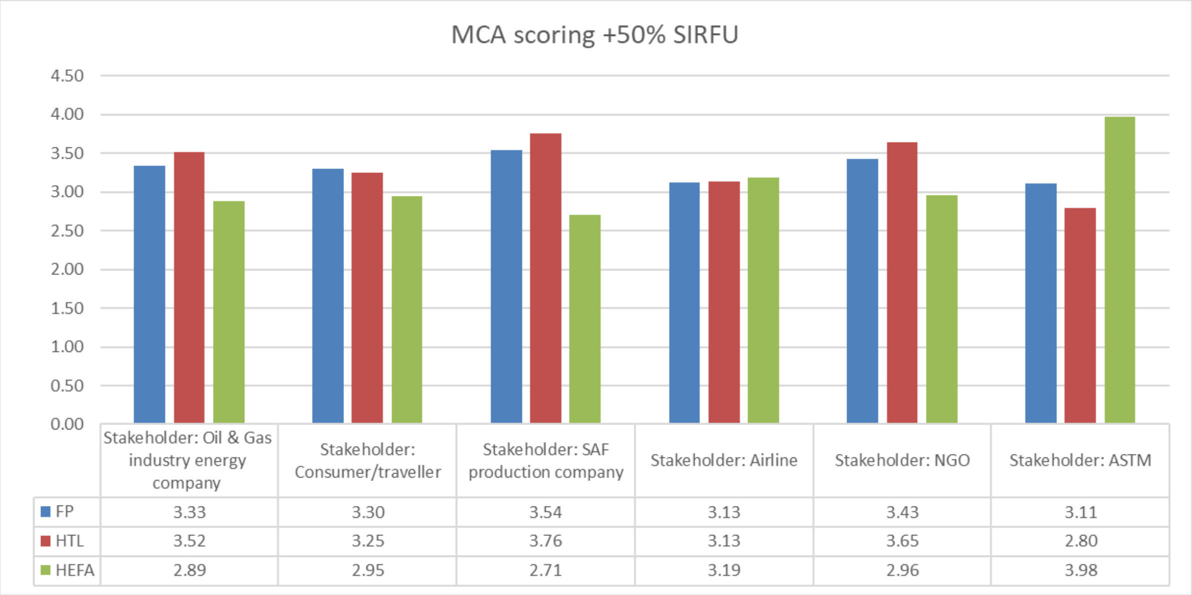
The used MCA rankings and final MCA scores are shown in the figure below.



	Stakeholder: Oil & Gas industry energy company	Stakeholder: Consumer/traveller	Stakeholder: SAF production company	Stakeholder: Airline	Stakeholder: NGO	Stakeholder: ASTM
🟦 FP	3.09	3.19	3.27	3.02	3.12	3.06
🟥 HTL	3.20	3.10	3.39	2.99	3.24	2.73
🟩 HEFA	2.81	2.92	2.62	3.15	2.85	3.96

Figure 31: Final MCA scores used in this study.

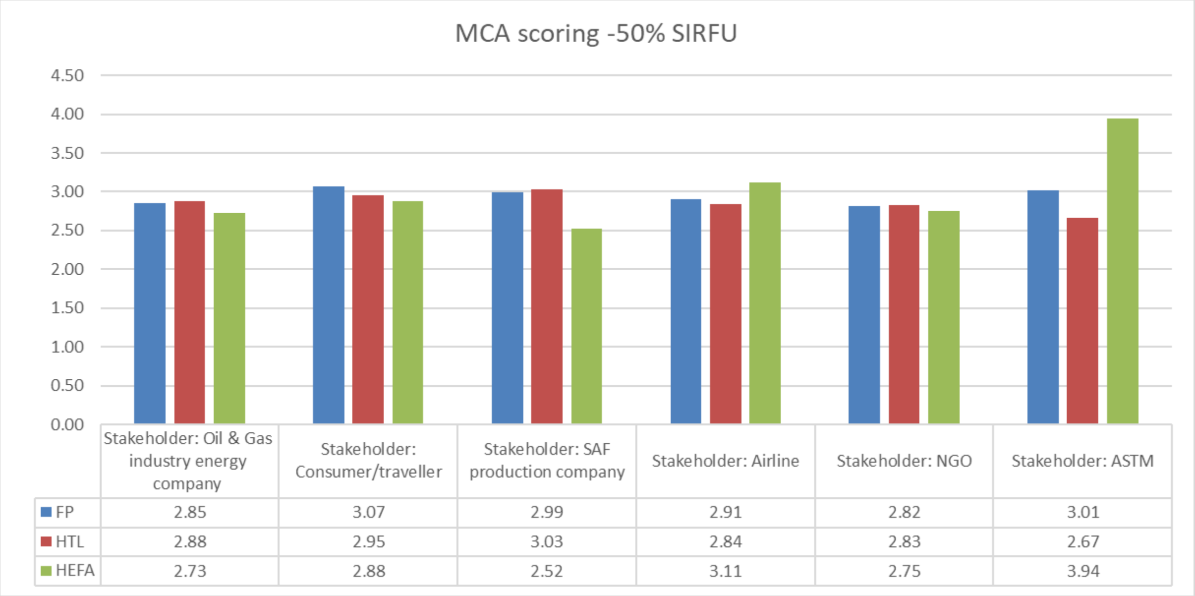
Results of the ±50% social impact related to feedstock use sensitivity analyses are shown below.



	Stakeholder: Oil & Gas industry energy company	Stakeholder: Consumer/traveller	Stakeholder: SAF production company	Stakeholder: Airline	Stakeholder: NGO	Stakeholder: ASTM
🟦 FP	3.33	3.30	3.54	3.13	3.43	3.11
🟥 HTL	3.52	3.25	3.76	3.13	3.65	2.80
🟩 HEFA	2.89	2.95	2.71	3.19	2.96	3.98

Figure 32: Results Sensitivity Analysis SIRFU +50%

For the social impacts related to feedstock use, the MCA ranking is almost the same after a 50% increase. Only for the airline, FP and HTL are now equally ranked. Furthermore, the MCA final scores show that HTL and FP are closer to each other in all cases. Where HEFA is the leading technology, the gap between TL technologies and HEFA narrows. Conversely, when TL technologies are leading, the gap with HEFA grows. This means that HEFA's relative advantages decrease as the social impact performance score increases.



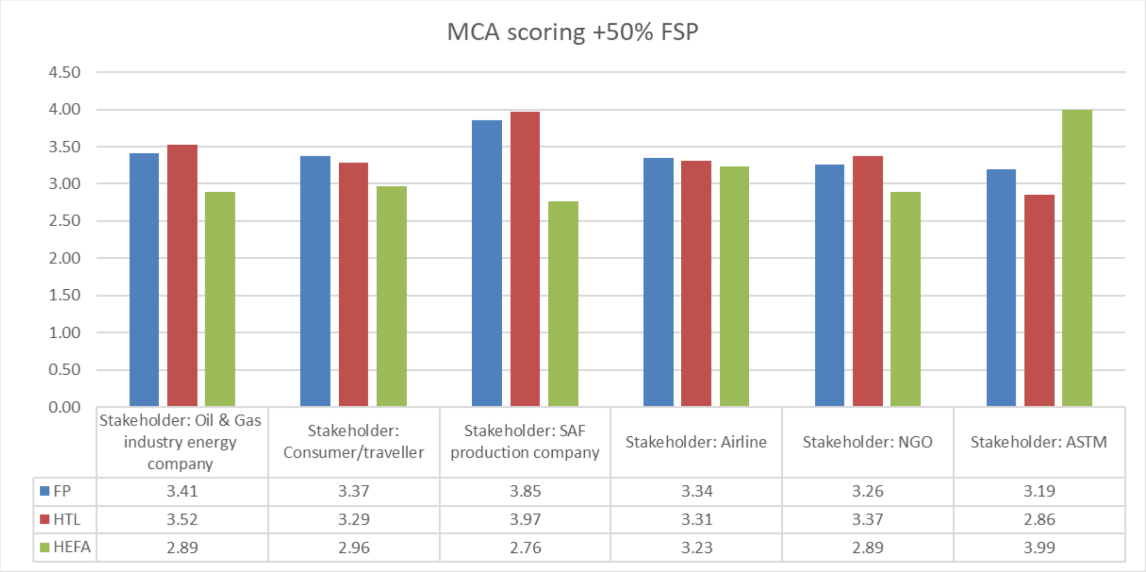
	Stakeholder: Oil & Gas industry energy company	Stakeholder: Consumer/traveller	Stakeholder: SAF production company	Stakeholder: Airline	Stakeholder: NGO	Stakeholder: ASTM
🟦 FP	2.85	3.07	2.99	2.91	2.82	3.01
🟥 HTL	2.88	2.95	3.03	2.84	2.83	2.67
🟩 HEFA	2.73	2.88	2.52	3.11	2.75	3.94

Figure 33: Results Sensitivity Analysis SIRFU -50%

For the social impacts related to feedstock use, the MCA ranking for all stakeholders after a 50% decrease is the same as in the situation without. Furthermore, the MCA final scores show that HTL, FP and HEFA are closer to each other in all cases. This suggests that a lower social impact performance score will make technologies more similar in terms of their overall final MCA score.

The MCA ranking is robust to social impacts related to feedstock use performance score, as the ranking remains almost unchanged when increasing/decreasing by 50%. This suggests that social impact is not the determining criterion for the ranking of SAF technologies. Although there are small shifts in the final MCA scores, the relative positions of the technologies remain largely stable.

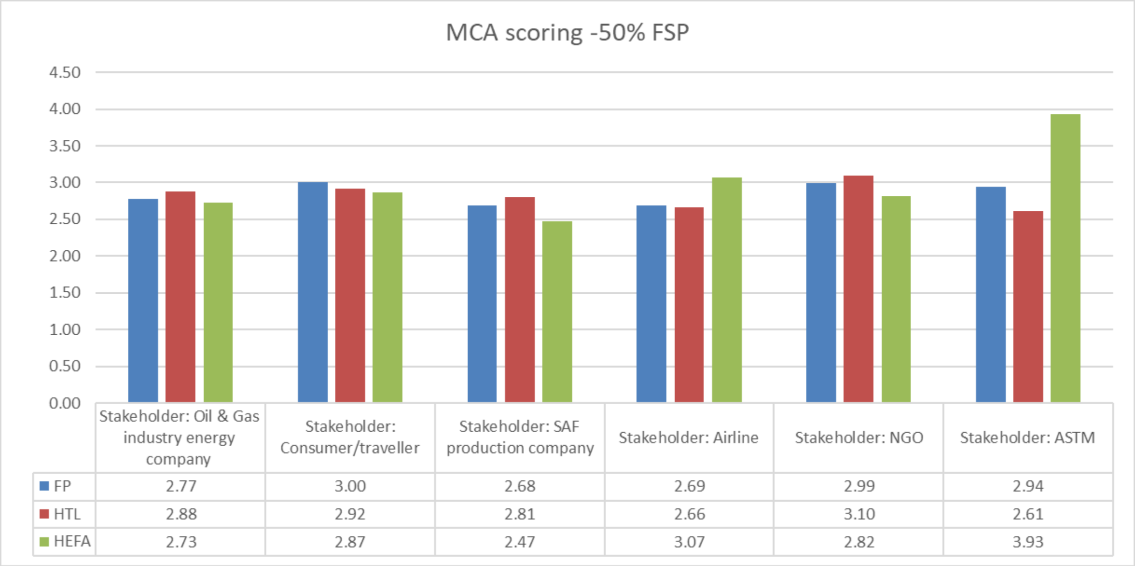
The results of the ±50% feedstock price sensitivity analyses are shown below.



	Stakeholder: Oil & Gas industry energy company	Stakeholder: Consumer/traveller	Stakeholder: SAF production company	Stakeholder: Airline	Stakeholder: NGO	Stakeholder: ASTM
🟦 FP	3.41	3.37	3.85	3.34	3.26	3.19
🟥 HTL	3.52	3.29	3.97	3.31	3.37	2.86
🟩 HEFA	2.89	2.96	2.76	3.23	2.89	3.99

Figure 34: Results Sensitivity Analysis FSP +50%

For feedstock price, the MCA ranking remains the same for almost all stakeholders after a 50% increase. For the airline only, the ranking changes, from HEFA>FP>HTL to FP>HEFA>HTL. Furthermore, the final MCA scores show that in all cases, HTL and FP are the same distance apart as in the situation without a 50% increase. The reason for this is that they both had the same performance score assigned by the experts, and therefore increased by the same proportion, which means that the difference does not change. Moreover, it shows that when TL technologies are dominating, the difference in final MCA score with HEFA increases. HEFA remains dominant for the ASTM, but the difference of the final MCA scores decreases with the TL technologies.



	Stakeholder: Oil & Gas industry energy company	Stakeholder: Consumer/traveller	Stakeholder: SAF production company	Stakeholder: Airline	Stakeholder: NGO	Stakeholder: ASTM
🟦 FP	2.77	3.00	2.68	2.69	2.99	2.94
🟥 HTL	2.88	2.92	2.81	2.66	3.10	2.61
🟩 HEFA	2.73	2.87	2.47	3.07	2.82	3.93

Figure 35: Results Sensitivity Analysis FSP -50%

For the feedstock price, the MCA ranking for all stakeholders after a 50% decrease is the same as in the situation without. Furthermore, the MCA final scores show that HTL, FP and HEFA are closer to each other in all cases. This suggests that a lower feedstock price performance score will make technologies more similar in terms of their overall final MCA score.

W. Example Informed Consent Form

Interview informed Consent Form

Research project title: Assessing Thermochemical liquefaction Technologies on their Application for Sustainable Aviation Fuel production (SAF).
Research investigator: Charlotte Taets van Amerongen
Research supervisor: Dr. Linda M. Kamp

You are being invited to participate in a research study titled "Assessing Thermochemical Liquefaction Technologies on their Application for Sustainable Aviation Fuel (SAF) production". This study is being done by Charlotte Taets van Amerongen from the TU Delft Complex System Engineering and Management Programme in collaboration with SkyNRG, a company at the forefront of making the aviation industry more sustainable.

The purpose of this research study is to assess the performance of thermochemical liquefaction technologies on their application for SAF production and will take you approximately 30 minutes to complete. to gather insights into your company's thermochemical liquefaction technology and its utilization in SAF production. During the interview, we will seek your input regarding specific aspects of this technology.

This consent form is necessary for us to ensure that you understand the purpose of your involvement and that you agree to the conditions of your participation. Would you therefore read the accompanying information sheet and then sign this form to certify that you approve the following:

1. The interview will be recorded, and a transcript will be produced.
2. You will be sent the anonymous summary and given the opportunity to correct any factual errors.
3. The anonymous summary of the interview will be analyzed by Charlotte Taets van Amerongen as the research investigator, and once the study is completed, only non-confidential information will be made publicly available.
4. Access to the interview transcript will be limited to Charlotte Taets van Amerongen and academic colleagues and researchers with whom she might collaborate as part of the research process (within TUD).
5. Any summary interview content, or direct quotations from the interview, that are made available through academic publication or other academic outlets will be anonymized so that you cannot be identified, and care will be taken to ensure that other information in the interview that could identify you is not revealed.

As with any online activity the risk of a breach is always possible. To the best of our ability your answers in this study will remain confidential. We will minimize any risks by taking the following measures:

1. Ask you, the interviewee, for as little sensitive information as possible—only what is absolute necessary. Identified necessary data: name, email address, gender (implicitly assumed from interviews, not explicitly asked), occupation and area of expertise, work experience regarding the studied field, audio, and video recording of interviews for transcription/analysis.
2. You will have the choice to have your interview audio-only recorded (so no video).
3. The interview will be conducted online through a secure platform (Microsoft Teams) and using a private internet network to avoid cyber-security threats.
4. The gathered information will be stored on a password protected, TUD institutional storage located in the Netherlands that only the research investigator and supervisors can access.
5. You will be referred to as they/them, your area of expertise will be the only thing indicated, and you will remain anonymous in the published work. For example: interviewee 1, who is in the technology team at a company that uses HTL to produce SAF, states the following: "It is more important to take into account the technological readiness of HTL than the operational costs associated with the SAF plant".
6. Upon completion of the research, expected in May 2024, all collected personal data will be promptly deleted within one month following the end of the study (recording, transcript, proof of consent).

Your participation in this study is entirely voluntary **and you can withdraw at any time**. You are free to omit any questions and to opt out of including data gathered during your interview before March 28th, 2024.

By signing this form, I agree that:

1. I am voluntarily taking part in this project. I understand that I don't have to take part, and I can stop the interview at any time;
2. The transcribed interview or extracts from it may be used as described above;
3. I don't expect to receive any benefit or payment for my participation;
4. I can request a copy of the transcript of my interview and may make edits I feel necessary to ensure the effectiveness of any agreement made about confidentiality;
5. I understand that I will receive the anonymous summary of the interview that is going to be publicly available and I can request change or address concerns;
6. I have been able to ask any questions I might have, and I understand that I am free to contact the researcher with any questions I may have in the future.

I agree to be anonymously quoted [] yes [] no.

Printed Name

____

Participants Signature Date

_______________________________________ _____________________

Should you have any questions or need to contact us, you can do so using the following details:
Charlotte Taets van Amerongen
c.l.s.taetsvanamerongen@student.tudelft.nl or charlotte.taets@skynrg.com
Corresponding Researcher