Delft University of Technology
Master thesis

Stakeholder preferences regarding sustainable aviation fuel technologies

Stakeholders' preferences regarding different SAF technology pathways, in order to comply with the proposed SAF blending mandate by the European Commission

Keywords: Best-Worst Method – multi-criteria decision-making method – SAF – Advanced biofuels – ReFuelEUInitiative

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Preface

This is the final version of my research report that I have worked on to obtain my Master's degree for my Master study Engineering and Policy Analysis, faculty of Technology, Policy and Management at Delft University of Technology.
The topic and scope were determined after I read about all the obstacles that still need to be overcome in the aviation industry to develop a more sustainable way of flying. After first mail contact, it quickly became clear that both my first supervisor as well as my second supervisor are interested in this topic. Setting up the supervision committee was therefore a smooth process. In this preface, I would like to give a word of appreciation to some people. First, I would like to thank Natalia Barbour, for her guidance, enthusiasm and wide availability during the writing process of my thesis. It was a pleasure to have her as my first supervisor. In the second place, my appreciation goes to Jan-Anne Annema for his generalist view, his brief and to the point feedback and his wide availability. Next to my supervision from the TU Delft, I would also like to thank my external supervisor Frank Gerard for his guidance as he thought along with me on how to perform the interviews and gave good overall feedback. Regarding the content of this study, it would have been quite impossible to write this thesis without the valuable input I received from all the sustainable aviation fuel experts. Therefore, I would like to thank all experts for their participation in this study.

Lastly, I would like to thank my family, my girlfriend and my roommates who showed great interest in my thesis. I'm thankful for their useful suggestions throughout the whole research period. Last but not least, they gave me useful and nice distraction when needed. Looking back, I am proud of this thesis that is in front of you.

Victor de Haas

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Executive summary

The aviation industry is expected to grow substantially in the next decades, both worldwide as well as in the European Union. This will result in a substantial growth of the aviation's contribution to global greenhouse gas emissions. As a reaction to these expectations, the International Civil Aviation Organization (ICAO) recently adopted a carbon-neutral growth for the international aviation industry and the International Air Transport Association (IATA) pledges for a 50% carbon emission reduction from 2005 levels by 2050. There are multiple ways for the aviation industry to reduce its carbon emissions of which one of the promising solutions is Sustainable Aviation Fuel (SAF). These Sustainable Aviation Fuels are considered crucial as they are deemed necessary to accomplish both goals set by the ICAO and the IATA. In order to comply with these goals, a vast upscale of SAF is needed. Currently, the SAF industry is still far away from this upscale as this industry faces a chicken and egg situation. The price gap between conventional jet fuel and SAF is a major barrier for the SAF demand side to increase. The price of SAF will decrease if the production rises. However, there's no incentive for the SAF production side to ramp up as long as there is no increase in the demand side. To overcome this vicious circle, the European Commission proposed the ReFuelEUAviation Initiative which includes a SAF blending mandate for fuel suppliers. Mandates levels start by 2025 and will gradually increase up to 2050. As synthetic fuels, also known as power-to-liquid or e-fuels, have large decarbonisation potential and are expected to play a large role in the SAF industry on the longer term, a specific sub-mandate is proposed for this SAF technology, which starts at 2030.

Ample research has been performed on the multiple facets of SAF and on how to stimulate the upscale of SAF. However, up till now, (1) research has mainly focused on cost competitiveness which results in little attention towards other aspects that are key for this market to develop as well. Besides, (2) little research is qualitative of its kind and limited attention is paid towards qualitative stakeholder consultation and therefore, there's no in-depth understanding of the contrasting advantages of different SAF technology pathways that are experienced by different stakeholder sections. Consequently, it is of importance to identify the most promising technologies and pathways according to all the different stakeholders rather than the SAF technology pathway with the best financial aspects or the best technological performance. As a third knowledge gap, (3) no multi-criteria analysis is performed which considered power-to-liquid fuels. This is mainly because this technology is still a state-of-the-art technology. On the long term however, this technology is expected to have a large potential for the SAF industry. This research therefore strives to contribute to this gap by exploring these three aspects; this study will not only focus on financial performance of SAF technologies but will consider multiple criteria, this study will conduct multiple stakeholders from different stakeholder sections in its analysis and the synthetic (power-to-liquid) SAF technology will also be considered in this study. Consequently, the following main research question is constructed: "*What are stakeholders' preferences regarding different SAF technology pathways, in order to stimulate the SAF upscale for 2030 and comply with the proposed SAF blending mandate by the European Commission?*" In order to address this main research question, a multi-criteria analysis (MCA) approach is used as this approach suits the exploratory nature of this research, since the SAF industry is at the beginning of the required upscale. In accordance with the MCA approach, the research is divided into the following categories.

The first section of this study is devoted to identifying different SAF technologies that are expected to have sufficient scale up potential. An extensive literature research is performed to map multiple approved and non-approved SAF technologies by the American Society for Testing Materials after which a selection of seven different SAF technologies are discussed more elaborately on their market potential. After excluding technologies that are not expected to play a role in the future SAF industry by 2030, four technologies are considered in this study (Fischer-Tropsch synthesis, hydroprocessed ester and fatty acids, alcohol to jet and synthetic fuels (power-to-liquid technology)). Additional research is conducted into promising feedstock types best suitable for these four technologies resulted in the following selection of SAF technology pathways considered in this study:

- Fischer-Tropsch with municipal solid waste as feedstock type (FT-municipal solid waste)
- Fischer-Tropsch with forestry residue as feedstock type (FT-forest residue)
- Alcohol to jet technology that uses sugarcane as feedstock (AtJ-sugarcane)
- Hydroprocessed esters and fatty acids technology with used cooking oil as feedstock (HEFA-used cooking oil)
- Power-to-liquid technology that uses point sourced CO_2 as feedstock (PtL-point sourced CO_2)

- Power-to-liquid technology with the use of direct air captured CO_2 as feedstock (PtL- direct air captured CO_2)

Following the MCA approach, the second section is determined to establish the set of criteria which are considered to score the performance of the SAF technology pathways. To establish this set of criteria, the model of transport innovations by Feitselson Salomon is used and a literature study is performed. Based on this, this study will assess the different SAF technology pathways on three main criteria: environmental performance, economic performance and technological performance. These three main-criteria are divided into multiple sub-criteria. The sub-criteria that belong to the main-criterion 'environmental performance' are: 1) greenhouse gas saving emissions, 2) land usage and 3) water usage. Within the economic main-criterion, the following sub-criteria are used: 1) minimum selling price, 2) feedstock alternative use, 3) feedstock profitability and 4) plant capital costs. The third main-criterion, the technological performance, is split up in two sub-criteria: 1) technology readiness level and 2) production volume availability and scalability.

To find the relative weights of the considered main- and sub-criteria, the novel Bayesian Best-Worst Method is applied in the third section of this study. This method determines the optimal group weight per criterion and is used to determine both the total optimal group weights as well as the weight per criterion for different stakeholder groups. The required input for deriving these weights is obtained via one-on-one interviews with stakeholders from different stakeholder groups within in the aviation industry. There are four different stakeholder groups identified: airline industry, demand side, supply side and experts/consultants' group. The obtained optimal group decision making weights when considering all these stakeholder groups together show that the sub-criterion 'greenhouse gas saving emissions' is considered as the most important sub-criterion affecting the stakeholders' preference regarding the six considered SAF technology pathways. It can be noted that this sub-criterion relates to the most-important main-criterion, the environmental performance. The sub-criterion 'production volume availability and scalability' is considered as the second most important sub-criterion and is closely followed by 'minimum selling price'.
Next to the group decision making weights for all stakeholder groups simultaneously, the weights for the criteria are also established per different stakeholder group. By establishing the criteria weights per stakeholder group, the perspectives of these groups are quantified. When considering the weights per group, it can be noted that the airline industry deviates from the weights from the other three stakeholder groups. The airline industry deviates from the other three groups due to an increased importance of the economic performance and a strongly decreased importance of the environmental performance. The decreased importance of the environmental performance is in large contrast with the other three stakeholder groups and shows the divergent perspective between the airline industry and the rest of the industry. Also the deemed increased importance of the economic performance of the SAF pathways by the airline industry contributes to this divergent perspective. This deviating perspective of the airline industry makes it difficult for the SAF industry to overcome the current chicken and egg situation in which the SAF industry finds itself.

In the fourth section of this study, the scorecards are determined after which these scorecards can be used to come to the final performance scores of the considered pathways. These scorecards are the scores of each pathway with respect to each criterion and are established by conducting both literature as well as expert knowledge. With the use of these scorecards and the earlier obtained weights per criterion, the total performance scores of the six considered SAF technology pathways are constructed by using the weighted sum method. First, the performance scores of the technology pathways are obtained when considering all stakeholder groups simultaneously. The results of this analysis show that the Fischer-Tropsch (FT) forest residue is the preferred SAF technology pathway and is closely followed by the same FT technology that uses municipal solid waste as feedstock. These pathways their high-performance scores are mainly because of their good performance on greenhouse gas saving emissions and their expected production volume availability and scalability, which are the most and the second-most important criteria in this analysis. The HEFA technology that uses used cooking oil is the third preferred SAF technology pathway. What is noticeable, is that this technology pathway is ranked as third preferred technology pathway, while in practice, it is not the FT technology, but the HEFA technology that dominates the current production of SAF in Europe. This difference can be explained by the fact that this study considers a 2030 timeline and although the HEFA technology currently still has sufficient level of feedstock availability, the feedstock availability and scalability by 2030 is expected to be minor. The alcohol-to-jet technology is well developed on its technological performance but experiences moderate performances on the environmental main-criterion and its expected minimum selling price is expected to only have a minor reduction by 2030. Because of these moderate performances, this technology scores as fourth preferred SAF technology pathway. Another noteworthy mentioning is that both power-to-liquid pathways experience

severe benefits in environmental performance as they both perform well all on the three considered sub-criteria within this main-criterion. Nevertheless, these two pathways are the least preferred ones as they are still relative state-of-the-art technologies with sufficient barriers to overcome. Their expected minimum selling price is expected to remain high, their production volume availability and scalability is considered inferior and both technologies still experience moderate performances on their technology readiness levels.
Next to performing an analysis where the weights of all the stakeholder groups combined are used, this section also performs an analysis in which the performances scores are derived per stakeholder group. This shows how these different obtained weights will effect the performance scores and the preferences for each stakeholder group. This analysis shows that the two FT technology pathways are still the two most preferred pathways, regardless of which stakeholder group is considered. This is due to the fact that both these technology pathways score well on seven out of the nine considered criteria. On the other hand, for the ranking in preference of the other four SAF technologies, shifts in preference can be observed. These shifts are mainly caused by the large difference in weights for the sub-criteria 'GHG saving emissions' and 'production volume availability and scalability' per stakeholder group.

Furthermore, this study contributes to the existing literature regarding SAF technologies multi-criteria studies as this study establishes a long list of 64 potential criteria which can be used to score the performance of a SAF technology pathway. This study also contributes to the same field of literature by facilitating a framework which systematically assesses the upscale potential and feasibility of different SAF technology pathways by considering both expert knowledge and literature. This framework can be used in future studies to establish performance scores of other or a broader selection of SAF technology pathways and enables making comparisons between SAF technology pathways. Next to this, it also contributes to identifying multiple stakeholder groups within the SAF industry and investigates different visions and preferences within these groups. Finally, this study contributes to the empirical application of the novel Bayesian BWM in the SAF industry. It can be concluded that the novel Bayesian Best-Worst Method is indeed a well developed and accurate method to arrive at the relative importance of criteria as the findings of this study are in line with finding of prior performed research regarding the assessment of SAF technologies on multiple criteria.

Future research could focus on where possible efficiency gains can be made with respect to the considered criteria for the different pathways as the score cards of the pathways can improve over time. As the performance of both power-to-liquid pathways are highly dependent on the price and availability of renewable energy and hydrogen, future research could perform a scenario analysis in which different future scenarios are sketched regarding this availability and price of renewable energy and hydrogen. In this way, insights can be gained in the performance of both power-to-liquid pathways and could evaluate which of the possible power-to-liquid pathways would have the highest chance of becoming implemented in practice under these sketched scenarios. Future studies could also try to focus on how to overcome the low production availability and scalability of the HEFA pathway that uses used cooking oil as feedstock type as this is the major pitfall of this pathway. As a final recommendation for future research, a future MCDM study could imply the social performance of a SAF in its analysis as in the future SAF may become more prominent and well known to a wider public. This future study could also imply a criterion which reflects the energy efficiency of a SAF pathways in its analysis as some of the interviewed experts argued for implying this criterion.
As this research shows the preferences and perspectives of the stakeholder groups and shows that the airline industry differs compared to other stakeholder groups, a possible recommendation for the SAF industry could be to focus on finding consensus between these stakeholder groups by establishing a long-term, strategic policy frame that provides certainty for all these stakeholder groups.

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Abbreviations

Table 1: List of abbreviations

Abbreviation	Meaning
AHP	Analytic hierarchy process
AJF	Alternative jet fuel
ANP	Analytic network process
ASTM	American Society for Testing Materials
AtJ	Alcohol-to-jet
BWM	Best-Worst Method
CHJ	Catalytic hydrothermolysis jet fuel
CL	Confidence level
CST	Clean Skies for Tomorrow
DAC	Direct air capture
EU	European Union
FAU	Feedstock alternative use
FP	Feedstock profitability
FR	Forestry residue
FT	Fischer-Tropsch
GHG	Greenhouse gas
HEFA	Hydroprocessed esters and fatty acids
HH	Hydroprocessed hydrocarbons
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
ILUC	Indirect land use change
LCA	Life Cycle Assessment
LU	Land usage
MCA	Multi-criteria analysis
MCDM	Multi-criteria decision making
MSP	Minimum selling price
MSW	Municipal solid waste
PCC	Plant capital costs
PSC	Point source captured
PtL	Power-to-liquid
PVA&S	Production volume availability & scalability
RES	Renewable energy supply
SAF	Sustainable aviation fuel
SIP	Synthesised isoparaffins
TRL	Technology readiness level
UCO	Used cooking oil
WU	Water usage

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1 Introduction

1.1 Background

The aviation industry is growing worldwide as well as in the European Union (EU). Expectations by the International Air Transport Association (IATA) are that global passenger numbers of the aviation industry will double by 2035 when compared to 2016 (O'Connell et al., 2019) and Airbus and Boeing expect an annual growth of approximately 4.5 - 4.8 % in the coming decades (Deane & Pye, 2018). This results in a substantial growth of the aviation's contribution to global fossil fuel emissions to 4.6 - 20.2 % by mid century (Staples et al., 2018). Although this industry is a relatively small contributor to annual CO_2 emissions with roughly 2.6% (ICAO, 2016), these emissions are significantly worse than other emission sources regarding environmental impact as they are released at a higher altitude (Kivits et al., 2010). As reaction to this expectations, the International Civil Aviation Organization (ICAO) adopted a carbon-neutral growth goal for international aviation starting in 2020 and the IATA pledges a 50% carbon emission reduction from 2005 levels by 2050 (Wise et al., 2017).
With current technology, there are multiple ways for the aviation industry to decrease these emissions. Direct decreasements can be made with engine technology improvements (Graham et al., 2014; Cansino & Román, 2017; Schäfer et al., 2016), operational improvements (Linke et al., 2017; Niklaß et al., 2019) and the use of sustainable aviation fuels (hereinafter referred to as SAF or SAFs) (Klein et al., 2018; Michailos, 2018; O'Connell et al., 2019), while indirect decreasements can be made with carbon offsets. However, the U.S. sustainable aviation roadmap showed that even with vast improvements in energy efficiency and operations, SAFs are deemed necessary to accomplish both goals set by ICAO and IATA (Federal Aviation Administration, 2015). In addition to this, multiple studies showed that in order to keep the annual aviation emissions below or at the 2020 level, this is only possible with combinations of technical, operational, and policy measures, together with a large-scale use of alternative jet fuel (Federal Aviation Administration, 2015; Staples et al., 2018). Research by L. Zhang et al. (2020) showed that SAF are the most promising option that can pace up with the aviation industry's growth and with the Paris Agreement's 2-degree C goal. With an absence of SAF, the mitigation potential of aviation CO_2 emissions seems limited and will be at the expense of less growth in demand for the industry (Wise et al., 2017). Also, research by Energy Transition Coalition (2020) states that SAF will play a crucial role in the decarbonisation of the aviation industry, as it is the main driver of reductions of carbon emissions in the industry in the future. For these reasons, switching to low carbon aviation fuels or SAFs is the main opportunity for the industry.

1.2 Research problem

In this section, earlier performed research on different aspects of SAF are reviewed. By conducting performed research, three knowledge gaps are identified. With the help of these knowledge gaps, the main research question is synthesised and multiple sub-research questions are provided.

1.2.1 Prior research

Performed economic research
Ample research has been performed regarding the economic characteristics of different aviation fuels. The aim of these researches was mainly to identify the minimum selling price (MSP) of SAF technology pathways. SAF technologies with corresponding possible feedstock types are called technology pathways. Research by Beal et al. (2021) investigated nine different SAF technology pathways and determined their production costs. This research showed that all SAF technology pathways have higher production costs than fossil jet fuels. Research by Diederichs et al. (2016) investigated the MSP of SAF and concluded that the MSP to be 2-4 times higher that fossil-derived jet fuels. Research by De Jong et al. (2015) concluded that the all of the SAF pathways approved by the American Society for Testing Materials (ASTM) are not able to reach price parity with fossil-derived jet fuels in near future. Other performed research by Martinez-Valencia et al. (2021) focused on possible pathways for the uptake of SAF by including environmental and social benefits. This research states that fossil fuels have a considerably lower price, partly due to a mature technology, economies of scale, raw material costs, established supply chains and yields but this selling price of fossil jet fuels doesn't include externalities of the negative impacts. This research states that quantifying consequences and avoided costs associated with environmental and social externalities is a strategy to address this market failure but also mentions that it is challenging to include these externalities as a revenue stream and needs additional, to be developed, methodologies. Scheelhaase et al. (2019) concluded that fuel suppliers and airlines are unlikely to blend fossil fuels with SAF, unless SAFs are available a at similar or even lower price than conventional fossil fuels. This study by Scheelhaase et al. (2019) argued that as fuel costs are one of the major cost items for airlines and account for 20 to 30% of

the total airline input costs (Holladay et al., 2020), the fuel costs are considered the main barrier for the uptake of SAF. Also other studies argue that, despite the continuous costs and efficiency improvements accomplished in the production process of SAF, the costs of SAF are currently seen as the foremost barrier for the uptake of these fuels (Martinez-Valencia et al., 2021; Smith et al., 2017; Wei et al., 2019). A proposal to accelerate the development of SAF in Europe written by Energy Transition Coalition (2020) states that the key barrier can be found in the price gap between SAF and fossil jet fuels. It states that the aviation industry faces a "chicken and egg" situation in which the price of SAF will decrease if the production scales up, but fuel providers are lacking demand signals to increase the production because of the high price of SAF. If there are no financial incentives for users and fuels suppliers of SAF, chances to adopt to SAF are deemed limited and therefore diminish the uptake (Energy Transition Coalition, 2020). This can be seen in practice as SAF production currently accounts for approximately 0.05% of total jet fuel consumption in Europe (World Economic Forum, 2021), of which only 0.015 billion litres of the 343 billion litres consumed annually is derived from renewable sources (Shahabuddin et al., 2020).

Research on political side of SAF

As mentioned earlier on, policy measures, together with technological, operational and large-scale usage improvements are required to keep the annual CO_2 emissions below the 2020 level (Federal Aviation Administration, 2015; Staples et al., 2018). Various research focused on the policy aspects of SAF. A Swedish case study by Kulanovic & Nordensvärd (2021) analysed the political discourse about governmental interventions on the future of sustainable aviation and showed the difficulties to invest in the future of sustainable aviation. This mainly because of the discursive path dependency in SAF and therefore is situated in a lock-in position. "Technological and institutional co-evolution driven by path-dependent economies of scale" are processes that characterise this lock-in position (Unruh, 2000). Besides, this study argues that there are little support structures for SAF and the conventional fuel, kerosene, is tax-free. It is therefore argued that there is little room for introduction of alternatives. Scheelhaase et al. (2019) showed that the lack of strategies towards the uptake of SAF is also seen as an important barrier and this research couldn't identify any regulations with the aim of stimulating the uptake of SAF. This importance of policy regulations is emphasized by the earlier mentioned study by Martinez-Valencia et al. (2021) as this research underlined the role of governmental regulations and policies in the uptake of SAF as they are often necessary to stimulate the growth of products with societal and environmental benefits.

Required action on the uptake of SAF and synthetic SAF

Despite this existing cost barrier and the low production levels, the European Commission recently took the lead on climate action in aviation by the ReFuelAviation initiative as a part for 'Fit for 55'. This initiative proposes a blending mandate for SAF and includes a 2% blending mandate of SAF on fuel suppliers by 2025, rising to 5% in 2030, steeply increasing to 32% by 2040 and arrives at 63% by 2050. In addition to this, a specific sub-mandate is applied for synthetic SAF as the European Commission argues that synthetic fuels (also known as e-fuels) have the largest decarbonisation potential of all aviation fuels available at the moment (European Commission, 2021a). This mandate starts at 0.7% by 2030, increases to 8% by 2040 and further rises to 28% by 2050.

Since the current SAF production in both synthetic form as well as in non-synthetic form are currently far away from these goals, a vast uptake of SAF is required. Questions about the feasibility of this uptake of SAF to comply with this initiative and according mandates have originated as the mandate for SAF production translates to a required 3.5 million tonnes of SAF by 2030 when compared to 0.1 million tonnes of global SAF production in 2020. According to SkyNRG (2021), the required volumes by 2030 seem to be achievable, however, there will be a big reliance on waste oils. According to this same study, the requirements can be met by the current SAF production platforms and yet-to-be-announced SAF production platforms but will also require switches from diesel production or SAF imports from outside to EU. The research by SkyNRG (2021) states that without these structural imports of SAF or intermediate products and shifts, the targeted volumes are unlikely to be met. On the longer terms, the period after 2030, an even stronger increase of SAF is proposed by this mandate. Especially in the period between 2030 and 2040, rapid year-on-year growth of SAF production capacity is needed to comply with this mandate.

Regarding the sub-mandate for SAF produced via a synthetic pathway starting at 2030, rapid deployments of operational synthetic SAF plants are needed as currently only small-scale plants are producing synthetic SAF and no commercial plants are built yet (SkyNRG, 2021; Energy Transition Coalition, 2020). The absence of these commercial powerplants is explained by the expected high costs for large scale production and currently faces technology readiness challenges, especially when the production of SAF is established with the use of Direct Air Capture (DAC) (Energy Transition Coalition, 2020; European Commission, 2021a).

So, even though SAF and synthetic SAF are not financially competitive when compared to conventional jet fuels and are hardly produced on commercial scale, a vast uptake of both technologies in terms of production is needed. It is therefore that the Energy Transition Commission states that is is crucial that a long-term, strategic policy frame needs to be established that provides greater certainty for both investors as well as producers in the SAF value chain in order to drive production volumes up and decrease the price (Energy Transition Coalition, 2020).

1.2.2 Identification of knowledge gaps

While reflecting on the conducted performed research, three conclusions can be drawn.

Too much focus on cost competitiveness
As argued in the latter section, the SAF sector currently faces a chicken and egg situation. Here, financial incentives are a major aspect that can influence the uptake of SAF. SAF prices will decrease if the production goes up (due to economies of scale and learning curves), but fuel providers don't have any financial inventive to increase its production. The other way around; demand is low because of the high SAF prices (Energy Transition Coalition, 2020). This imposes a lock-in position in which it is unlikely to arrive at a SAF uptake.
This lock-in situation is also expressed by Kulanovic & Nordensvärd (2021) and this research also states that this lock-in leaves little room for the introduction of alternatives. However, despite this lock-in position, the scale up of SAF and synthetic SAF is necessary. In order to stimulate this scale up, the joint policy proposal to accelerate the development of SAF in Europe clearly argues that a combination of short-term technology improvements and financial support is needed to support initial scale up (Energy Transition Coalition, 2020). It is argued that these financial supports can progressively be phased out as different SAF technologies will reach a cost-competitive position. Regarding this cost-competitiveness, ample research focused on this, considering multiple SAF pathways and other economic characteristics.
Various research is performed on the identification of the barriers and cost competitiveness was a major aspect in all of these researches, which resulted in little attention towards other criteria that are important for the development of a technology. What's more, by focusing on costs competitiveness and trying to solve this barrier, other related criteria are ignored and this can eventually create other barriers (Clapp & Dauvergne, 2011). So, by focusing too much on this cost competitiveness, this lock-in position will not be overcome and other criteria that might form barriers aren't considered while these need to be overcome as well to scale up SAF.

Qualitative research and relative importance of criteria
Little performed research is qualitative of kind and limited attention is paid towards qualitative stakeholder consultation. Most of the economic performed research followed a quantitative approach. This finding is also backed by research of S. Ahmad & Xu (2021) who stated that limited attention has been given to stakeholder-based qualitative approaches. As these actors are the ones who influence on which SAF pathway technology will be invested or which technologies will be promoted, it is of importance to map their expert opinions and expectations. Consequently, it is of importance to identify the most promising SAF technology pathways that are promising according to all the different stakeholders rather than the SAF technology pathway with the best financial aspects or the SAF technology with the most promising reduction in carbon emissions. Therefore, a framework is required which systematically considered the often-divergent perspectives of the different stakeholders.

Selection of SAF technologies in MCDM studies
As will be discussed later in section 4, there are several studies identified that use qualitative methods. However, this section also discusses the fact that none of these studies considered synthetic fuels in their analysis while some of these studies suggest that future research should incorporate these synthetic fuel pathways in their analysis. As synthetic have the biggest potential for the uptake of SAF (European Commission, 2021a) and no qualitative study on these synthetic fuels can be found, this represents a knowledge gap.

So to conclude, (1) much research focused on the financial analysis of SAF technologies which resulted in little attention towards other aspects that are important for a technology to develop. Secondly, (2) little research is qualitative of its kind and limited attention is paid towards qualitative stakeholder consultation and therefore, there's no in-depth understanding of the contrasting advantages of different SAF technology pathways. Finally, (3) there are no multi-criteria analysis (MCA) that considered synthetic fuel technology pathways in their analysis while they have the biggest potential for the uptake of SAF on long term, according to the European Commission and a specific sub-mandate is proposed for this SAF technology (European Commission, 2021a).

As synthetic fuels are deemed important for the SAF industry to develop, more research needs to be performed on the relative performance of different SAF technologies, both synthetic as well as non-synthetic. This relative performance will be scored on different criteria that are important for the performance and scale up possibilities of these different technologies for EU countries to comply with this proposed SAF blending mandate by 2030. When non-synthetic technologies are studied as well, comparisons can be easily made between the two of them and the contrast in advantages and drawbacks between the different SAF technology pathways can be discovered. Apart from that, when the perceived importance of all criteria that are identified will be mapped, insights can be gained on what criteria are considered most important by different stakeholder groups. The different technology pathways, both non-synthetic as well as synthetic, of SAF can then be scored on these identified criteria and their importance. This reflects the differences between the different technology pathways and these insights can be used to determine on which criteria future developments should focus and which criteria might form barriers. Future policy frameworks can meet these differences and support the development of SAF types which score best on the different criteria and weighted trade-offs between different SAF types and their criteria can be made. Furthermore, these insights can help on pointing out possible areas that diminish the scale up of different SAF technologies.

1.2.3 Main research question

It is stated that the aviation industry grows substantially and large-scale usage of SAF is deemed necessary to allow this growth while realising the sustainability goals set by the IATA and the ICAO. In addition to that, and even more important, the European Commission recently proposed the ReFuelAviation Initiative which mandates the uptake of SAF and synthetic SAF. The literature study performed in this research showed that prior performed research tends to focus too much on financial barriers. Focusing on just one criterion can ignore other related problems, in turn create other problems and doesn't help in overcoming the lock-in position in which SAF is situated. Next to this, limited attention is paid towards qualitative stakeholder consultation. Besides, little research has been performed on the relative prominence of the identified criteria and no studies were found that considered synthetic fuel in their analysis while this technology seems to have the biggest potential for the uptake of SAF and a specific sub-mandate is proposed for this SAF technology.

By mapping the relative importance of the criteria and including a selection of promising SAF technology pathways, future developments could focus on the criteria and tackling the barriers that are deemed most important by the different stakeholders to produce SAF, both synthetic as well as non-synthetic, in order to stimulate required large scale production. Therefore, the goal of this research is to give an insight-full answer to the following main research question:

What are stakeholders' preferences regarding different SAF technology pathways, in order to stimulate the SAF upscale for 2030 and comply with the proposed SAF blending mandate by the European Commission?

1.2.4 sub-research questions

To help answering the main research question different sub-research questions are constructed and listed below. These contribute from different angles to help answering the main research question.

1. *What specific technologies to produce SAF are feasible and have scale up potential?*
2. *What criteria are deemed relevant for the uptake of different SAF technology pathways?*
3. *What are the perceived relative weights of these criteria and their corresponding sub-criteria?*
4. *Given these criteria and their obtained optimum weights, how do the different SAF technology pathways score and compare in terms of performance and preference?*

In contrast to previous studies, this study therefore delivers contributions towards the uptake of SAF by (1) mapping different promising SAF technologies and technology pathways, (2) providing their relevant criteria for performance and scale up potential, (3) mapping the relative importance of these identified criteria and (4) quantifying their total performance by quantifying their performance on these criteria. This study therefore develops a framework which can systematically consider the perspectives of different stakeholders in the aviation industry and can be used in future research to imply more stakeholders or a different set of criteria. Besides, next to the theoretical contributions, this study provides practical contribution by proving empirical evidence on how different actors perceive the uptake of synthetic and non-synthetic SAF, what criteria they consider important and their relative importance.

1.3 Situation related to grand challenges

There are many grand challenges that we, as people of the same planet, face. The one that is – in my opinion – the most pressing and demanding is that of climate change. Our aviation habits greatly contribute towards this, which increases the relevance of this study. To dive deeper into the preferences, barriers and perspectives of stakeholders in the aviation industry, this study will perform multiple stakeholder consultations to take the socio-economic and political environment in which SAF technologies are embedded into account. Gaining insights that help contributing the uptake of SAF for the transition towards sustainable aviation contributes to the grand challenge of sustainable transport. In doing so, this study will attempt to be able to contribute to increasing the share of renewable energy in the global energy mix as stated in the UN Sustainable Development Goal 7 with the knowledge that can be derived from it.

1.4 Outline

The research approach is explained in chapter 2. This chapter discusses how the main-and sub-research questions will be answered by discussing the methods used for this. After which, in chapter 3, 4, 5 and 6 respectively sub-research question 1, sub-research question 2, sub-research question 3 and sub-research question 4 will be discussed. Subsequently, a discussion of the findings is provided in chapter 7, together with the conclusion, limitations and recommendations for future research and the SAF industry.

2 Research approach

This chapter will discuss how the main- and sub-research questions will be answered by discussing the methods that will be used for this. The answers to the sub-research questions lead to partial knowledge which are required to answer the main-research question. The sub-research questions are split up in a logical way and represent different parts of the study. This is visualized in the research flow diagram which is presented in the first section of this chapter.

2.1 Research Flow Diagram

As this research consists of multiple steps regarding different sub-research questions, a clear overview of this research is provided which visualizes all the research phases (figure 1). It shows the corresponding research question(s) which is/are covered per phase, the method used and tools in this phase and the input and output per phase. The following sections will provide brief elaborations on how each sub-research question is answered and what methods will be used for answering these.

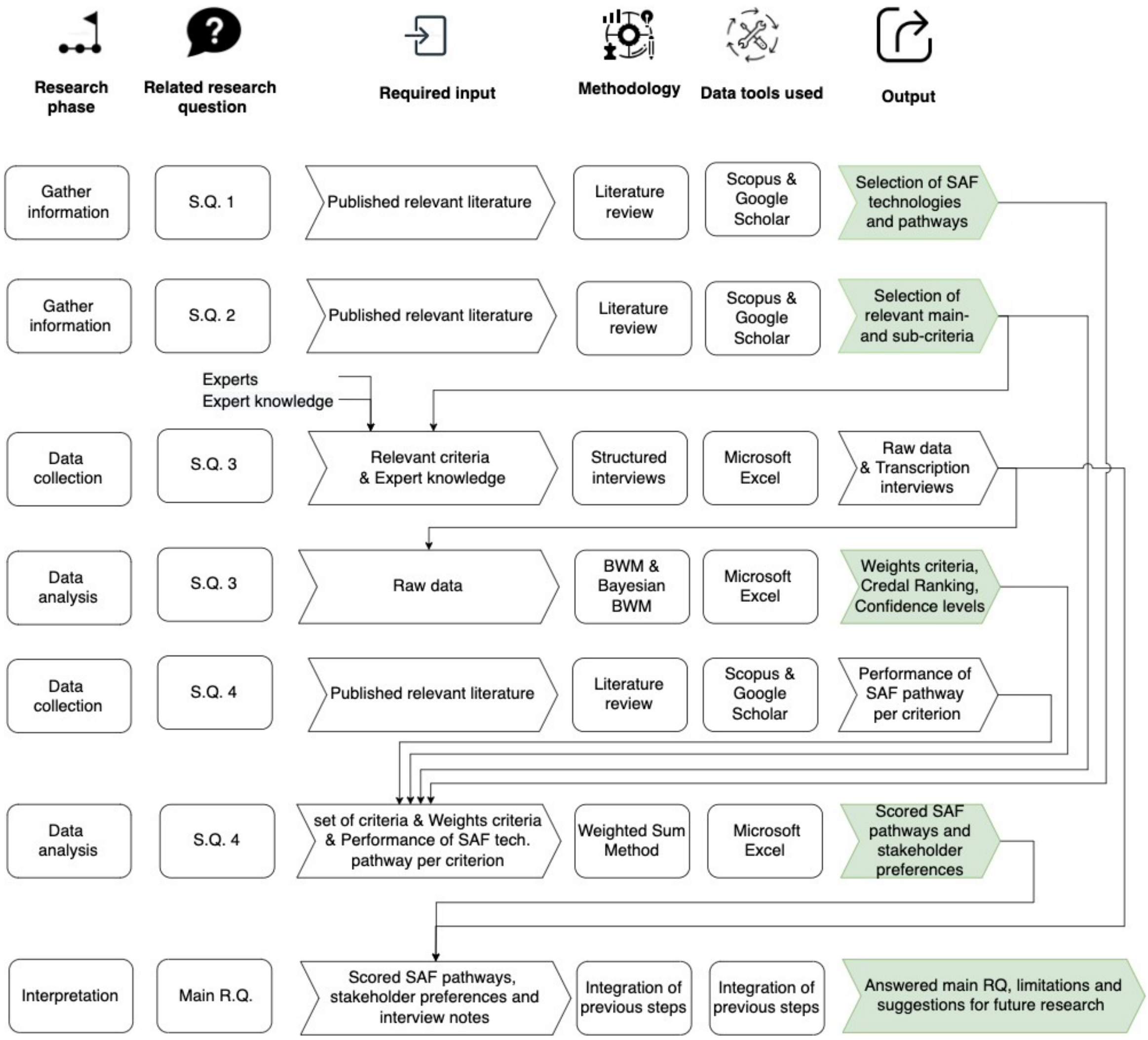


Figure 1: Research Flow Diagram

2.2 Research approach: Exploratory approach

The goal of the main research question is gaining insights in multiple aspects that are important for different SAF technologies in order to stimulate the uptake in production of synthetic and non-synthetic SAF technologies. This research will not be able to provide specific policies or regulations to overcome the identified barriers but can provide valuable insights for better understanding of the area, which makes it feasible for an exploratory research method. This method is suitable for determining the nature of the problem rather than providing conclusive evidence (Dudovskiy, 2018). As little qualitative research is performed on the relative importance of criteria relevant for the performance of SAF technologies and no research included synthetic SAF in their analysis, this research implies tackling a new problem on which no research has been performed. Exploratory research is well suited for these situations (Brown & Brown, 2006). This exploratory research approach will form an effective groundwork for future studies to implement policy regulations/solutions.
The research questions will be answered with the help of different research method deemed well suited for these questions. Each sub-question and the methodologies used for answering these questions are discussed in the following section. More detailed descriptions of how these methods are applied in practise are given in the sections in which the method(s) is/are used.

2.2.1 Sub-research question 1: Literature study on which specific synthetic and non-synthetic SAF technology pathways to consider

Currently, the ASTM approved seven different technologies to produce SAF (IATA, n.d.). Aside from these ASTM approved SAF types, there are other technologies that currently aren't approved by the ASTM but are expected to play important roles in the next decade Energy Transition Coalition (2020). These approved and non-approved technologies feasible differ in many aspects as they entail different levels of greenhouse gas (GHG) emissions, have different sustainability risks and a number of different feedstock types can be used through different pathways. For example, the carbon used in the synthetic fuel technology can be sourced from three different options: as industrial waste gas, from sustainable biomass or from direct air capture (DAC) (World Economic Forum, 2020). For practical reasons, it is not feasible to consider all different kinds of feedstock types for all different technology pathways. Therefore, the first step that needs to be taken is to do more research about which specific technologies and feedstock sources have the most potential to develop. Only this selection will be considered in this research. Therefore, this sub-question will be answered by performing literature research. For a more elaborate description on how this literature research is performed, the reader is referred to chapter 3.

2.2.2 Sub-research question 2: Literature study for selecting relevant criteria

The second sub-research question will consist of multiple steps.
At first, a more in-depth literature study will need to be performed to get a complete view of all the possible criteria that are mentioned in literature which are deemed relevant for the evaluation of different SAF technologies. This literature research will discuss earlier performed research regarding assessments of possible alternative jet fuels (AJF)/sustainable aviation fuels. A complete list of possibly relevant criteria will be made from this performed research (hereinafter referred to as longlist). Scopus and Google Scholar will be used for this more in-depth literature study and are considered reliable data sources suitable for this research.
After the establishment of the longlist, the list is made more concise by only considering criteria that have a substantial amount of importance. This needs to be done as some criteria are irrelevant for the scope of this study and the complexity of the Best-Worst methodology, which is explained in the following sub research questions, increases significantly if many factors are taken into account (Rezaei, 2015). Moreover, the required time for interviewing experts will increase significantly when a lot of criteria will be taken into account. As a result, the corresponding willingness for the experts to participate in the interview will decrease as well as the feasibility to provide adequate information. So for these reasons, the constructed longlist will be reduced to a short list which will only take into account a relevant selection of (aggregated) criteria which will be used in this study. A more detailed description on how and why this needs to be done and how this selection is done can be found in section 4.3.

2.2.3 Sub-research question 3: Best-Worst Method (BWM)

As already indicated, the SAF uptake is at the early beginning of the required uptake. Multiple SAF pathway technologies are feasible, but it is still unclear which technologies are preferred by which stakeholders in the aviation industry. As these actors are the ones who influence on which technologies will be invested or which

technologies will be promoted; it is interesting to find out what criteria they value most and least when it comes to the development of these SAF pathway technologies. This being said, this research is approached from multiple stakeholders' perspectives in the actor field.
Deriving the relative importance of the identified criteria is something which is hard to quantify. Therefore, in order to gather the weights of each criterion and thus answer this sub-research question, the Best-Worst Method (BWM) is used. The BWM is a multi-criteria decision-making (MCDM) method which can be used to find the importance of variables that are not easily quantified (Rezaei, 2015). How this BWM is used explicitly in this study can be found in section 5.1. Furthermore, it is a relatively novel method, developed in 2015 by Jafar Rezaei, and has already been used in various fields of study. It uses pairwise comparisons to find the weights of the selected criteria and requires 2n-3 comparisons (Rezaei, 2015). It is an innovative methodology in which the number of pairwise comparisons are less when compared to other MCDM methods like Analytic Hierarchy Process (AHP) and has been successfully used in studies to measure the relative importance of criteria (Rezaei, 2015; Udoh, 2019; W. Ahmad, 2016; Kalpoe, 2020; Janssen, 2019). In literature, various other MCDM methods can be found, of which Analytic Hierarchy Process (AHP) and the Analytic Network Process (ANP) are two very common methods. These methods are used to infer the weights of criteria based on the preference of the decision makers (Saaty, 2004). The AHP also uses pairwise comparisons and uses the same scale but in AHP each alternative is compared and rated towards all other alternatives, which requires n(n-1)/2 comparisons (Saaty, 2004). This increases the number of comparisons to be made when compared to the BWM in which only the comparisons of alternatives with respect to the worst and the best alternative need to be made (Gupta et al., 2017). So the BWM has benefits over AHP in terms of less comparisons. Furthermore, the BWM makes the comparisons in a structured way, which makes it easier to judge and to understand, and more importantly leads to more consistent comparison, hence more reliable values for ranking (Rezaei, 2015, 2016). Because the BWM method requires less comparisons of the criteria, this methodology has the benefit of being time efficient for the decision makers as well as the researcher.
MCDM methods are also criticized. The most featured criticism on this method is its subjectivity or biased value judgements of decision-makers, which could affect the outcome of the analysis (Choo et al., 1999; Annema et al., 2015). To mitigate this potential pitfall, the consulted stakeholders in this research are asked to sign the declaration of competing interest, in which they state that they have no competing financial interests, personal relationships or personal motives that could have appeared to influence the results of the work reported in this research. Finally, the consistency of stakeholders is checked and only respondents with acceptable consistency rates are considered in this study, as can be seen in section 5.3. Others are excluded from the analysis.

The BWM consists of the following six steps:

- **step 1**: Determine a set of criteria c1, c2, c3, ... cn (see figure 2)
  In this step the longlist of criteria is discussed and the decision is made which criteria seem most important. Only a selection of relevant criteria is considered.

Figure 2: BWM step 1: Determining a set of criteria

- **step 2**: Determine the "best" and the "worst" criteria (see figure 3)
  The "best" criterion is in this case the most important criterion and the "worst" criterion is the least important criterion. This is done to account for pairwise comparison and serve as a reference point for this. In each structured interview this is done by asking the expert which criterion he/she thinks is considered most important and least important.

Figure 3: BWM step 2: Determining the "best" and the "worst" criteria

- **step 3**: Determine the preference of the best criterion over all other criteria, using a number between 1 and X (see figure 4)
  The preference of the best criterion versus all other criteria is set up in this step. 1 Here means that i

is equally important to j, X means that i is extremely more important than j. With this, measurements are made to what extent the most important criterion is more important than other criteria and result is a Best-to-Others vector: AB = (aB1, aB2, ...aBn) where aBj is the preference of best criterion B to criterion j. This step is also done by the experts during the performed interviews. For this research, the Likert scale with a corresponding numerical scale from 1 to 9 is used to show preference, which is suitable for the BMW method according to Rezaei (2015).

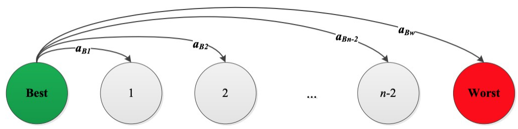


Figure 4: BWM step 3: Determining best over others

- **step 4**: Determine the preference of the criterion j over the "worst" criterion (see figure 5)
  Same steps taken as in step 3. This results in the Others-to-Worst vector: A_W = (a1W, a2W,...anW) where a_{jW} indicates the preference of criterion j over the worst criterion. Again, this step is done by the experts during the structured interviews.

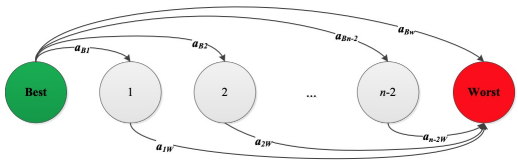


Figure 5: BWM step 4: Determining others over worst

- **step 5**: Establishing the optimal weights of the criteria
  In this step the aim is to determine the optimal weights for each criterion. Since the analysis of multiple experts needs to be taken into account here, this research uses a group decision-making approach of the BWM to calculate the optimal weight for each criterion. To get to these group decision-making weights, the Bayesian BWM is used. The Bayesian BWM is almost the same as the initial BWM. The primary input data (step 1 to step 4) are the same as the initial BWM, but the data and output are modelled as a probabilistic distribution, instead of multinominal distribution. To see the sub-steps of this Bayesian BWM, the reader is referred to the work of Mohammadi & Rezaei (2020).

2.2.4 Advantages of the Bayesian BWM over the original BWM

The Bayesian BWM doesn't only arrive at the optimal weights of the criteria but also elaborates on credal ranking between each pair of criteria and computes the confidence level (CL). This confidence level indicates the group its perceived importance of one criterion over another and touches upon the confidence/certainty that a criterion is more important than another criterion (Mohammadi & Rezaei, 2020). More than that, because the Bayesian BWM uses the combined distribution of each-and-every expert his/her preferences, it arrives at more reliable criteria weights when compared to the initial BWM (Mohammadi & Rezaei, 2020).

2.2.5 Sub-research question 4: Completion of Best-Worst Method

The weights of the criteria which are determined in the previous sub-research question, sub-research question 3, are needed for the completion of the Multi Criteria Analysis (MCA); scoring the different SAF technology pathways on these weights and arriving at the preference of these SAF technology pathways. This will be done by establishing performance scores which shows the performance of each SAF technology pathways on each sub-criterion. This data is not collected via interviews as this requires substantial in-depth knowledge about these pathways from the experts. Therefore, the decision is made to establish most of these performance scores via literature as this is a conventional way to do so if experts need to have substantial in-depth knowledge. This method, obtaining the scorecards through extensive literary research, has been successfully performed in prior Multi Criteria Decision-Making (MCDM) studies (Brispat, 2017; Ellens, 2018). If literature regarding the performance of the considered pathways seems absent, the decision will be made to base the performance scores on experts' knowledge. This is also a convenient way of deriving at the performance scores and is used in prior performed MCA studies which used the BWM (Kalpoe, 2020; Janssen, 2019). This performance matrix is qualitative and uses scores between one and ten. A score of one means an extremely poor performance of a SAF technology pathway on this criterion while ten stands for extremely good performance of a SAF technology on this criterion. A more detailed description of how this literature study is performed can be found in section 6.1. After these weights are gathered and the scoring is done, the performance of each technology is derived by applying the weighted sum method (WSM). The weighted sum method is a common form of performing a multi criteria analysis and forms the final score of each technology. The formulate used for the WSM is as follows:

$$P_i = \sum_{j=1} w_j a_{ij}.$$

In this way, (1) the relative performance of criteria can be quantified, (2) the preference of SAF technology pathways can be determined and (3) comparisons can be made between the different technology pathways. As the BWM will not only be used to gather the group decision-making weights for all the stakeholder groups combined but will also be used to gather the group decision-making weights per stakeholder group in the SAF industry, (4) comparisons can also be made between the preferences of each stakeholder group.

3 Selection of promising SAF technology pathways

As "SAF" refers to any kind of feedstock with any kind of technology, specifications need to be made on what "SAF" technologies exist, what their potential is and their characteristics, like the feedstock type their require, need to be given. These technologies with corresponding possible feedstock types are called technology pathways. This chapter will therefore elaborate of different SAF technologies and technology pathways and is dedicated to justify the selection of different SAF technologies and feedstock types in this research. The remainder of this chapter will be as follows: the first section, section 3.1, will briefly touch upon the requirements for a SAF to become certified and briefly discusses other, noncertified SAF technology pathways, that will be considered in this study. The second section, section 3.2, will address these considered SAF technology pathways more elaborately by briefly addressing their technology readiness level (TRL), advantages, expectations for future developments and their limitations. Based on these descriptions, choices are made in section 3.3 on which technologies to further consider in this study. The last section of this chapter, section 3.3.1 will address the potential feedstock types per SAF technology pathway and selections are made on which specific SAF technology pathways to include in the further analysis of this research.

3.1 Technical certification of SAF

In order for a potential SAF to become certified, the SAF must meet the same qualities and characteristics as conventional jet fuel, as the industry is focused on producing SAF in the form of so called "drop-in" fuels that replace conventional jet fuel kerosene. These "drop-in" fuels must be entirely fungible with the existing conventional kerosene. The decision to focus on drop-in fuels is made as otherwise, the aviation industry would have to undergo a major transition in the whole supply chain and the engines of aircrafts itself (IATA, n.d.). So in order for a potential SAF to become a certified SAF, these drop-in characteristics need to be ensured. As an aircraft flies around the world and must have the opportunity to be fueled in countries abroad, these specifications are internationally applied. Globally, the most widely used standard for this is rewarded by the American Society for Testing Materials (ASTM). This organisation sets requirements in terms of composition, volatility, fluidity, combustion, corrosion, thermal stability, contaminants and additives, to ensure that the certified fuel is compatible when fueled by an airplane (IATA, n.d.). Any other SAF type that is not certified according to this drop in characteristics would present possible safety issues and would require different a different infrastructure, which results in unnecessary risks and costs.

Currently, the ASTM has certified seven different technology pathways that are capable of the production of this drop-in SAF (see table 2). These technologies (in chronological approved order) are Fischer-Tropsch (FT-SPK), Hydroprocessed Esters and Fatty Acids (HEFA), Synthetic Iso-Paraffins (SIP), Fischer-Tropsch containing aromatics (FT-SKA), alcohol-to-jet (ATJ), alcohol-to-jet with added ethanol and the recently approved Catalytic Hydrothermolysis Jet fuel (CHJ) and Hydroprocessed Hydrocarbons (HH-SPK or HC-HEFA).

This report however will not discuss all ASTM approved technologies. Catalytic Hydrothermolysis Jet fuel (CHJ), a variant of lipid conversion, transforms fatty acids into jet fuel and has blending limit of 50% and is approved in 2020 but specific feedstock availability is still unclear (World Economic Forum, 2020). Also, the hydrocarbon HEFA (HC-HEFA), which has been developed for micro-algae-based jet fuel, will not be discussed as the maximum approved blending limit is 10% and the algae's commercial potential and scale-up potential is uncertain (World Economic Forum, 2020). This low maximum blending limit of 10% is also the reason for Synthesised isoparaffins (SIP) to be left out of further analysis.

Besides the ASTM approved SAF technology pathways, other technologies will be discussed in this study because of their deemed prominence and/or recent developments. Synthetic fuels are not ASTM approved yet, but due to the expected prominence of this technology and the proposed mandate by the European Commission, this technology will be discussed (European Commission, 2021a). Also, as battery and hydrogen technologies are becoming more advanced technologies, the decision is made to further elaborate on these technologies and discuss their potential. The pyrolysis technology will be discussed as this technology could become a comparable cheap alternative due to inexpensive agricultural residues, forestry residues and municipal solid waste.

Table 2: ASTM-approved SAF technology pathways

Technology	Year of approval	Blending limit	Possible feedstock
FT & FT-SKA	2009 & 2015	50%	Wastes (e.g. municipal solid waste), coal, gas, sawdust
HEFA	2011	50%	Vegetable oils (palm, camelina, jatropha, used cooking oil)
SIP	2014	10%	Sugarcane, sugarbeet
AtJ Isobutanol & AtJ ethanol	2016 & 2018	50%	Sugarcane, sugarbeet, sawdust, lignocellulosic waste
CHJ	2020	50%	Waste oils or energy oils
HH-SPK or HC-HEFA	2020	10%	Oils produced from algae

3.2 Considered technologies

Following up on the previous section, this section will discuss the considered technology pathways more elaborately by addressing their technology readiness level, current market deployment, advantages, expectations and limitations. To provide a clear overview, the following section of SAF technologies will be considered in this study:

- **(3.2.1) Fischer-Tropsch synthesis**
- **(3.2.2) Pyrolysis**
- **(3.2.3) Hydrogen and direct electrification**
- **(3.2.4) Hydroprocessed esters and fatty acids (HEFA)**
- **(3.2.5) Alcohol to Jet**
- **(3.2.6)Synthesised Isoparaffins**
- **(3.2.7) Synthetic SAF**

3.2.1 Fischer-Tropsch synthesis

This thermochemical process consists of multiple steps in which input sources can be used in order to produce sustainable aviation fuels. Possible suitable sustainable feedstock types are lignocellulosic biomass, wood waste, agricultural waste and municipal solid waste (MSW) (ETIP Bioenergy, 2021). Natural gas can also be used as a feedstock for this technology. Natural gas is the most abundant feedstock and is cost-effective and recent commercial FT plants rely on low-cost natural gas as feedstock (Dayton & Foust, 2020). However, this feedstock isn't considered as a renewable feedstock as it is a fossil fuel. A Fischer-Tropsch(FT) plant consists of 4 major components: a gasifier, a gas cleaning and conditioning unit, the FT reactor and the product upgrading units (Basu, 2018; Hari et al., 2015). Feedstock pre-treatment can be seen as a pre-component of a FT plant as some feedstock types do not purely consist out of prepared combustable material (Shahabuddin et al., 2020; Hari et al., 2015). This technology has some serious advantages as FT fuels are characterized by non-toxicity, zero emission of nitrogen oxides, high cetane number and low emissions of particulate matter. Next to this, the combustion of FT fuels is CO_2 and hydrocarbon free (Saynor et al., 2003).
As to the technical feasibility of this technology, this technology seems to score well and has a TRL of 6-8 (Prussi et al., 2019). Level 6 refers to prototype systems, level 8 to first of a kind commercial system. Appendix 11 gives a more elaborate view on this benchmarking tool and on definitions of the levels. The TRL level of this technology is higher for coal and natural gas-to-liquid routes and is commercially available, which refers to TRL 10 (Bauen et al., 2020).
Regarding the market deployment of this technology pathways, it can be seen all over the world. 114 biomass gasification plants are in operation, an additional 15 are inactive or on hold and 13 plants are planned or are currently under construction, of which 24 plants are used for liquid fuel production (Shahabuddin et al., 2020). However, these FT plants are mostly used for production processes next to the production process of SAF as the production of aviation fuel via this technology is still at demonstration phase (European Commission, 2021a). With respect to the economic feasibility of this technology, it has some challenges due to the availability of input sources. Concerning natural gas as an input, economies of scale can be gained as the costs per fuel unit decreases when scale increases, but the financial risks will increase more steeply due to the capital expenditure required (Dayton & Foust, 2020). With respect to renewable fuels as an input source, less attractive economies of scales are seen here as these feedstocks aren't available in the size comparable of natural gas (Dayton & Foust,

2020). Besides, even though a wide range of feedstock types can be used, the sources are highly distributed and therefore are higher in costs (Dayton & Foust, 2020; Hari et al., 2015). Other issues regarding FT fuels are the low lubricity level which is caused by the absence of sulphur (Kreutz et al., 2008). Furthermore, F-T fuels are an expensive option to produce SAF because of the required high pressure and temperature (Hari et al., 2015).

3.2.2 Pyrolysis

This technology converts lignocellulosic biomass or solid waste into a bio-crude oil which can be refined to fuels (Perkins et al., 2018). The main benefit of lignocellulosic biomass is that it is non-edible and it therefore overrides the food versus fuel debate (Michaga et al., 2021). This same benefit can also be found in municipal solid waste as feedstock. MSW is largely available and for little, zero, or sometimes even negative costs (Jones et al., 2009). The conversion of lignocellulosic biomass/solid waste to bio-crude oil is commercially available on the market and is at TRL 8. However, the process of upgrading the bio-crude oil to fuels is only at TRL 6, the early demonstration phase (Bauen et al., 2020). This translates to limited batch productions via trail runs. Other routes for bio-crude to fuels are at a TRL 4 which makes the total TRL of this technology from biomass or solid waste to fuels at level 6 highest (Bauen et al., 2020). An American company had embarked the process of becoming an approved SAF by the ASTM but the company bankrupted. Shell also started this ASTM SAF approval process but only got to phase one of this process. Currently, this technology is not approved by the ASTM and no processes are run. Challenges are still present for this technology as a state of the art research by Perkins et al. (2018) showed that high water level, acidity and oxygen content, pose issues. Viscosity and chemical instability are other challenges that are identified by this study. Currently, no existing commercial plants that upgrade the pyrolysis oil to fuels exist.

3.2.3 Hydrogen and Electricity

Hydrogen
Hydrogen could be used as a fuel source for the aviation industry. It has some serious benefits in terms of noise pollution reduction, increased efficiency and reduction of greenhouse gasses as long as the hydrogen itself is produced by renewable sources (Bauen et al., 2020). When compared to conventional kerosene, hydrogen causes low emission of greenhouse gasses (Hari et al., 2015). However, hydrogen has significant technical limitations as this technology requires major aircraft, airport and infrastructural adaptations (IATA, n.d.). Without fundamental redesigns of airplanes, this technology will not be able to power the long-haul aviation industry (Energy Transition Coalition, 2020). For these two main reasons, this technology is still far away from making its entree to the commercial market (World Economic Forum, 2020). Also, hydrogen has a energy density that is significantly lower when compared to conventional kerosene. This characteristic is critical for the required airplane adaptations which would need to accommodate highly insulated tanks that can store the liquid hydrogen (Baroutaji et al., 2019). One particular safety issue associated with liquid hydrogen is that upon mixing with air, hydrogen in low concentrations easily ignites and thus needs to be stored at very low temperature (Midilli et al., 2005).

Electricity
Hybrid and full electric airplanes are gaining attention with several project and prototypes being developed. Two major advantages of a battery-electric airplanes need to be raised. At first, a 100% reduction in climate impact can be obtained with this technology, as long as the electricity that is used in these batteries is made of 100% renewable electricity. Secondly, same, or even shorter turnaround times for aircraft operations are expected with direct electrification (World Economic Forum, 2020). Expectations are that small (up to 10-seater) full electric airplanes will become commercially available in short term. Expectations by World Economic Forum (2020) are that these smaller aircrafts, such as commuter and regional planes, could be the first airplanes to switch to new propulsion technologies. However, full electric medium to long-haul airplanes cannot be met with current battery technology (Bauen et al., 2020) and approximately 95% of CO_2 emissions are emitted from airplanes in larger segments (World Economic Forum, 2020). Also, it is expected that without dramatic and currently unforeseeable improvements battery energy density, this technology will not by suitable for the long-haul aviation industry (Energy Transition Coalition, 2020). Next to this limitation, the replacement of kerosene by the current battery technology would result in extra weight for the airplane. Using current technology, a plane would need over 50kg of batteries to replace 1kg of kerosene for a maximum range of 500-1000 km (World Economic Forum, 2020). Furthermore, the battery weight doesn't decrease as a kerosene tank does by burning the fuel, so the plane would need to carry the full load of the battery for the entire flight, resulting in extra required energy. Aside from the barriers in terms of aircraft design and required technology improvements,

the airport infrastructure needs to be changed for the implementation of battery-electric aircrafts. The infrastructure would require fast-charging or battery exchange systems, which form another major challenge for this technology (World Economic Forum, 2020).

Expected pathway for electricity and hydrogen
Research and innovations costs for these adaptations are considered as important barriers for the hydrogen technology and electricity technology to develop. Given that the aviation industry is characterised by long research and development cycles, including lengthy certification processes, long lifetime spans of aircrafts and substantial required costs associated to develop these technology, the European Commission argues that it is unlikely that hybrid or full electric airplanes or hydrogen-powered airplanes will represent a substantial part of the European airline fleet before 2050 (Undertaking, 2020). Besides, other industry compete with the demand for hydrogen and the expectations are that hydrogen, as a fuel, will become increasingly more cost-competitive for decarbonising road transport (World Economic Forum, 2021).

3.2.4 Hydroprocessed esters and fatty acids

In this process, lipid feedstock types like used cooking oil and animal fats are used to producing a pure hydrocarbon fuel blending component (IATA, n.d.). Other feedstock types like algae and different kind of vegetable oils can be used as well (Tao et al., 2017). The HEFA technology mainly consists of the following three steps: hydrotreatment, cracking and isomerization and fractionation. (Klein et al., 2018; Richter et al., 2018). Depending on which feedstock is used for production and its quality, the refinement process can be expensive and different methods for the extraction are feasible (de Araújo et al., 2013).
As to technical feasibility, HEFA fuels are completely conventional for aircraft engines without the need of any engine modifications. HEFA fuels avoid the chance of deposit formation in the engine and engine corrosion (Mikkonen et al., 2013). supplementary to the fact that the combustion of the fuel is completely ash free (Hari et al., 2015). The HEFA pathway is considered the most mature pathway that scores a TRL of 9 (European Commission, 2021a).
Regarding the market deployment of this SAF technology pathways, there are several existing plants which produce SAF with this technology, but are at lower output compared to crude oil refinery production (Doliente et al., 2020). Several pilot scale plants exists and since 2008 multiple demonstration flight have been performed using SAF produced with this technology pathway (Doliente et al., 2020; Wang & Tao, 2016). Because of its maturity and simple process compared to other technologies, HEFA is the only SAF technology that is commercially active on large scale (Bauen et al., 2020). Expectations are that the number of SAF plants will increase heavily resulting in the majority of the SAF mandate uptil 2030 likely being produced by this technology due to the fact that HEFA plants are the cheapest and have the highest TRL (World Economic Forum, 2021; Energy Transition Coalition, 2020).
Despite being the technically feasible for commercial production and the low production costs, this technology is mainly constrained by resource availability (Energy Transition Coalition, 2020; Bosch et al., 2017; Bauen et al., 2020). Used cooking oil and tallow, two of the main feedstock sources, represent only a small resource globally and the supply of virgin vegetable oil is constrained by land availability and its sustainability is questioned (Bauen et al., 2020). Bosch et al. (2017) argues that the current supply of the input sources are deemed insufficient to meet industrial demands and expectations by European Commission (2021a) are that this limiting availability will be even more in the future. Moreover, the are other applications for these feedstock types in competing technologies (Energy Transition Coalition, 2020). Rye et al. (2010) argues that these feedstock types are more suitable for diesel production instead of sustainable jet fuel. On the contrary, investigations on novel crops like camelina, carinata and oil-bearing algae are performed and assessed on their potential and sustainability (Bauen et al., 2020). These sources could be alternative feedstock sources that could be used to produce HEFA fuels.

3.2.5 Alcohol to Jet

This technology consists of a fermentation process that extracts sugars from different kind of possible feedstock types via mechanical, biological or chemical ways and are transformed into hydrocarbon molecules that can be blended into conventional jet fuel (IATA, n.d.). The main used feedstock types are lignocellulosic feedstock and forestry residues. The technology consists of dehydration of biomass, oligomerization, hydroprocessing and fractionation (Klein et al., 2018) and can produce drop-in hydrocarbon fuels ranging from gasoline, to diesel and jet fuel (Gutiérrez-Antonio et al., 2017).
The advantage of this technology is the availability of cost-effective feedstock that does not harm the food industry and land usage (Hari et al., 2015). Besides, the AtJ technology can convert many different types of

alcohol from a wide range of sources into SAF or other hydrocarbons (Bauen et al., 2020). Furthermore, this technology benefits from the fact that the AtJ route offers logistical flexibility in the fact that the catalysis plant that converts to alcohol doesn't need to be in the same location as the alcohol production process and the alcohols can be transported and stored (Bauen et al., 2020). In 2012 and 2014, test flights were performed with AtJ SAF (C. Zhang et al., 2016). Due to the maturity of these technologies, the technology readiness of the alcohol-to-jet pathway is quite high and scored with TRL 7-8 (European Commission, 2021a; Dayton & Foust, 2020). Despite the relative high technology readiness level, the production costs of this SAF technology pathway are still high and are considered to form the greatest barrier for AtJ fuels to become commercialized, according to Gutiérrez-Antonio et al. (2017).

3.2.6 Synthesised Isoparaffins (SIP)

This technology converts sugars into hydrocarbons or lipids with the use of genetically modified microorganisms. This method is called direct sugars to hydrocarbons (DSHC) and there are three different methods that can further transform these hydrocarbons or lipids into a SAF: heterotrophic algae or yeast converting sugars into lipids, converting sugars to long-chain liquid alkenes with the help of genetically modified yeast and the transformation of sugars to short-chain gaseous alkanes with genetically modified bacteria as catalyst. Conventional sugar is currently by far the dominant feedstock type that is used by existing producing plants and there are several pilots that are testing cellulosic sugars as feedstock. This DSHC technology with the use of conventional sugar as feedstock is at TRL 7-8 (pre-commercial/commercial level), while this technology with cellulosic sugar feedstock is at TRL 5 (prototype level). One specific route within the technology of Synthesised Isoparaffins is certified as hydroprocessing of fermented sugars to farnesene, which can be used as a blendstock in conventional jet fuels and is SAF approved by the ASTM and can be blended up to a maximum of 10% (CAAFI, n.d.). Currently, however, the DSHC production and development is targeted at a different market than alternative (jet) fuels. Chemical, food and feed markets and pharmaceutical markets are being addressed, in which these DSHC are of higher value than when used in bulk transport fuels (Bauen et al., 2020). One could argue that this hinders the development of this technology for sustainable fuels but this technology in turn helps to mature and prove itself. With the maturation of this technology, it grows and reaches scale benefits and therefore lower production costs. Lower production costs are desirable for this technology as this technology is the most expensive ASTM approved SAF technology because of the low efficiency of converting lignocellulosic sugars into SAF through DSHC. This low efficiency translates to high volumes of feedstock needed and high energy consumption.

3.2.7 Synthetic SAF

Although this technology is not yet approved by the ASTM as a certified SAF technology pathway, this technology is deemed important for the uptake of SAF (European Commission, 2021a). This technology is also referred to as electro fuels, e-fuels or power-to-liquid (PtL) fuels. Research by Energy Transition Coalition (2020) emphasizes the importance of synthetic SAF as synthetic fuels are likely to represent the most scalable long term solution for SAF production, given lower land-usage when compared to bio-based technologies. This report states that the energy produced per square kilometer is 100 times bigger for solar than for biomass. Other research by World Economic Forum (2021) also points out the importance of PtL as they expect that the vast majority of financial support for new SAF plants will be directed to the commercialization of lignocellulosic and PtL production pathways, despite the lower TRLs of both. This report also proposes that the SAF-blending mandate should include sub-targets for the deployment and cost reduction of novel technological pathways, being lignocellulosic and PtL. In other respects, the Clean Skies for Tomorrow (CST) Joint policy proposal, developed by the European CST members, also proposed to support innovation to bring lignocellulosic and PtL pathways to the market (Energy Transition Coalition, 2020). This report also expects synthetic fuels to be the long term solution for the production of SAF. According to this study, synthetic fuels are expected to represent the largest SAF volume of all feasible technologies from the mid-2030s onwards. This is expected by this study because synthetic fuels have the largest potential to reduce the production costs from economies of scale and are expected to become a cost-competitive solution at 2040 by the latest. Expectations are that by 2050, this technology is likely to become more-cost competitive than other technologies (Energy Transition Coalition, 2020). When synthetic SAF is produced with the use of renewable electricity and carbon captured directly from the air, the potential GHG saving emissions can reach up to 100% when compared to conventional jet fuel (European Commission, 2021a). This fuel type also has advantages compared to other SAF technologies with regards to resource efficiency of the production process and water needs (European Commission, 2021a).

The main resources for the production of PtL fuels are water, CO_2 and electricity (Drünert et al., 2020). PtL fuels are produced by converting electricity into liquid hydrocarbons, via electrolyzing water to produce hydrogen

before combining it with CO_2. To be labeled as a SAF, this technology must use renewable or zero-carbon electricity as required input and on renewable sources of CO_2. The required CO_2 can be captured via direct air capture (DAC)or via related industrial emissions (Drünert et al., 2020). It is expected that CO_2 from industrial waste sources will be available in short term as this source is cheaper than DAC. This source of CO_2 can be used to drive op volumes, prove production at large scale and arrive at economies of scale after which the switch will need to be made towards DAC (Energy Transition Coalition, 2020). Next to CO_2, electricity is also an input source for this technology. The electricity can be of many different sources, as long as it it produced in a climate-neutral way (Drünert et al., 2020).
One of the limitations of this technology is that it highly relies on the availability and price of renewable energy supply (RES). Currently, synthetic aviation fuels are estimated at 3 to 6 times the production costs of conventional jet fuel (European Commission, 2021a). In case of abundant RES, the price will decrease resulting in major benefits for this technology. Other way around, when there's little RES, the price of will increase and the production costs of this technology will increase as well. Besides, other technologies which require ample of RES to scale up, also rely heavily on renewable energy sources and therefore present competition with this technology.

3.3 Selection of technologies

As mentioned in the introduction of this chapter, for practical reasons only relevant technologies with sufficient technology readiness, sufficient feedstock availability and potential and sufficient beneficial aspects will be selected in this study. Therefore, after a more in-depth analysis of the different SAF technology pathways in the latter section, this section further reduces the number of SAF technology pathways that are further taken into account in this study.
Although the hydrogen and battery-electric technology have potential and come with substantial climate benefits, the decision is made not to further investigate these technologies but to exclude these from this research. This decision is made because 1) significant and continuous additional research and developments will be needed for these technologies, and 2) these technologies require major changes in aircraft design, aircraft operations and airport infrastructure. This choice is also backed by the research by World Economic Forum (2020), which argues for the same barriers and states that HEFA, ATJ, FT and synthetic fuels as most likely technologies to scale up and attract industry attention. Research by European Commission (2021a) also backs this decision as the European Commission argues that hydrogen and electricity aren't considered as primary fuels for aviation and argue that it is too early to consider regulatory action on fuel technologies such as hydrogen or electricity.
The decision is also made to further exclude pryolysis from this research. This since there are currently no processes running for this technology to become ASTM approved. On top of that, research by Perkins et al. (2018) argues for multiple challenges that this technology needs to overcome. Furthermore, research by S. Ahmad et al. (2021) concluded that this technology proved to be the least preferred SAF technology and was outranked in their study by other alternative technologies.
By excluding hydrogen, electricity and pyrolysis, the following selection of technologies will be further discussed in this research:

- Hydroprocessed esters and fatty acids-synthetic paraffinic kerosene (HEFA-SPK)
- alcohol-to-jet-SPK
- Fischer-Tropsch-SPK (FT-SPK)
- power-to-liquid (PtL)

3.3.1 Selection of feedstock types

After the selection of the relevant and promising SAF producing technologies, a selection of feedstock types feasible per technology needs to be performed as "SAF" only refers to any kind of feedstock as long as the sustainability of the end product is assured. Meanwhile, as argued earlier on, a SAF technology pathway is a combination of the technology of the production process and the feedstock type that is used. As can be seen in the latter section, multiple feedstock types are feasible per technology. These feedstock types will be briefly described and selections will be made on what feedstock type(s) to consider per technology. A visualisation of the considered SAF technology pathways can be seen in figure 6.

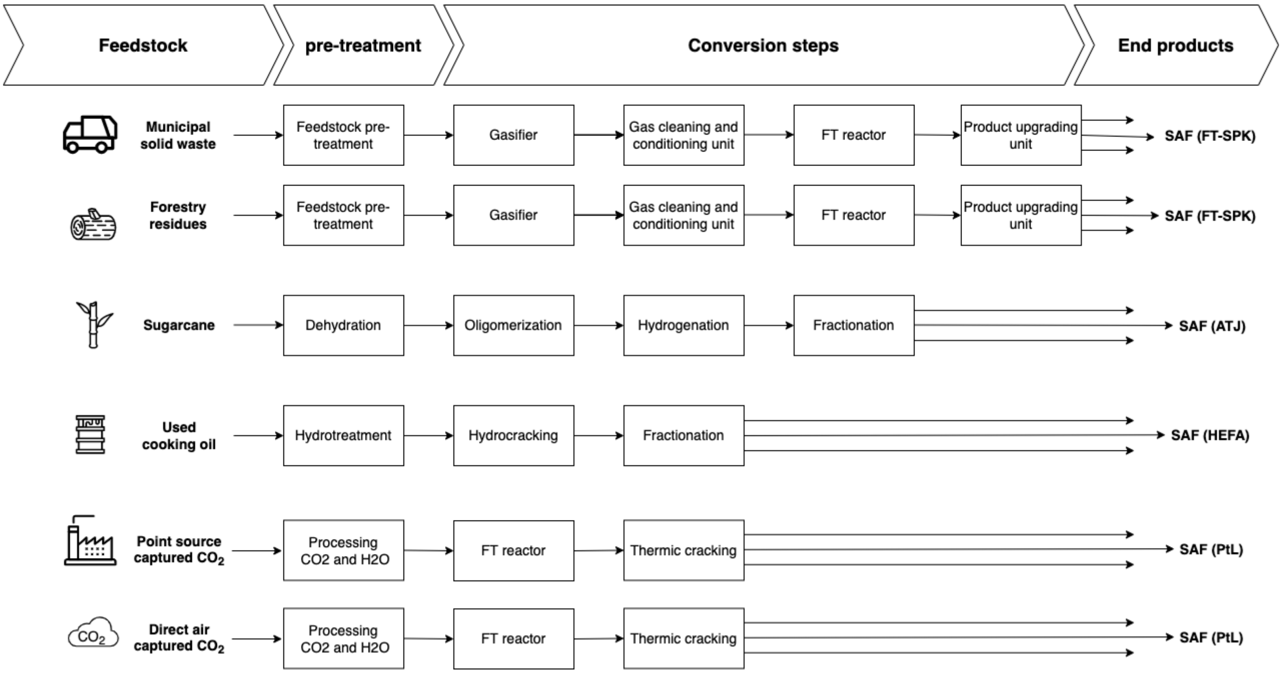


Figure 6: Visualisation of considered SAF technology pathways in this study

For the HEFA-SPK technology, many different feedstock types can be used (Tao et al., 2017). Of these different feedstock types, waste lipids (used cooking oil and animal fats) is the most promising option as this feedstock benefits from relatively low prices when compared to other feedstock types and is therefore increasingly used (Tao et al., 2017; S. Ahmad & Xu, 2021). Other feedstock types are less used and cope with technology readiness issues, availability issues or are costly when compared to this feedstock type (Tao et al., 2017; European Commission, 2021a; S. Ahmad & Xu, 2021). Besides, used cooking oil outperforms other possible feedstock types in terms of GHG emission savings (Pavlenko et al., 2019; European Commission, 2021a). For these reasons, this study will focus on the HEFA technology that uses used cooking oil as feedstock.

For the alcohol-to-jet technology, there are multiple feedstock types feasible of which lignocellulosic biomass, agricultural crops and starch crops are the most common. Among the agriculture crops that are used as feedstock for the production of ATJ fuels, sugarcane and sugar beet have the highest sucrose content and therefore have a major contribution to the ATJ industry (Pasa et al., 2022). Other feedstock types such as wheat and lignocellulosic biomass have a minor contribution in ATJ industry (Pasa et al., 2022). Therefore, this study considers sugarcane as feedstock for the ATJ technology.

Also, the Fischer-Tropsch technology is feasible with a range of different feedstock types as it transforms any carbon containing feedstock and splits it into individual building blocks in synthetic gas (ETIP Bioenergy, 2021). As the sustainability of the Fischer-Tropsch depends on the feedstock type that is used to derive at thhis synthetic gas, the decision is made to consider this technology with two different pathways: forestry residues and municipal solid wastes. Forestry residues are considered because of their high potential in GHG saving emissions while municipal is considered because of its financial aspects and also performs well on GHG saving emissions (Roland Berger, 2020; Suresh et al., 2018; Pavlenko et al., 2019). Also, forestry residues and municipal solid waste are more abundant than other possible feedstock types as argued in the report by O'malley et al. (2021).

The fourth and last SAF technology that is considered in this study is the power-to-liquid technology. For this technology, capturing CO_2 is a critical element (European Commission, 2021a). Currently, there are two different promising technologies for capturing this CO_2: Via direct air capture (DAC) and via CO_2 emissions from fossil point sources like factories/plants (European Commission, 2021a). These two technologies have differences in their TRL, sustainability performance and in their cost perspectives. Because of the deemed importance of this technology on the longer term and the differences in characteristics between the two different technologies of CO_2 capturing, both DAC as well as capturing form fossil point sources (point source captured CO_2) are considered in this study.

4 Acquisition and selection of relevant criteria

This chapter will address the second sub research question of this research, namely: *What criteria are deemed relevant for the uptake of different SAF technology pathways?* In order to answer this question, an acquisition of possibly relevant criteria is made with the help of a literature research. Conducting a literature study to come to a selection of criteria has been successfully performed by prior researches that used the Best-Worst Method (Kalpoe, 2020; Septian, 2019).

4.1 Identified studies

In this section, the studies which used multiple criteria in order to assess the performance of different SAF pathway technologies are discussed. These studies are identified through the literature study, which can later be used to assess the performance of the selected SAF technologies in this study.
For this literature research, the scientific database Google Scholar was consulted. The literature search was limited only to search within article title, abstract and keywords. Further limitations were set to only include literature since 2018. After having tried multiple different search terms, the following search term was used: "multi criteria decision making" AND "sustainable aviation fuels", This search term yielded 21 results. Of these 21 results, fifteen results were not relevant to the topic or access was not granted to the full article. The other six results were relevant to the topic and are further reviewed. Out of these six identified studies, only one study, the study by S. Ahmad & Xu (2021) performs a MCDM on multiple SAF technologies and none of the identified studies included the power to liquid (e-fuel) technology in its analysis. The study by Michaga et al. (2021), which is one of these six identified studies, refers to multiple other relevant studies of which three new relevant studies were not yet identified. These are also included in this literature research. A visualisation of this literature research can be seen in figure 7.

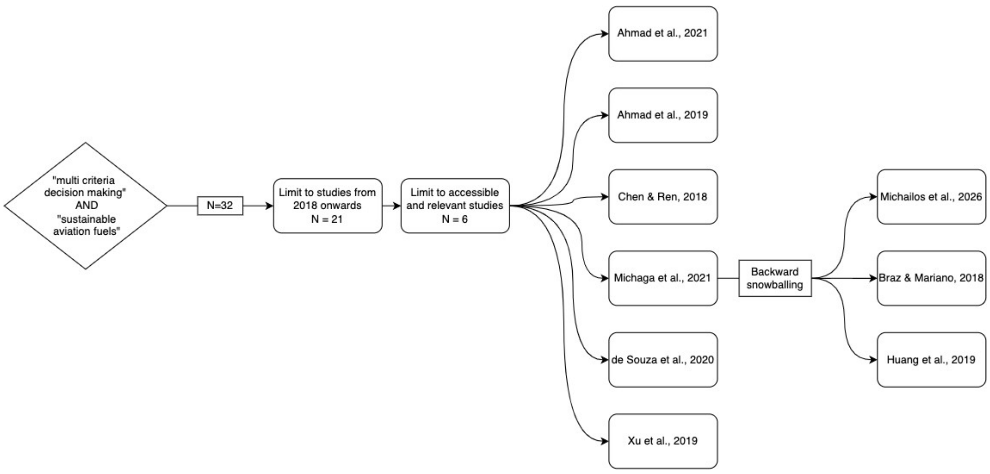


Figure 7: Visualised literature review showing 'the identified studies'

The underlying table, table 3, gives an overview of the identified studies. A more elaborate discussion on the content, used methods and pitfalls of these studies can be found in appendix 9.

Table 3: Identified studies in literature research

	Title	Study	Method	Field of study	Key takeaway(s)
1	A stakeholders' participatory approach to multi-criteria assessment of sustainable aviation fuels production pathways	(Ahmad et al., 2021)	MCDM for assessing different SAF pathways. Uses the PROMETHEE II and point-allocation method	SAF technology pathways. No synthetic pathways considered	Environmental and economic criteria are of main importance while social performance is considered less important. Future research should include synthetic SAF pathways
2	A value tree for multi-criteria evaluation of sustainable aviation fuels	(Ahmad et al., 2019)	Delphi method with Likert scale	Stakeholders' perspectives on criteria that could be relevant to assess SAF pathways	Develops a generic value tree which maps relevant criteria for assessing SAF. Gives insights in differences per stakeholder category
3	Multi-attribute sustainability evaluation of alternative aviation fuels based on fuzzy ANP and fuzzy grey relational analysis	(Chen Ren, 2018)	Fuzzy Analytic Network Process (ANP) and Fuzzy Grey Relational Analysis (FGRA)	Develops a multi-attribute sustainability evaluation model for assessing the sustainability performance of different SAF types. Considers two fossil-based jet fuels and two biofuels	The two biofuels are identified as most sustainable. Technology maturity and production costs per unit are key criteria
4	Performance Evaluation of Alternative Jet Fuels using a hybrid MCDA method	(Xu et al., 2019)	Analytic Hierarchy Process (AHP), point-allocation and Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE II)	MCDM for assessing different SAF pathways. Analysis done under assumption of equal importance of criteria	Result section only considers three out of ten identified criteria. HEFA technology performs the best
5	Oleaginous feedstocks for hydro-processed esters and fatty acids (HEFA) biojet production in Southeastern Brazil: A multi-criteria decision analysis	(de Souza et al., 2020)	Analytic Hierarchy Process (AHP) Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS)	Ranking of potential oleaginous feedstocks for HEFA biojet production in southeastern Brazil	Soybean performs best in the analysis due to low production costs and high agricultural maturity but is subject to competition with biodiesel industry

6	Techno-economic and life cycle assessment review of sustainable aviation fuel produced via biomass gasification	(Michaga et al., 2021)	Review of performed techno economic and LCA studies	Techno-economic and LCA studies on biomass gasification	Not used for its content but used for identifying other studies
7	A multicriteria comparison of utilizing sugarcane bagasse for methanol to gasoline and butanol production	(Michailos et al., 2016)	Aspen Plus and SuperPro Desiner simulation and Mathlab used for modelling reaction	MCA based on exergy, financial and environmental efficiencies of methanol-to-fuel, butanol-to-fuel and sugarcane-to-fuel	No focus on aviation but addresses the importance of exergy analysis
8	Jet fuel production in eucalyptus pulp mills: Economics and carbon footprint T of ethanol vs. butanol pathway	(Braz Mariano, 2018)	Economic and carbon footprint assessment of alcohol-to-jet fuel production	Eucalyptus pulp for ethanol and butanol jet fuel production (alcohol-to-jet fuel)	Stresses the importance of Internal Rate of Return for economic performance and competitiveness analysis of importance for MCDM on SAF
9	Multi-objective optimization for sustainable renewable jet fuel production: A case study of corn stover based supply chain system in Midwestern U.S.	(Haung et al., 2019)	Mixed-integer linear programming model (MILP) based on spatial, agricultural, techno-economic and environmental data	Sustainability performance of ATJ, FT and HTL SAF in Midwestern U.S. under optimal supply chain configurations	Visualises and stresses the trade-off curve (pareto-optimum curve) between production cost and greenhouse gas saving emissions. FT is suggested to be the most promising sustainable jet fuel pathway out of the three considered

4.2 Categorisation of all possibly relevant criteria

The nine identified studies, mentioned in the latter section, all take into account criteria that are relevant for the performance of the different SAF technology pathways. In order to select an appropriate selection of criteria, a longlist of all the different identified criteria is established (figure 8). This figure visualises that all criteria for ranking sustainable aviation technologies are split up under four main criteria. These four main criteria are based upon the political economy model of transport innovations by Feitelson & Salomon (2004). This framework is a theoretical lens that determines the level of analytical sufficiency regarding the adoption of transport innovations. It argues that the implementation of of most transport innovations requires large investments and changes in policy, and thus cannot be analysed purely as an outcome of automatic decision-making processes. This study states that it should rather be an outcome of societal processes and argues that the adoption of transport innovations is predicated on economic, technical, social and political feasibility (Feitelson & Salomon, 2004). As for feasibility reasons, the decision is made to merge social and political feasibility into one main criterion for the longlist of all criteria. As the environmental performance is another crucial aspect for the aviation industry as the whole aviation industry pledges for a carbon-neutral growth and pledges for a 50% carbon reduction (Wise et al., 2017). Therefore, the decision is made to include this environmental as a fourth main aspect of the adoption process of SAF technologies. So partly based on the framework by Feitelson & Salomon (2004) and partly based on the literature review, the following four main-criteria are established: economic, social, technical and environmental. The main criteria itself consist out of multiple sub-criteria and are characteristics of the main-criteria. However, given the practical goal of this study, not all the identified main-criteria and sub-criteria are key aspects in this study. The next section will elaborate on the importance of the main- and sub-criteria and decisions are made on which to exclude for further analyses.

4.3 Selection of main-criteria and their sub-criteria

In the longlist of all criteria, it can be seen that all of the identified studies use a different set of criteria. However, consensus can also be found as there seems to be overlap in the selection of the criteria. For example, the criterion GHG saving emissions, is selected in seven out the nine researches. In order to acquire a suitable, manageable set of main-criteria and their sub-criteria, not all identified sub-criteria can be considered in this study. When too much sub-criteria are taken into account, it can become difficult to understand, handle and compare the information (Choo et al., 1999). What's more, the literature study indicated a total of 64 sub-criteria. Considering all these sub-criteria would not only result in difficulties to understand but would also require ample time. For these reasons, the first decision is made to exclude the social performance of the different SAF technology pathways. The argumentation for this decision is based on three arguments: The first reason for this decision is the phase of this study. As SAF are at the early beginning of the required uptake and technologies are still developing, this study is at an exploratory phase. Therefore, it is still too early to include social performance of SAF as a main-criterion in this study. Consequently, this study focuses on environmental, technical and economic performance as prioritisation needs to be on these three main criteria. It makes no sense to discuss social performance when one of the other three main-criteria is significantly lacking. Besides, the decision to exclude the social performance is also based on the high uncertainty that comes to play when scoring the SAF types on the social performance. This is since SAF are still at this early development. Estimating their performance will be therefore inconvenient and difficult. As a final argument to leave out the social performance, the relevance of the social performance needs to be addressed here. In the prior performed researches regarding SAF the social criteria were considered least important out of all criteria considered (Markevičius et al., 2010; S. Ahmad & Xu, 2021). Although the social criteria and its performance might not be of key relevance, this study still addressed this criterion and its corresponding sub-criteria in appendix 10 as these may be usefull for future studies.

Next to the decision to leave out the social performance, the total number of sub-criteria is also reduced. This will be done by aggregating sub-criteria that have a high correlation between the definitions of each other. Other, non aggregated sub-criteria will also be left out of this study. These sub-criteria were initially gathered from other researches in which they were of importance, but due to the scope and the selected SAF technologies, these sub-criteria are not relevant and left out of scope.

Figure 8: longlist of all criteria

(a) Longlist of social criteria

Category	Criterion	Description	Selected in study by
Social	**Traceability**	Concerns the transparency of the production pathway from feedstock to the final product	(Ahmad et al., 2021), (Ahmad et al., 2019)
	Contribution to economy	Concerns the creation of new commerce, industrial districts, rural developments etc.	(Ahmad et al., 2021)
	Food security	Impact of feedstock used for SAF production on food security	(Ahmad et al., 2021), (Ahmad et al., 2019), (de Souza et al., 2020)
	Social acceptability	General public's perception on SAF production and usage	(Ahmad et al., 2021), (Chen & Ren, 2018)
	Social acceptability	Collective judgment or collective opinion on the production and use of SAF	(Ahmad et al., 2019)
	International mandates/ agreements	Binding obligation issued from an intergovernmental organisation to a country which is bound to follow the instructions of the organisation	(Ahmad et al., 2019)
	Governmental spendings	Governmental financial support to the development of SAF technologies	(Ahmad et al., 2019)
	Contribution to economy	The gross change in economic activity associated with the SAF industry	(Ahmad et al., 2019)
	Innovation on technology	The innovations compared with the traditional aviation on heavy oils	(Chen & Ren, 2018)
	Stakeholders' interest	It is important to gather the views and opinions from various stakeholders (e.g., airline companies; government bodies; energy companies) regarding to their interests and concerns to a specific AJF technology	(Xu et al., 2019)
	Wealth and job creation	Process of providing new jobs building wealth	(Xu et al., 2019)
	Extractivism dependence	Dependence on the natural resources that are extracted from the Earth	(de Souza et al., 2020)

(b) Longlist of environmental criteria

Category	Criterion	Description	Selected in study by
Environmental	**Feedstock sustainability**	Continuity of feedstock supply for SAF production	(Ahmad et al., 2021), (Ahmad et al., 2019)
	GHG emission savings	Net CO2 emission savings compared to conventional jet fuel	(Ahmad et al., 2021), (Ahmad et al., 2019), (Chen & Ren, 2018), (Xu et al., 2019), (Braz & Mariano, 2018), (Michailos et al., 2016), (Huang et al., 2019)
	Land-use change impact	Both direct and indirect land-use change due to SAF production	(Ahmad et al., 2021), (Ahmad et al., 2019)
	Soil and water pollution	Impact of usage of fertilizer and pesticides to produce biomass	(Ahmad et al., 2021), (Ahmad et al., 2019)
	Combustion efficiency	Effectivity of the heat content of a fuel transferred into usable heat	(Ahmad et al., 2019)
	Local air quality	The degree to which the air in a particular place is pollution-free	(Ahmad et al., 2019)
	Ecologic impact of the production chain	Include toxic waste, water pollution, loss of biodiversity, deforestation, long-term damage to ecosystems, hazardous air emissions as well as greenhouse gas emissions and energy use.	(Ahmad et al., 2019)
	Water consumption	The total water consumption during the whole life cycle of aviation fuels	(Chen & Ren, 2018), (de Souza et al., 2020)
	PM10	PM10 emissions during the whole life cycle of aviation fuels	(Chen & Ren, 2018)
	PM2,5	PM2,5 emission during the whole life cycle of aviation fuels	(Chen & Ren, 2018)
	Cropland area	Areas used for the production of adapted crops for harvesting	(Huang et al., 2019)
	Biomass/RJF Transportation emissions	Net CO2 emission originating from the transportation of biomass and RJF	(Huang et al., 2019)
	Centralized storage and preprocessing and biorefinery facility emissions	Net CO2 emissions originating from the centralized storage and prepocessing and biorefinery facility	(Huang et al., 2019)
	Land productivity	Inclusion of short rotation crops or intensive farming techniques	(Ahmad et al., 2021), (Ahmad et al., 2019), (de Souza et al., 2020)

(c) Longlist of economic criteria

Category	Criterion	Description	Selected in study by
Economic	**Feedstock alternative use**	Other uses of feedstock aside from SAF production (e.g., biofuels for road transport or electricity)	(Ahmad et al., 2021), (Ahmad et al., 2019), (Xu et al., 2019)
	Feedstock profitability	Financial benefits in producing a specific feedstock	(Ahmad et al., 2021), (Ahmad et al., 2019)
	Minimum selling price MSP	Expected minimum selling price of a SAF technology	(Ahmad et al., 2021), (Ahmad et al., 2019), (Chen & Ren, 2018), (Braz & Mariano, 2018)
	Input energy use	Amount of energy required for producing SAF technology	(Ahmad et al., 2021), (Ahmad et al., 2019), (Chen & Ren, 2018)
	Land productivity	Inclusion of short rotation crops or intensive farming techniques	(Ahmad et al., 2021), (Ahmad et al., 2019), (de Souza et al., 2020)
	Operations & Maintenance costs	Operating and maintenance costs of SAF producing facility	(Ahmad et al., 2021), (Ahmad et al., 2019), (Xu et al., 2019), (Huang et al., 2019)
	Feedstock costs	Costs to produce the primary feedstock material for SAF technology	(Ahmad et al., 2021), (Ahmad et al., 2019), (Huang et al., 2019), (de Souza et al., 2020)
	Plant capital costs	Establishment of the SAF plant and required facilities	(Ahmad et al., 2021), (Ahmad et al., 2019), (Chen & Ren, 2018), (Huang et al., 2019)
	Long term supply contract	Agreement between different parties in SAF industry that provides for buyer to purchaase products/services from seller through the release of purchase orders against tat long term supply agreement	(Ahmad et al., 2019)
	Competitive advantage	A condition or circumstance that puts a company in a favourable or superior business position	(Ahmad et al., 2019)
	Market demand	Total quantity demanded across all consumers in SAF industry	(Ahmad et al., 2019)
	SAF availability	The quality of being able to be used or obtained	(Ahmad et al., 2019)
	Process integration with current refineries	The ease of the integration and feasability of feedstocks in current refineries	(Ahmad et al., 2019)
	Investment costs	Additional investment required to provide a business-as-usual scenario on the standard production of jet fuel. This can include but is not limited to technology, specialist services, advice and consultancy, construction of physical structures and transport structures to support production of alternative jet fuels	(Xu et al., 2019)
	Revenue	Total revenues would potentially generate from selling fuel products such as LPG, naphtha, middle distillates, gasoline heavy oil	(Xu et al., 2019)
	NPV	Net Present Value in case of jet fuel production and is sold at MSP	(Braz & Mariano, 2018), (Michailos et al., 2016)
	Return on Capital Employed (ROCE)	Amount of profit that each invested capital dollar in jet fuel production and co-products makes	(Braz & Mariano, 2018)
	Resistance to Market Uncertainty (RTMU)	Vulnerability of investment to production cost (raw material plus energy)	(Braz & Mariano, 2018)
	Internal Rate of Return - Phase 1 (IRR-1)	Internal rate of return in case financial investments in the development of ATJ technology isn't done	(Braz & Mariano, 2018)

(d) Longlist of technical criteria

Category	Criterion	Description	Selected in study by
Technical	**Blending limit**	Percentage of maximum blend with conventional jet fuel	(Ahmad et al., 2021)
	Conventional jet fuel compatibility	Degree to which the alternative fuel comes close to conventional jet fuel	(Ahmad et al., 2021), (Ahmad et al., 2019)
	Domestic technological ability	Availability of domestically available production technology	(Ahmad et al., 2021), (Ahmad et al., 2019)
	Process integration	Integration of SAF with existing conventional jet fuel infrastructure	(Ahmad et al., 2021)
	Process technical maturity	Current development status of a production pathway: pilot, demonstration or at commercial level	(Ahmad et al., 2021), (Ahmad et al., 2019), (Chen & Ren, 2018), (Xu et al., 2019)
	Process yield	Amount of SAF obtained from a conversion pathway	(Ahmad et al., 2021), (Ahmad et al., 2019), (Huang et al., 2019), (de Souza et al., 2020)
	Production volume scalability	Capacity for later expansion of the SAF processing facility	(Ahmad et al., 2021), (Ahmad et al., 2019)
	Quality and composition of feedstock	SAF batch quality	(Ahmad et al., 2021), (Ahmad et al., 2019), (de Souza et al., 2020)
	Fuel safety	Fuel safety	(Ahmad et al., 2019)
	Energetic content	The amount of heat produced by the burning of 1 gram of a fuel	(Ahmad et al., 2019)
	SAF flash point	The temperature at which a particular organic compound gives off sufficient vapour to ignite in air	(Ahmad et al., 2019)
	SAF viscosity	Quantity expressing the magnitude of internal friction in a fluid, as measured by the force per unit area resisting uniform flow	(Ahmad et al., 2019)
	Fuel handling infrastructure modification	Adaptations required in current infrastructure to handle SAF	(Ahmad et al., 2019)
	Ease of transport and storage	Ease of transport and storage	(Ahmad et al., 2019)
	Process efficiency	Refers to the production rate of jet fuel based upon required resources	(Ahmad et al., 2019), (Xu et al., 2019)
	Process flexibility	The flexibility of stopping, starting, upscaling and downscaling the productionprocess of SAF	(Ahmad et al., 2019)
	Technology Risk	The risk of a technology pathway not performing as expected (e.g. lower yields than expected). This could influence the M.S.P.	(Braz & Mariano, 2018)
	Exergy efficiency	The maximum useful work that can be obtained from a system at a given state in a given environment	(Michailos et al., 2016)
	Transport costs	Biomassa transportation costs	(Huang et al., 2019)
	Production scale of feedstock	Annual agricultural production, planted area, content of feedstock that is usable for production process, harvest period (seasonality) and registered cultivars	(de Souza et al., 2020)

4.3.1 Environmental performance

The environmental criteria address not only the environmental consequences for the production of the specific SAF technology, but some studies also implied other, non-direct, environmental consequences as they take into account a broader scope and consider the whole supply chain and its environmental consequences.

Importance of criteria
In order for the aviation industry to keep realising their expected growth while complying to the carbon-neutral growth goal set by the ICAO, the environmental impact of SAF on the aviation industry is of high importance. As stated in the introduction of this research, the large scale implementation of SAF is deemed necessary for the aviation industry to accomplish both goals set by the ICAO and the IATA (Federal Aviation Administration, 2015). As a response to these goals and in combination with the context of the European Green Deal, European members of Clean Skies Tomorrow developed a joint strategy for the required transition towards climate neutral flying in Europe. This with a particular focus on the uptake of SAF over the next decade (Energy Transition Coalition, 2020). Since this research will evaluate and rank different SAF pathways technologies, with different characteristics, benefits and pitfalls in environmental impact, the environmental aspects of these SAF technologies are deemed as important criteria for the analysis of this research.

Greenhouse gas saving emissions
This criterion can be defined as the net greenhouse gas emissions saving compared to conventional jet fuel. In view of GHG saving emissions, every study took this criterion into account. Because of this, the decision is made to include this criterion in this study as well. The only study which didn't include the GHG saving emissions as criterion, is the study performed by de Souza et al. (2020). This study considered the environmental performance and addressed the environmental impact and relevance of SAF. However, this study excluded this criterion, as this study argued that there's a limited number of studies related to the Life Cycle Analysis (LCA) of different HEFA feedstock and not all feedstock sources used in their study are discussed in LCA studies. Besides, this study argues that oilseed reduces the carbon footprint by 50%, regardless of which specific type of oilseed feedstock is used. Therefore, the GHG saving emissions is excluded as criterion in the study by de Souza et al. (2020). Next to the studies that were found in the literature research of this study, other studies also emphasize the importance of GHG emission savings. The LCA study by O'Connell et al. (2019) concludes that this criterion, together with energy efficiency, are the most important criteria in their study. The study by Staples et al. (2018) indicated that the usage of SAFs can have a big impact on the GHG emissions. It concluded a lifecycle reduction of GHG emissions from the aviation industry by a maximum of 68.1% in 2050.
The degree of GHG saving potential highly depends on what is included in the definition and what is excluded. A literature study by Zemanek et al. (2020) concludes this as it reviewed 20 CLAs of HEFA jet fuels and noticed a wide variety in reported life cycle GHG emissions for HEFA fuels. They argue that this wide range in emissions forms a barrier for the development of HEFA fuels. Therefore, it needs to be clear what is considered in scope when considering GHG saving emissions. The study by Huang et al. (2019) took into account a broad scope when evaluating the GHG saving emissions by including the CO_2 emissions of the whole supply chain. This included both the centralized storage and pre-processing and bio-refinery facility emissions and the biomass transportation emissions and the SAF transportation emissions. Other studies only considered parts of this supply chain in their scope when assessing GHG saving emissions. To be as clear as possible on the scope of GHG saving emissions in this study, the decision is made to consider "GHG saving emissions from the well-to-wake" for this study. This is also in line with LCA studies on SAFs as they take into account the whole lifecycle of a fuel.

Land usage (change) impact
Next to air quality, the identified studies took into account different other environmental aspects like "land use change impact". This criterion is used in studies by S. Ahmad et al. (2019) and S. Ahmad & Xu (2021) and includes both direct land use change as well as indirect land use change (ILUC). Indirect land use change can put additional demand on land and could lead to an extension of new or other areas with high carbon-stock, like wetlands, forests and peatlands. ILUC can therefore reduce the sustainability potential of a biofuel and could even lead to an increase in CO_2 emissions when compared to fossil fuels. Therefore, the decision is made to include ILUC within this criterion.

Water usage

Next to GHG emissions and land usage (change) impact, water usage is also an important aspect to consider, especially given the constraints in water availability that are expected to occur in the coming decades (Roland Berger, 2020). Most of the identified studies also took 'water consumption' (Chen & Ren, 2018; de Souza et al., 2020) and 'soil and water pollution' (S. Ahmad et al., 2019; S. Ahmad & Xu, 2021) into account. According to the definition of environmental sustainability, 'water quality and quantity' makes a part of this (McBride et al., 2011). In other, non identified, socioeconomic studies regarding the assessment of biofuels, water usage (Gerbens-Leenes et al., 2014) and water availability (Venteris et al., 2013) are also taken into consideration. The study by Efroymson et al. (2017) states that water usage and the source of water influences the profitability of certain biofuels and accounts for a non-negligible part of the production costs. Other studies also emphasize the importance of the water scarcity and link this to poor public opinion of water-intensive bioenergy sources (Chaudhry & Barbier, 2013). As most of the identified studies take 'water consumption' or 'water availability' into account, the decision is made to include the sub-criterion 'water usage' in this study.

As can be seen in table 4, the following set of sub-criteria is considered to evaluate the environmental aspect of the SAF technology pathways.

Table 4: Subset of criteria regarding environmental performance

Main-criterion	Sub-criterion	Description
Environmental	GHG saving emissions	Net CO2 emission savings from the well-to-wake (compared to conventional jet fuel)
	Land usage	Direct and indirect land use change (ILUC)
	Water usage	The total water consumption during the whole life cycle of aviation fuels

The other sub-criteria are left out scope: The identified criterion "Combustion efficiency", which is used in the study by S. Ahmad et al. (2019), has more to do with the technical analysis and highly correlates with the criterion "Energetic content". Therefore, the decision is made to leave this sub-criterion out of scope for the environmental part of the analysis. Also, the criterion "feedstock sustainability", as used by S. Ahmad et al. (2019) and S. Ahmad et al. (2021), has more to do with the continuity of feedstock supply and therefore forms more of a technical aspect for the uptake of a specific SAF technology pathway. For this reason, this sub-criterion isn't considered in the environmental analysis.

4.3.2 Economic performance

The economic aspects mainly refer to the criteria directly related to costs, but also include other financial aspects like competition in other industries, profitability and capital expenditure.

Importance of criteria

Currently, the aviation industry relies heavily on oil products and this can be partly explained by the lack of price competitive alternatives to power commercial aircrafts (European Commission, 2021a). As argued before, currently, the production of SAF is still very limited, mainly due to the price difference between SAF and conventional jet fuel. Currently, there are no plants in the EU that produce SAF on a large commercial basis (European Commission, 2021a). However, the mandate set by the European Commission will require this volume to be increased vastly over the following thirty years. Therefore, the SAF technology pathways are at the early beginning of the required uptake. This also means that there are uncertainties in which SAF pathway will become dominant in the market. For this early phase of this uptake, the financial strength of a specific SAF pathway technology is of importance, as argued in the study performed by van de Kaa et al. (2011), who identified factors that are of importance for a technology to become dominant and develop. The Impact assessment on the ReFuelEU report by the European Commission also identified two main problems of which one problem concerned the lack of SAF supply of reasonable costs (European Commission, 2021b). In their stakeholder analysis they concluded that 90% of their respondents agreed or strongly agreed that this low supply and lack of supply at reasonable costs in the EU forms a problem (European Commission, 2021b). For these reasons, the financial aspect of different SAF technology pathways is deemed an important aspect of the assessment and will therefore be included in this study.

Minimum selling price

Four of the identified studies in the literature research used the criterion 'minimum selling price' in their research (S. Ahmad et al., 2019; S. Ahmad & Xu, 2021; Chen & Ren, 2018; Braz & Mariano, 2018). When considering all the identified sub-criteria of the Economic aspects of the SAF technologies, the conclusion can be drawn that most of the sub-criteria are highly correlated with the sub-criterion Minimum Selling Price (MSP). The MSP tells the minimum selling price in which the costs are still covered. 'The costs' in this case are defined as the total fixed costs divided by the total produced volume plus the variable costs per unit produced. Under this definition, the sub-criterion 'Input energy use' is part of the MSP as the energy that is required for to produce a specific SAF technology influences the variable costs per unit produced. Same accounts for the sub-criteria 'Operations maintenance costs', 'Feedstock costs', and 'Transport costs'. These sub-criteria are all part of the costs that influence the MSP. Therefore, the decision is made to aggregate these sub-criteria under the 'Minimum Selling Price'.

Feedstock alternative use

The 'feedstock alternative use' is a criterion which is deemed relevant as there can be competition between the SAF producing industry and other industries that require biomass, solid waste streams of non-renewable origin or renewable sources other than biomass (e.g. renewable based hydrogen) as feedstock. For example, first generation biodiesel, which is used in road transport, also relies on the same feedstock as HEFA fuels for aviation (Sandquist & Guell, 2012). As an example, although the potential SAF production capacity in the EU amounts to an estimated 2.3 million tonnes per year, the EU biofuel producers optimise their production setup for other, non SAF, outputs. This is because the choice of biofuel producers favours road transport biofuels over aviation biofuels. This choice is driven by a higher return on investment and regulatory obligations (European Commission, 2021b,a).

Feedstock profitability

Furthermore, the decision is made to include 'feedstock profitability' as sub-criterion. This criterion is identified in the studies by S. Ahmad et al. (2019) and S. Ahmad & Xu (2021) and concerns the financial benefits in producing a specific feedstock. Besides, this criterion has large correlation with another criterion, 'internal rate of return', which is used in the study by Braz & Mariano (2018). Feedstock profitability is perceived as a relevant criterion because if a feedstock has no financial benefits, the financial incentives to invest in increasing the feedstock production lack and the feedstock supply will maintain at low level.

Plant capital costs
As a final sub-criterion, the sub-criterion 'plant capital costs' will be considered in this research. This criterion highly correlates with the criterion 'investment costs'. The decision is made not to consider both but to consider plant capital costs. The plant capital costs are considered in multiple identified researches and concern the costs related to the establishment of a SAF producing plant and accompanied required facilities. This criterion is considered as new SAF production plants will be required in order to comply with the SAF mandates by 2030 (European Commission, 2021a). Building new SAF production plants will result in high-risk and high upfront investment expenditures. High upfront costs are expected because the feasible SAF technologies require physical assets like pre-treatment, gasificiation or fermentation units. High risk is also involved here as there still is high uncertainty in policy framework and demand from SAF demaning companies like airlines (European Commission, 2021a). Moreover, these SAF producing plants tend to have long amortisation periods, which contributes to the investment risks. The impact assessment on the ReFuelEU report also emphasized these high upfront costs and their risks and concluded that 85% of the experts that were interviewed agreed or strongly agreed that high upfront costs and operational costs for novel conversion technologies are a challenge for the SAF producing industry (European Commission, 2021b).

Table 5 provides an overview of the selected sub-criteria that are selected to assess the economic performance of the SAF technology pathways considered in this research.

Table 5: Subset of criteria regarding economic performance

Main-criterion	Sub-criterion	Description
Economic	Minimum selling price	Expected minimum selling price of a SAF technology pathway
	Feedstock alternative use	Other uses of the specific feedstock aside from SAF production
	Feedstock profitability	Financial benefits of producing a specific feedstock
	Plant capital costs	Costs related to the establishment of a SAF producing plant and accompanied required facilities

Other sub-criteria are left out of further analysis. The identified sub-criterion 'Process integration with current refineries', which was identified in the study by S. Ahmad et al. (2019), has much to do with the technical aspects of a SAF technology and specifically correlates much with the sub-criterion 'Conventional jet fuel compatibility'. For this reason, this sub-criterion is left out of the economic part of this study. The decision is also made to exclude the criteria 'NPV', 'Return on Capital Employed', 'Internal Rate of Return', 'Long term supply contract', 'Revenue' and 'Resistance to Market Uncertainties' as these sub-criteria are case- and plant-specific and are therefore too specific for this study. Furthermore, the decision is made to exclude the criterion 'Competitive advantage'. This criterion is identified by representatives of the aircraft manufacturers stakeholder group in the study by S. Ahmad et al. (2019), but also this criterion is location/plant specific. Another point is that no further explanation or comments are given on what is meant by this criterion.

4.3.3 Technological performance

The technological criteria mainly consist of different chemical properties, technology developments, ease of implementation in the refining process, availability of feedstock and potential for this feedstock to scale up and the maturity/readiness of a certain SAF technology pathway.

Importance of criteria

SAFs are also associated with technical and performance issues. As argued in the framework by Feitelson & Salomon (2004), probably the most fundamental question is whether the innovation would be seen as technically feasible - that it can be used. It is argued that an innovation will only be adopted if this is technically feasible. Next to the primary question whether the production process of a specific SAF technology is feasible, the technical characteristics of an innovation like SAF technologies also refer to specific innovative elements that can help the technology to become technologically superior towards the other SAF technologies and therefore increase its chances of reaching dominance in the SAF market (Christensen et al., 1998). Currently, there are big differences in technological performance between the different SAF technology pathways. For example, some SAF technologies, like RFNBOs currently still exist only at demonstration phase and phase industrial challenges, while other technologies are at a technology market readiness level close to being commercially ready for market deployment (European Commission, 2021a). Because of the deemed importance whether a technology is technically feasible as argued in the framework by Feitelson & Salomon (2004), the technological aspects of SAF technology pathways are considered in this study.

Technology readiness level

Technology readiness is considered as this partly describes the development of a SAF technology and there are big differences in the technology readiness levels between different SAF technologies. Synthetic fuels for example, have significant potential to reduce GHG emissions but currently are at a low TRL. On the other side are crop based biofuels which are commercially mature and have a high TRL but cope with feedstock availability and raise sustainability concerns. Besides, the TRL/maturity has a lot to do with the learning orientation. "Learning orientation" is also identified as a factor that is of importance for a technology to become dominant in the study by van de Kaa et al. (2011). Research by Duncan (1979) describe the learning capabilities of a technology by which knowledge and the effects of the environment of these relationships is developed. Failure to invest in learning can decrease the likelihood of a technology to become dominant and increase its likelihood to become irrelevant and being locked out (Schilling, 2002). By learning, a technology can improve its know-how: the core capabilities and new knowledge-absorptive capacity (van de Kaa et al., 2011). This absorptive capacity includes technological know-how and market pioneering know-how (whether the technology can have technological breakthroughs and can be commercialized) (Agarwal et al., 2004). For these reasons, the TRL is considered an important criterion and is therefore included in this study.

Production volume scalability and availability

Another criterion that is identified as a factor of importance is 'production volume scalability and availability'. This criterion is an aggregated criterion of 'production scale of feedstock', 'production volume scalability', 'Domestic technological ability' and the related criterion 'SAF availability'. All these four criteria are related to scalability. Therefore, the decision is made that these three criteria are merged into one, slightly broader technological criterion, named 'Scalability and availability'. This scalability can provide economies of scale. The availability of SAF feedstock also has influence on economic aspects as it will partly determine the profitability of fuel distributors, as argued in the study by Turcksin et al. (2011). These economies of scale are currently not yet experienced by the SAF production industry as the production is still very limited. Therefore, the capital and operational costs are still high in comparison with conventional jet fuel (European Commission, 2021a). It is therefore that the European Commission emphasizes this feedstock availability in the Sustainable and Smart Mobility Strategy and tries to ensure sufficient feedstock availability for renewable and low carbon fuels in all transport and energy sectors towards a climate neutral economy (European Commission, 2022).
This makes that the technical performance will be evaluated by two sub-criteria; 'Technology Readiness Level' and 'Production volume scalability and availability', as can be seen in table 6.

Table 6: Subset of criteria regarding technological performance

Main-criterion	Sub-criterion	Description
Technological	Technology readiness level	Current development status of a SAF producing technology pathway
	Production volume scalability and availability	Availability and level of scalability of feedstock required for a certain SAF technology pathway

Other sub-criteria are left out of this study. The sub-criteria "Conventional jet fuel compatibility", "process integration", "ease of transport and storage" and "process flexibility", which are all taken into account in the studies by S. Ahmad et al. (2021) or S. Ahmad et al. (2019), are criteria that have slightly different meanings but can all be scaled under the term "compatibility". According to the study by van de Kaa et al. (2011), this is an important factor that can contribute to the market dominance of certain SAF technology. If a SAF is completely compatible with the current aviation infrastructure for transport, distribution and usage, this is considered as an important advantage. Fuels that are fully compatible, are labeled drop-in fuels. For these benefits in compatibility, the focus of the European Commission in their mandate is on drop-in fuels only. Moreover, in the ReFuelInitiative, the European Commission proposes to help airports with providing information on the infrastructure available allowing for seamless distribution and refuelling of aircraft operations with SAF, provided that these airports are located within EU memberstates (European Commission, 2021a). So although these sub-criteria are relevant, they're irrelevant for this study as all of the SAF technologies that are promoted by the European Commission are drop-in fuels. Also, the decision is made to exclude 'blending limit' in this study. This criterion concerns the maximum certified blending limit of a SAF with conventional jet fuel but the fuels considered in this study have maximum blending limits of 50% and are labeled as drop-in fuels which are entirely fungible with conventional kerosene and don't require any adaptions of engines (IATA, n.d.).

In underlying figure 9, an overall overview of the main-criteria and sub-criteria is presented which are considered in this study to assess the experts' preference regarding SAF technology pathways.

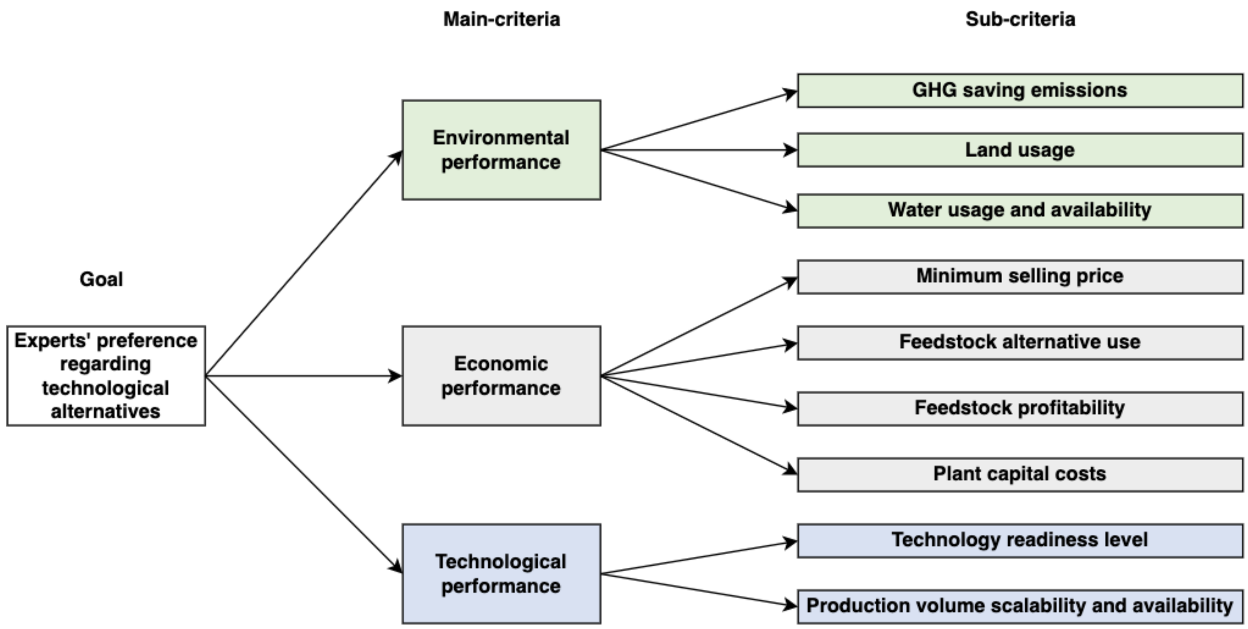


Figure 9: Shortlist of main-criteria and their sub-criteria used to evaluate the different SAF technology pathways

5 Obtaining criteria weight

This chapter is devoted to addressing the third sub-question, namely: *"What are the perceived relative weights of these criteria and their corresponding sub-criteria?"*. In this chapter, the identified main-criteria and their corresponding sub-criteria derived from the latter sub-questions, sub-question 2, are weighted with the use of the Bayesian Best-Worst Method (BWM).

5.1 Interviews with experts in the aviation industry and brief description of interviews

In order to derive an answer to this sub-question, interviews with experts in the aviation industry were held. These interviews were structured interviews as the interviews were constructed by using the imposed structure of the BWM. All the interviews were performed online using Microsoft Teams. The interviews began with a general introduction after which the structure of the interview and the background section were provided. In the general introduction, it was explicitly mentioned that the interviewee should answer from the perspective of his/her expertise as the goal of this study is to gather experts' preferences. After this was made clear, the main-criteria and sub-criteria were explained and the Best-Worst Method was explained. Depending on the interviewee his/her understanding, more time was spent on explaining the Best-Worst Method. The next step was the application of the BWM after which a recap was held. To guarantee reproducibility of this study, a more elaborate version on how these interviews were performed can be seen in appendix 12.

After the BWM was performed, a reflection session was held. In this reflection, it was questioned whether the interviewee agreed on the main-criteria and sub-criteria that are used in this study. E.g., the interviewee could argue that there were some criteria missing or that he/she would leave some criteria out of scope. Furthermore, the question whether the respondent agreed on the selection of the selected SAF technology pathways included in this study. This reflection is considered an essential step of the application of the BWM as it can address possible limitations of this study. The results of this reflection section and the corresponding limitations of this discussion will be addressed in the discussion of this study (section 7). Finally, it was questioned whether the respondent had any feedback on the BWM itself.

As a final step during the interview, the respondent was thanked for his/her participation in this study and they were asked if they had any recommendations for other possibly suitable and interested experts to participate in this study. Contact details were exchanged in this final step to send the analysis of the BWM afterwards. Shortly after the interview, the afterwards analysis was sent to the interviewee and it was questioned whether the interviewee agreed on the analysis, if anything was misunderstood and it was questioned whether this respondent agreed on possibly using his/her quotes from the interview to discuss the findings of the interview.

5.2 Selection of experts

As this research compares different SAF technology pathways on a broad range of different criteria, not everyone can be interviewed for this study. To give a valuable answer, substantial expertise and working experience is needed. Therefore, a critical selection was held and only experts with substantial expertise on sustainable aviation fuels and work experience in the aviation industry were selected for this study. This selection was performed by checking possibly suitable 'experts' their background and years of working experience. If any doubt arose on their expertise, they were asked if they considered themselves an expert on the field of sustainable aviation, sustainable aviation fuels and the aviation industry. Besides, the list of considered main-criteria and corresponding sub-criteria was shown if any uncertainty arose if they would have sufficient knowledge on the content of all the criteria. The considered SAF technology pathways were also shown for the same reason. Anonymity was guaranteed when participating in the study, which is why some characters have been anonymised. All the interviewees were either contacted via email, phone or by the social media platform Linked-In. In total, eleven experts were interviewed. Table 7 shows the characteristics of the interviewed experts.

Table 7: Characteristics of interviewees

#	Area	Function/Expertise	Indication years of experience
A	SAF producer	Analyst future fuels. Contributes to research and events to expand knowledge on sustainable air travel	1-5 year(s)
B	Airline industry	Sustainability consultant & SAF portfolio holder. Developing sustainability strategy of the company and coordinating sustainability projects. Designing sustainability governance	5-10 years
C	SAF producer	SAF business development manager. Expertise in hydrogen and carbon capture and storage (CCS) technologies	5-10 years
D	SAF producer	Vice president of renewable aviation. Accountability for SAF sales in the continental region. Background in M&A and corporate finance in the global energy sector	15-20 years
E	SAF consumer	Senior manager corporate sustainability and program manager of circular economy. Trying to achieve 100% climate neutrality within the company for which this person works	5-10 years
F	SAF expert/ consultant	Business strategist for energy and sustainable development. Expertise in renewable energy, biofuels, SAF and marine biodiesel	1-5 year(s)
G	SAF expert/ consultant	Expert sustainable transport and tourism. Specialist environmental impacts of tourism and tourism transport in general and climate change mitigation in particular. Former aircraft design engineer	25+ years
H	Airline industry	Senior director, sustainability strategy, Global enterprise sustainability. Leading aviation climate strategy and Sustainable Aviation Fuel (SAF) program. Developed global carbon offset program (CORSIA) and airplane CO_2 emissions standard at UN International Civil Aviation Organization (ICAO)	25+ years
I	Airline industry	Program manager for one of the airline companies which is a member of the sustainable flight challenge	1-5 year(s)
J	SAF expert/ consultant	Researches the development of advanced biofuels and their financing. Advisor on the development of biofuels	10-15 years
K	Airline industry & SAF expert/ consultant	Sustainable aviation fuels Specialist and ETS specialist	5-10 years

5.2.1 Different stakeholder groups in the SAF industry

Apart from the requirement of having substantial knowledge to participate in this study, it is also an important part to reflect different perspectives of a potentially diverse group of stakeholders. Therefore, a brief stakeholder analysis is performed to indicate relevant parties/stakeholder groups who have vested interests in the development and deployment of SAF and could potentially influence the acceleration of this development and deployment. The stakeholder groups are classified into different categories depending on their main business and the nature of their organisation. The stakeholder analysis and the different classifications are shown below in figure 10.

Figure 10: SAF stakeholder groups

5.3 Inconsistency ratios

Before deriving the weights for each criterion, it needs to be checked whether expert answered in a reliable way when making comparisons. This is necessary because inconsistency when performing these pairwise comparisons is proven to be a significant challenge in practice (Herman & Koczkodaj, 1996; Rezaei, 2015). When questioning the expert to perform these pairwise comparisons, checking the acceptable inconsistency is therefore an important step. As an inconsistent analysis can blur the outcome of the analysis, the decision is made to exclude the experts who made inconsistent pairwise comparisons that exceed any of the acceptable inconsistency values. The study by Liang et al. (2020) is used to obtain the maximum level of inconsistency that an expert can have in his/her analysis before being considered as inconsistent. The maximum levels of inconsistencies from this study are shown in table 9. The maximum inconsistency ratios that apply to the comparisons made in this study are shown in bold in this table 9. In this study, four pairwise comparison sessions are held (one for the main-criteria, and one for each of the three sub-criteria). The BWM application for the main-criteria and the environmental criteria consists of three criteria and the interviewees can answer on a scale from 1 to 9, therefore the maximum allowed inconsistency is 0.1359. The BWM application for the economic criteria consists of four criteria. Also here, the interviewees can answer on a scale from 1 to 9, so therefore, the maximum allowed inconsistency is 0.2681. The technological BWM application only consists of two sub-criteria which automatically causes that the expert cannot make inconsistent comparisons. So as a first step of analysing the results of the performed interviews, the inconsistencies are checked. The inconsistency ratios of the interviews are shown in table 8. It can be noted from this table that none of the experts had higher inconsistency ratios than maximum allowed. Therefore, all the performed BWM comparisons can be considered consistent and none of the experts need to be excluded from further analysis. Another minor thing that can be noted from this table, is that the average inconsistency for the economic sub-criteria is slightly higher when compared to the other average inconsistencies. As it is harder for respondents to make consistent pairwise comparisons when more criteria are taken into account , this explains the higher average of inconsistency ratios for the economic sub-criteria which considers four sub-criteria while the pairwise comparisons for the main-criteria and the environmental criteria only considered three sub-criteria (Liang et al., 2020). It is also for this reason that the maximum inconsistency ratios allowed increase when the number of considered criteria gets bigger, as can be seen in table 9.

Table 8: Inconsistency ratios of the experts

Pairwise comparison session	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**K**	**Average inconsistency**
main-criteria	0.042	0.089	0.077	0.089	0.123	0.036	0.053	0.000	0.109	0.089	0.109	0.074
Environmental criteria	0.104	0.089	0.126	0.000	0.066	0.000	0.000	0.000	0.111	0.000	0.123	0.056
Economic criteria	0.091	0.161	0.052	0.000	0.135	0.192	0.137	0.089	0.015	0.000	0.171	0.095
Technological criteria	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Table 9: Maximum inconsistency ratios according to study by Liang et al. (2020)

Scales	**3 criteria**	**4 criteria**	**5 criteria**	**6 criteria**	**7 criteria**	**8 criteria**	**9 criteria**
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	0.2577	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

5.4 Obtained group decision-making main-criteria weights

This section will discuss the obtained optimal group weights for the main-criteria. When considering the optimal group weights in this section, all experts within all the four considered stakeholder groups are considered simultaneously. This can therefore be seen as the average off all considered experts together. The obtained group weights per stakeholder group, will be discussed later in section 5.6.

In the underlying table, table 10, the optimal group weights of the three main-criteria are shown. These optimum weights are constructed by using the Bayesian BWM as this tool is constructed to calculate the group decision-making weights and arrives at more reliable criteria weights when compared to the initial BWM, as mentioned earlier on in section 2.2.4. In addition to deriving the weights, the Bayesian BWM provides a ranking scheme for the criteria. This is called the credal ranking of the criteria and shows a weighted directed graph on which the interrelations between the criteria are given. The Bayesian BWM also provides information on the certainty that a criterion is more important/has a higher weight than another criterion in this directed graph. This is called the confidence level (CL). So the CL shows whether the rankings of the criteria, based on their weights, are consistent with the evaluation of all considered experts. The closer the CL is to 1.0, the more evident the degree about the certainty of the relation (Mohammadi & Rezaei, 2020). The traditional ranking of criteria can be performed by applying a threshold value of 0.5 to the credal ranking (Mohammadi & Rezaei, 2020).

Table 10: Optimal group decision-making weight per main-criterion

Main-criterion	Group decision-making weight
Environmental performance	0.380
Economic performance	0.321
Technological performance	0.299

Table 10 shows the obtained group weights for all the experts within all of the four considered stakeholder groups together. From this table, it can be seen that the "Environmental performance" is the most important main criterion for determining experts their preference regarding the upscale potential and feasibility for the SAF mandates by 2030. This main criterion has a weight of 0.380 and implies that, on average, experts assign more value to the environmental performance of a SAF when assessing a SAF, rather than the technological or economic performance. According to expert D, it is obvious that the environmental performance is the most important main criterion as it makes no sense to develop and further upscale SAF technology pathways if these pathways don't have substantial environmental benefits over conventional jet fuels. Also expert C was determined in his/her decision on which main-criterion is the most important criterion as this expert argued that in the end, only SAF pathways with well developed environmental and sustainable benefits will be scaled up, despite the price that needs to be payed for this.
However, not all experts considered the environmental performance the most important main criterion as the environmental performance is perceived as the most important main criterion in 5 out of the 11 performed interviews while in 4 out of the 11 performed interviews it was considered as the least important main criterion. This therefore affects the confidence level of the relationship between the environmental performance and the economic performance as well as the confidence level between the environmental performance and the technological performance. As the weights of the three main-criteria are relatively close to each other, this may not be surprising. So when providing the obtained group weights for the four stakeholder groups together, no full certainty can be granted for the environmental performance being more important than the other two main-criteria.
This can also be seen in the credal ranking and provided confidence levels of the relationships between the three main-criteria. These are presented in figure 11, which shows the visualisation of the outcomes using a weighted directed graph, as proposed in the study by Mohammadi & Rezaei (2020). As the CL of the environmental performance over the two other main-criteria in both cases is relatively low, the certainty of the environmental performance being more important than the other two main-criteria should be interpreted carefully and is not very sure. The uncertainty of the relations between the three main-criteria is also addressed by expert H as this expert argued that all the three main-criteria are equally important as it makes no sense to prefer one above the other two if one of these two other main-criteria is seriously lacking. This expert argued that all the three main-criteria should comply with a minimum required level before you can make solid comparisons between the importance of the main-criteria.

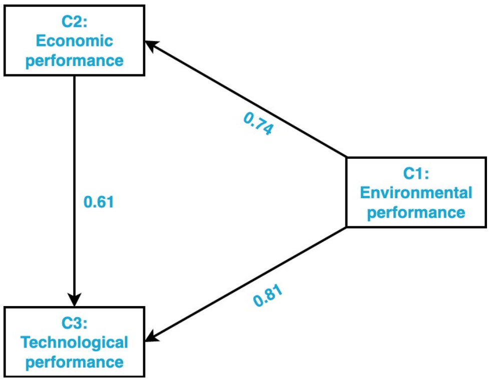


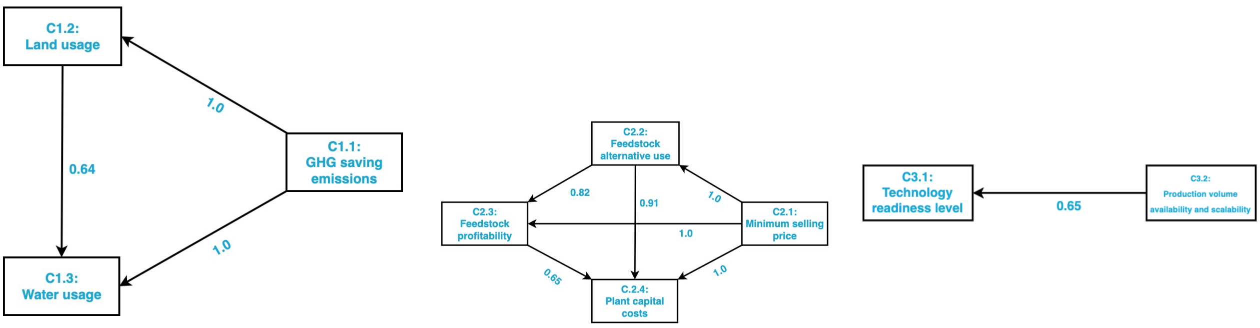
Figure 11: Credal ranking and confidence level of main-criteria

5.5 Obtained group decision-making sub-criteria weights

After the weights of the main-criteria are established, the global optimal group weights of the sub-criteria can be constructed. The global weight of a sub-criterion is constructed by multiplying its local weight by the weight of its corresponding main-criterion. The local weight of a sub-criterion can be used to compare to the other sub-criteria that belong to the same main-criterion with each other while the global weight of a sub-criterion can be used to compare with other sub-criteria regardless of its main-criterion. Table 11 shows the obtained optimal local and global group weights.

Table 11: Obtained local and global weight main- and sub-criteria for all stakeholder groups together

Main-criteria	Weight main	Sub-criteria	Local weight	Rank within category	Global weight	Overall rank
ENV (C1)	0.380	GHG SE (C1.1)	0.574	1	0.218	1
		LU (C1.2)	0.221	2	0.084	5
		WU (C1.3)	0.204	3	0.078	6
ECO (C2)	0.321	MSP (C2.1)	0.441	1	0.142	3
		FAU (C2.2)	0.230	2	0.074	7
		FP (C2.3)	0.187	3	0.060	8
		PCC (C2.4)	0.141	4	0.045	9
TECH (C3)	0.299	TRL (C3.1)	0.470	2	0.141	4
		PVA&S (C3.2)	0.530	1	0.158	2



(a) Credal ranking and CL of environmental sub-criteria

(b) Credal ranking and CL of economic sub-criteria

(c) Credal ranking and CL of technological sub-criteria

Figure 12: Credal ranking and confidence levels for sub-criteria within the three main-criteria

5.5.1 Environmental sub-criteria

Table 11 shows that out of all sub-criteria, the 'GHG saving emissions' (C1.3) is perceived as the most important sub-criterion for assessing SAF types their feasibility and upscale potential for the proposed SAF mandates by

2030 and has a global weight of 0.218. This implies that the interviewed experts assign the most value to this sub-criterion. When looking at this sub-criterion, it can be seen that it relates to the most-important main-criterion as well, the environmental performance (C1). When looking at the credal ranking and confidence levels within the environmental sub-criteria (as shown in figure 12a), the certainty of the relation between the sub-criterion 'GHG saving emissions' and the other two sub-criteria within this main-criterion can be noted. For both relations, the confidence level of the relationships is 1.0, which is the highest obtainable value. In other words, we can be very sure about the fact that GHG saving emissions is more important than 'land usage' (C1.2) and 'water usage' (C1.3). This CL of 1.0 may not be so surprising as nine out of the eleven respondents argued that the 'GHG saving emission' was the most important environmental sub-criterion. The other two experts, expert F and expert D, argued that GHG saving emissions was equally important to 'land usage' or 'water usage'. No expert argued that another sub-criterion was more important than this sub-criterion. One could argue that it is not surprising that this sub-criterion is identified as the most important sub-criterion by the experts as in the introduction, section 1, it is argued that the International Civil Aviation Organization (ICAO) adopted a carbon-neutral growth goal for the international aviation industry (Wise et al., 2017). This goal requires a 50% carbon emission reduction from 2005 levels by 2050. In the introduction it is also argued that despite expected vast improvements in energy efficiency and operations, SAFs are necessary to accomplish the goal by the ICAO (Federal Aviation Administration, 2015). Therefore, the GHG saving potential of a SAF is a key indicator to evaluate its performance. The credal ranking in figure 12a also shows that 'land usage' is the second most important sub-criterion within the environmental performance, closely followed by the sub-criterion 'water usage'. The given CL for this relationship however is relatively low as it has a value of 0.64 out of 1.0. Therefore, the certainty that 'land usage' is more important than 'water usage' should be interpreted carefully. Furthermore, difference can be observed between experts. Most experts argued for a low importance of these criteria, while other experts emphasized the importance of these two sub-criteria. For example, expert A and expert B argued that these two sub-criteria are not relevant as the geographical scope of this study is Europe and the time horizon for this study set at 2030 while expert G argued that these two other sub-criteria within the environmental main-criteria are also very important criteria to considered. This expert G argued that although these sub-criteria might not play a major role nowadays, this expert argued that these two would become more important when a large upscale occurs in the future.

5.5.2 Economic sub-criteria

Table 11 also shows the importance of the sub-criterion 'Minimum selling price'(C2.1). This sub-criterion is the third most important sub-criterion out of all sub-criteria and implies that after GHG saving emissions and production volume scalability and availability, experts' assessment of different SAF types is mostly influenced by this sub-criterion. Besides, it is this sub-criterion that is considered the most important sub-criterion within the 'Economic performance'(C.2). This implies that the economic performance of SAF types is mostly influenced by its expected minimum selling price. When considering the credal ranking and the confidence levels in figure 12b, it can be seen that the certainties that the 'Minimum selling price' are more important than the three other sub-criteria within the economic main-criterion are all unquestionable since the CL of all the three relations has the maximum obtainable value of 1.0. Expert B argued that the MSP is the most important sub-criterion and that most of the sub-criteria are in some way, directly or indirectly, related to this sub-criterion. This expert argued that if a certain SAF technology pathway lacks on an environmental criterion, this doesn't matter as this can be compensated by its environmental performance. Another thing that can be noted from table 11 is the relatively low importance of the other three sub-criteria that are considered within the economic main-criterion. These three sub-criteria together form the three least important sub-criteria in global weights. This is not surprising as these three criteria are correlated with the MSP as expert B and J also argued during their interviews. Expert F argued that the 'Plant capital cost' is totally irrelevant for the potential of a SAF technology pathway as long as technology is sufficiently developed. This expert argued that if this technology readiness level is developed well enough, acquiring financial needs to build a SAF production plant would not be an issue. Also, according to this expert F, the high upfront costs when building a SAF plant would would have no inhibitory effect on a SAF technology pathway potential.

5.5.3 Technological sub-criteria

'Production volume availability and scalability' (C3.2) is perceived as the second most important sub-criterion, after the earlier mentioned most important sub-criterion 'GHG saving emissions' (C1.3). This suggests that the availability of the required feedstock and the expected scalability of the required feedstock for a certain SAF technology pathway also significantly affects the assessment of the considered SAF pathways. Looking at the credal ranking of the technological main-criterion in figure 12c, this sub-criterion is perceived as more important than the other sub-criterion, the technology readiness level. However, in this same figure, it can be noted that the confidence level of this relationship is not very certain as it has a value of 0.65. The relatively low CL is due to different opinions within different stakeholder groups and will be discussed more elaborately in section 5.6 where the obtained weights per stakeholder group will be discussed. The second sub-criterion within the technological main criterion is the 'technology readiness level' of a SAF pathway. This sub-criterion has a weight of 0.141 and is therefore quite an important sub-criterion as well. Multiple experts argued for a large role of this sub-criterrion given the relatively short timespan for the 2030 SAF blending mandate. Expert D summarised the relationship between both technological sub-criteria with the following quote "If the time horizon for this assessment would be 2050, the production volume scalability would be extremely more important than the technology readiness level. However, the time horizon for this study is set at 2030. Given this short timespan, the technology readiness level is way more important than the potential to upscale".

5.6 Obtained group decision-making criteria weights per stakeholder group

This section will consider the obtained group decision-making weights per stakeholder group. First, in subsection 5.6.1, the obtained weights for the main-criteria will be discussed per stakeholder group after which subsection 5.6.2 will elaborate on the differences between the four stakeholder groups within the sub-criteria.

5.6.1 Obtained main-criteria weights per stakeholder group

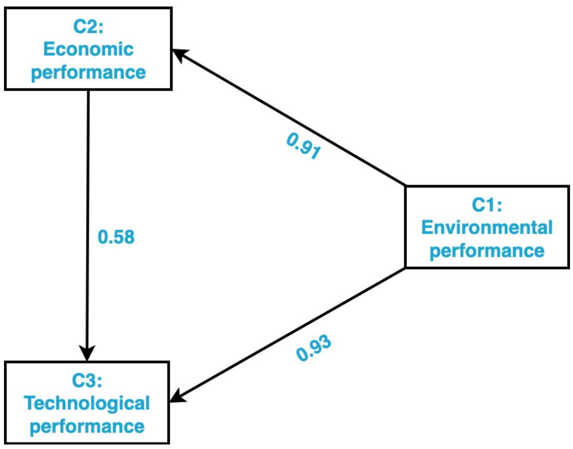
This section will dive deeper in the weights of the main-criteria by providing the obtained weights per stakeholder group and by showing the credal ranking and confidence level of the main-criteria, also per stakeholder group.

Table 12: Optimal group decision-making weight per main-criterion per stakeholder group

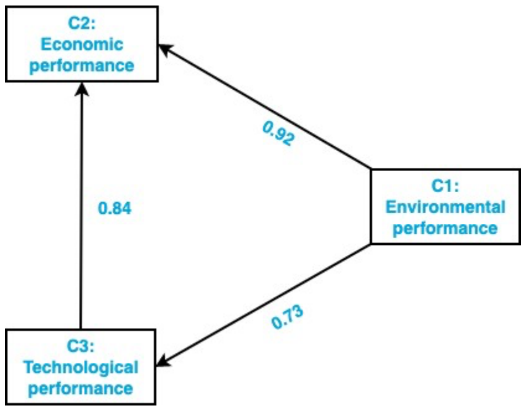
Main-criterion	Weight SAF producers	Weight SAF consumers	Weight airline industry	Weight experts
Environmental performance	0.496	0.522	0.161	0.526
Economic performance	0.264	0.144	0.457	0.269
Technological performance	0.240	0.334	0.382	0.205

Table 12 shows the obtained group decision-making weights per stakeholder group. In this table it is noticeable that weights of the stakeholder group airline industry deviate significantly from the weights of the other three stakeholder groups. It can be seen that the airline industry assigns more value to economic performance compared to the other three stakeholder groups. The airline industry devotes the economic main-criterion a weight of approximately 0.46 which means that almost half of the total weight is devoted to this main-criterion, while the other three stakeholder groups all identify environmental performance as most important main criterion. It can also be noticed that the airline industry devotes a remarkable lower weight to the environmental performance when assessing SAF types. With a weight of just 0.16, this is significantly lower than the other three stakeholder groups. As the other stakeholder groups attain a substantial higher value to the environmental performance and a lower weight for the economic performance, the airline industry is in large contrast compared to the other stakeholder groups. What's also noticeable from table 12 is the low weight of the economic main-criterion for the SAF consumer stakeholder group. Expert E argued for this low importance of this main-criterion because SAF consumers voluntarily purchase SAF for their flight(s) and accept the fact that SAF is currently more expensive than conventional jet fuel. Therefore, the economic performance of a SAF would therefore be of a low importance for the SAF consumer. This expert argued that a SAF consumer would rather look at the environmental performance as this is the main aspect for a SAF consumer to purchase SAF voluntarily.

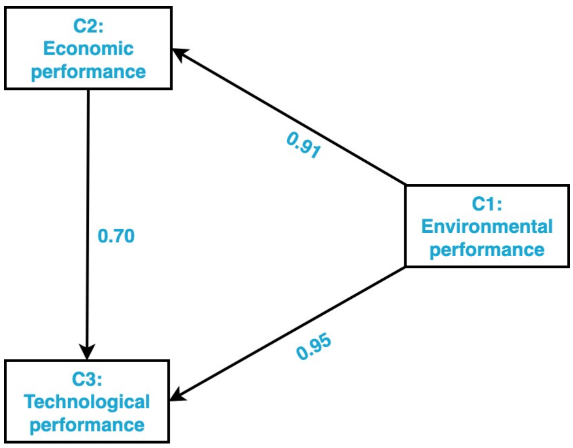
When looking at the credal ranking and CL of the airline industry in figure 13d, it can be noticed that the relationships between the environmental main-criterion and both other main-criteria are very certain as they have a confidence level of 1.0 and 0.99. This means that one can say that it is very sure that the environmental main criterion is less important than the other two main-criteria within the airline industry. Another remarkable aspect is that when looking at the credal rankings per stakeholder group in figure 13, we generally see higher confidence levels than when all the stakeholder groups are considered together in figure 11. As the airline industry deviates from the other three stakeholder groups, this causes the lower CL values when all stakeholders are considered together (see section 5.4).



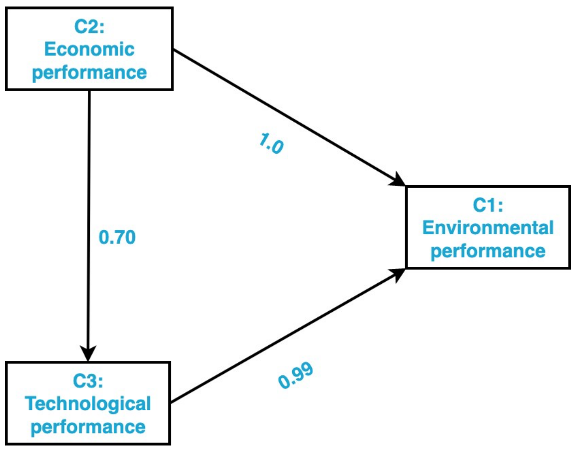
(a) Producers' credal ranking and confidence level of main-criteria



(b) Consumers' credal ranking and confidence level of main-criteria



(c) Experts' credal ranking and confidence level of main-criteria



(d) Airline industries credal ranking and confidence level of main-criteria

Figure 13: Credal ranking and confidence level of the main-criteria per stakeholder group

5.6.2 Obtained sub-criteria weights per stakeholder group

This subsection provides the obtained local and global weights for the main-criteria and sub-criteria for the different stakeholder groups and the differences between these weights are discussed. Differences between the weights of different stakeholder groups are discussed below and quotes are provided which further elaborate on why these weights were given during the interviews.

Obtained weights for the expert/consultant group
Table 13 shows the obtained weights for the first stakeholder group, the expert/consultant group. Compared to the obtained weights of all stakeholder groups together, the obtained weights of the expert group devote higher weights to the environmental main- and sub-criteria. It can be noticed that the environmental sub-criterion 'water usage' makes a jump in overall rank as this sub-criterion is in this case the second-most important sub-criterion, instead of being ranked at the sixth place in the overall analysis. The low weight of the sub-criterion 'production volume availability and scalability' is also striking. In the overall analysis, this sub-criterion is ranked as second most important criterion while the experts attain a significantly lower weight to this sub-criterion.

Table 13: Obtained local and global weight main- and sub-criteria for the expert group

Main-criteria	Weight main	Sub-criteria	Local weight	rank in category	Global weight	Overall rank
ENV (C1)	0.526	GHG SE (C1.1)	0.500	1	0.263	1
		LU (C1.2)	0.181	3	0.095	4
		WU (C1.3)	0.319	2	0.168	2
ECO (C2)	0.269	MSP (C2.1)	0.309	2	0.083	7
		FAU (C2.2)	0.343	1	0.092	5
		FP (C2.3)	0.175	3	0.047	8
		PCC (C2.4)	0.173	4	0.047	9
TECH (C3)	0.205	TRL (C3.1)	0.578	1	0.119	3
		PVA&S (C3.2)	0.422	2	0.087	6

Obtained weights for the producer group

The obtained weights for the producer group are shown in table 14. Also this stakeholder group attains little weight for the sub-criterion 'production volume availability and scalability'. On the other hand, this stakeholder group attains more value to the other sub-criterion within the technological performance, the 'technology readiness level'. With a devoted weight of 0.174 this sub-criterion is considered as the second most import sub-criterion. The importance of this criterion is explicitly mentioned by expert C as this expert argued that for the SAF producing industry, it would make no sense to invest largely in technologies that are still far away from achieving market readiness. Only SAF pathways with either already high technology readiness levels or pathways with promising expectations are interesting, according to this expert.

Table 14: Obtained local and global weight main- and sub-criteria for the producer group

Main-criteria	Weight main	Sub-criteria	Local weight	rank in category	Global weight	Overall rank
ENV (C1)	0.496	GHG SE (C1.1)	0.600	1	0.298	1
		LU (C1.2)	0.246	2	0.122	3
		WU (C1.3)	0.154	3	0.076	6
ECO (C2)	0.264	MSP (C2.1)	0.323	1	0.085	4
		FAU (C2.2)	0.177	4	0.047	9
		FP (C2.3)	0.299	2	0.079	5
		PCC (C2.4)	0.201	3	0.053	8
TECH (C3)	0.240	TRL (C3.1)	0.727	1	0.174	2
		PVA&S (C3.2)	0.275	2	0.066	7

Obtained weights for the consumer group

The obtained weights for the consumer group are shown below in table 15. This stakeholder group attains a much value to the environmental performance and attaches little value to the economic performance of a SAF pathway. As mentioned in the previous subsection, according to expert E this is since a SAF consumer already accepts the fact that SAF is substantially more expensive than conventional jet fuel and is still willing to buy SAF on voluntarily basis. Within the environmental main-criterion, it is mainly the 'GHG saving emission' sub-criterion that makes up the total weight of this main-criterion. With a global weight of 0.338, a SAF its performance on this sub-criterion makes up over a third of the total weight. Compared to the other three stakeholder groups, who also devote a large weight to this sub-criterion, this still is a substantial difference. The relatively high weight obtained for the 'production volume availability and scalability' is another difference that strikes the eye.

Table 15: Obtained local and global weight main- and sub-criteria for the consumer group

Main-criteria	Weight main	Sub-criteria	Local weight	rank in category	Global weight	Overall rank
ENV (C1)	0.522	GHG SE (C1.1)	0.647	1	0.338	1
		LU (C1.2)	0.221	2	0.116	3
		WU (C1.3)	0.132	3	0.069	6
ECO (C2)	0.144	MSP (C2.1)	0.498	1	0.072	5
		FAU (C2.2)	0.231	2	0.033	7
		FP (C2.3)	0.156	3	0.022	8
		PCC (C2.4)	0.115	4	0.017	9
TECH (C3)	0.334	TRL (C3.1)	0.219	2	0.073	4
		PVA&S (C3.2)	0.781	1	0.260	2

Obtained weights for the airline industry group

Table 15 shows the obtained weights for the last stakeholder group, the airline industry group. As mentioned in the previous subsection, it is this stakeholder group who deviates the most compared to the other three stakeholder groups. The airline industry devotes a substantial lower weight to the environmental performance of a SAF while it rewards a substantial higher weight for both the technological and the economic performance. Logically, the three sub-criteria within the environmental main-criteria have a lower weight and it is only within this stakeholder group that the sub-criterion 'GHG saving emission' isn't the most important sub-criterion. What is noticeably, is that for the airline industry, both 'minimum selling price' and 'production volume availability and scalability' have paramount global weights. The two sub-criteria have a combined weight of 0.559, which means that the total performance of a SAF pathway heavily relies on the performance on these two sub-criteria and rewards only little value to the other seven sub-criteria. The major role of the performance on the 'minimum selling price' was expressed by expert B with the following quote: "for the large-scale deployment of SAF, it is primarily important to us what the price will do over the years. If it's not attractive, then it's over for us because we're not pioneers and the momentum is not there yet from the consumer side".

Table 16: Obtained local and global weight main- and sub-criteria for the airline industry group

Main-criteria	Weight main	Sub-criteria	Local weight	rank in category	Global weight	Overall rank
ENV (C1)	0.161	GHG SE (C1.1)	0.527	1	0.085	3
		LU (C1.2)	0.214	3	0.034	9
		WU (C1.3)	0.259	2	0.042	8
ECO (C2)	0.457	MSP (C2.1)	0.538	1	0.246	2
		FAU (C2.2)	0.177	2	0.081	4
		FP (C2.3)	0.137	4	0.063	7
		PCC (C2.4)	0.149	3	0.068	6
TECH (C3)	0.382	TRL (C3.1)	0.180	2	0.069	5
		PVA&S (C3.2)	0.820	1	0.313	1

A visualisation of the global optimum weights for all main- and sub-criteria for each stakeholder group is shown in figure 14. With this graph, it can easily be noticed that it is mainly the airline industry which deviates from the other three groups.

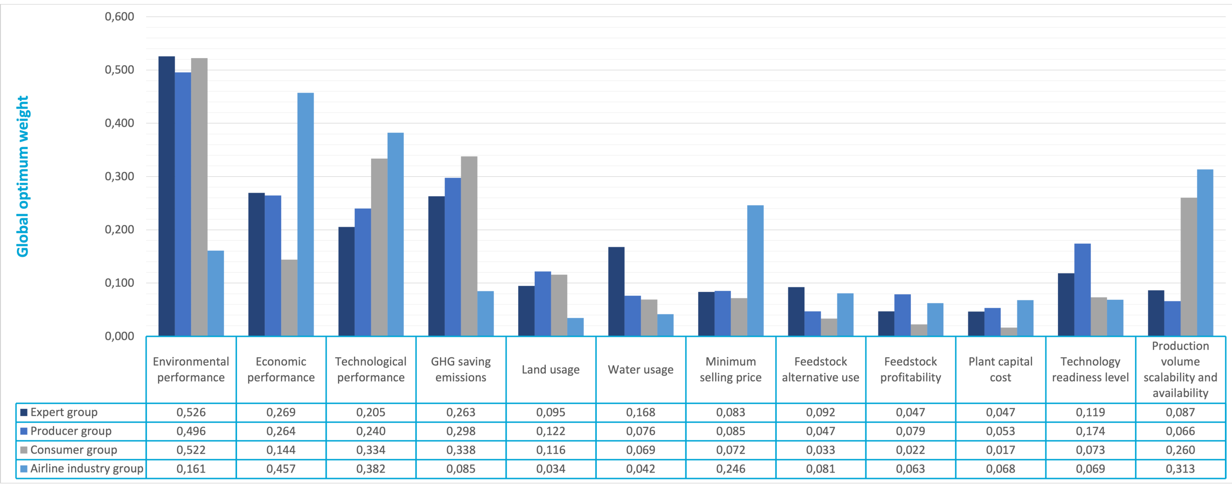


Figure 14: Visualisation of global optimum weights for all main- and sub-criteria per stakeholder group

6 Scoring the considered SAF technology pathways on the criteria

The output of sub-question 1 is a selection of SAF technologies and SAF technology pathways that will be considered in this study. The selection of relevant main- and sub-criteria is the final product of sub-question 2 and 3 is proposed to derive the global weights for all the main- and sub-criteria. Now that all these sub-questions are answered, this chapter integrates the results of these latter sub-questions to establish the experts' preference regarding the selected SAF technology pathways. It uses the SAF technology pathways from sub-question 1 by using the identified criteria from sub-question 2 and the obtained optimal group weights from the Bayesian Best-Worst Method which is applied in sub-question 3. So by combining the results of the latter sub-questions, the following fourth and final sub-question can be answered: *Given these criteria and their obtained optimum weights, how do the different SAF technology pathways score and compare in terms of performance and preference?* The first section of this chapter is constructed from three subsections in which the score cards of the sub-criteria with respect to each of the three main-criteria are discussed. The second section provides the total score card of the pathways considered. The third section provides the final scores and ranking of the pathways that are constructed by using the obtained group decision-making weights for all the stakeholder groups together. The final section of this chapter will discuss what differences there would be if only one certain stakeholder group would be selected and how this influences the preferences and therefore influence the ranking of the SAF pathways.

6.1 Literature study to acquire the performance score on the criteria

In order to come to a score per SAF technology pathway and therefore complete the MCDM, a score card needs to be established. During the interviews, it quickly became clear that the interviewee would need to have a substantial expertise and moreover broad knowledge on the performances of the different SAF types on all the considered criteria to come to a well-balanced score card. As not all the respondents had this knowledge and therefore could influence the outcome of the scoring process, the decision was made to establish these score cards via literature as this is a conventional way to do so if experts need to have substantial in-depth knowledge. This method, obtaining the score cards through extensive literary research, has been successfully performed in prior Multi Criteria Decision-Making (MCDM) studies (Brispat, 2017; Ellens, 2018). Besides, for establishing the scores, literature was sought and used that provides information on as many as possible considered SAF technology pathways simultaneously per sub-criterion. By trying to use as little different sources possible per sub-criterion and establishing the score cards on a limited number of different sources, the score cards are more reliable and comparisons between the scores can be made in a more valid way. For most of the sub-criteria, there's sufficient literature available to derive at a score card to quantify the performance of this SAF technology pathway on this specific sub-criterion. However, after an extensive literature study in order to find data to establish score cards for the sub-criterion 'Feedstock profitability' (C2.3), it turned out that there's hardly any data available to construct scientifically backed score cards for this sub-criterion. For this reason and for the fact that the weight of this sub-criterion is minor, the decision is made to establish the score cards of this criterion based on the opinion of two SAF experts as they both had substantial expertise to come to well considered score cards for this sub-criterion. This way of deriving score cards is also a convenient method and has been used in earlier performed studies that make use of the BWM (Kalpoe, 2020; Janssen, 2019). The rest of the scores for the sub-criteria are established by consulting earlier performed studies that provide insights on the performances of the SAF technology pathways on these sub-criteria.

6.1.1 Environmental performances

The following table, table 17, gives the score cards of the SAF technology pathways on all considered sub-criteria. Argumentation and references that are used to establish these scores are addressed in the following section.

Table 17: score card environmental sub-criteria

Sub-criterion	Score					
	FT-MSW	FT-Forest residue	ATJ-Sugarcane	HEFA-UCO	PtL-PSC	PtL-DAC
GHG SE (C1.1)	7	9	6	6	9	10
LU (C1.2)	10	10	3	10	9	9
WU (C1.3)	3	3	7	5	6	9

GHG saving emissions. To come to a score card for the performance of the SAF pathways a limited number of studies is consulted. This is done on purpose as this enhances the reliability of the score cards and makes comparisons between the scores more valid, as argued before. These are addressed below per SAF technology pathway:

- FT-MSW. For the conversion of MSW to SAF through gasification-FT, the GHG saving emissions are 83% as argued in the study by Pavlenko et al. (2019). The study by European Commission (2021a) argues similar GHG saving emissions (85%) when MSW is used as feedstock for this technology. Therefore, this SAF pathways scores a 7/10.

- FT-Forest residues. GHG saving emissions can be up to 95% when this feedstock type is used, according to the study by Bosch et al. (2017). Therefore, score 9/10.

- ATJ-Sugarcane. 70% GHG saving emissions, according to studies by Bosch et al. (2017) and European Commission (2021a). Score 6/10

- HEFA-UCO. 69% GHG saving emissions, according to studies by Bosch et al. (2017) and European Commission (2021a). Score 6/10

- PtL-PSC. Theoretically this could be 100%. This can be reached when the whole supply chain will be decarbonised and the assumption needs to be made that only 100% renewable energy is used as feedstock. The study by World Economic Forum (2020) therefore argues a 99% GHG saving emission potential. However, without the sustainability protection to ensure that only renewable electricity is used for the PtL process, the non-renewable electricity attributes to the GHG emissions for this technology. Therefore, the GHG saving emissions highly depends on the GHG emissions of the electricity that is used in the production process. S. Searle & Christensen (2018) did research on the decarbonisation potential in the European Union and argue that although theoretically it could be 100%, the GHG saving emission potential is 84%. This value is used in this study. Another issue with this point-source capturing is that this technology has no incentive to reduce GHG emissions by industries as their GHG emissions are captured by this technology (World Economic Forum, 2020). It therefore may create 'lock in' effects in sectors that otherwise would try to reduce their CO2 emissions (German Environment Agency, 2022). Because 84% GHG reduction but no incentive to reduce GHG emissions in industries, this technology is scored a 8/10.

- PtL-DAC. This pathway is based on the technology and therefore same GHG saving emission potential as PtL-PSC although this pathway avoids sustainability concerns regarding double-claiming emissions reductions, unlike when point source capturing is used as feedstock type (World Economic Forum, 2020). Therefore, this technology has a higher GHG saving potential and is ranked at 9/10.

Land usage. To come to a score card for the performance of the SAF pathways a number of studies is consulted. These are addressed below per SAF technology pathway:

- FT-MSW. Because this pathway uses waste as feedstock, it has a negligibly small land use. Also, zero ILUC, according to ICAO (2021). Score 10/10.
- FT-Forestry residues. Because this pathway uses waste as feedstock, it has a negligibly small land use. Also, the ILUC is considered to be very low, according to a study which investigated the ILUC potential of wastes and residues for biofuels (Saynor et al., 2003) Therefore, also score 10/10.
- ATJ-Sugarcane. Sugarcane cropping requires high land usage (Roland Berger, 2020). Regarding ILUC, this feedstock type is not necessarily ILUC-free as this feedstock type was formerly used as animal feed and nowadays, more more land is required to compensate for this change (Saynor et al., 2003). The studies by Valin et al. (2015) and Staples et al. (2014) also both argue for moderate ILUC for this feedstock type. Because of the high land usage requirements and moderate ILUC, this pathway scores a 3/10 for this sub-criterion.
- HEFA-UCO. Zero direct land usage as this is a waste source. Ample of ILUC free used cooking oil is available in the European Union (Saynor et al., 2003). ICAO (2021) also argues for zero ILUC when using used cooking oil in the HEFA process. Therefore, score 10/10.
- PtL-PSC and PtL-DAC. Requires modest low land usage compared to other feedstock types, as argued in the studies by German Environment Agency (2022) and Roland Berger (2020). No differentiations made between PtL point source captured feedstock and DAC feedstock. Score 9/10

Water usage. To come to a score card for the performance of the SAF pathways a number of studies is consulted. These are addressed below per SAF technology pathway:

- FT-MSW. The water usage for the feedstock itself is neglectfully low although MSW could potentially pollute surrounding groundwater when placed in landfills (Michaga et al., 2021). However, the Fischer-Tropsch conversion process itself uses a lot of water and generates wastewater streams, which form one of the biggest disadvantages of this technology according to Michaga et al. (2021). Therefore, 3/10.
- FT-Forestry residues. As this feedstock is a waste source, it doesn't require any water usage. However, as argued above the Fischer-Tropsch process itself uses substantial amounts of water. Therefore, also 3/10.
- ATJ-Sugarcane. The cropping of sugarcane has high water use requirements (3.9 liter water/liter SAF), although this usage is relatively small when compared to other biomass based feedstock types (Roland Berger, 2020; German Environment Agency, 2022). Therefore, 7/10.
- HEFA-UCO. The HEFA technology itself requires water but consumption is relatively limited when compared to the AtJ technology (Staples et al., 2013). The water consumption also depends on the feedstock type that is used. Given that waste is a residue, water consumption for the feedstock itself is zero. Score 5/10.
- PtL-PSC. For point sourced CO2, the water consumption is estimated as 3.2-4.5 liter per liter of jet fuel (German Environment Agency, 2022). Therefore, also 7/10.
- PtL-DAC. PtL-DAC. The water consumption is estimated at 0.6-1.5 liter per liter of jet fuel(German Environment Agency, 2022). This water consumption is significantly lower than the water consumption when point source captured CO2 is used. This is because DAC is capable of extracting 1kg of water per kg CO2 from the air and can therefore meet up to 80% of the water demand for the electrolysis process (German Environment Agency, 2022). However, the amount of water that can be captured with DAC depends on the local temperature and the humidity of the air. For these reasons, this pathway scores 9/10.

6.1.2 Economic performances

Table 18 provides the score cards of the SAF technology pathways on the economic sub-criteria. Sources and argumentation on why these scores are given will be discussed in the next section.

Table 18: score card economic sub-criteria

Sub-criterion	Score					
	FT-MSW	FT-Forest residue	ATJ-Sugarcane	HEFA-UCO	PtL-PSC	PtL-DAC
MSP (C2.1)	9	7	6	10	3	2
FAU (C2.2)	8	9	9	4	7	7
FP (C2.3)	9	9	7	6	4	4
PCC (C2.4)	2	3	6	9	7	5

Minimum Selling Price. To come to a score card for the performance of the SAF pathways on their MSP the study by World Economic Forum (2020) is used. This study gives a detailed cost breakdown per SAF technology pathway and is used in the ReFuelAviation plan by the European Union (European Commission, 2021a). The MSP of the SAF pathways are addressed below:

- FT-MSW. 1866 US dollar/ton of jet fuel in 2020. The lion's share of the MSP is driven by capital expenditure. As the capital expenditure makes up such a big part of the total MSP, low-cost reductions are expected for this pathway (World Economic Forum, 2020). This results in an expected MSP of 1853 US dollar/ton SAF in 2025. In return for this high capital expenditure, the process is flexible regarding the feedstock requirements. As MSW is a low-costs resource, this feedstock adds almost nothing to the MSP for this technology. However, demand for MSW might rise in the future due to increased fuel production or uses in other industrial sectors which may increase the value of MSW but despite this expectations, the price of MSW is expected to remain low (World Economic Forum, 2020). Score; 9
- FT-Forestry residues. As argued above, high capital expenditure for this technology but when forestry residues are used as feedstock, the capital investments are lower. However, feedstock costs itself are higher resulting in a total MSP of 2100 US dollar/ton of jet fuel (World Economic Forum, 2020). Therefore, score 7.
- ATJ-Sugarcane. MSP mainly depends on ethanol costs. The production process of using residues to produce ethanol are still immature so apart from feedstock type, the MSP also depends on scale and learning curves (World Economic Forum, 2020). In 2020, MSP of AtJ with sugarcane as feedstock was 2370 US dollar/ton of jet fuel (World Economic Forum, 2020). The main cost reduction restraints are the relatively high operational costs of the refining steps. Next to this, the expected learning rates for the fixed costs are already realized and no further reductions are expected. Therefore, little additional potential in MSP is expected. Expectations are that the MSP of this pathway will decrease to 2013 US dollar/ton SAF in 2025, after which only little further reductions are expected (World Economic Forum, 2020). Therefore, score 6.
- HEFA-UCO. The MSP of this technology highly depends on the costs of the feedstock. Feedstock costs of UCO are 700 US dollar/metric ton UCO. Costs of other feedstock types typically vary between 600 and 900 US dollar/metric ton. Technology requires little capital expenditure. MSP in 2020 was 1375 US dollar/ton SAF and is expected to decrease to 1234 US dollar/ton (World Economic Forum, 2020). Because of low MSP, score 10/10.
- PtL-PSC. Operating and input factor costs today make up to 90% of the MSP for PtL technology. These are high because of the price of renewable electricity and because of high capital expenditure and high variable costs for producing hydrogen. The point sourced CO2 nowadays costs around 80 US dollar/metric ton but could drop a to approximately 65 US dollar in 2030. High costs reductions are expected for this technology. In 2020, MSP was 3847 US dollar/ton SAF. Expectations for 2025 expect 2575 US dollar/ton (World Economic Forum, 2020). Scores 3.
- PtL-DAC. Same argumentation as point above although the technology that is used for obtained the CO2 as feedstock is obviously different. DAC is still a novel technology and therefore its costs are relatively high. Today direct air captured CO2 costs around 250 to 600 US dollar/ton resulting in an expected MSP of 4017 to 4367 US dollar/ton SAF (World Economic Forum, 2020; Lebling et al., 2022). Therefore, score card 2/10.

Feedstock alternative use. To come to scores for the feedstock alternative use, different sources are used. The scores, sources and argumentation for this is provided below:

- FT-MSW. MSW is available in large quantities and is available for little, zero or even sometimes negatives costs as argued in the study by Michaga et al. (2021). On the other hand, expectations are that the demand for MSW will increase due to applications in other industrial sectors (World Economic Forum, 2020). Besides, recycling rates of MSW starts to increase and as can be seen in data from Eurostat (2022) less and less MSW ends up as landfill in the European Union. Other end uses apart from recycling, landfill and thermal usage are limited (Abis et al., 2020). Therefore, 8/10.
- FT-Forestry residues. Forestry residue contains little commercial value and has no other identified end uses than feedstock for heat and power production (S. Y. Searle & Malins, 2016a). Research by S. Y. Searle & Malins (2016a) argues that there's only little data available on how much forestry residues is used in Europe for power and heat end uses but based on the data available, they estimate an end use of 5%. Because of the low usage of forestry residues in other sectors, a 9/10.
- ATJ-Sugarcane. Sugarcane is mainly cropped for the ethanol industry and the production of sugar (Escalante et al., 2022). Although sugar itself is food, the production of SAF with sugarcane as feedstock is not considered as first generation biofuels but is considered as an advanced biofuel pathway and is therefore compatible for the ReFuelAviation plan by the European Commission (European Commission, 2021a). The study by Cantarella et al. (2015) shows that sugarcane is important in the food market, both for internal consumption and for export in Brazil, although sugarcane is already used to produce biofuels in large scale. Brazil is the world's biggest producer of sugarcane and biodiesel made from sugarcane makes up 30% of its national energy matrix (Escalante et al., 2022). However, for the European Union, the approximate output share can be 77% if optimized for the aviation industry (road fuels 6%) (World Economic Forum, 2020). Other end uses of sugarcane are still limited. The usage of sugarcane to produce biogas is still very limited and shows that biogas is still chemically, economically, and politically invisible (Junior et al., 2022). Because of the relatively low competing end uses in biodiesel industry, sugarcane scores a 9/10.
- HEFA-UCO. In Europe, UCO cannot be used in livestock feed and it has no other beneficial use apart from the biofuel sector (S. Searle et al., 2017). UCO as feedstock for SAF phases a lot of competition as almost all UCO in the European Union is already used for the production of on-road biofuel (Philips et al., 2019). Also in the study by Prussi et al. (2019), the use of UCO in other competing and therefore the limited availability of UCO is considered as a serious bottleneck for this technology pathway. If the product slate would be optimized for the aviation industry, the SAF yield would still be only 46%, equal to that of road fuels (World Economic Forum, 2020). This shows the high usage of UCO in competing end uses. Therefore, score 4/10.
- PtL-PSC and PtL-DAC. If the production slate is optimized for aviation fuel, the SAF yield can be 60% (22% for road fuels) (World Economic Forum, 2020). Therefore, 7/10.

Feedstock Profitability. As argued before, data that indicates the feedstock profitability of the considered feedstock types are absent. Therefore, the decision is made to establish the scores for this sub-criterion with the help of two SAF experts: expert K and expert J. The following scores are established.

- FT-MSW. 9/10.
- FT-Forestry residues. 9/10.
- ATJ-Sugarcane. 7/10.
- HEFA-UCO. 9/10.
- PtL-PSC. 4/10.
- PtL-DAC. 4/10.

Plant capital costs. To come to score cards for this sub-criterion, the studies by Pavlenko et al. (2019), Ingvarsdóttir (2020) and World Economic Forum (2020) are considered. Pavlenko et al. (2019) performed an extensive study on the capital expenditure of different SAF technologies.

- FT-MSW. As already argued, relative to other SAF technology pathways, this pathway has high capital expenditures (World Economic Forum, 2020). Although the technology is anticipated to improve a little in future, even Nth-of-akind projects are expected to have very high capital costs in the future (Pavlenko et al., 2019). Therefore 2/10.
- FT-Forestry residues. Also here high fixed asset expenses although a bit lower when compared to the pathway that uses MSW as feedstock (World Economic Forum, 2020). Therefore, 3/10.
- ATJ-Sugarcane. Capital costs are mainly driven by the production of ethanol (Pavlenko et al., 2019). When compared to Fischer-Tropsch technology they are relatively limited, although they are still substantial. Therefore, 6/10.
- HEFA-UCO. Low asset expenditure, especially when compared to other considered technologies (World Economic Forum, 2020; Pavlenko et al., 2019). Score 9/10.
- PtL-PSC and PtL-DAC. Substantial capital expenditures according to Pavlenko et al. (2019). DAC has a higher capital investments, mostly because of the relatively low concentration of CO_2 in ambient air, which leads to large units to capture air and therefore high capital expenditures (Ingvarsdóttir, 2020). Therefore, PSC scores 7/10 and DAC 5/10.

6.1.3 Technological performances

The table below, table 19 provides the score cards of the SAF technology pathways on the sub-criteria that are part of the third and last main criterion, the economic sub-criteria. Also for these score cards, sources and argumentation on why these scores are given will be discussed below.

Table 19: score card technological sub-criteria

Sub-criterion	Score					
	FT-MSW	FT-Forest residue	ATJ-Sugarcane	HEFA-UCO	PtL-PSC	PtL-DAC
TRL (C3.1)	7	7	8	10	5	4
PVA&S (C3.2)	10	10	8	1	1	1

Technology readiness level. The score cards for this sub-criterion are based on the technology readiness level itself. These levels are based on the levels according to European Commission (2016) and the definiions of these levels can be found in appendix 11. Each technology pathway will be discussed below:

- FT-MSW. TRL of this technology is disputable but ranges somewhere between TRL 6 and 8 (Prussi et al., 2019; European Commission, 2021a). The report by European Commission (2021a) presents that zero plants are in operation today, but 324 plants are planned to be constructed. Therefore, score 7/10.
- FT-Forestry residues. Same point as above, TRL between 6 and 8 so therefore scores a 7/10.
- ATJ-Sugarcane. Scientific literature argues for a TRL of 6-7, although the supply of SAF for commercial flights shows a higher maturity level for this technology (Prussi et al., 2019). Nonscientific literature like European Commission (2021a) argues for a TRL 7-8. Report by European Commission (2021a) gives insights in the production of SAF with this technology; 30 plants are operational within countries that are part of the European Union. Because SAF is produced via this pathway, this study assumes a TRL of 8, therefore score 8/10.
- HEFA-UCO. This technology has the highest TRL (TRL 9) and in 2019, already 5000 HEFA plants were operational (European Commission, 2021a). Therefore, this pathway scores 10/10.
- PtL-PSC. The point source capturing is rewarded the highest TRL (TRL 9) (German Environment Agency, 2022). The total process of producing SAF by the PtL technology has a TRL of 5-6 (Bauen et al., 2020). Therefore, score of 5/10.
- PtL-DAC. The DAC process has a low RTL of 3-6 (European Commission, 2021a) and as argued above, the total process of producing SAF with this technology is rewarded a TRL of 5-6. Because of the low RTL of the air capturing process, a score of 4/10.

Product volume availability and scalability. For the determination of the score cards, the following argumentation and sources are used:

- FT-MSW. As argued before, data from Eurostat (2022) showed that the recycling rates of MSW start to increase. In the research by S. Y. Searle & Malins (2016b) it is assumed that this increased recycling continues due to policies like the EU Waste Framework Directive and the Packaging and Packaging Waste Directive and additional further reduction measures are expected on top of these directives as there's a strong political interesting in reducing waste generation and landfilling. Despite these expected reductions which are taken into account by O'malley et al. (2021), this study expects a total amount of 21.2Mt of available MSW feedstock in 2030 for all uses. This study also calculates the maximum number of operational SAF producing plants and its respective maximum amount of SAF production, based on construction expectations for the 2025–2035-time frame. This study concludes that in the outlined scenario of maximum scale up of SAF production plants, between 14 and 35% of this 21.2Mt available feedstock would be needed. This means that the vast majority of MSW available (between 18.2Mt and 13.8Mt of available feedstock) would remain unused. Therefore, one could argue that there's more than sufficient feedstock available, even in a scenario of maximum scale-up. Therefore, 10/10.

- FT-Forestry residues. The study by O'malley et al. (2021) estimates a total amount of 5.1Mt of available forestry residues available for alternative fuel production. Also for this feedstock type, with an outlined scenario of maximum scale-up of SAF productions plants, between 11 and 39% of the available forestry residues feedstock would be required for this production. So for this feedstock type, one could argue the same as bulletpoint above: more than sufficient feedstock available. Therefore, scores 10/10.

- ATJ-Sugarcane. In Brazil, by far the world's biggest producer of sugarcane, large amount of sugarcane are produced for the production of ethanol as feedstock for the ATJ technology and there's more than sufficient amount of sugarcane feedstock available for the production of biofuels (Cantarella et al., 2015; Pasa et al., 2022). In terms of production numbers, Brazil produces 35 million tonnes of sugar and 28 billion liters of ethanol (Pasa et al., 2022). Sugarcane mills are also quite flexible as they can change their output from sugar to ethanol quite easily and mainly do so as a response to fluctuations in the energy markets (Teixeira, 2022). In Europe, no exact data can be found on the feedstock availability of sugarcane, although multiple studies showed that there's ample agricultural feedstock practically available for the production of biofuels and the majority is imported from abroad Europe (World Economic Forum, 2020; O'malley et al., 2021). It is also expected that there's sufficient ethanol (produced from sugarcane) available in Brazil for export to meet the European Union its increased demand by 2030 (Follador et al., 2021). The disadvantage of sugarcane as feedstock, however, is the limited shelf life. The sugarcane stalks, used to produce ethanol, need to be processed in less than one week and therefore the industrial plants can operate only during the harvesting season, which is almost nine months per year (Cantarella et al., 2015). Because of the long harvesting season, this has not been a problem in the ethanol industry but could potentially become one if the production of SAF with sugarcane as feedstock is vastly ramped up. Because of the wide availability of agricultural feedstock in Brazil and the large export of ethanol produced via sugarcane, it is expected that ethanol is also widely available in Europe to meet the 2030 demand. The limited shelf life of sugarcane however might pose an issue if the production of SAF via this feedstock is ramped up. Therefore, scores 8/10.

- HEFA-UCO.UCO is already utilized in high quantities and nearly all collected UCO is used for the production of road fuels in the European Union (European Commission, 2021a; Philips et al., 2019). As argued before, the limited availability of UCO is considered a strong bottleneck for this technology pathway (Prussi et al., 2019). Besides, in the report by European Commission (2021a), it is stated that Europe's demand for UCO already has necessitated imports from abroad which leads to allegations of fraud. The report by SkyNRG (2021) also emphasises this dependency on foreign feedstock availability. On the other hand, the study by International Council on Clean Transportation (2016) argued that a program for household collection of UCO could possibly increase the overall collection of UCO in Europe, which gives some potential for SAF production. With this additional collection, a maximum potential of 1.7Mt UCO could be available for the production of biofuel. However, it is questionable whether this UCO would then be used for the production of SAF or that it would be used for the production of road fuels. Because of this low availability, the score card is given a 1/10.

- PtL-PSC and PtL-DAC. In theory, the feedstock availability for these SAF pathway is immense. However, it is deemed unlikely that this potential would be met by 2030 due to the high cost and time required to commercialize this pathway (O'malley et al., 2021). Expectations are that by 2030 the amount of PtL feedstock is still minimal as it requires a lot of renewable energy supply to produce E-fuels. Because the conversion efficiency of E-fuels is at best 50%, twice as much energy is needed as the amount of fossil fuel displaced (S. Searle & Christensen, 2018). Europe has ambitions to increase its renewable energy supply (RES) and its target for RES for transport needs in the Renewable Energy Directive II (RED II) is set at 32%. If this target is met by 2030 (and not exceeded) any production of E-fuels would thus result in a shortfall of the total renewable energy usage and therefore increase the fossil fuel usage in Europe (S. Searle & Christensen, 2018). It is therefore expected that E-fuel pathways will deliver limited - if any - SAF at all by 2030 (S. Searle & Christensen, 2018). Volumes of E-fuels will only be significant if high financial policy measures will be taken in Europe to stimulate this production (S. Searle & Christensen, 2018). It is therefore that the contribution of E-fuels in the SAF mix is more cost-constrained than feedstock constrained (O'malley et al., 2021). Because of the very low expected volumes of PtL availability, a score of 1/10 will be used.

6.2 Total score cards

Table 20 shows the total score cards of the SAF pathways that are considered in this study with respect to the sub-criteria. This table is an aggregation of the three score cards of the previous section. With the use of this total score card, the final scores and ranking of the pathways can be constructed, as discussed in the next section.

Table 20: Total score card of SAF pathways with respect to the sub-criteria (based on literature review and experts' interviews)

Main-criterion	Sub-criterion	Score					
		FT-MSW	FT-Forest residue	ATJ-Sugarcane	HEFA-UCO	PtL-PSC	PtL-DAC
Environmental	GHG SE (C1.1)	7	9	6	6	9	10
	LU (C1.2)	10	10	3	10	9	9
	WU (C1.3)	3	3	7	5	6	9
Economic	MSP (C2.1)	9	7	6	10	3	2
	FAU (C2.2)	8	9	9	4	7	7
	FP (C2.3)	9	9	7	9	4	4
	PCC (C2.4)	2	3	6	9	7	5
Technological	TRL (C3.1)	7	7	8	10	5	4
	PVA&S (C3.2)	10	10	8	1	1	1

6.3 Performance scores of all the four considered stakeholder groups together

Now that the final score card is constructed, the final step of the MCDM can be performed. This step is the weighted sum method (WSM) and is applied in order to come to a final score per SAF technology pathway. For this analysis, the obtained group decision-making weights for all the stakeholder groups combined will be used. The WSM is the simplest and well-known form of performing a MCDM and is calculated with the following formula:

$$P_i = \sum_{j=1} w_j a_{ij}.$$

- w_j represents the obtained global weight for criterion j
- a_{ij} represents the score of the score card of SAF pathway i with respect to criterion j
- P_i represents the overall score of the SAF pathways and is determined by multiplying w_j with a_{ij} for all considered criteria j.

This WSM is applied in table 21 and shows the final scores of the six considered SAF technology pathways in this study. Based on the obtained group decision-making weights of all stakeholder groups together, it can be observed from this table 21 that the Fischer-Tropsch technology with Forestry residues has the highest overall performance score although this pathway is closely followed by Fischer-Tropsch technology with Municipal Solid Waste as feedstock. It can be seen that both pathways that use the Power-to-Liquid technology have the lowest performance scores and are thus ranked as the least preferred SAF technologies for the upscale to comply with the proposed SAF mandate by the European Commission for 2030. These results and why these results are found will be discussed more elaborately in the sensitivity analysis (section 6.4) and in the discussion section (section 7.2).

Table 21: Final scores and ranking of the SAF technology pathways by using the obtained weights for all the four stakeholder groups combined

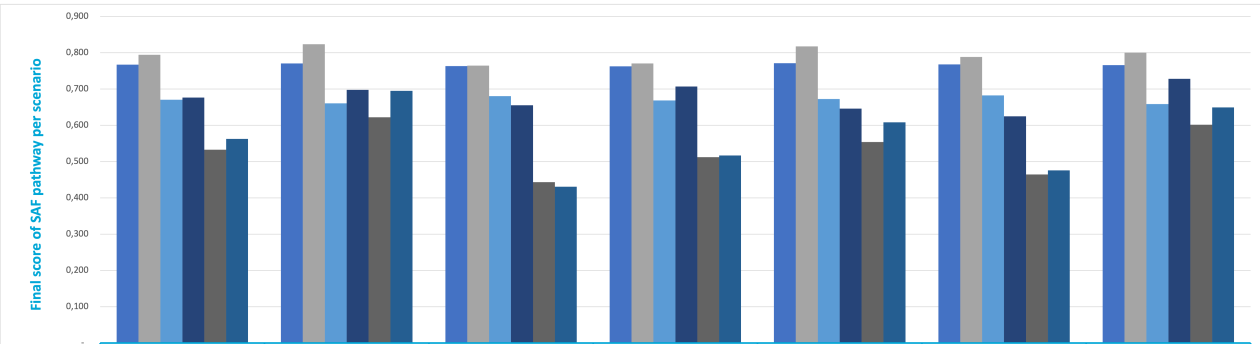
Sub-criterion	Global weight (w_j)	Score					
		FT-MSW	FT-Forest residue	ATJ-Sugarcane	HEFA-UCO	PtL-PSC	PtL-DAC
GHG SE (C1.1)	0.218	0.153	0.196	0.131	0.131	0.196	0.218
LU (C1.2)	0.084	0.084	0.084	0.025	0.084	0.076	0.076
WU (C1.3)	0.078	0.023	0.023	0.054	0.039	0.047	0.070
MSP (C2.1)	0.142	0.127	0.099	0.085	0.142	0.042	0.028
FAU (C2.2)	0.074	0.059	0.067	0.067	0.030	0.052	0.052
FP (C2.3)	0.060	0.054	0.054	0.042	0.054	0.024	0.024
PCC (C2.4)	0.045	0.009	0.014	0.027	0.041	0.032	0.023
TRL (C3.1)	0.141	0.098	0.098	0.112	0.141	0.070	0.056
PVA&S (C3.2)	0.158	0.158	0.158	0.127	0.016	0.016	0.016
Total score		**0.767**	**0.794**	**0.671**	**0.6763**	**0.533**	**0.563**
Ranking		**2**	**1**	**4**	**3**	**6**	**5**

6.4 Sensitivity analysis

In this section, a sensitivity analysis is performed to examine how the overall ranking of the considered SAF pathways, that is constructed by using the obtained weights of all the four stakeholder groups together, changes according to sketched scenarios that present different values for the the weights of the main-criteria. In order to perform this sensitivity analysis, six different scenarios are considered of which the results are shown in table 22. This table shows the ranking of SAF pathways changes according to the different sets of weights that are used in the sketched scenarios. The total scores of the pathways are also provided and visualised in figure 15. In this figure, the leftmost graph in this figure represents the baseline scenario. Other scenarios have either increased or decreased the weight of a main-criterion with 50%. This 50% increase/reduction is not so much an arbitrary value but rather to get more feeling on how and how much different scenarios influence the performance scores of the considered SAF pathways. So this sensitivity analysis provides some insight into how fluctuations in input will have an effect on the output.

Table 22: Sketched scenarios with different weights for the main-criteria

Scenario	Description	Ranking of SAF pathways
Baseline	**Baseline scenario**	**FT-FR >FT-MSW >HEFA-UCO >ATJ-SC >PtL-DAC >PtL-PSC**
1	50% increased weight of ENV main-criterion	FT-FR >FT-MSW >HEFA-UCO >PtL-DAC >ATJ-SC >PtL-PSC
2	50% decreased weight of ENV main-criterion	FT-FR >FT-MSW >ATJ-SC >HEFA-UCO >PtL-PSC >PtL-DAC
3	50% increased weight of ECO main-criterion	FT-FR >FT-MSW >HEFA-UCO >ATJ-SC >PtL-DAC >PtL-PSC
4	50% decreased weight of ECO main-criterion	FT-FR >FT-MSW >ATJ-SC >HEFA-UCO >PtL-DAC >PtL-PSC
5	50% increased weight of TECH main-criterion	FT-FR >FT-MSW >ATJ-SC >HEFA-UCO >PtL-DAC >PtL-PSC
6	50% decreased weight of TECH main-criterion	FT-FR >FT-MSW >HEFA-UCO >ATJ-SC >PtL-DAC >PtL-PSC



	Baseline scenario	50% increase ENV	50% decrease ENV	50% increase ECO	50% decrease ECO	50% increase TECH	50% decrease TECH
FT-MSW	0,767	0,770	0,763	0,763	0,771	0,768	0,766
FT-FR	0,794	0,823	0,765	0,771	0,817	0,788	0,800
ATJ-SUGARCANE	0,671	0,661	0,680	0,669	0,673	0,682	0,659
HEFA-UCO	0,676	0,698	0,655	0,707	0,646	0,625	0,728
PTL-PSC	0,533	0,622	0,444	0,512	0,554	0,464	0,602
PTL-DAC	0,563	0,695	0,431	0,517	0,608	0,476	0,649

Figure 15: Scores of SAF pathways in different scenarios

In the baseline scenario, it can be seen that the FT-FR pathway ranks first with a total performance score of 0.794. This is mainly due to its outstanding performance in terms of GHG saving emissions (C1.1) and its excellent score on the product volume availability and scalability (C3.1). These two sub-criteria have respectively the highest and second highest weights of all nine considered sub-criteria. Also, the performance of this SAF pathway on other important sub-criteria like the MSP (C2.1) and the TRL (C3.1) are relatively well. The only sub-criteria for which this SAF pathway does not score well are the sub-criteria WU (C1.3) and PCC (2.4). However, the effect of the poor score on these 2 sub-criteria is quite limited given the low weights of these 2 sub-criteria. In all other sketched scenarios, the superiority of the FT-FR is visible as this pathway is the first ranked pathway in all scenarios.

Some other points emerge from this sensitivity analysis as well. In scenario 1, a 50% increase is made for the weight of the environmental sub-criteria. Within this scenario, a jump forward can be noticed for the Power to Liquid technology that uses Direct Air Capture as source for the CO2 that is required in this technology. This shows that, if in a potentially future scenario with more awareness/importance for the environmental aspects of a SAF technology, this technology pathway would score significantly better than in the baseline scenario. This jump in preference can be explained by the fact that PtL-DAC has an excellent performance (10 out of 10) on GHG saving emissions, as argued earlier on in section 6.1.1. This sub-criterion, GHG saving emissions, is within the environmental main-criterion, by far the most important sub-criterion. Because of this excellent performance of this technology pathway on this important sub-criterion, the jump in performance score, and therefore the jump in preference, is well explainable.

Logically, in the exact opposite situation of scenario 1, scenario 2 (with a decreased interest in environmental performance), a big negative jump can be seen in the performance score of both PtL pathways. In scenario 3 it can also be noticed that the difference between FT-FR and FT-MSW decreases to only a minor difference. This is because the sub-criterion GHG saving emissions, which causes the biggest difference between these two pathways, is now decreased in its relevance. Therefore, the performance scores of these two pathways pulls together. Scenario 3 is also the only scenario in which the PtL-PSC pathway performs better than the PtL-DAC. This is because, apart from the environmental criteria, the PtL-PSC performs better than the PtD-DAC technology. Advantages of this technology can be seen in a better minimum selling price, better Plant capital costs and a higher technology readiness level. Therefore, it can be concluded that in a scenario in which the environmental criteria have a lower weight, the PtL-PSC pathway is preferred over the PtL-DAC pathway.

In scenario 3 is can be noted that the performance score of the HEFA technology pathway increases relatively strong. In scenario 4, this is the other way around. The increase in performance of the HEFA technology in scenario 3 is due to the increased weights of the economic performance and the fact that this pathway has an excellent score on the important sub-criterion Minimum selling price. Besides, this pathway also scores very well on the sub-criterion Plant capital costs and Feedstock profitability and therefore contributes to this increased performance score of the HEFA pathway in this technology.

In scenario 5, raised weights are set for the technological sub-criteria. As both the PtL-DAC and the PtL-PSC score relatively bad on these sub-criteria, a decrease in performance score can be noted. The other way around, in scenario 6, an increase in performance score can be seen as the weights of the technological sub-criteria are decreased. Pertaining to the baseline scenario, these two pathways now perform better and the distance between the other technology pathways is decreased. Because of this, the conclusion can be drawn that if both the technology readiness level and the production volume scalability and availability increases, these pathways start to perform better and could possibly compete in some way with other pathways.

6.5 Performance scores per stakeholder group

After having performed the weighted sum method and deriving the performance scores of the considered pathways by using the obtained weights of all the four stakeholder groups together, a better understanding can be gained by deriving the performance scores per stakeholder group. This will show how the different obtained weights of the main- and sub-criteria per stakeholder group will influence the performance scores. For each stakeholder group, the final performance scores and ranking of the SAF technology pathways will be performed and the differences between the stakeholder groups will be discussed.

6.5.1 Performance scores for the experts/consultant group

Table 23: Final scores and ranking of the SAF technology pathways by using the obtained weights for the experts/consultant stakeholder group

Sub-criterion	Global weight (w_j)	Score					
		FT-MSW	FT-Forest residue	ATJ-Sugarcane	HEFA-UCO	PtL-PSC	PtL-DAC
GHG SE (C1.1)	0.263	0.184	0.237	0.158	0.158	0.237	0.263
LU (C1.2)	0.095	0.095	0.095	0.028	0.095	0.085	0.085
WU (C1.3)	0.168	0.050	0.050	0.117	0.084	0.101	0.151
MSP (C2.1)	0.083	0.075	0.058	0.050	0.083	0.025	0.017
FAU (C2.2)	0.092	0.074	0.083	0.083	0.037	0.065	0.065
FP (C2.3)	0.047	0.042	0.042	0.033	0.028	0.019	0.019
PCC (C2.4)	0.047	0.009	0.014	0.028	0.042	0.033	0.023
TRL (C3.1)	0.119	0.083	0.083	0.095	0.119	0.0559	0.047
PVA&S (C3.2)	0.087	0.087	0.087	0.069	0.009	0.009	0.009
Total score		**0.699**	**0.749**	**0.662**	**0.654**	**0.632**	**0.679**
Ranking		**2**	**1**	**4**	**5**	**6**	**3**

Table 23 presents the performance scores of the SAF production pathways according to the obtained weights by this stakeholder group. Compared to the performance scores of the pathways performed by taking all stakeholder groups simultaneously in account, this performance score doesn't deviate much. However, there are some differences. In this analysis, the HEFA-UCO pathway performs worse. On the other hand, it is the the PtL-DAC pathway that performs better in this analysis. These differences are mostly due to the increased weight of the environmental main- and sub-criteria. The HEFA-UCO has a relatively low score card regarding its 'water usage' and its 'GHG saving emissions' where it is the PtL-DAC pathway that performs very well on these two criteria. This results in a shift in preference. Another aspect noteworthy mentioning is the decreased difference in performance score of both the PtL-PSC and the PtL-DAC pathways relative to the other four pathways. This is caused by the low weight that is devoted by the experts/consultants on the criterion 'production volume availability and scalability' combined with the poor performance of these two pathways on this sub-criterion.

6.5.2 Performance scores for the producer group

Table 24: Final scores and ranking of the SAF technology pathways by using the obtained weights for the producer group

Sub-criterion	Global weight (w_j)	Score					
		FT-MSW	FT-Forest residue	ATJ-Sugarcane	HEFA-UCO	PtL-PSC	PtL-DAC
GHG SE (C1.1)	0.298	0.208	0.268	0.179	0.179	0.268	0.298
LU (C1.2)	0.122	0.122	0.122	0.037	0.122	0.110	0.110
WU (C1.3)	0.076	0.023	0.023	0.053	0.038	0.046	0.069
MSP (C2.1)	0.085	0.077	0.060	0.051	0.085	0.026	0.017
FAU (C2.2)	0.047	0.037	0.042	0.042	0.019	0.033	0.033
FP (C2.3)	0.079	0.071	0.071	0.055	0.047	0.032	0.032
PCC (C2.4)	0.053	0.011	0.016	0.032	0.048	0.037	0.027
TRL (C3.1)	0.174	0.122	0.122	0.139	0.174	0.087	0.070
PVA&S (C3.2)	0.066	0.066	0.066	0.053	0.007	0.007	0.007
Total score		**0.737**	**0.789**	**0.641**	**0.719**	**0.644**	**0.660**
Ranking		**2**	**1**	**6**	**3**	**5**	**4**

The performance scores and their preferences of the producer group is shown above in table 24. Also this stakeholder group doesn't show much deviation from the analysis in which all the stakeholders their weights are considered simultaneously. There are only little differences in the ranking of the pathways as the three most preferred pathways are still the same and are in same order. However, the difference in total score between these top three preferred pathways shrinks as this stakeholder group attains more value to the 'technology readiness level' of a SAF pathway and it is the HEFA-UCO pathway that has an excellent performance on this sub-criterion. This narrows the gap between both FT pathways and this pathway. Also here it can be noticed that due to the decreased weight of the sub-criterion 'production volume availability and scalability', the gap in performance score between both PtL pathways and the other four pathways decreases.

6.5.3 Performance scores for the consumer group

Table 25: Final scores and ranking of the SAF technology pathways by using the obtained weights for the consumer group

Sub-criterion	Global weight (w_j)	Score					
		FT-MSW	FT-Forest residue	ATJ-Sugarcane	HEFA-UCO	PtL-PSC	PtL-DAC
GHG SE (C1.1)	0.338	0.236	0.304	0.203	0.203	0.304	0.338
LU (C1.2)	0.116	0.116	0.116	0.035	0.116	0.104	0.104
WU (C1.3)	0.069	0.021	0.021	0.048	0.034	0.041	0.062
MSP (C2.1)	0.072	0.065	0.050	0.042	0.073	0.022	0.014
FAU (C2.2)	0.033	0.027	0.030	0.030	0.013	0.023	0.023
FP (C2.3)	0.022	0.020	0.020	0.016	0.013	0.009	0.009
PCC (C2.4)	0.017	0.003	0.005	0.010	0.015	0.012	0.008
TRL (C3.1)	0.073	0.051	0.051	0.058	0.073	0.037	0.029
PVA&S (C3.2)	0.260	0.260	0.260	0.208	0.026	0.026	0.026
Total score		**0.799**	**0.857**	**0.651**	**0.565**	**0.577**	**0.614**
Ranking		**2**	**1**	**3**	**6**	**5**	**4**

Due to the steep increase in the weight of the environmental main- and sub-criteria and the 'production volume availability and scalability' that are devoted by the consumer group, the gap between both Fischer-Tropsch pathways and the other four SAF pathways increases, as shown in table 25. The HEFA-UCO pathway makes a drop in preference and becomes the least preferred pathway in this analysis. The cause of this is three folded: 1) the poor performance on its 'GHG saving emissions' which increased in weight, 2) the reduction in the weight of the 'MSP' which causes that the excellent performance on this sub-criterion becomes irrelevant and 3) the poor performance on its 'production volume availability and scalability' which is an important sub-criterion according to the consumer group. The latter cause is also the cause that both PtL pathways score poorly in this analysis, despite their good performance on 'GHG saving emissions'.

6.5.4 Performance scores for the airline industry

Table 26: Final scores and ranking of the SAF technology pathways by using the obtained weights for the airline industry

Sub-criterion	Global weight ()	Score					
		FT-MSW	FT-Forest residue	ATJ-Sugarcane	HEFA-UCO	PtL-PSC	PtL-DAC
GHG SE (C1.1)	0.085	0.059	0.076	0.051	0.051	0.076	0.085
LU (C1.2)	0.034	0.034	0.034	0.010	0.034	0.031	0.031
WU (C1.3)	0.042	0.012	0.012	0.029	0.021	0.025	0.037
MSP (C2.1)	0.246	0.221	0.172	0.148	0.246	0.074	0.049
FAU (C2.2)	0.081	0.065	0.073	0.073	0.032	0.057	0.057
FP (C2.3)	0.063	0.056	0.056	0.044	0.038	0.025	0.025
PCC (C2.4)	0.068	0.014	0.020	0.041	0.061	0.048	0.034
TRL (C3.1)	0.069	0.048	0.048	0.055	0.069	0.034	0.028
PVA&S (C3.2)	0.313	0.313	0.313	0.251	0.031	0.031	0.031
Total score		**0.823**	**0.806**	**0.701**	**0.583**	**0.401**	**0.377**
Ranking		**1**	**2**	**3**	**4**	**5**	**6**

The airline industry is the stakeholder group that deviates the most from the other three stakeholder groups and therefore causes large differences in performances scores and preferences when compared to the other groups. This can be seen in the table above, table 26. As mentioned in section 5.6.2, the airline industry devotes a substantial lower weight to the environmental performance while both the technological and economic performance of SAF pathways become more important due to the increased weights that are rewarded by the airline industry to these two main-criteria. This makes that the environmental sub-criteria become less relevant and this stakeholder group is the only stakeholder group which doesn't devotes the 'GHG saving emissions' as most important sub-criterion. Instead, the sub-criterion 'production volume availability and scalability' becomes significantly more important. This makes that both Fischer-Tropsch pathways perform very well in this analysis as these two pathways perform excellent on this sub-criterion. Next to this, these two pathways also perform well on the 'minimum selling price', which also has an increased weight compared to other stakeholder groups and becomes the second most important sub-criterion in this analysis. Due to the lower weight of the 'GHG saving emissions' criterion and the higher weight of the 'minimum selling price' the FT-forest residue pathway isn't the most preferred pathway anymore. The last shift noteworthy mentioning is that although the HEFA-UCO scores a 10/10 on the 'minimum selling price', this pathway becomes the fourth most preferred pathway. This is caused by its poor performance on the 'production volume availability and scalability'. Therefore, this pathway is overtaken in score by the alcohol-to-jet pathway.

7 Discussion and conclusion

The aim of this research was to answer the following main research question: "What are stakeholders' preferences regarding different SAF technology pathways, in order to stimulate the SAF upscale for 2030 and comply with the proposed SAF blending mandate by the European Commission?" In order to answer this, four sub-research questions were formulated that lead to partial knowledge which are required to answer the main research question. Based on the answers of these four sub-research questions, this chapter will elaborate on these sub-research questions by providing a discussion, a conclusion and by providing recommendations for future research. These will be addressed in the following sections.

7.1 Criteria ranking and comparisons to findings in the literature

Based on the results from all the different experts within the four identified stakeholder groups in the aviation industry, it can be noticed that the environmental and economic performance are perceived as the most important criteria to consider when assessing different SAF technology pathways with a weight of relatively 0.38 and 0.30 out of 1.00, respectively. The recently published multi-criteria analysis by S. Ahmad & Xu (2021), who used the well known PROMOTHEE II method, also assessed different SAF types. This study by S. Ahmad & Xu (2021) concluded that, based on the performed pairwise comparisons, the sub-criterion 'GHG saving emissions', is also ranked as the most important sub-criterion. Another aspect that is noticeable from this study by S. Ahmad & Xu (2021), is that the environmental main-criterion is, just like in this study, considered as the most important main-criterion when assessing SAF technology pathways. Besides, in this same study by S. Ahmad & Xu (2021), the weight of the economic main-criterion was close to the environmental weight and was also ranked as second most important main criterion.

As a logical next step after discussing the findings of S. Ahmad & Xu (2021), a comparison needs to be made with the impact assessment on the ReFuelEU report by the European Commission. This impact assessment also interviewed multiple stakeholders in its analysis and identified problems in the SAF industry. One of the major problems in the SAF industry that is identified in this study is the lack of SAF supply at reasonable costs (European Commission, 2021a). Their stakeholder analysis concludes that 90% of their respondents agreed or strongly agreed that the low supply and lack of supply at reasonable costs in the EU forms a problem for the SAF industry. This problem is in line with the findings of this study, as from the analysis in the previous chapter (table 21) it can be noticed that the production volume availability and scalabilty is deemed the second most important sub-criterion and is followed by the minimum selling price as third most important sub-criterion when considering all stakeholder groups simultaneously.
Concluding; Based on the similarities between this study and the recently published study by S. Ahmad & Xu (2021) and the impact assessment study on the ReFuelAviation report by the European Commission, the novel Bayesian Best-Worst Method is indeed a well-developed and accurate method to arrive at the relative importance of criteria.

7.2 SAF technology pathways ranking based on the weights of all four stakeholder groups combined

Based on the obtained criteria-weights for all the stakeholder groups combined and the performance scores based upon literature research, it can be observed that the Fischer-Tropsch technology that uses forestry residues as feedstock type is considered as preferred SAF technology pathway. This pathway is closely followed by the same technology (the Fischer-Tropsch technology), with the use of municipal solid waste as feedstock. The high-performance scores of both these technology pathways are mainly because of their excellent (FT-forest residue) and very good (FT-municipal solid waste) performance in terms of 'GHG saving emissions' and their excellent score on the 'product volume availability and scalability'. These two sub-criteria have respectively the highest and second highest weights of all nine considered sub-criteria. Also, the performance of this SAF pathway on other important sub-criteria like the 'minimum selling price' and the 'technology readiness level' is relatively good. The only sub-criteria for which these SAF pathway does not score well are 'water usage' and 'plant capital costs'. However, the effect of this poor score on these 2 sub-criteria is quite limited given the low weights of these 2 sub-criteria.

The HEFA-used cooking oil pathway comes out as third in line when ranking SAF technology pathway by experts. This pathway scores very well on the sub-criteria 'technology readiness level' and on the 'minimum selling price'. Of all considered pathways, it is the only pathway that is commercially exploited and benefits from the lowest expected minimum selling price. On the other hand, this pathway scores very low on the 'production volume availability and scalability'. What is noticeable, is that although this technology pathway is only ranked as third preferred technology pathway in this study, that in practice, it are mostly HEFA technology plants which deliver SAF. The report by European Commission (2021a) shows that the yearly production capacity of HEFA plants is 100 kilotonnes of SAF, while only 40 kilotonnes is produced by plants that use the Fischer-Tropsch technology. From the result of the analysis performed in this study, HEFA is not the preferred technology pathway but is ranked as third most preferred SAF pathway by all experts. The results of this study therefore do not match the status. This may sound surprising at first, but this study does not investigate the current preference of SAF technology pathways but considers a future state (year 2030). This difference between today's reality and the outcome of this study can be explained by the fact that although the HEFA technology currently still has a sufficient level of feedstock availability, scalability and availability of this technology pathway is deemed very low when considering a 2030 timeline. This is mainly because almost all used cooking oil is currently used in roadfuels and heavily depends on import from foreign countries (European Commission, 2021a). Because of this low expected availability of used cooking oil in the future for producing SAF, this pathway is not the most preferred SAF technology but is ranked as third most preferred technology pathway.

With a minor difference in total score, the alcohol-to-jet-sugarcane ranks as fourth most preferred SAF technology. The low performance on the most important sub-criterion, the 'GHG saving emissions', is remarkable for this pathway. Together with the HEFA-used cooking oil, this pathway arrives at a performance score of 6 out of 10 and therefore, these pathways are lacking on this important sub-criterion. Because of this poor performance on environmental aspects, it can also be noted that in a scenario with increased interest in environmental performance, this technology pathway scores even worse. It is also noticeable that this technology has a moderate performance on the expected minimum selling price. In contrast to the both power-to-liquid pathways, who even have worse scores on this sub-criterion, minimum selling price reductions are only expected to be minor for the alcohol-to-jet-sugarcane pathway. In favor of this technology pathway, however, is the good performance on technological performance. For both sub-criteria within this main-criterion, good performances can be seen. This can also be noticed in the sensitivity analysis: In a scenario with increased importance for the technological performance, an upward shift can be seen for this pathway due to the good performance of this pathway on the two technological sub-criteria.

Both the power-to-liquid pathway that uses direct air capture and the power-to-liquid pathway that uses Point sourced captured CO_2 are the least preferred technology pathways. This is mainly because they are still relatively state-of-the-art technologies with numerous barriers to overcome. These barriers are reflected in the results of this study. As can be seen in the total scorecards and the experts' preference regarding the considered SAF technologies, both power-to-liquid technologies have a poor performance on their expected minimum selling price and their production volume availability and scalability. These criteria are the second-most and third-most important sub-criteria. Apart from that, both pathways currently still experience moderate performances on their technology readiness level. Therefore, the low scores on these relatively important sub-criteria make that these technologies don't perform well when establishing the experts' preference. On the other hand, it are precisely these two technology pathways which score best on environmental performance. Both these technologies have high potential in GHG saving emissions compared to conventional jet fuel and their land usage and water usage also outperform the other technology pathways.

7.3 SAF technology pathways ranking per stakeholder group

Next to obtaining the performances scores of the considered pathways by using the obtained weights of all the four stakeholder groups combined, the performances scores are also calculated per stakeholder group by using their obtained weights. This shows how different perspectives of those stakeholder groups can influence the performance scores of the considered pathways, as shown in section 6.5. Although this analysis shows that there are quite some differences between the four identified stakeholder groups, it can be noticed that for every stakeholder group the two Fischer-Tropsch technologies are still the two most preferred SAF technology pathways. However, shifts can be noticed in the preference of the other four SAF technology pathways. These shifts are mainly caused by the large difference in weights for the sub-criteria 'GHG saving emissions' and 'production volume availability and scalability' by the different stakeholder groups. Other sub-criteria also experience different weights per stakeholder group but the differences in weights are mainly observed in the latter mentioned sub-criteria.

7.4 Discussing the method

7.4.1 One on one interviews

All interviews were performed in an online environment using Microsoft Teams and during each interview, the same PowerPoint slide deck was shown. This method has both advantages as well as some disadvantages. The first advantage of using a PowerPoint slide deck is the visual guidance when performing the interview. By simply following the slides and the questions in order to answer all the comparisons that need to be made for the BWM, the chances of skipping questions are minimised. Secondly, by making use of images how the BWM works and how experts need to interpret these pairwise comparisons, the interviewee can get a better feeling for the comparisons that need to be done and benefits from the accuracy of the method. Furthermore, questions regarding the definition of criteria can be answered on the spot. Finally, performing the BWM with individual interviews contributes to getting more data than just the numbers required for making the pairwise comparisons as multiple experts gave explanations for why they argued for this numbers in the pairwise comparisons. On the other hand, with the use of a slide deck, the questions are not structured in a proper survey form that could be filled in individually by the experts. Therefore, the pairwise comparisons are implemented in the slide deck and were shown during one-on-one interviews, which was a time-consuming task. Another disadvantage of these one-on-one interviews is that the expert can not complete the BWM on his/her own at a time that was convenient for him/her but had to plan a timeslot in advance for this.

7.4.2 Practicality of the BWM

BWM is considered as a more practical method when compared to the commonly known AHP method as this method requires a fewer number of pairwise comparisons (Rezaei, 2015). As this study considered three main criteria which are divided in eight sub-criteria, the BWM required twelve pairwise comparisons while the AHP method would have required 31 pairwise comparisons. In addition to that, the BWM makes the comparisons in a structured way, which makes it easier to judge and to understand, and more importantly leads to more consistent comparison, hence more reliable values for ranking (Rezaei, 2015). Nevertheless, some issues were also discovered while performing the interviews with the use of the BWM. Some experts had difficulty understanding the term 'pairwise comparisons'. Also, as the list of considered criteria was determined before performing the interviews, no changes could me made in the selection of criteria during the interviews. Some experts had difficulty with this as they argued for a slightly different selection of criteria.

7.5 Contributions to the SAF industry

As this study established a longlist of 64 potential criteria and considering a total of nine criteria scheduled within three main-criteria, this study contributes to existing literature regarding SAF technologies multi-criteria studies. It facilitates a framework which systematically assesses the upscale potential and feasibility of different SAF technology pathways by considering both expert knowledge and literature. This framework can be used in future studies to establish performance scores of other or a broader selection of SAF technology pathways and enables making comparisons between SAF technology pathways. Next to this, it contributes to identifying multiple stakeholder groups within the SAF industry and investigates different visions and preferences within these groups. Finally, this study also contributes to the empirical application of the novel Bayesian BWM in the SAF industry. It can be concluded that the novel Bayesian Best-Worst Method is indeed a well developed and accurate method to arrive at the relative importance of criteria as the findings of this study are in line with finding of prior performed research regarding the assessment of SAF technologies on multiple criteria.

7.6 Conclusion

The goal of this study was to examine what experts in the aviation industry their preference is regarding different SAF technology pathways that can be upscaled EU member states, to comply with the proposed 2030 SAF blending mandate proposed by the European Commission. By performing an extensive literature research, a selection of promising SAF technology pathways is determined. Building upon this selection of pathways, relevant criteria for the upscale potential of these pathways are determined and with the use of experts and the Best-Worst Method the weight of all the criteria are established. As a final step, the considered pathways are all scored on the criteria with the use of literature in order to derive at a final scoring of these pathways. The main findings of this study are summarised as follows:

- The HEFA, alcohol-to-jet, Fischer-Tropsch and power-to-liquid technologies are promising technologies to comply with the 2030 SAF blending mandate that is proposed by the European Commission. Municipal solid waste and forestry residue are considered as promising feedstock types within the Fischer-Tropsch technology. These feedstock types are considered widely available for these technologies and benefit from low alternative use and low costs. Within the HEFA technology, it is mainly used cooking oil that is used for this technology. On the other hand, this feedstock type experiences a low expected availability for future demands and is subjective to alternative use in the road-fuel industry. Sugarcane is a widely available feedstock type within the alcohol-to-jet technology that is sufficiently available. For the power-to-liquid technology, two main sources for the supply of CO_2 are expected; point source captured CO_2 and direct air captured CO_2.
- The uptake of different SAF technology pathways can be determined by using three main criteria: Environmental performance, economic performance and technological performance. Within the environmental main-criterion, the GHG saving emission, land usage (change) impact and water usage make up the sub-criteria. The economic main-criterion consists of the expected minimum selling price, the feedstock alternative use, the feedstock profitability and the plant capital costs. The third and final main criterion, the technological main-criterion, is split up into two sub-criteria; technology readiness level and production volume availability and scalability.
- Given these main-criteria and their corresponding sub-criteria, the environmental and the economic performance are perceived as the most important criteria to consider when assessing different SAF technology pathways with relatively 0.38 and 0.30 out of 1.00, respectively. Within the environmental main-criterion, the GHG saving emission is considered the most important sub-criterion. The expected minimum selling price dominates in importance within the economic criterion. Also, the production volume availability and scalability is an important sub-criterion. Therefore, in addition to its GHG saving emission, it is essential for a SAF technology pathway to perform well on these two sub-criteria for the development and upscale potential.
- Given these criteria and their perceived importance when considering all the stakeholder groups simultaneously, it is the Fischer-Tropsch technology that uses forestry residues as feedstock type that is the most preferred technology pathway for the proposed SAF blending mandate. The high-performance score of this technology pathway is mainly because of its excellent performance in terms of GHG saving emissions and product volume availability and scalability. This technology pathway is closely followed by the same technology, the Fischer-Tropsch technology, that uses municipal solid waste as feedstock type. Even though this technology performs better on expected minimum selling, this technology is outranked by the same technology that uses forestry residue as feedstock, mainly due to its somewhat lower GHG saving emission. Although the expected large role of both power-to-liquid technology pathways, these two pathways are the least preferred technology pathways. This low preference is mainly due to their high expected minimum selling price and their low expected production volume availability and scalability by 2030.
- It can be noted that different weights are found for the criteria weights within each stakeholder group. The airline industry deviates the most from the other three stakeholder groups as this stakeholder group devotes a substantial higher weight to the economic criteria and rewards a significantly lower weight to the environmental criteria. Different weights per criteria can also be observed within the other three stakeholder groups. The differences between the four stakeholder groups stresses the divergent perspectives of these groups. However, when considering the obtained weights per stakeholder group, it can be concluded that this causes no shift in preference for the two Fischer-Tropsch technologies as they remain the two most preferred SAF technology pathways, regardless of which stakeholder perspective is considered. However, for the ranking of the other four SAF pathways, some shifts in preference can

be noticed between the stakeholder groups. These are mainly caused by the large differences in weights that are devoted to the sub-criterion 'GHG saving emissions' and 'Production volume availability and scalability'.

- The development of MCDM methods that consider multiple criteria (in this study: environmental, economic and technological) is a potent tool that aids decision makers when choosing the best option from a range of options, and for this reason, this study can be considered as an essential guideline for decision makers in the uptake of sustainable aviation fuels.

7.7 Limitations

The first limitation that needs to be addressed is that this study performed a multi-criteria decision-making method for a future situation. This automatically results in uncertainty as the experts' opinions regarding the weights of the criteria might change over time. The same applies for the performance scores of the SAF technology pathways on the considered criteria. For example, a SAF technology pathway might experience a low technology readiness today and expectations could be that this will not increase in the future. However, the future could prove different. Therefore, this uncertainty in both the weights of the criteria as well as the performance scores of the pathways on the criteria forms a limitation of this study. Suggestions for future studies would be to select the same set of criteria and try to map changes for the weights and performance scores over time.

As a second limitation of this study the number of performed interviews can be addressed. This study only performed eleven one-on-one interviews as getting in contact with experts, planning the interviews and conducting the interviews is a time-consuming process. Although these eleven interviews were considered sufficient to obtain the total group weight decision making weights, more one-on-one interviews within each stakeholder group will probably provide better understanding of the different views of these stakeholder groups.

The third limitation that needs to be addressed regarding the selection of criteria, is the overlap between the sub-criteria within the economic main criterion. This overlap was mentioned by multiple experts during the one-on-one interviews. One expert argued that the plant capital costs could be part of the minimum selling price. Also, feedstock profitability is indirectly linked to the minimum selling price. Future research could focus on a selection of criteria that minimizes the overlap between the considered economic criteria.

Although the majority of the interviewees agreed on the selection of criteria, the final limitation that needs to be addressed is the selection of criteria. Multiple experts argued for implying a criterion which assesses the energy efficiency of a SAF technology pathway. They argued for implying this criterion as they stated that certain SAF technology pathways have a low energy efficiency which makes them either expensive or makes them so inefficient that the energy required for these pathways would be spent on other applications. Future research could imply this criterion within the selection of considered criteria.

7.8 Suggestions for future research and the SAF industry

Although this research indicates that the Fischer-Tropsch technology with forestry residue as feedstock is the most preferred SAF pathway, this cannot be guaranteed with full certainty. Table 21 shows that the Fischer-Tropsch technology that uses municipal solid waste is not far behind as the total score of this pathway is just slightly less than the same technology that uses forestry residues as feedstock. Apart from the fact that the difference between these two pathways is minor, no guarantees can be granted on the performance scores of the pathways as these are based on expectations and these might differ in future. Some sub-criteria are only partially amenable to changes over time while performances of technology pathways on other sub-criteria could change over time, i.e., it could be that the future proves different and therefore influences the performance scores. Future research could therefore focus on where possible efficiency gains can be made with respect to the considered criteria for the different SAF pathways.

As mentioned in the discussion, both power-to-liquid pathways are still relatively state-of-the-art which have sufficient barriers to overcome. These barriers are reflected in this study: their expected minimum selling price remains high, both severe moderate technology readiness levels and their production availability and scalability is expected to remain very little by 2030. Future research could therefore seek to explain how the performances and the ranking will be once these two power-to-liquid pathways perform better on production volume availability and scalability, have a more competitive minimum selling price and have a more developed technology readiness level. This future research could also try to evaluate which of these two pathways would have the highest change of achieving success when these future states are achieved. Since the production volume availability for these two pathways highly depends on the price and availability of renewable hydrogen and the price and availability of renewable electricity, this future research could perform a scenario analysis for different future states regarding the availability and price of both renewable hydrogen and renewable electricity.

The discussion also emphasized the major pitfall of the HEFA pathway that uses used cooking oil as feedstock type: The low expected production volume availability and scalability. If more feedstock would be available, this pathway would score better on the 'production volume availability and scalability' and therefore would shift up in terms of preference. Future research could focus on how to overcome this low expected feedstock availability by investigating if new resource streams can be generated or how the usage of used cooking oils could shift towards the aviation industry instead of biofuels for the road industry.

A final limitation may lay in the fact that this study comes too early to include the social performance of different SAF technology pathways. This is because the SAF industry is at the early beginning of the required uptake and the technologies are still developing. As SAF technologies will no doubt become more prominent and better known to a wider public, future multi-criteria decision-making methods regarding SAF technologies can include this criterion in their analysis.

As already addressed in the limitation section of this study, the final recommendation would be to include the criterion energy efficiency in future MCDM research. As this research excluded this criterion in its analysis and multiple experts argued for implying a criterion which assesses the energy efficiency of a SAF technology pathway, this forms a limitation. So future research could therefore overcome this limitation by implying this criterion within the selection of considered criteria.

As this research shows the preferences and perspectives of the stakeholder groups and shows that the airline industry differs compared to other stakeholder groups, a possible recommendation for the SAF industry could be to focus on finding consensus between the divergent perspectives of the stakeholder groups. Future policies regarding the upscale and development of the SAF industry could focus on finding this consensus as this contributes to overcoming the chicken and egg situation in which the SAF industry is currently situated.

8 Declaration of competing interest

The author hereby declares that he has no competing financial interests, personal relationships or personal motives that could have appeared to influence the results of the work reported in this research.

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9 Appendix A

This appendix discusses all the nine identified studies that are identified in the literature study of this research (section 4.1). It discusses the used methodologies and elaborates on some pitfalls of these studies.

S. Ahmad et al. (2021)
Research by S. Ahmad et al. (2021) proposes a multi criteria based framework to assess different SAF production pathways. With the help of this MCDM framework, 11 different SAF technologies are ranked against different sub-criteria grouped under social, environmental, economic, and technical impact categories. This study suggested to include synthetic SAF production pathways in future research. This study was performed with the PROMETHEE II methodology, which has the ability to use both quantitative and qualitative data for alternative evaluation.

S. Ahmad et al. (2019)
Other research, by S. Ahmad et al. (2019), which partly consists of the same researchers as the first mentioned research, concerns the preliminary results of a survey that integrates stakeholders' perspectives into SAF production options and proposes a methodology to define a criteria framework for SAF assessment. In this survey, experts are asked to value criteria based on a Likert scale varying from very important (5) to negligible (1) and is based on a preference elication model. The consulted experts are grouped under different main stakeholder groups; public, government/NGO, airliner, aircraft manufacturer, distributor of SAF, producers of SAF and feedstock providers. The data gathered from this survey is visualised in an aggregated value tree of criteria and regards 32 criteria. This study emphasizes the importance of multi-criteria decision to support decision-making in complex situations like choosing between different SAF pathways.

Chen & Ren (2018)
The multi-attribute sustainability evaluation performed in research by Chen & Ren (2018) was performed to evaluate the sustainability of different alternative jet fuels. For this research, different groups of stakeholders were interviewed and analysed with the help of the fuzzy grey relational analysis (FGRA) because other, more traditional methods, have issues with reliability due to lack of data and information and this method has the advantage of achieving reliable measurements under uncertainties and lacking information. The following alternative jet fuel pathways were considers in this research; Conventional petroleum refining, Fischer-Tropsch synthesis with natural gas as feedstock, algal-based fuel and soybean-based fuel. Based on five principles, a selection of ten sub-criteria was set up and grouped under economy, environment and society. The research showed that out of these four alternative jet fuel pathways, algal-based fuel was identified as most sustainable fuel. However, the research also mentioned that the algal-based jet fuel is not competitive compared to other aviation fuels because it's low performance on economic and technological criteria. The four discussed pathways are also ranked according to real data based on a study performed by Zhao & Li (2016) and showed some inconsistency in ranking algal-based fuel as most sustainable aviation fuel. Another issue regarding this study needs to be mentioned: when the SAF definition of the European Commission is held, only two out of the four pathways can be considered as SAF. Conventional petroleum refining and FT synthesis with the use of natural gas aren't considered as SAF because of the use of non-renewable feedstock. Despite two of the four pathways cannot be considered as SAF, this study is still deemed relevant since it concerns a multi-criteria decision-making method which is based on alternative jet fuels.

Xu et al. (2019)
The study performed by Xu et al. (2019) investigated the performance of different Alternative Jet Fuels in two sketched scenarios while using a hybrid MCDA method. In this study, the criteria are split up into four aspects: financial, environmental, technical and social dimensions. This report did not interview any stakeholders to arrive at the relative weights of these criteria but sketched two scenarios and according to these scenarios, weights are given to each dimension. One scenario in which the focus was on arriving at as low as possible investment costs while the other scenario assumed equal weights for all the three considered dimensions.

de Souza et al. (2020)
de Souza et al. (2020) investigated different feedstock sources for HEFA biojet production in South-East Brazil with the use of a MCDM model. The study considered seven different feedstock sources and based the performance of these feedstock sources on their performance in Brazil. Despite this study only considered one SAF technology and focuses on different feedstock sources, this study still provides insights in the way criteria are determined, how the AHP method can be combined with the TOPSIS application and discusses why these

methods were chosen. Besides, this study showed which feedstock has the highest potential for the HEFA technology. A notion needs to be made that the performance of the different feedstock types are based on South-East Brazil and considered criteria that are specifically relevant for the HEFA technology. Therefore, the selection of criteria cannot not be used for this study although it gives a good feeling on what could be considered. Also, because the geographical boundary of this study is South-East Brazil, performances of the HEFA fuels may be completely different when the geographical boundary is set for Europe.

Michaga et al. (2021)
Although the study by Michaga et al. (2021) was found on Google scholar when the applying search terms were used, this study doesn't concern a MCDM method. Because it doesn't concern a MCDM method, this study isn't helpfull for determining the criteria. However, this study is still relevant as it provides insights in several technology pathways, several feedstock sources, chemical properties of SAFs and reviews different techno-economic studies and LCAs on SAFs. It also reviews complementary methodologies for techno economic and LCA studies and mentions the MCDM method. This study highlighted performed MCDM studies on SAFs. Three of these studies were initially not found in the literature study of this research but are added and the following three paragraphs will elaborate on these studies.

Michailos et al. (2016)
The study by Michailos et al. (2016) developed a MCDM model for methanol to gasoline and biochemical butanol based on the overall exergy analysis, economic valuations and the CO_2 calculations. This study is more technical of its kind, when compared to the earlier mentioned researches. Although this study performed a MCDM study, the study is of limited relevance since it doesn't concern aviation fuels but showed the relevance of the exergy criteria of different fuels. It concluded that the exergy and economic analysis both favour gasoline production, while the environmental analysis showed that the biochemical butanol is preferred.

Braz & Mariano (2018)
Braz & Mariano (2018) constructed a multi-criteria decision-making framework to elucidate the competition between the ethanol and butanol technology pathway when eucalyptus pulp is used as feedstock. This MCMD gives insights in the criteria that are deemed relevant for the production processes of these technologies. The framework consists of an economic analysis and a carbon footprint analysis with multiple criteria relevant for this analysis. As an addition to earlier mentioned studies, this study emphasized the importance of the competitiveness and performed and analysis about this. This competitiveness is implemented in the MCDM with the use of three criteria: Minimum Selling Price (MSP), Resistance to Market Uncertainty (RTMU) and the Technology Risk (TR). This study also implemented Internal Rate of Return as a criterion for the Economic analysis. Other, earlier mentioned studies did not use this criterion in their economic analysis. Furthermore, this study gives insights in the assumptions that need to be made when performing the economic analysis and analysis the technology pathways under different scenarios.

Huang et al. (2019)
The last identified study which is deemed relevant for the identification process of the criteria concerns the research performed by Huang et al. (2019). Although this study is multi-objective of its kind, this study doesn't concern a MCDM method. A Mixed-Integer Linear Programming (MILP) model is constructed to perform a multi-objective optimisation for renewable jet fuel supply chain system. Three technology pathways are included in this research: Alcohol-to-Jet (ATJ), Fischer-Tropsch (FT) and Hydrothermal liquefaction (HTL). These technologies are evaluated against spatial, agricultural, techno-economic, and environmental data/performance. Spatial in this research being Midwestern U.S.. As the research that will be performed in this research will focus on the European uptake of SAF, the spatial analysis is left out of scope in the long list of criteria in this research. This study provides insights in the differences in performance when technologies are compared on different analysis. When this study considers this analysis simultaneously, a Pareto optimum curve arises. This curve visualizes the difference in conflicts of interest. What's more, is the fact that this study takes into account a broader scope when considering environmental issues as it evaluates not only the direct GHG saving when using the fuel but also considers the biorefinery facility GHG emissions and biomass and SAF transportation GHG emissions.

10 Appendix B

As argued in the main text of this study (section 4.3) the social performance of different SAF technology pathways is excluded since this research is exploratory and SAF are still at the early beginning of the required development. Besides, due to this stage of early beginning, it is very hard to score the different SAF technology pathways on the social performance. Although this aspect is not included in this study, it is still briefly addressed in this appendix as it can be useful for future studies.

Importance of criteria
Social performance can be assessed on a broad range of criteria. Individuals, for example, could perceive societal benefits of SAF technology in the form of job creation, energy security, and social and economic growth through direct and indirect employment, leading them to support such technologies as well as a desire for overall energy security/independence.

Social acceptability
Social acceptability is sub-criterion that used in studies by Chen & Ren (2018), S. Ahmad et al. (2019) and S. Ahmad & Xu (2021). Other, non identified studies regarding assessment of possible biofuels also emphasize the importance of social acceptability (Gegg & Wells, 2017; Efroymson et al., 2017; Zhu et al., 2015). Social acceptability can be split up into multi other sub-criteria as argued by the study of Dale et al. (2013).

Oil dependency
Another criterion that is not identified by the performed literature study regards 'Reduction of oil dependency'. None of the identified studies were published since the start of the Russia-Ukraine war and therefore the assumption is made that this criterion was not used in these studies. Other non-identified studies do consider the reduction of oil dependency as a criterion of importance Schillo et al. (2017). Since the start of this war, the European Union decided to decrease this oil dependency. Therefore, this criterion has risen in its prominence and can be considered as a relevant criterion for the social performance of a SAF technology pathway.
Conventional jet fuel (kerosene) is produced from crude oil while SAFs are not produced with the use of petroleum or other fossil fuels. Therefore, SAF could diminish the level of 'fossil fuel dependency' to counter the currently experienced increasing prices of different fossil fuels. These are mainly caused by the war in Ukraine. Since the war in Ukraine, there's a raised awareness on the EU its dependency on other countries and their supply of fossil fuels. The prices of oil and other commodities have been rising for a substantial period, but the war in Ukraine accelerated this (Khan, 2022). Shortly after the start of the war in Ukraine, the European Union decided to decrease EU countries there dependence on Russian gas by 80%. The International Energy Agency recommended a ten-point plan to decrease this dependency, in which an increase in new renewable energy is one of them (International Energy Agency, 2022). Renewable energy resources, like SAF, could therefore offer a solution to mitigate the conflicts in the gas and oil market. Renewable fuels can increase Europe its energy security of supply and reduce the consequences of conflicts (Khan, 2022).

International agreements/Mandates
The third sub-criterion that can be relevant for the social performance is 'International agreements/Mandates'. This criterion is used in the study by S. Ahmad et al. (2019) and concerns the binding obligation issued from an intergovernmental organisation to a country/countries which is/are bound to follow the instructions of the organisation. Other, non identified studies in the literature study also emphasize the importance of governments having the urge to comply with international targets (Schillo et al., 2017). Given the ambitious SAF mandate proposed by the European Commission, and the fact that this study will assess different SAF technology pathways with different blending mandates, this sub-criterion can be considered relevant for the social performance.

Other sub-criteria could also be addressed in future studies. 'Food security' is one of these sub-criteria. This criterion is addressed in the studies by S. Ahmad et al. (2019), S. Ahmad & Xu (2021) and de Souza et al. (2020). In this stuy, the decision is made to exclude this criterion as this study will not assess any SAF feedstock that is crop based. Only non-crop-based feedstock types (advanced biofuels and e-fuels) will be assessed in this study. This same argumentation is used on why to exclude the land-use change impact as an environmental sub-criterion. Any biofuel feedstock that will potentially harm food security will be subjected to a cap, and in case of high direct land-use change-risk, they are due to be phased out by 2030 (European Commission, 2021a). If future studies will imply crop-based feedstocks in their analysis, 'food security' and 'land-use change impact' are both feasible as sub-criteria for their analysis.

11 Appendix C

The Technology Readiness Level (TRL) index is a widely used benchmarking tool for monitoring development of a particular technology through the early stages of the innovation chain. It ranges from the very early steps of basic principles observed, which refers to TRL level 1, to the actual system proven in operational environment, which refers to TRL 9. When a section in this study refers to a TRL level, the following definitions apply, unless otherwise stated:

Table 27: Levels of TRL

Technology Readiness Level	**Definition**
TRL 1	Basic principles observed
TRL 2	Technology concept formulated
TRL 3	Experimental proof of concept
TRL 4	Technology validated in lab
TRL 5	Technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies)
TRL 6	Technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies)
TRL 7	System prototype demonstration in operational environment
TRL 8	System complete and qualified
TRL 9	Actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies; or in space)

This RTL rating scale corresponds to the rating scale that is used within the European Commission (European Commission, 2016).

12 Appendix D

This appendix provides the slidedeck that was shown to the interviewees during the interviews. This slidedeck was made to contribute to the interviewee his/her knowledge on what the Best-Worst Method is, how it works, what criteria were considered, what they meant and how to answer the pairwise comparisons. The following section touches upon the slides that were shown during the interviews.

- **Stakeholder interview**
  In the first slide a general introduction was given and some practical points were raised. The following information was given on the anonymity: *"This interview will be performed on behalf of my Master thesis which I'm currently writing for my study at the Technical University of Delft. The gained results, remarks and insights will be used only for this study and shall not be shared. Any information that could lead to the identity of the interviewee will be decontextaulized or anonymised. If the interviewee doesn't feel comfortable to answer certain questions or would like to stop the interview, the interview will be closed and the whole interview will be deleted. If the interviewee agrees, the interview will be recorded. The recordings will only be available to the interviewer and will be used for this study only and shall not be shared with anyone."*. If the interviewee agreed on this and a declaration of competing interest was given, the interview was started.

- **Structure of the interview**
  During this slide, the structure of the interview is provided.

- **Background information**
  During this slide, the background information is given. It is mentioned that the aviation industry is growing and carbon neutral growth is the International Civil Aviation Organization (ICAO) its goal. Also, the role of SAF and the proposed blending mandate by the EU is mentioned. The knowledge gap is explained and the goal of this study emerges from this knowledge gap and is explained.

- **Multi-criteria-Decision making method**
  It is explained that this study uses a multi criteria decision making method. It is explained what this means it is explained that these criteria are assessed on the 'scale up potential and feasibility for the SAF mandate by 2030'.

- **Best-Worst Method**
  This slide explains the Best-Worst Method. It explains what pairwise comparisons are and what the final analysis of the BWM will look like. Depending on the interviewee his/her understanding of BWM so sar, an example of a realistic simplified BWM application was shown. This example was sometimes further explained by showing visualised pairwise comparisons between the example criteria and it was explained how to interpret these pairwise comparisons.

- **Considered technology pathways**
  In this slide, the four main technologies are listed and it was made clear which SAF technology pathways are considered in this study.

- **Main criteria and sub-criteria**
  The main criteria are explained and their corresponding sub-criteria are listed. It was mentioned that these sub-criteria were selected and constructed out of a long list of potentially relevant criteria. All the sub-criteria are briefly explained and it was questioned whether all main and sub-criteria were clear to the interviewee. This was done as it is an essential aspect that the interviewee clearly understands all the criteria before starting with the BWM. If there's any misunderstanding of the main- and sub-criteria, the interviewee could possibly give answer on wrong perceptions and therefore influence the outcome of the analysis. Also, a finalised fictitious end result of the quantification of all main and sub-criteria was shown on this slide to visualise the end result of the interview. It was explicitly mentioned that this visualisation was fictitious.

- **Best-Worst Method applied**
  The next step was the performance of the BWM itself. Because all the three main-criteria were split into multiple criteria, four BWM comparison analysis were required in order to obtain the optimal weights for the main-criteria and their sub-criteria. At first, the comparison analysis was performed for the environmental, economic and technological sub-criteria. Secondly, the comparison analysis was performed for the main-criteria. The decision to perform the comparisons for the sub-criteria first was done on purpose. During the first three comparison analysis, the interviewee gains good insights on which sub-criteria are

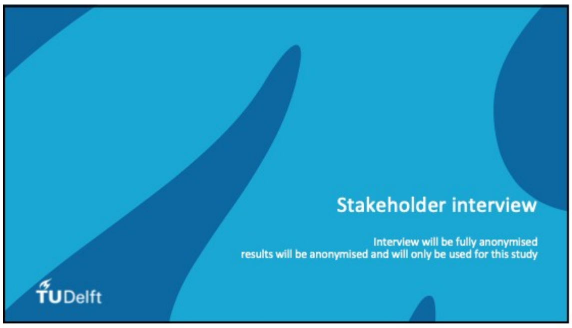
considered per main criterion. These insights can therefore help the interviewee to make a well considered pairwise comparisons during the fourth comparison analysis, the comparisons between the main-criteria itself. Per BWM comparison analysis (four in total), at first, the **most** and **least** important criteria regarding the feasibility and upscale potential for the SAF mandate by 2030 were identified by the interviewee. After this has been done, the pairwise comparisons were made between the most important criterion and other criteria and pairwise comparisons were made between the other criteria and the least important criterion, as the BWM requires (Rezaei, 2015). This pairwise comparisons require answering in terms of 'distance' between the criteria in which the preference of the expert is asked on "the Best criterion over all the other criteria", and the preference of "all the other criteria over the Worst". To answer this preference, a quantification of the distance between the criteria is used and is shown in table 28.

Table 28: Quantification of distance between criteria

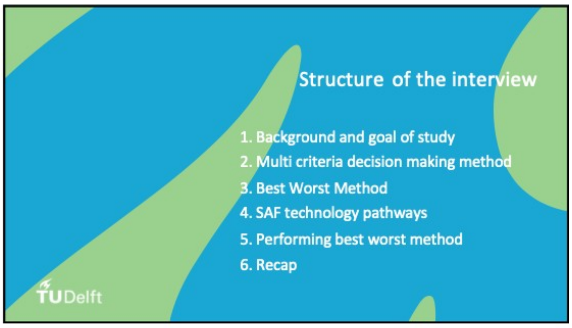
Number	**Meaning of the numbers 1-9**
1	Equal importance
2	Somewhat between Equal and Moderate
3	Moderately more important than
4	Somewhat between Moderate and Strong
5	Strongly more important than
6	Somewhat between Strong and Very strong
7	Very strongly important than
8	Somewhat between Very strong and Absolute
9	Absolutely more important than

- **Recap**
  After the BMW was completed a recap was held. First of all, it was discussed what the interviewee thought of the BWM and whether he/she had any comments or suggestions about this method. Afterwards, the interviewee was asked whether the interviewee agreed with the selection of the main and sub criteria. It may be that the interviewee might not fully agree with the selection of criteria and argues for leaving some criteria out of scope and/or implying criteria that were not considered. They were also asked whether the interviewee agreed with the selection of SAF technology pathways or whether he/she had chosen a different selection.

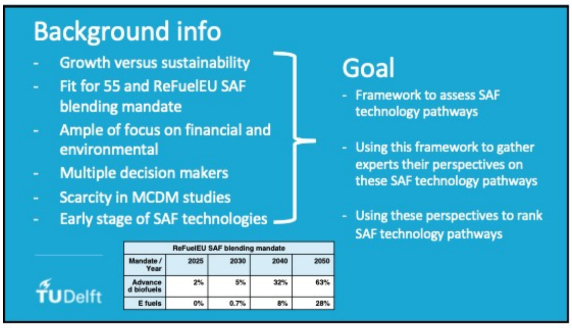
- **Ending**
  As a final part of the interview the interviewee was thanked for his/her time and was questioned whether he/she would be interested in receiving the BWM applied on their answers and whether he/she would be interested in receiving the final report.


Stakeholder interview
Interview will be fully anonymised
results will be anonymised and will only be used for this study
TUDelft

1


Structure of the interview
1. Background and goal of study
2. Multi criteria decision making method
3. Best Worst Method
4. SAF technology pathways
5. Performing best worst method
6. Recap
TUDelft

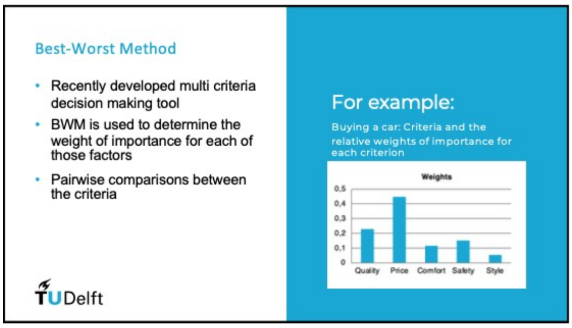
2


Background info
- Growth versus sustainability
- Fit for 55 and ReFuelEU SAF blending mandate
- Ample of focus on financial and environmental
- Multiple decision makers
- Scarcity in MCDM studies
- Early stage of SAF technologies
Goal
- Framework to assess SAF technology pathways
- Using this framework to gather experts their perspectives on these SAF technology pathways
- Using these perspectives to rank SAF technology pathways
ReFuelEU SAF blending mandate
Mandate / Year | 2025 | 2030 | 2040 | 2050
Advanced biofuels | 2% | 5% | 32% | 63%
E fuels | 0% | 0.7% | 8% | 28%
TUDelft

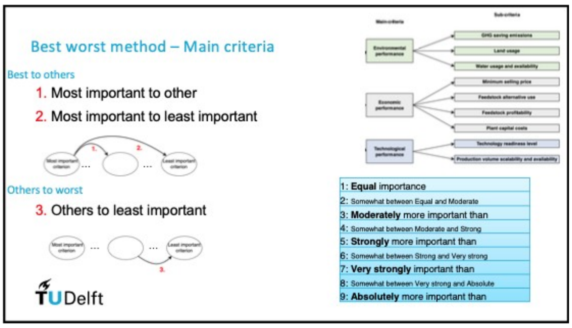
3


Multi Criteria Decision making method
Evaluate different SAF technology pathways based scale up potential and feasibility for SAF mandate by 2030
MSc thesis Victor de Haas
TUDelft

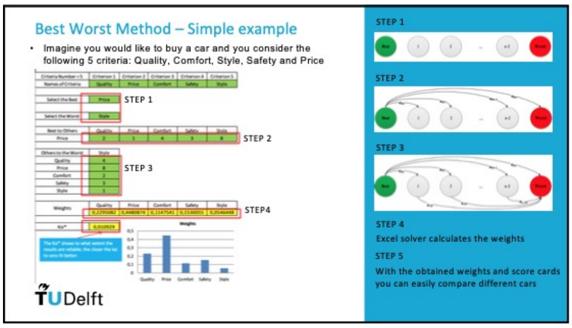
4


Best-Worst Method
• Recently developed multi criteria decision making tool
• BWM is used to determine the weight of importance for each of those factors
• Pairwise comparisons between the criteria
For example:
Buying a car: Criteria and the relative weights of importance for each criterion
Weights
0,5
0,4
0,3
0,2
0,1
0
Quality
Price
Comfort
Safety
Style
TUDelft

5


Best worst method – Main criteria
Best to others
1. Most important to other
2. Most important to least important
Others to worst
3. Others to least important
Main criteria
Sub-criteria
Environmental performance
GHG saving emissions
Land usage
Water usage and availability
Economic performance
Minimum selling price
Feedstock alternative use
Feedstock profitability
Plant capital costs
Technological performance
Technology readiness level
Production volume scalability and availability
1: Equal importance
2: Somewhat between Equal and Moderate
3: Moderately more important than
4: Somewhat between Moderate and Strong
5: Strongly more important than
6: Somewhat between Strong and Very strong
7: Very strongly important than
8: Somewhat between Very strong and Absolute
9: Absolutely more important than
TUDelft

6



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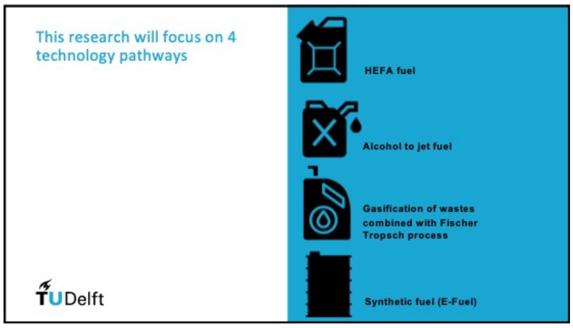

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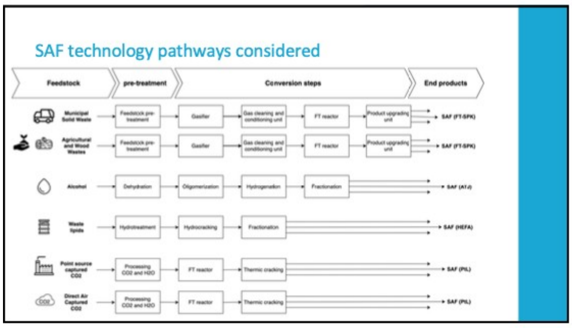

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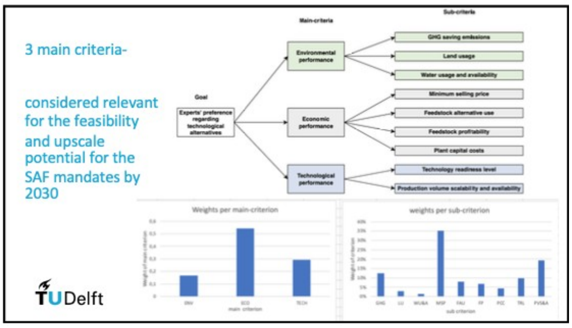

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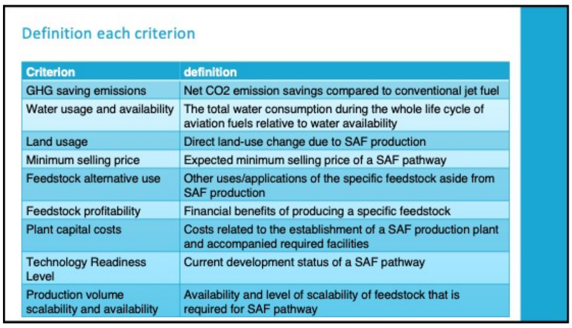
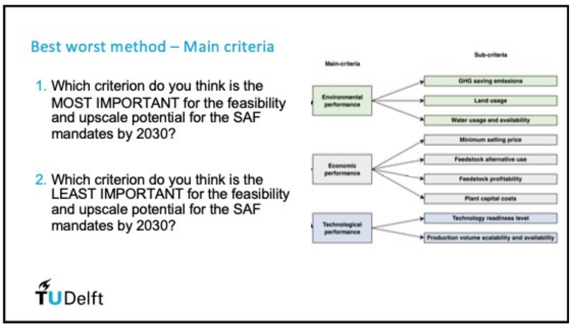


Definition each criterion

Criterion	definition
GHG saving emissions	Net CO2 emission savings compared to conventional jet fuel
Water usage and availability	The total water consumption during the whole life cycle of aviation fuels relative to water availability
Land usage	Direct land-use change due to SAF production
Minimum selling price	Expected minimum selling price of a SAF pathway
Feedstock alternative use	Other uses/applications of the specific feedstock aside from SAF production
Feedstock profitability	Financial benefits of producing a specific feedstock
Plant capital costs	Costs related to the establishment of a SAF production plant and accompanied required facilities
Technology Readiness Level	Current development status of a SAF pathway
Production volume scalability and availability	Availability and level of scalability of feedstock that is required for SAF pathway

11



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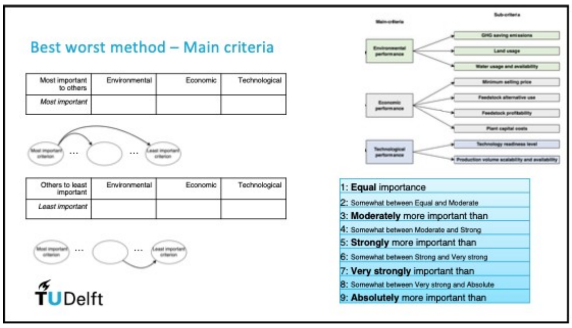

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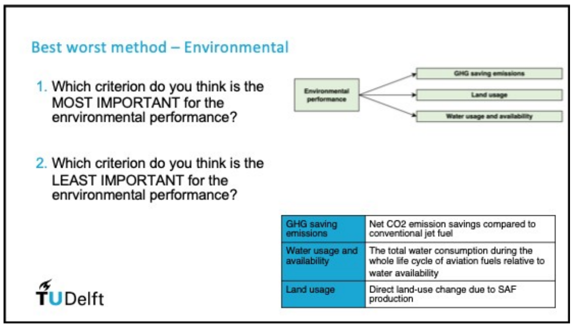

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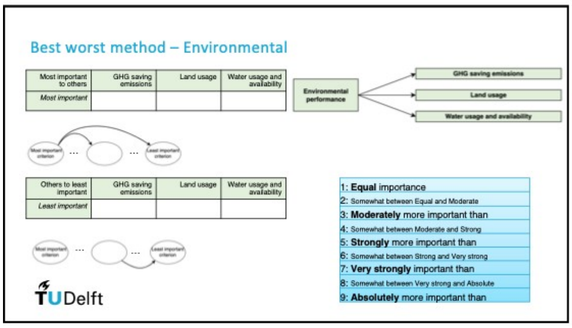
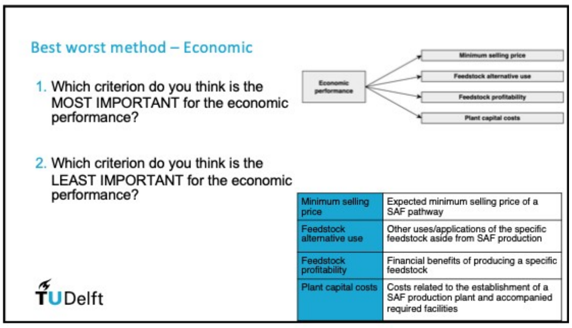
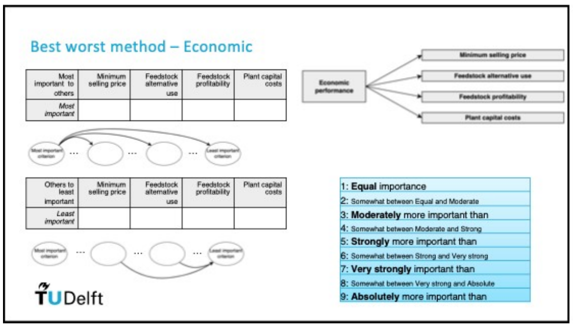


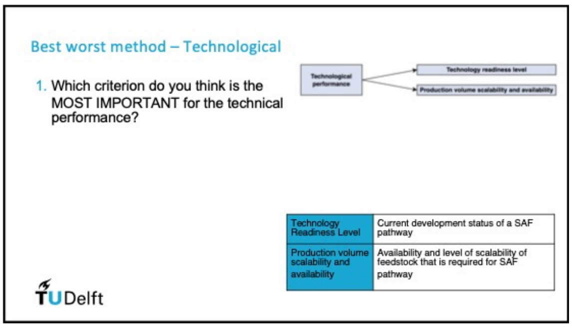
15



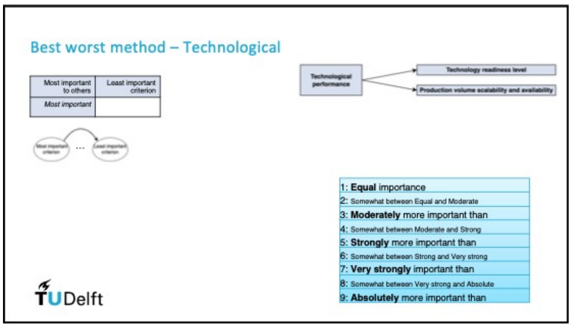
16



17



18



19

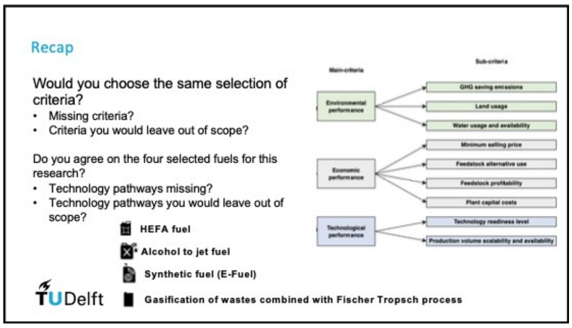


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Figure 16: Presented slide deck during the interviews