Delft University of Technology

Master Thesis Research
CoSEM

Determining Stakeholders' Preferences towards Sustainable Aviation Technologies

A Bayesian Best-Worst Method in Assessing Sustainable Aviation Technologies Preferences

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Preface and Acknowledgement

Presented before you is the Master Thesis report titled "Determining Stakeholders' Preferences towards Sustainable Aviation Technologies - A Bayesian Best-Worst Method in Assessing Sustainable Aviation Technologies Preferences." This paper was created to complete the Technical University of Delft's Master Complex Systems Engineering and Management program.

From a young age, I have always been interested in technology and societal issues. Initially, my decision for Delft was not obvious due to my strong interest in societal issues. However, I found the Bachelor of Technology, Policy, and Management, which combined the technological and societal perspectives in addressing problems. Furthermore, within this Bachelor, I was interested in the transport sector, leading me to follow the track of Transport and Logistics.

After completing my Bachelor's degree, I started the Master of Complex System Engineering and Management. This Master's program attracted me because of its focus on tackling problems in socio-technical systems. During this Master's program, I followed the Transport and Logistics as I was intrigued with this track in the Bachelor's program. Within this track, I had the opportunity to select elective courses. I decided to follow the course of Airport and Cargo Operations at the Aerospace Engineering faculty, as I have been fond of aircraft since childhood. During this course, I noted that I was very interested in sustainable aviation, leading me to the topic of my Master's thesis

I would like to thank my supervisors, Jan Anne Annema and Ivo Bouwmans, for their guidance through my Master's thesis. Furthermore, I want to thank Jafar Rezeai, who helped me with questions about the use and application of the Bayesian Best-Worst Method. Finally, my thesis project was an unforgettable and educational journey. Reflecting on it now, I see this as a very educational experience and I appreciate everyone who offered me support in any way throughout this journey.

Tom van Santen
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Executive Summary

In October 2022, all member states of the International Civil Aviation Organization (ICAO) committed to achieving a net-zero CO_2 future by 2050, marking a groundbreaking shift from mostly compensating for emissions toward decisive action at significantly reducing CO_2 emissions from aviation. The critical importance of reducing greenhouse gas emissions in the transport sector has long been acknowledged, with the first steps made in the Paris Agreement. However, aviation is significant within the transportation sector as it accounts for 12 percent of carbon emissions and 2 percent of all global energy-related emissions. Because of the relevance of climate change and substantial investments related to this problem, the aviation industry and governments have to make considered choices about the transition towards sustainable aviation to meet the net zero carbon dioxide goal of 2050. One of these choices encompasses the adoption of sustainable aviation technologies (SATs). In this research, sustainable aviation technologies are defined as the combination of both the fuel and corresponding aircraft technology required.

However, a literature review revealed a knowledge gap regarding the stakeholder preferences towards the SATs and emphasized the importance of knowing these preferences for the successful adoption of SATs. This study aims to address this knowledge gap, thereby contributing to a research field that currently lacks extensive literature on preferences for SATs. Therefore, this research aims to explore more insight into the stakeholder preferences towards SATs, leading to the formulation of the research question:

"What are stakeholder preferences towards sustainable aviation technologies for transition to net zero CO_2 aviation in 2050?"

To tackle this question of an exploratory nature, a Multi-Criteria Analysis approach, specifically the Best-Worst Method (BWM), is chosen due to its aptness for exploring stakeholder preferences. The research, guided by the BWM, is divided into four sections: 1) identifying specific SATs that hold promising potential for adoption, 2) establishing a set of criteria deemed relevant for the evaluation of SATs, 3) obtaining weights for these criteria according to stakeholder preferences, 4) establishing the SAT performance scores on the criteria and final SAT scores regarding stakeholder preferences.

The initial section of this research focuses on identifying the specific SATs within the technology categories of hydrogen, electric, electrofuels, and biofuels. A literature search is carried out to make a selection of the SATs that hold promise for potential adoption. During this literature search, it was found that electric technologies are not considered suitable for medium- and long-haul commercial passenger flights, leading to their exclusion from further consideration. Among the remaining technology groups, the literature identified the following specific SATs as most promising for potential adoption: 1) Liquid hydrogen with PEM fuel cell aircraft (LH_2), 2) HEFA-produced biofuel with used cooking oils and required aircraft modifications (HEFA), 3) n-octane electrofuel and required aircraft modifications.

The second section of this research establishes a set of criteria deemed relevant for the evaluation of SATs. To determine this set of criteria, an extensive literature review was conducted. Additionally, the political economy of transport innovations feasibility framework of Feitelson & Salomon (2004), in combination with the Triple Bottom Line theory, guided the categorization of these criteria. As a result of this combined approach, 3 main criteria were established: "Environmental", "Economic" and "Technological" performance. Each main criterion encompasses three sub-criteria derived from the literature review, totaling 9 sub-criteria. The sub-criteria of "Environmental performance" include "greenhouse gas emissions", "Water consumption", and "Land use impact". The sub-criteria of "Economic performance" include "Minimum jet fuel selling price", "Investment costs", and "Operational costs". Finally, the sub-criteria for "Technological performance" are "Technological readiness level", "Scalability", and "Efficiency". During the interviews, the stakeholders agreed upon the relevance of these criteria regarding the evaluation of SATs.

The third section utilizes the Bayesian BWM to establish the optimal weights for all main criteria and sub-criteria regarding the stakeholder perspectives. The Bayesian BWM is applied to determine the optimal weight for all stakeholder groups together and the optimal weights for the stakeholder groups separately. Data necessary for this analysis is derived through semi-structured interviews with eleven stakeholders from the aviation industry, using pairwise comparisons. These stakeholders are categorized into three stakeholder groups: the airline, the expert/advisor, and the producer/manufacturer stakeholder group. The optimal weights analysis across all stakeholders together highlights "Greenhouse gas emissions" as notably paramount among all sub-criteria. This sub-criterion of "Greenhouse gas emissions" is a significant distance, followed by the economic

sub-criterion of "Operational costs", closely succeeded by the third-ranked sub-criterion "Land use impact". Additionally, separate weights for each stakeholder group are derived. The stakeholder group weights are obtained to provide deeper insight into the different perspectives between stakeholder groups. Notably, the airline stakeholder group diverges significantly in its weighting from all stakeholder groups together. This group assigns high weight to "Economic performance" and, remarkably, significantly lower weight to "Environmental performance" of SATs compared to all stakeholder groups together as well as to the separate stakeholder groups. Moreover, the expert/advisor stakeholder group attributes significantly higher weight to the "Technological performance" compared to the other stakeholder groups together as well as separate stakeholder groups. These variations in weights regarding the criteria emphasize the distinct perspectives of the individual stakeholder groups.

Finally, the performance scorecards of the SATs are conducted based on scientific literature, representing their performance scores on each sub-criterion. By using these performance scorecards of the SATs in combination with the obtained optimal weights for the criteria, the final scores of the SATs regarding the stakeholder preferences are determined, applying the Weighted Sum Method (WSM). These final scores cover the years 2024, 2030, and 2050, selected due to the goal of net zero CO_2 emissions by 2050 and to identify potential changes over time. The results of the final scores and rankings are presented in Table 7.17.

Table 7.17: Final scores and rankings on SATs regarding stakeholder preferences

Year	Stakeholder group	N-octane	HEFA	LH_2	Ranking
2024	All together	4.75	**6.15**	5.05	HEFA > LH_2 > N-octane
	Airline	4.56	**5.76**	4.43	HEFA > N-octane > LH_2
	Expert/advisor	5.06	**6.48**	5.68	HEFA > LH_2 > N-octane
	Producer/manufacturer	4.61	**5.72**	4.96	HEFA > LH_2 > N-octane
2030	All together	5.92	**6.92**	6.08	HEFA > LH_2 > N-octane
	Airline	5.73	**6.68**	5.70	HEFA > N-octane > LH_2
	Expert/advisor	6.55	**7.13**	6.69	HEFA > LH_2 > N-octane
	Producer/manufacturer	5.56	**6.56**	5.94	HEFA > LH_2 > N-octane
2050	All together	8.23	**8.58**	8.39	HEFA > LH_2 > N-octane
	Airline	8.31	**9.20**	8.64	HEFA > LH_2 > N-octane
	Expert/advisor	**8.49**	8.23	8.41	N-octane > LH_2 > HEFA
	Producer/manufacturer	8.02	**8.48**	8.41	HEFA > LH_2 > N-octane

As shown in Table 7.17, the final rankings derived from the scores indicate a preference for HEFA for all stakeholder groups together over all the years. This first-ranked position of HEFA is not due to outstanding scores in any single sub-criterion but results from consistently high scores across most sub-criteria. In 2024, HEFA scores significantly higher than n-octane and LH_2. By 2030, this difference decreases, and by 2050, the scores of LH_2 and n-octane converge closely to HEFA's for all stakeholders together. This convergence is driven by significant performance increases on the highest weighted sub-criterion of "Greenhouse gas emissions" for LH_2 and n-octane, resulting from increased renewable electricity availability. However, these gains are partly offset by decreasing performance scores on the "Land use impact", the third-ranked sub-criterion, resulting from the deployment of solar PV and wind turbines for renewable electricity. Despite this offset, the higher weighting of the increases in "Greenhouse gas emissions" performances allows n-octane and LH_2 to nearly approach HEFA's score by 2050. Furthermore, even though criteria weights vary among stakeholder groups, HEFA consistently remains the most preferred SAT among all separate stakeholder groups for the years 2024, 2030, and 2050. With the exception of the expert/advisor stakeholder group in 2050, n-octane ranks the highest and HEFA is ranked lowest.

To conclude, regarding the main research question from this study, HEFA consistently emerged as the highest-ranked SAT among all years for all stakeholder groups together, as well as for the separate stakeholder groups. The only exception is the expert/advisor stakeholder group in 2050, where n-octane ranks highest and HEFA is ranked lowest. It is important to note that these conclusions should be considered indicative rather than definitive due to the limited number of interviews used, causing a potential lack of representativeness of the entire aviation industry.

Therefore, further research is recommended to conduct a larger number of stakeholder interviews to ensure the representativeness of the aviation industry and prevent the results from potential biases. Additionally, further research is recommended to explore the impacts of contrails. This is necessary to address the discussions between stakeholders and the limited literature on the effects of contrails, mainly regarding increased vapor production with the use of hydrogen. Moreover, further research is recommended to explore fuel infrastructure, production plants, and manufacturer fabrics regarding the SATs, as these components are important for the widescale adoption of SATs but were not covered in the scope of this research. It is also recommended to explore whether there is enough feedstock availability for the SATs, such as used cooking oils for HEFA, to produce enough for wide-scale adoption in the aviation sector with regard to the demand of other sectors. Further research is recommended to explore the potential of using different SATs in combination to achieve net-zero CO_2 emissions in aviation. This research only focused on individual SATs, although stakeholders argued for further investigation towards the potential of combining SATs, such as HEFA for long-haul and LH_2 for medium-haul flights. Lastly, additional research could focus on exploring how policy measures might affect the preferences of different SATs. For example, what impact would the implementation of carbon taxes have regarding the differences in greenhouse gas emissions of HEFA, LH_2, and n-octane?

Contents

Abbreviations

Abbreviation	Meaning
AHP	Analytic Hierarchy Process
ANP	Analytic Network Process
BWM	Best-Worst Method
CL	Confidence Level
CO_2	Carbon dioxide
CoSEM	Complex System Engineering & Management
GHG	Greenhouse gas emissions
HEFA	Hydroprocessed Esters and Fatty Acids
IC	Investment costs
KSI	Consistency ratio
LH_2	Liquid Hydrogen
LRT	Literature reference table
LUI	Land use impact
MCA	Multi-Criteria Analysis
MCDA	Multi-Criteria Decision Analysis
MCDM	Multi-Criteria Decision-Making
MJFSP	Minimum Jet Fuel Selling Price
NO_x	Nitrogen oxides
$PM_{2.5}/PM_{10}$	Particulate matter
PRISMA	Preferred Reporting Items for Systematic reviews and Meta-Analyses
OC	Operational costs
SAF	Sustainable Aviation Fuel
SAT	Sustainable Aviation Technology
TBL	Triple Bottom Line (theory)
TRL	Technological Readiness Level
WC	Water consumption
WSM	Weighted Sum Method

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1 Introduction

Problem introduction

In October 2022, the 193 member states of the International Civil Aviation Organization (ICAO) agreed upon the long-term goal of net-zero CO_2. This agreement indicates a shift away from solely compensating for emissions and toward implementing measures aimed at significantly reducing CO2 emissions from aircraft and fuels (ICAO, 2023).

The relevance of the reduction of greenhouse gas emissions (GHG) in the transport sector is nothing new, as in the Paris Agreement, the first steps were made to fight against climate change with the reduction of GHG emissions (UNFCCC, 2016). Within the transport sector, aviation is a crucial part as it is responsible for 12 percent of the carbon emissions (*Aviation Sustainability: facts and figures*, n.d.). Furthermore, according to the International Energy Agency, aviation was responsible for 2 percent of all global energy-related carbon emissions (*Aviation - IEA*, n.d.). This relatively large share of emissions, in combination with the long-term aspirational goals of net-zero CO_2 from the ICAO, reveals the social relevance of making aviation more sustainable to fight climate change for the future of the next generations (ICAO, 2023).

To attain the member states goal of achieving net zero CO_2, following the agreements in the ICAO (ICAO, 2023), substantial work and efforts are needed to be undertaken before 2050. The Economist (2023) calls this "mission impossible". In other words, this is only possible by the adoption of incredible fuel-efficiency gains and aircraft with innovative technologies in combination with sustainable fuel. These measures must be enacted around the year 2035 to ensure the emission goals of 2050 (The Economist, 2023). Furthermore, The Economist (2023) also argues that there are large investments related to the transition towards sustainable aviation, approximately 820 billion euros.

The problem is that there are too many uncertainties about which is the most promising innovative solution for a transition towards net zero CO_2 aviation (Delbecq et al., 2023). Because of the relevance of climate change, and substantial investments related to this problem, the aviation industry and governments have to make considered choices about the transition towards sustainable aviation to meet the net zero carbon dioxide goal of 2050. These choices encompass options related to alternative technologies aimed at achieving sustainable aviation transportation. The main alternative sustainable aviation technologies (SATs) include biofuel-, electrofuel-, electric-, and hydrogen-powered aircraft technologies (Su-ungkavatin et al., 2023). Hence, research into SATs holds significant societal relevance, as it aids policymakers and the aviation industry in making informed decisions that reduce the environmental impact of aviation and promote societal well-being.

1.1 Knowledge gap and research questions

Knowledge gap and main research question

In the problem introduction, it is highlighted that there are uncertainties regarding the potential technology solution for transitioning aviation to a net-zero carbon dioxide emission state, which is pursued given the ICAO's net zero carbon dioxide emissions long-term aspirational goals by 2050 (ICAO, 2023). The literature review in Chapter 2 reveals a knowledge gap regarding the stakeholder preferences and the importance of those preferences for the successful adoption of Sustainable aviation technologies (SATs). Therefore, this research aims to give more insight into the potential of SATs based on the preferences of the stakeholders towards these technologies. Thus, the main research question being undertaken is as follows:

"What are stakeholders preferences towards sustainable aviation technologies (SATs) for transition to net zero CO_2 aviation in 2050?"

Wherefore, the main considered SAT groups are: electrofuel-powered, hydrogen-powered, electric-powered, and biofuel-powered aircraft (see Section 1) (Su-ungkavatin et al., 2023).

Sub-questions

In this paragraph, the sub-questions to the main research question are introduced. These sub-questions are necessary to answer the main research question indirectly. In Section 3.2, the methodologies used to answer the sub-questions are elaborated.

1. *What are the specific SATs within each technology group (electrofuel, hydrogen, electric, biofuel) with promising potential for adoption?*
2. *What criteria are considered important in the evaluation of sustainable aviation technologies?*
3. *What are the weights of the different criteria based on stakeholder perspectives?*
4. *How do these alternative sustainable aviation technologies differ concerning stakeholder preferences, considering the criteria and corresponding weights?*

1.2 Link to CoSEM Program

This problem is a typical CoSEM-related topic with a complex issue in a social-technical system because the aircraft industry is highly interconnected to numerous other sectors; thereby, it has an impact on the global economy. Therefore, this research aims to evaluate sustainable aviation technologies to provide oversight of stakeholder preferences in this multi-actor aviation environment towards alternatives for sustainable aviation transitions. This research has the aim to contribute to making decisions for policymakers and the aviation industry to reach the net zero CO_2 goals of the ICAO by 2050 (ICAO, 2023).

1.3 Research scope

This research solely focuses on the evaluation of the preferences of SATs regarding aircraft and their performances. For the environmental performances, this entails the full life cycle of fuels used by the SATs (Section 5). Therefore, in this research, the definition of sustainable aviation technologies is the combination of the fuel and the aircraft technology necessary to operate with that fuel. Thus, when there is referred to HEFA, n-octane or LH_2, this means the fuel and the aircraft technology corresponding with this fuel. When addressing the fuel aspect of the SAT, specific mention is made of HEFA biofuel, electrofuel n-octane, or LH_2 as fuel.

Furthermore, it is important to state that the infrastructure for the fuels of the different SATs, the production plants of fuels and fabrics of new aircraft technologies are left out of scope. Thereby, it is assumed that the infrastructure, production of fuels, and manufacturer fabrics for aircraft have no constraining factors regarding the SATs. However, the possible scales of economies regarding the costs of SATs are included in this research, as this is deemed relevant for the evaluation of SATs (Section 5). These decisions are made due to the time of the research of 24 weeks.

Moreover, the scope of the research is aimed at 2050; this is according to the goal of the ICAO (ICAO, 2023). The definition of aviation is medium- & long haul commercial passenger aviation. Thus, short-haul, private jets and cargo transportation are excluded from this research. Lastly, no consideration has been given to any aircraft design that would improve performance, and this is also left out of the scope.

1.4 Report structure

In the following chapter, Chapter 3, the research approach is discussed, outlining how the main research question will be addressed with the help of the sub-questions and their corresponding methods. The subsequent chapters follow the structure of the RFD, presented in Figure 3.1. In specific, Chapter 4 addresses sub-question 1, Chapter 5 addresses sub-question 2, Chapter 6 deals with sub-question 3, and Chapter 7 addresses the final sub-question 4. Finally, the concluding Chapter 8 offers a discussion, addresses the main research question, presents additional findings, elaborates on limitations, and provides recommendations for further research.

2 Literature review on identification of knowledge gap

This section initiates a literature review to identify potential knowledge gaps related to the problem introduction (Section 1). The first section (2.1) of this chapter focuses on defining key concepts introduced in the problem introduction to ensure unambiguous understanding. In the following subsection (2.2), a literature review is conducted and presented in the form of a literature reference table (LRT), succeeded by . Lastly, the gathered scientific articles are synthesized, which resulted in the identified knowledge gap (Section 2.4).

2.1 Key concepts

Based on the problem introduction, the following key concepts are identified: climate change, net zero CO_2, electric-powered aircraft, electrofuel-powered aircraft, hydrogen-powered aircraft, and biofuel-powered aircraft. First of all, climate change is defined as an increase in global long-term average temperatures and changes in weather patterns (United Nations, n.d.). A major driver of climate change is the greenhouse gases emitted by human activities, of which carbon dioxide is the primary (US EPA, 2023). Therefore, greenhouse gas emissions are defined equivalently to CO_2 emissions. The second important definition is that of net zero CO_2. The concept of net zero CO_2 necessitates substantial reductions in emissions originating from aircraft and their associated fuels. If necessary, additional actions outside of the aviation sector, such as removing CO2 from the atmosphere, may be employed to deal with any remaining emissions (ICCT, 2023). Furthermore, the last key concepts concern the main innovative technologies for the transition towards sustainable aviation. The hydrogen- and electric-powered aircraft are considered straightforward because, as the name states, it is a switch towards hydrogen and electricity as fuel. The last two technologies are the use of electrofuel and biofuels, these are both drop-in Sustainable Aviation Fuels (SAFs) that are sustainable alternatives for the conventional fuel kerosine (EASA, n.d.). Electrofuel, or synthetic fuel, is a type of fuel produced as a combination of hydrogen and carbon; more in-depth explanation follows in Section 4.4 (Su-ungkavatin et al., 2023). Biofuels are derived from renewable biological feedstocks (e.g. plants, algae, or waste)(Su-ungkavatin et al., 2023). Moreover, a drop-in fuel means that the fuel is interchangeable with conventional kerosine-powered aircraft propulsion (Su-ungkavatin et al., 2023). Lastly, it is important to note that, in this research, net zero carbon dioxide emissions and sustainable aviation are assumed interchangeably.

2.2 Literature review

In this section, the literature review is conducted using the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) method, and the final selection of articles is presented in Table 2.1. Subsequently, this section consists of the synthesis based on the literature review.

In this literature review, the only database used is Scopus. Figure 1 illustrates the selection process of the scientific literature selected using the PRISMA method. The first step was conducting a search string based on the problem area's key concepts. The finalized search string encompasses the key concepts of 'electric aircraft,'' electrofuel aircraft', 'hydrogen-powered aircraft', and 'biofuels'. These technologies are chosen for the base of the search string because they are seen as the main technologies in the aviation industry towards sustainable aviation (Su-ungkavatin et al., 2023). Additionally, the concept of 'aviation ' is included to ensure the relevance of the technologies concerning sustainable aviation. Based on these concepts in combination with their synonyms, the following search string is conducted:

(hydrogen OR "hydrogen-powered" OR "hydrogen propulsion") AND (electricity OR "electric-powered" OR "electric propulsion" OR electric) AND (electrofuel OR "electrofuel-powered" OR "electrofuel propulsion") AND (SAF OR BAF OR "sustainable aviation fuel" OR "drop-in fuel" OR biofuel) AND (aircraft OR airplane OR aviation OR "sustainable aviation").

The search conducted within article titles, keywords, and abstracts resulted in an initial result of 28 scientific articles. The selection process for the final included articles for this literature process is conducted using the PRISMA method, which resulted in a total of 9 scientific articles (see Figure 2.1).

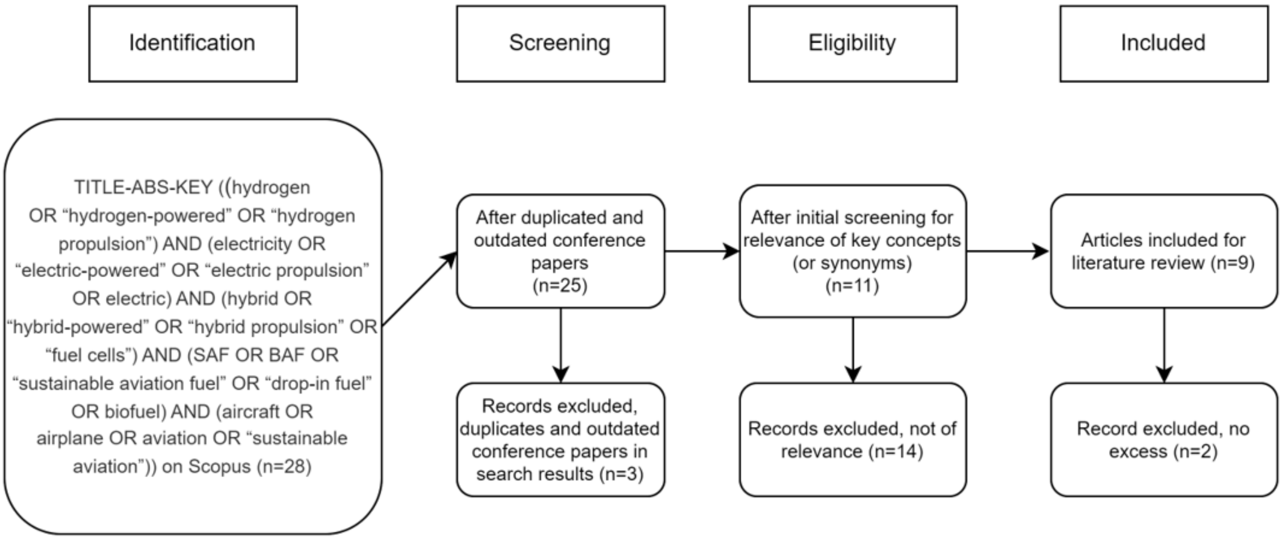

Figure 2.1: PRISMA identifying knowledge gap

In Table 2.1, there is an overview of the 9 articles that are included in the literature review. These articles are chosen with the help of the PRISMA method (Figure 2.1). The first column shows the titles of the scientific articles, the second one shows the authors and the last one shows the reference in text in APA style.

Table 2.1: Literature reference table - knowledge gap

No.	Title	Authors	Reference
1	A review in redressing challenges to produce sustainable hydrogen from microalgae for aviation industry	Ardo, F. M., Lim, J. W., Ramli, A., Lam, M. K., Kiatkittipong, W., Abdelfattah, E. A., Shahid, M. K., Usman, A., Wongsakulphasatch, S., & Sahrin, N. T.	Ardo et al. (2022)
2	Arriving at certifiable novel airliner using liquid hydrogen & efficiency metrics	R. K. Nangia & L. Hyde	Nangia and Hyde (2022)
3	Sustainable aviation fuels	Bauen, A., Bitossi, N., German, L., Harris, A., & Leow, K.	Bauen et al. (2020)
4	Hydrocarbon bio-jet fuel from bioconversion of poplar biomass: techno-economic assessment	Crawford, J. T., Shan, C. W., Budsberg, E., Morgan, H., Bura, R., & Gustafson, R.	Crawford et al. (2016)
5	The future of transportation in sustainable energy systems: Opportunities and barriers in a clean energy transition	Dominković, D. F., Bačeković, I., Pedersen, A. S., & Krajačić, G.	Dominković et al. (2018)
6	An open thinking for a vision on sustainable green aviation	Ficca, A., Marulo, F., & Sollo, A	Ficca et al. (2023)
7	Novel aircraft propulsion and availability of alternative, sustainable aviation fuels in 2050	In J. Kos, J. Posada-Duque, B. Peerlings, N. Ben Salah, W. Lammen, I. Stepchuk, E. Van Der Sman, & M. Palmeros-Parada.	Kos et al. (2022)
8	Technology Assessment for Sustainable Aviation	Stauch, A., & Müller, A. (2022)	Stauch and Müller (2022)
9	Biofuels, electrofuels, electric or hydrogen?: A review of current and emerging sustainable aviation systems	Su-ungkavatin, P., Tiruta-Barna, L., & Hamelin, L.	Su-ungkavatin et al. (2023)

2.3 Analysis

In this section, the selected articles from the literature review are analyzed related to the problem introduction (1) to identify potential knowledge gaps. The literature content table presents an overview of the analysis (Table 2.2). Subsequently, in the last section (2.4), a synthesis of the identified knowledge is presented.

Table 2.2: Literature content table - knowledge gap

No.	Reference	Analysis related to the problem statement to identify knowledge gaps
1	Ardo et al. (2022)	The article mainly discusses the challenges of producing hydrogen from microalgae for aviation. Nevertheless, the article also points out some research gaps regarding the use of hydrogen in the aviation industry. They suggest more research on the possibility of leak detection, to asses load, structure, and aerodynamics regarding the large tanks needed to transport hydrogen safely.
2	Nangia and Hyde (2022)	The paper mentions various technologies that are explored, including synthetic aviation fuels, biofuels, electric batteries, and liquid hydrogen. The paper discusses the advantages and disadvantages of the technologies. In this research, they suggest that LH2 aircraft are promising for future aviation. The article focuses especially on technical aspects and does not reflect stakeholders' preferences.
3	Bauen et al. (2020)	The article discusses the need for sustainable aviation and the challenges of it. Various alternative fuels and electrification technologies are reviewed. The paper argues that the choice of technology for sustainable aviation depends on several factors, such as policy, economics, performance, and public acceptance. This means that the stakeholders' preferences are very important to the adoption of a certain technology.
4	Crawford et al. (2016)	The article discusses the biorefinery process of producing hydrocarbon bio-jet fuel from popular biomass. This study evaluates the technical and economic feasibility and compares it to other bio-jet fuel products. The article concludes that it is feasible and economically viable. Furthermore, the article concludes that it has the potential to reduce greenhouse gases. According to the problem statement is it interesting that this would be a potential technology for the transition towards sustainable aviation, although the recommendations for further research for optimization and improvement. Nevertheless, the research focuses only on this technology and does not reveal other competing technologies. Therefore, further research for an evaluation between competing sustainable aviation technologies would be useful.
5	Dominković et al. (2018)	This article is about a literature review on the challenges and opportunities for a transition towards a sustainable transport sector. This literature review also includes the aviation sector. It points out the lack of research on the total additional energy demand for sustainable alternatives. In other words, the paper argues that the different transport sectors must be seen together, as a holistic view, and not separately. The literature review identified that some research about the aviation industry was done independently from the whole energy system (non-holistic). Therefore, it can be inferred that the research done is missing stakeholders' perspectives, for example; petroleum producers, to conduct a holistic research towards a sustainable aviation.
6	Ficca et al. (2023)	The article emphasizes the need for transdisciplinary research into the technological, operational, and economic fields to successfully introduce long-term solutions for aviation decarbonization. Furthermore, the article refers to certification and operational standards for newly adopted technologies; what institutional rules are needed? Lastly, stakeholders will be impacted in the aviation industry towards carbon-neutral aviation. (such as petroleum producers, financiers, lessors, airlines, and airports)
7	Kos et al. (2022)	The article provides a comprehensive analysis of the potential of different alternative fuels and propulsion concepts for sustainable aviation. The article mainly focuses on the technical and economic aspects of the fuels and propulsion concepts. The analysis of the social and environmental impacts of their potential adoption is limited. Therefore, the article argues

		for further research into these social and environmental impacts. Also, further research is recommended on the technical and economic feasibility. Lastly, important to note is that the article highlights the importance of stakeholder input as they need to collaborate for the adoption of sustainable aviation technologies.
8	Stauch and Müller (2022)	The document discusses some of the challenges facing the implementation of policies for sustainable aviation, including the difficulty of coordinating different nations and stakeholders with different opinions. The paper discusses technological innovations but does not compare them and their potential.
9	Su-Ungkavatin et al. (2023)	There is a need for more research and development to fully understand the potential of the different sustainable aviation technologies discussed in this article: biofuels, electrofuels, electric, or hydrogen. This is necessary to identify challenges or limitations associated with their implementation. Furthermore, the article argues that there is no standardized set of metrics to compare the different technologies and argues that the ICAO claims that it is necessary to evaluate the different technologies on their environmental performance.

2.4 Scientific knowledge gap: stakeholder preferences

The literature review highlights the importance of stakeholder input in the adoption of sustainable aviation technologies (SATs). Overall, the selected articles suggest that stakeholder preferences are crucial to understanding how to reach net zero carbon dioxide aviation by 2050. Furthermore, Stauch & Müller (2022) highlights the challenges facing the implementation of policies regarding the coordination of varying stakeholder opinions towards alternative SATs. This suggests the need for further research to understand stakeholder diverse preferences according to SATs to identify alignments to achieve net zero carbon dioxide aviation in 2050. Kos et al. (2022) also emphasizes the importance of stakeholder preferences because these stakeholders must cooperate for a successful transition toward SATs. Furthermore, Ficca et al. (2023) and Dominković et al. (2018) also argue for the importance of the inclusion of stakeholder perspectives

Furthermore, the content table shows that the articles argue for the need for additional research to fully understand the potential of alternative SATs, including hydrogen propulsion, electric propulsion, electrofuels, and biofuel (Su-ungkavatin et al., 2023; Ardo et al., 2022; Nangia & Hyde, 2022; Crawford et al., 2016). The article argues that additional research is necessary to identify potential adoption challenges. One of the potential adoption challenges, as mentioned in the former paragraph, is the alignment of stakeholders, as they need to cooperate for the successful adoption of technology.

Moreover, the selected article points out the importance of considering multiple criteria/factors during the adoption of new technologies. Criteria such as policy, economics, performance, and public acceptance (e.g. price changes)(Bauen et al., 2020). These criteria are important as they influence the stakeholder preferences. Therefore, further research is needed to identify how these criteria impact stakeholder preferences concerning alternative innovative technologies

This identified knowledge gap emphasizes the scientific relevance of the research because there is an ask from existing literature towards further knowledge of stakeholder preferences for SATs. Moreover, the stakeholder preferences derived weights obtained through the Multi-Criteria Analysis (MCA) of a BWM could serve as valuable data for further research in the aviation technology domain, offering reusable insight within the same actor area, as elaborated on in Section 3.

To conclude, the primary knowledge gap identified in this literature review addresses the scarcity of research examining the preferences of stakeholders in the context of SATs and the importance of knowing these preferences for the successful adoption of SATs.

3 Research approach

In this section, the research methods used to answer the different sub-questions are discussed. These research methods play a crucial role in providing answers to the sub-questions, which enable the answering of the main research question. Furthermore, an overview of the sub-questions with their research methods is given in the form of a research flow diagram (RFD) for a comprehensive illustration of the research as a whole.

3.1 Exploratory research

The knowledge gap implies that there is a lack of understanding regarding different stakeholder preferences on which technology has the potential to be widely adopted to reach net zero CO_2 aviation in 2050 (Section 2.4). This resulted, as indicated in Section 1.1, in the main research question: "What are stakeholder preferences towards the alternative technologies for transition to net zero CO_2 aviation in 2050?". Therefore, this research aims to gain insights into the stakeholder preferences towards the innovative technologies available in the aviation industry. The research goal to gain insight into the lack of knowledge makes it a typical exploratory research. To tackle this main question of an exploratory nature, the study utilizes a Multi-Criteria Analysis (MCA) methodology as detailed in Section 3.2.3. The MCA methodology, specifically the BWM, is chosen due to its suitability for exploring stakeholder preferences. Lastly, it is an exploratory approach with quantitative analysis through an MCA using the Best Worst method (BWM) (Section 3.2.3), thus defining the research as a quantitative exploratory research approach.

3.2 Research Flow Diagram & Research methods

Figure 3.1 presents the research flow diagram (RFD) of this research. This RFD illustrates the research phases with the corresponding sub-questions, data requirements, methods used, data tools used, and required output. The methods used to answer the sub-questions are elaborated on in the next subsections.

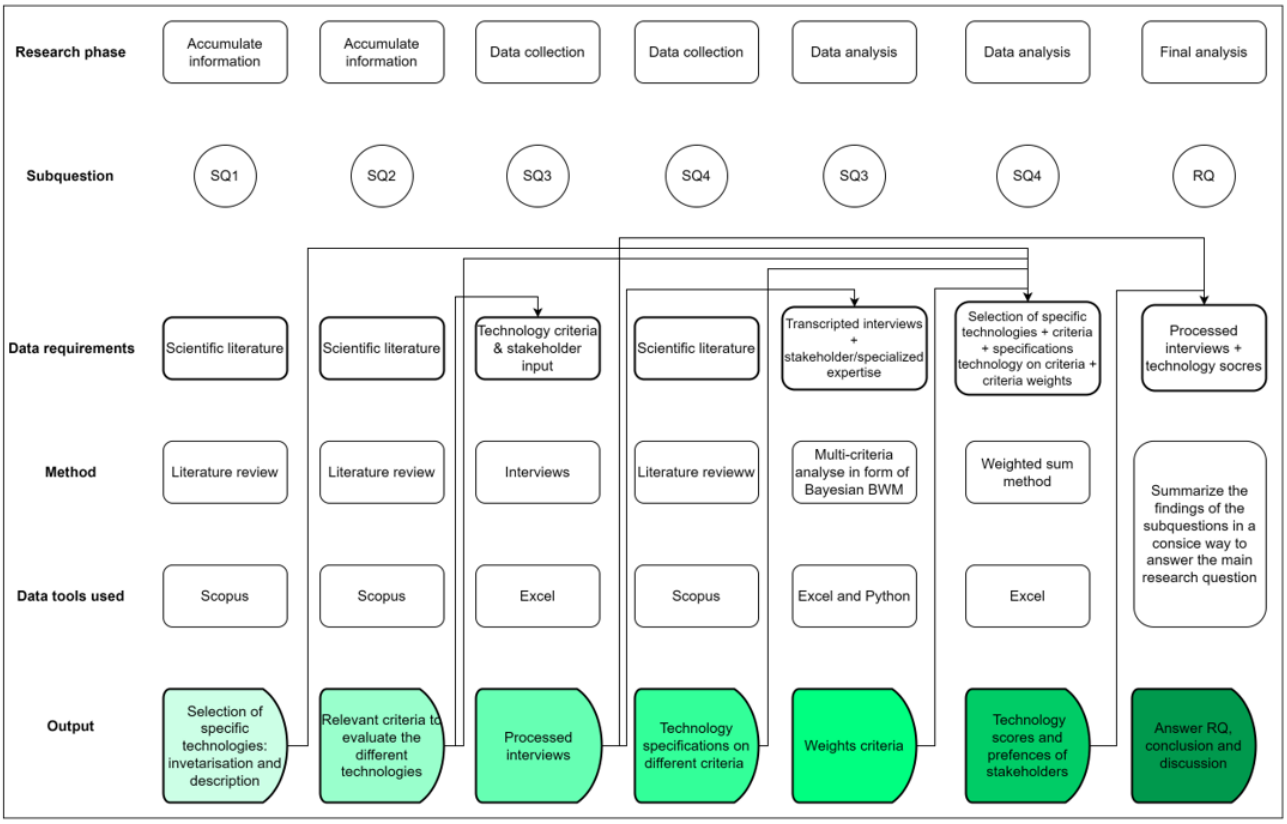

Figure 3.1: Research Flow Diagram

3.2.1 Sub-question 1: identifying specific sustainable aviation technologies

The first sub-question is answered by using literature. This literature is used to delineate four specific sustainable aviation technologies within the four technology groups mentioned in the problem introduction (Section 1): electrofuel-propulsed, hydrogen-propulsed, electric-propulsed, and biofuels-propulsed aircraft. The selection of these specific SATs was guided by scientific articles, emphasizing their promising potential for adoption. Furthermore, literature is used as a source for comparing various technologies, as their precise specifications are essential for evaluation. Scopus and Google Scholar are utilized as databases due to their provision of reliable scientific articles. Finally, the data obtained to answer this sub-question are the four identified specific SATs within the technology groups.

3.2.2 Sub-question 2: selection relevant criteria for evaluation

Secondly, literature is used to address the second sub-question. This literature review focused on identifying the main criteria for evaluating the technologies. It aimed to specify the essential criteria necessary for the evaluation of alternative aviation technologies. In this literature review, the objective is to identify the criteria that are needed for the multi-criteria analysis of the best-worst method (BWM)(Figure 3.1).

The output of this literature review, answering the second sub-question, is a list of main criteria based and sub-criteria for evaluating SATs. For this literature review, the search machine Scopus and Google Scholar are used again. It is crucial that the list comprises only crucial criteria rather than an exhaustive compilation. This is because a list of too many criteria makes it complex and hard to compare information (Choo et al., 1999). According to Rezaei (2015), there is a maximum of nine criteria for the appropriate use of a BWM, or the criteria have to be clustered with sub-criteria. In this research, there are three main criteria with each three sub-criteria. It is chosen to cluster the 9 identified criteria into three main criteria. This choice is made to make the BWM interviews (see Section 3.2.3) shorter, making them more accessible for participation. The clustering of the criteria into main criteria is done on the basis of the framework of Feitelson & Salomon (2004) in combination with the Triple Bottom Line (TBL) theory, as is further elaborated in Section 5.2.

3.2.3 Sub-question 3: bayesian BWM to obtain the weights of criteria

SATs hold the potential for net-zero CO_2 aviation, but as identified in Section 2.4, there are uncertainties about the stakeholder preferences towards those alternative technologies. These stakeholders play a crucial role in the potential adoption of one of these technologies because they are the users and investors of sustainable aviation technologies. Therefore, determining the criteria that stakeholders prioritize within this multi-actor field is crucial.

Moreover, several multi-criteria decision-making (MCDM) tools are used in the existing literature. The Analytic Network Process (ANP) and the Analytic Hierarchy Process (AHP) are the most prevalent among these tools. Their primary function involves deducing the criteria weights based on decision-makers expressed preferences. In these MCDM tools, there are pairwise comparisons between an alternative and all the other alternatives (Saaty, 2004). Moreover, with the use of MCDM tools of ANP and AHP, there are a lot more comparisons needed than with the use of the BWM, where alternatives are only compared between the worst alternative and the best alternative (Gupta et al., 2020). This makes the BWM less time-consuming for research and easier to understand because fewer comparisons between criteria are made.

The BWM is chosen to address the third sub-question because, compared with other MCDM tools, the BWM is less time-consuming and conducts, according to Rezaei (2015), more structured and consistent comparisons with more reliable weights. For conducting the BWM, the criteria identified after sub-question two are important inputs. This method requires limited main criteria because the complexity of a BWM enlarges a lot by taking more criteria into account, as already mentioned in Section 3.2.2 (Rezaei, 2015). Therefore, when conducting a constructive BWM, it is important to keep the criteria limited to a certain level.

In MCDM, quantifying the weights of different criteria is challenging (Rezaei, 2015). The BWM is a method especially used to conduct the relative weights between different criteria. Furthermore, the BWM is a moderately new methodology (Rezaei, 2015), but it has already proven effective in scientific studies. For example: 'Inland terminal location selection using the multi-stakeholder best-worst method' (Liang et al., 2021), 'Barriers and overcoming strategies to supply chain sustainability innovation'(Gupta et al., 2020), 'How to weigh values in value value-sensitive design: A best-worst method approach for the case of smart metering' (van de Kaa et al., 2020).

There is also criticism of the use of MCDM methods. One of the main criticisms is the subjectivity of decision-makers affecting the conclusive result (Annema et al., 2015). The interviewed stakeholders could probably have their advantages or disadvantages from the chosen technology, emphasizing the importance of verifying interviewee consistency before integrating their preferences into research. This criticism appeared justified during the first interview, where it was clear that the stakeholder interviewed made pairwise comparisons between criteria based on personal advantages for a highly ranked SAT. Therefore, this first interview was excluded from the research. To address this issue, in subsequent interviews, the evaluated SATs were presented to the interviewees only after they had conducted pairwise comparisons between the criteria, as detailed in Appendices D and F. This ensured that their choices were solely based on their perspectives regarding the criteria, rather than the SATs evaluated in this research. Furthermore, the consistency of the interviewees' responses in the pairwise comparisons is checked using consistency ratios, as explained in Section 6.2.1.

Before the weights of the criteria could be derived from the BWM, stakeholder interviews were conducted. The selection of stakeholder groups for the interviews is conducted via a stakeholder analysis, as detailed in Section 6.1.2. These face-to-face interviews were transcribed in Excel. During these interviews, the BWM was performed with the stakeholders, and the criteria considered were derived from sub-question 2 (Chapter 5). The methodology for conducting these interviews is outlined in Section 6.1, with more detailed elaboration provided in Appendix D. The BWM performed in these stakeholder interviews encompasses the subsequent steps (Rezaei, 2015):

Step 1: Identify and establish a criteria set $\{c_1, c_2, ..., c_n\}$ that should be taken into account to evaluate sustainable aviation technologies to arrive at a decision (Figure 3.2) (Rezaei, 2015). These criteria are identified in the second sub-question of the research.

Figure 3.2: Step 1: establishing criteria

Step 2: Establish the "best" and "worst" criteria (Figure 3.3). In other words: the "most important" and the "least important" criteria. This is done by asking in the interviews the stakeholders (interviewees) to identify the most and least important criteria (Rezaei, 2015).

Figure 3.3: Step 2: establishing the most and the least important

Step 3: Establish the preference of the "most important" criterion to the other criteria using a Likert scale between 1 and 9 (Figure 3.4). For this scale, 1 means that i is equally important to j and 9 means that i is absolutely more important than j, as detailed in Figure B.1 in Appendix B.1. This results in the "most important"-to-others vector: $A_B = (a_{B1}, a_{B2}, ..., a_{Bn})$, wherefore a_{Bj} reveals the preference of the "most important" criterion to the criterion j (Rezaei, 2015).

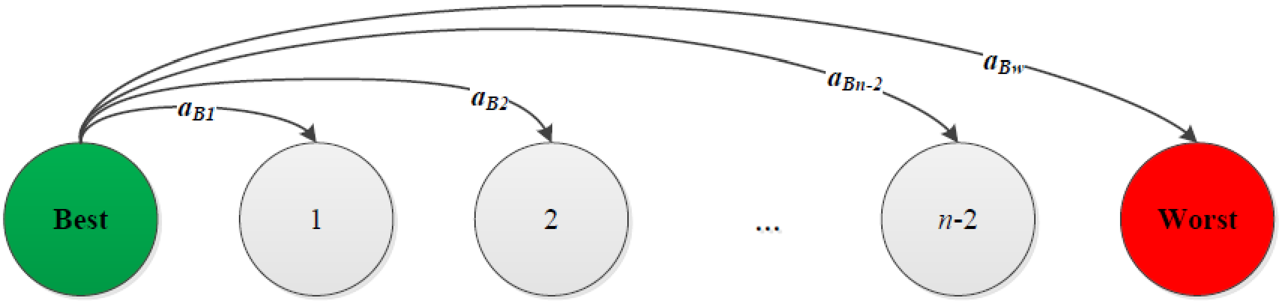

Figure 3.4: Step 3: establishing the preference of the "most important" criterion to all other criteria

Step 4: Establish the preference of all the criteria, except the "most important" as already done in step 3, to the "least important" (Figure 3.5). This results in the others-to-"least important" vector: $A_W = (a_{1W}, a_{2W}, ..., a_{nW})^T$, wherefore a_{jW} reveals the preference of criterion j over the least important criteria (Rezaei, 2015). The initial four steps are executed within the stakeholder interviews, as visualized in Appendix F.

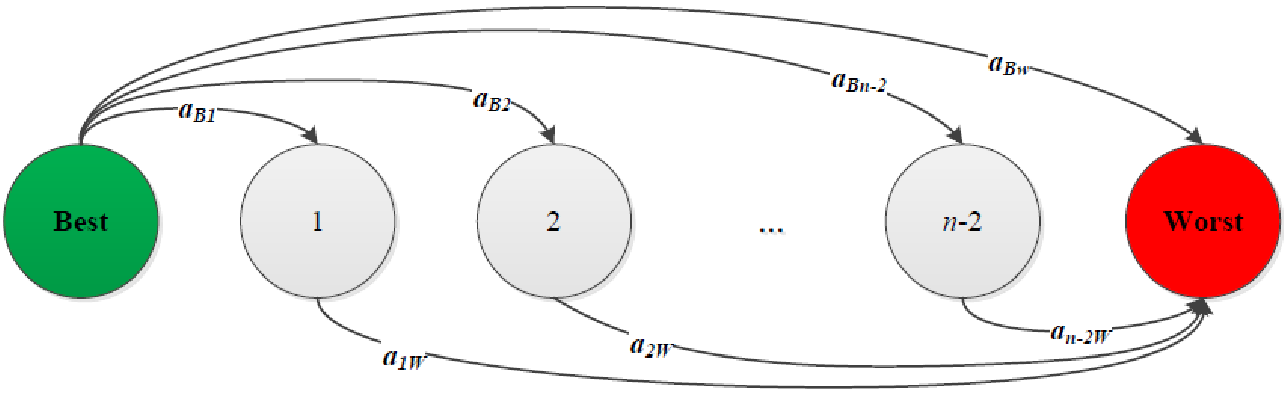

Figure 3.5: Step 4: establishing the preference of all other criteria to the "least important" criterion

Step 5: finding the optimal weights for the criteria.
The research aims to explore the stakeholders' preferences towards SATs. Therefore, this research aims to find the optimal group weights of stakeholders on the criteria. The normal BWM is only suitable for determining criteria weights for a single decision-maker. Therefore, the group decision-making approach of the Bayesian BWM is utilized (Mohammadi & Rezaei, 2020).

The Bayesian BWM has the same main input data, i.e. initial four steps, as the normal BWM. However, in the fifth step, the input and output data are modeled in a probabilistic distribution to address the optimization problem of the normal BWM (Mohammadi & Rezaei, 2020). Specifically, the pairwise comparisons are modeled using the multinomial distribution, and the optimal group weights are modeled using the Dirichlet distribution (Mohammadi & Rezaei, 2020).

Additionally, the Bayesian BWM is also preferred due to its credal ranking and confidence level (CL) (Mohammadi & Rezaei, 2020). Therefore, step 5 of the Bayesian BWM includes the following sub-steps: construction of the probability distribution, calculation of the optimal group weight, and establishment of the credal ranking and CL. For further details into these sub-steps of step 5, readers are directed to the study by Mohammadi & Rezaei (2020) concerning the Bayesian BWM.

3.2.4 Sub-question 4: additional literature search and Weighted Sum Method to complete BWM

For the completion of the BWM, it is essential to have the weights of the criteria derived from sub-question three. Additionally, a final literature review is necessary to obtain the technology performance scores related to the criteria of the SATs derived in sub-question 1. This literature research aims to procure the performance scores of the SATs concerning the criteria for the years 2024, 2030, and 2050. With the weights of the criteria and the derived technology performance scores on the criteria, the Weighted Sum Method (WSM) is conducted.

Through the WSM, the BWM is completed, and final scores of the SATs based on the stakeholder preferences are derived. Within the realm of MCDM analysis, the WSM is a commonly used method to compute the final scores for each technology. Once the WSM is finalized and the relative performance scores of the criteria are quantified, stakeholder preferences regarding the alternative technologies are derived and compared.

4 Identifying specific sustainable aviation technologies

This chapter aims to answer the following sub-question: "What are the specific SATs within each technology group (electrofuel, hydrogen, electric, biofuel) with promising potential for adoption?" Based on scientific literature, this section carefully selects the specific SATs within each technology group - hydrogen, electric, electrofuels, and biofuels. In the following subsections, the selected SATs are expounded in detail. Furthermore, within the identified scientific articles, the main costs, advantages, and disadvantages were also revealed within the scope (Section 1.3). Even if this was not necessary to answer sub-question 1, they are still noted in this chapter because they are considered supportive of conducting the performance scores for each SAT in Chapter 7. The following section consists of the selection of an SAT within the hydrogen technology group, followed by the electric and biofuel technology group, and lastly, the electrofuel technology group.

Identifying relevant scientific literature

This chapter aims to identify the main leading SATs within the distinct technology group, namely electrofuel, hydrogen, electric, and biofuel. A literature search is carried out to employ four specific search strings customized to each technology.

The initial search string employed for electrofuel, utilizing Scopus and Google Scholar, is as follows: (electrofuel OR “electrofuel-powered” OR “electrofuel propulsion”) AND (aircraft OR airplane OR aviation OR “sustainable aviation”) AND (promising OR adaption OR alternatives OR “most promising”). This search yielded over 1.100 results. The approach for this search follows a ’funnel’ methodology, where a broad search string is initially utilized and progressively refined based on findings. This leads to the insights presented in Section 4.4.

Similar funnel approaches were executed for the other three technology groups. For hydrogen, the initial search string utilized is: (electricity OR “electric-powered” OR “electric propulsion” OR electric) AND (aircraft OR airplane OR aviation OR “sustainable aviation”) AND (promising OR adaption OR alternatives OR “most promising”). Likewise, for electric, the search string deployed is: (electricity OR “electric-powered” OR “electric propulsion” OR electric) AND (aircraft OR airplane OR aviation OR “sustainable aviation”) AND (promising OR adaption OR alternatives OR “most promising”). Lastly, for biofuels, the employed search string is: (saf OR baf OR "sustainable aviation fuel" OR "drop-in fuel" OR biofuel) AND (aircraft OR airplane OR aviation OR "sustainable aviation") AND (promising OR adaption OR alternatives OR “most promising”).

Definition of cost concepts

Three definitions need clarification when discussing costs for alternative aviation fuels and technologies: Minimum Jet Fuel Selling Price (MJFSP), investment costs, and Direct Operating Costs (DOC). The MJFSP is the minimum price a customer could purchase fuel at, such that a zero net present value of profit is achieved (Dahal et al., 2021). A lower MJFSP indicates that the alternative fuel is more economically feasible for use in aviation; thereby, the MJFSP is considered a critical factor influencing the economic viability and returns on investment associated with SATs. Furthermore, DOCs are the direct costs related to flight operation, including costs such as total financial cost, total crew cost, total charges and fees, aircraft maintenance cost, engine maintenance cost, and fuel operating cost (Dahal et al., 2021). Hence, DOCs and the MJFSP are indicators for evaluating the economic feasibility of SATs. The MFJSP measures the financial viability of economics for the fuels of SATs, whereas the DOCs provide insight into the operational expenses (Dahal et al., 2021).

Scope

The infrastructure and production constraints of SATs are left out of scope in the overall advantages and disadvantages (Section 1.3).

4.1 Hydrogen-powered aircraft

Considering hydrogen technology as an SAT, there are two utilization methods: fuel cells and direct combustion in gas turbine engines (Dahal et al., 2021; Cabrera & de Sousa, 2022). This research concentrates on hydrogen with fuel cells because this is the most promising technology for using hydrogen as an aviation fuel (Afonso et al., 2023). Fuel cells facilitate an electrochemical reaction between hydrogen and oxygen to produce electricity, generating electricity with water as the only emission (Dahal et al., 2021). The generated electricity is used to drive electric turbofans, similar to conventional turbofans but replaces conventional fuel for electricity. There are different types of fuel cells, but the most promising for use in aviation is the Proton Exchange Membrane (PEM) (Dahal et al., 2021; Bauen et al., 2020). The PEM is considered promising due to its compatibility with aviation because of its large operating temperature and quick start-up time (Dahal et al., 2021).

The specific form of hydrogen chosen for this research is liquefied hydrogen (LH_2), necessitating cooling to -253 °C to transform gaseous hydrogen into a liquid state. At ambient temperature, hydrogen is gaseous and exhibits a low volumetric energy density (MJ/m^3), requiring extensive spatial accommodation and high-pressure storage systems to be used as fuel (Dahal et al., 2021; Detsios et al., 2023). To address the challenges associated with using gaseous hydrogen, the process of cooling down is employed to convert hydrogen into a liquid state (LH_2), resulting in an enhanced volumetric energy density. The practicality of using liquid hydrogen (LH_2) for transportation and storage is emphasized by its significantly smaller volume compared to gaseous hydrogen - a difference of a factor of 800 (Dahal et al., 2021). However, even in its liquid state, the volumetric energy density of conventional fuel is still 4 times higher than LH_2 (Bauen et al., 2020).

4.1.1 Costs for the usage of hydrogen

Firstly, it is important to delineate the DOCs associated with conventional fuels. These costs are reported within the range of 3.9-4.8 US dollar cents per passenger-kilometer ($/PAX/km) for medium-haul (MH) and long-haul (LH) aircraft, respectively. In contrast, the estimated DOCs for hydrogen utilization in aviation significantly exceeds the range of conventional fuels, ranging between 8.1-23.9 US dollar cents per passenger-kilometer ($/PAX/km) for MH and LH aircraft, respectively (Dahal et al., 2021).

Furthermore, according to Dahal et al. (2021), hydrogen has the potential for improvements in the production process, such as improvements in the process of electrolysis to produce hydrogen and a decrease in the costs of renewable energy. With these possible cost reductions, the DOC of hydrogen will become longer, and hydrogen could be more viable.

4.1.2 Advantages hydrogen

Adopting LH_2 as aviation fuel presents several advantages in comparison to the use of conventional fuels and conventional aircraft:

1. **Hydrogen production: only water + renewable energy** (Dahal et al., 2021; Su-ungkavatin et al., 2023).
2. **Carbon-neutral**: if renewable electricity is used for the production hydrogen has the potential for near-zero carbon emissions (Dahal et al., 2021; Ansell, 2023; Cabrera & de Sousa, 2022; Bauen et al., 2020; Yusaf et al., 2022). With the use of hydrogen, also other pollutants are reduced, mainly for LH flights (Su-ungkavatin et al., 2023).
3. **Potential for LH flights** (Dahal et al., 2021).
4. **Performance improvement**: improvement is expected in hydrogen fuel cells for aviation with higher performance (Bauen et al., 2020).
5. **Long-term sustainability**: hydrogen, an aviation fuel, has the long-term opportunity for sustainable aviation with renewable energy sources (Bauen et al., 2020; Yusaf et al., 2022).

4.1.3 Disadvantages hydrogen

However, hydrogen as a fuel for the aviation sector faces challenges and disadvantages:

- **Technical challenges; storage + handling**: the use of hydrogen brings technological challenges related to storage (cryogenic storage requirement) and handling, regarding its low volumetric energy density and safety protocols (Dahal et al., 2021; Su-ungkavatin et al., 2023; Ansell, 2023; Detsios et al., 2023; Yusaf et al., 2022).
- **Reduced performance due to low volumetric energy density**: the lower volumetric energy density has the following consequences with the current state of technology: reduced range, increased storage volume, and performance trade-offs (Bauen et al., 2020).
- **Engine modifications**: the characteristics of hydrogen and conventional fuel for aviation are different. The aircraft design needs modifications of the engine in several parts (Bauen et al., 2020).

- **Production with fossil fuels**: the majority of hydrogen is nowadays produced from fossil fuels. This is expensive and limits the sustainability (Yusaf et al., 2022).

4.2 Electric-powered aircraft

There are three different technology pathways within the category of electric aviation: full-electric, turbo-electric, and hybrid-electric configurations (Dahal et al., 2021). The turbo-electric and hybrid-electric configurations still use fuel, unlike the full-electric configurations. This study focuses on the full-electric configuration, which relies not on fuel but solely on batteries as the energy source for aircraft.

The specific batteries considered to have the potential for technology advancements are lithium-ion, solid-state or lithium-sulfur batteries (Afonso et al., 2023)(Su-ungkavatin et al., 2023). These batteries stand out due to their high energy densities, in contrast to other batteries, making them suitable for aviation applications (Su-ungkavatin et al., 2023). Among them, lithium-sulfur (Li-s) technology emerges as the most promising, featuring lithium metal, sulfur cathodes, and a high (theoretical) energy density of 2600 Wh/kg. Furthermore, sulfur's cheapness, non-toxicity (safe), lightweight nature, and availability enhance the appeal of Li-S batteries for aviation applications (Adu-Gyamfi & Good, 2022).

A limiting factor for using Li-S batteries so far was the lower discharge rate (0.2 C°) and short life cycles (180-300), posing challenges for energy-intensive applications such as aircraft. According to Adu-Gyamfi & Good (2022), researchers have conducted Li-S batteries with a higher discharge rate (3-6 C°), longer life cycles (1350-1500), and two times higher energy densities than commonly used lithium-ion batteries (500 Wh/kg). Successful demonstrations of Li-S batteries in relevant contexts underscore their potential viability for electric aviation. (Adu-Gyamfi & Good, 2022).

4.2.1 Exclusion electric aircraft from further research

Despite these promising prospects, the electric aircraft SAT is excluded further from this research. This is because the literature identified emphasized that medium- & long haul commercial passenger aircraft are not viable within the timespan till 2050. As Dahal et al. (2021) stated, the expectation for the first fully electric aircraft for 50-100 passengers is the most optimistic forecast. For medium- & long haul, this is not even considered feasible because of significant challenges with electric aircraft. Before excluding the electric aircraft from the research, the opinions of the stakeholders are checked regarding electric aircraft. These stakeholders have emphasized that they don't expect an emergence of electric-powered aircraft for medium- or long-haul commercial passenger transportation in the foreseeable future (Section 6.1.4).

4.3 Biofuel-powered aircraft

Biofuels represent a category of fuels produced from non-petroleum feedstocks, such as animal fats, plant oils, and waste cooking oils. This alternative fuel source holds promise for reducing emissions within the aviation sector. Biofuels can be used as a drop-in fuel, exhibiting nearly identical characteristics to conventional kerosine (Afonso et al., 2023). The adoption of biofuels typically requires minimal modifications to conventional aircraft technologies or, in some cases, no modifications at all are needed (Dahal et al., 2021). On the other hand, Dahal et al. (2021) emphasizes that this is the case for blending biofuels with conventional fuel. The use of biofuels solely for aircraft requires modifications at the aircraft because of the lack of aromatics in biofuel compared to conventional kerosene.

In this research, the specific biofuel known as 'HEFA' is selected for evaluation due to its perceived promise, widespread utilization, and maturity in the market (Dahal et al., 2021; Su-ungkavatin et al., 2023). Furthermore, HEFA has achieved full commercial utilization, is market-proven, and American Society for Testing and Materials (ASTM) D7566 certified, signifying compliance with aviation biofuel standards certified (Su-ungkavatin et al., 2023; van Dyk et al., 2021; Detsios et al., 2023; Cabrera & de Sousa, 2022; Bauen et al., 2020; Abrantes et al., 2021; Okolie et al., 2023). HEFAs compatibility streamlines further integration with existing aircraft and fuel systems up to 50% blending (Dahal et al., 2021).

The feedstocks utilized for biofuel production encompass renewable sources such as vegetable oils, animal fats, used cooking oil, and other (waste) oils. Consequently, the selection of the feedstock has an impact on the sustainability and environmental performance of the biofuels (Dahal et al., 2021). Therefore, in this research, the specific HEFA with the waste feedstock of used cooking oils is considered, as this can be seen as the feedstock with the smallest impact on the environment (Bauen et al., 2020; Dahal et al., 2021; Su-ungkavatin et al., 2023).

The production of HEFA can be divided into a three-step process, as detailed by Dahal et al. (2021); Okolie et al. (2023):

1. **Hydrogenation**: fatty acid methyl esters (FAMEs) are produced through hydrogenation.
2. **Isomerization**: the FAMEs are isomerized to produce hydrocarbons.
3. **Hydrogcracking**: hydrocarbons undergo hydrocracking to attain the final production with compositions aligning with conventional aviation fuel standards.

4.3.1 Costs of the usage HEFA

The DOCs associated with biofuel utilization are between 5.0-9.2 US dollar cents per passenger-kilometer ($ /PAX/km). Additionally, the MJFSP of hydrogen is between 0.42-1.20 euro/L or 15.1-43.2 $/GJ. The hydroprocessed esters and fatty acids (HEFA) alternative, evaluated in this article, stands out as one of the biofuels with the lowest MJFSP (Dahal et al., 2021; Okolie et al., 2023). However, it is noteworthy that the DOC of HEFA remains higher than the DOC with the utilization of conventional fuel.

Furthermore, according to Dahal et al. (2021), there is potential for reducing the costs associated with biofuel production. This potential arises from possible improvements in the availability of feedstocks, advancements in conversion techniques, and the realization of economies of scale. These reductions in costs for the production of biofuels hold promise for lower DOC of biofuel.

4.3.2 Advantages HEFA

The use of the HEFA biofuels for the aviation industry has the following advantages concerning conventional fuels and propulsion systems:

- **Renewable feedstock of used cooking oils** (Dahal et al., 2021; Su-ungkavatin et al., 2023; Okolie et al., 2023).
- **Compatibility up to 50% with existing aircraft + possible gradual transition**: HEFA is ASTM D7566 certified for blending up to 50%, which emphasizes the compatibility with existing aircraft (Su-ungkavatin et al., 2023; Abrantes et al., 2021; Okolie et al., 2023). Because HEFA is certified up to 50% blending limit, a gradual transition is possible while modifying existing aircraft for the use of 100% HEFA (Dahal et al., 2021; Su-ungkavatin et al., 2023; Ansell, 2023; Cabrera & de Sousa, 2022; Bauen et al., 2020; Abrantes et al., 2021; Okolie et al., 2023).
- **Lower carbon emissions**: lower carbon emissions compared to conventional fuels (Dahal et al., 2021; Ansell, 2023; Bauen et al., 2020). According to different scientific articles, biofuels are produced via the HEFA pathway to reduce emissions up to 60 to 80% in comparison with conventional aviation fuel (Dahal et al., 2021; Cabrera & de Sousa, 2022; Ansell, 2023; Okolie et al., 2023).
- **Comparable energy density**: HEFA has almost the same energy density as conventional aviation fuels (Afonso et al., 2023).
- **High TRL**: high level of fuel technological readiness level (Abrantes et al., 2021).

4.3.3 Disadvantages HEFA

The use of HEFA biofuels in the aviation industry could also face challenges and disadvantages:

- **Higher price**: the price of HEFA is currently higher than conventional aircraft fuel, which is a significant challenge for adoption (Bauen et al., 2020). For airlines, is this an obstacle to transition towards biofuels because the fuel price is 20-30% of the operating cost of airlines(Holladay et al., 2020).
- **Questionable overall sustainability**: the production of biofuels can entail a lot of water and energy. This is important to consider regarding the overall sustainability of the biofuel (Su-ungkavatin et al., 2023).

4.4 Electrofuel-powered aircraft

The last technology group discussed in this research pertains to the utilization of electrofuels. While seemingly associated with hydrogen usage, the process is 'inverted'. Instead of generating electricity with hydrogen, this approach involves employing renewable electricity for water electrolysis, using carbon or nitrogen to produce electrofuels. Electrofuels encompass fuels such as kerosene, methane, methanol, hydrogen, ammonia, and n-octane (Dahal et al., 2021; Goldmann et al., 2018).

Electrofuel production starts with electrolysis, wherein electricity stimulates a chemical reaction to split water into hydrogen and oxygen. Subsequently, carbon capture, sourced from industrial emissions or ambient air, is conducted to obtain a carbon-neutral electrofuel. Furthermore, when the hydrogen and CO_2 have been produced through electrolysis, fuel synthesis is the next process step, wherein hydrogen and CO_2 can be combined into various fuels (Dahal et al., 2021; Detsios et al., 2023). The synthesis methodology is dependent on the specific electrofuel desired. Lastly, the synthesized electrofuel is ready for utilization in propulsion systems. The utilization of electrofuel in propulsion systems varies based on aircraft configuration and fuel characteristics but is based on fuel combustion for thrust generation(Dahal et al., 2021).

In this study, n-octane is the selected electrouel for evaluation due to its comparable physical and combustion characteristics to conventional fuels, in contrast to other electrofuels (Goldmann et al., 2018). Additionally, according to Goldmann et al. (2018), n-octane exhibits the potential to be a viable drop-in fuel, substituting conventional aircraft fuel.

4.4.1 Costs for the usage of electrofuels

The DOC associated with electrofuels is estimated between 9.2-23.7 $/PAX/km for MH and LH aircraft, respectively. This places the estimated DOC for electrofuels in a comparable range to that of hydrogen (Section 4.1.1). Secondly, the MJFSP is considered 6.87 $/kg (Dahal et al., 2021).

According to Dahal et al. (2021), the production of electrofuel exhibits prospective technological enhancements. The integration of these technological advancements, coupled with the possible realization of economies of scale, holds promise for reducing the production costs associated with electrofuels. Consequently, electrofuel has the potential to mitigate the DOC.

4.4.2 Advantages n-octane

The use of electrofuel, in comparison with conventional fuels and propulsion, has the following advantages:

- **Production from renewable electricity, hydrogen, and CO_2**: electrofuels can be produced from renewable electricity, hydrogen and CO2 (Dahal et al., 2021; Su-ungkavatin et al., 2023; Ansell, 2023).
- **Carbon-neutral**: lower carbon emissions in comparison with conventional fuel. If the electrolysis is conducted with renewable energy sources, there is potential to create carbon-neutral aviation (Dahal et al., 2021; Su-ungkavatin et al., 2023; van Dyk et al., 2021; Goldmann et al., 2018).
- **Aircraft modifications**: electrofuels can be used in existing aircraft with modifications on the engine but without replacement of the entire aircraft (Goldmann et al., 2018; Su-ungkavatin et al., 2023).

4.4.3 Disadvantages n-octane

Nevertheless, the adoption of electrofuel as aviation fuel could also face some challenges and disadvantages:

- **High production costs**: the production costs of electrofuels are higher than conventional fuels (Dahal et al., 2021; van Dyk et al., 2021). This is mainly caused by the use of green hydrogen, which costs about 70% of the electrofuel production (Detsios et al., 2023). Therefore, the adoption of electrofuels on a widescale is dependent on future developments of green hydrogen production (Cabrera & de Sousa, 2022). These high production costs impact the MJFSP.
- **Commercially not viable**: the technology is not in a majority phase, which makes n-octane commercially not viable (Dahal et al., 2021).

- **Importance renewable electricity**: the production of electrofuels necessitates a substantial amount of electricity, emphasizing the significance of sourcing this electricity from renewable sources. This consideration is essential to ensure the overall sustainability of the electrofuel production process (Su-ungkavatin et al., 2023).

4.5 Identified SATs within each technology group

In this chapter, within the technology groups of hydrogen, electricity, biofuels, and electrofuels, specific SATs are selected with promising potential for adoption to answer sub-question 1. This resulted in the following SATs: LH_2 with the use of PEM fuel cells, HEFA used cooking oils and n-octane. For the respective groups of hydrogen, biofuels, and electrofuels. As can be seen, there is no SAT selected within the electricity technology group. This is because of the lack of potential for electricity-powered aircraft within the scope of medium- & long haul commercial passenger aircraft (Section 1.3). This exclusion is also emphasized in the stakeholder interviews (Section 6.1.4). In conclusion, the following identified SATs within the hydrogen, biofuel, and electrofuel categories are recognized for their promising potential for adoption, addressing sub-question 1:

- **Liquid hydrogen with PEM fuel cell aircraft (LH_2)**
- **HEFA produced biofuel with used cooking oils and required aircraft modifications (HEFA)**
- **N-octane electrofuel and required aircraft modifications (N-octane)**

5 Criteria selection

This chapter addresses the second sub-question, "What criteria are considered important in the evaluation of sustainable aviation technologies?". This chapter is structured as follows to acquire a relevant set of criteria. The first section, 5.1, describes the literature review regarding the selection of criteria for the evaluation of the technologies, which includes a literature reference table (LRT). The main criteria are identified in the second section, 5.2. Finally, the selected sub-criteria are defined and presented in the last section.

5.1 Literature review on identifying criteria

In this section literature is searched to identify the relevant criteria for evaluating alternative aviation technologies to perform the Best-Worst method. Identifying criteria for an MCDM, such as a BWM with the conduction of a literature review, to search for earlier used criteria in an MCDM in the same field, is earlier performed (Kalpoe, 2020; de Prieëlle, 2018; Septian, 2019). The literature review conducted to answer the second sub-question uses the Preferred Reporting Items for Systematic Reviews and the Meta-Analysis method (PRISMA) for identifying relevant articles (Figure 5.1). The final selection of 14 articles is presented in the form of a literature review table in Table 5.1 With the key findings, methods, and authors presented.

For this literature review, the only databases used are Scopus and Google Scholar, which are used from February 19th to February 23rd, 2024. Figure 5.1 illustrates the selection process of the articles using the earlier mentioned PRISMA method. In this case, there is a hybrid of a double search of search strings in two different search engines: one for using Scopus and one for using Google Scholar. For the search in Google Scholar, the search string is more specific to reduce the number of results and only include relevant literature, as visualized in Figure 5.1. The first step of the literature review was conducting a search string.

The final search string conducted for the search in Scopus was the following: ("multi-criteria decision making" OR "MCDM") AND ("aviation" OR "aircraft") AND ("sustainability" OR "sustainable"). As outlined earlier in this section, the search criteria included a focus on previous MCDM methodologies, hence the inclusion of "Multi-criteria decision making" OR "MCDM" in the search string. The terms "Aviation" OR "aircraft" are used to narrow down the search within the MCDM field, especially to the aviation industry. Initially, "net-zero" was considered for the search, but this led to only 1 irrelevant result. Therefore, "sustainability" OR "sustainable" was chosen to broaden the scope while maintaining a focus on sustainability within the aviation sector. Moreover, using this search string in Scopus resulted in 29 found articles within a range from 2018. After screening, duplicates, and unaccessible articles, the final selected articles are 3. With the application of snowballing, an additional six articles are included, as presented in the PRISMA in Figure 5.1.

The iterated search string conducted for the search in Google Scholar is: ("multi criteria decision making" OR "MCDM") AND "sustainable aviation" AND ("electric" OR "biofuel" OR "electrofuel" OR "hydrogen"). Using this search string in Google Scholar resulted in 168 articles being found. After the selection method, only five articles are included for the literature review, as presented in the PRISMA in Figure 5.1.

With additional snowballing, these two searches concluded in a final selection of 14 articles. The time frame of the selected articles was not a criterion, but all the articles are relatively new, from 2018 up to 2023. The two articles from Tzeng et al. (2005) and Yavuz et al. (2015) derived with the snowballing method from Chen & Ren (2018) fall outside the time frame. Still, these articles include studies of transport that are assumed to be less time-relevant according to the already existing technologies discussed in the studies. Via snowballing from the article of Markatos & Pantelakis (2023), the following 4 articles are derived: Demircan & Kaplan (2023), Kiracı & Akan (2020), Kiracı & Bakır (2018), and Dožić et al. (2018).

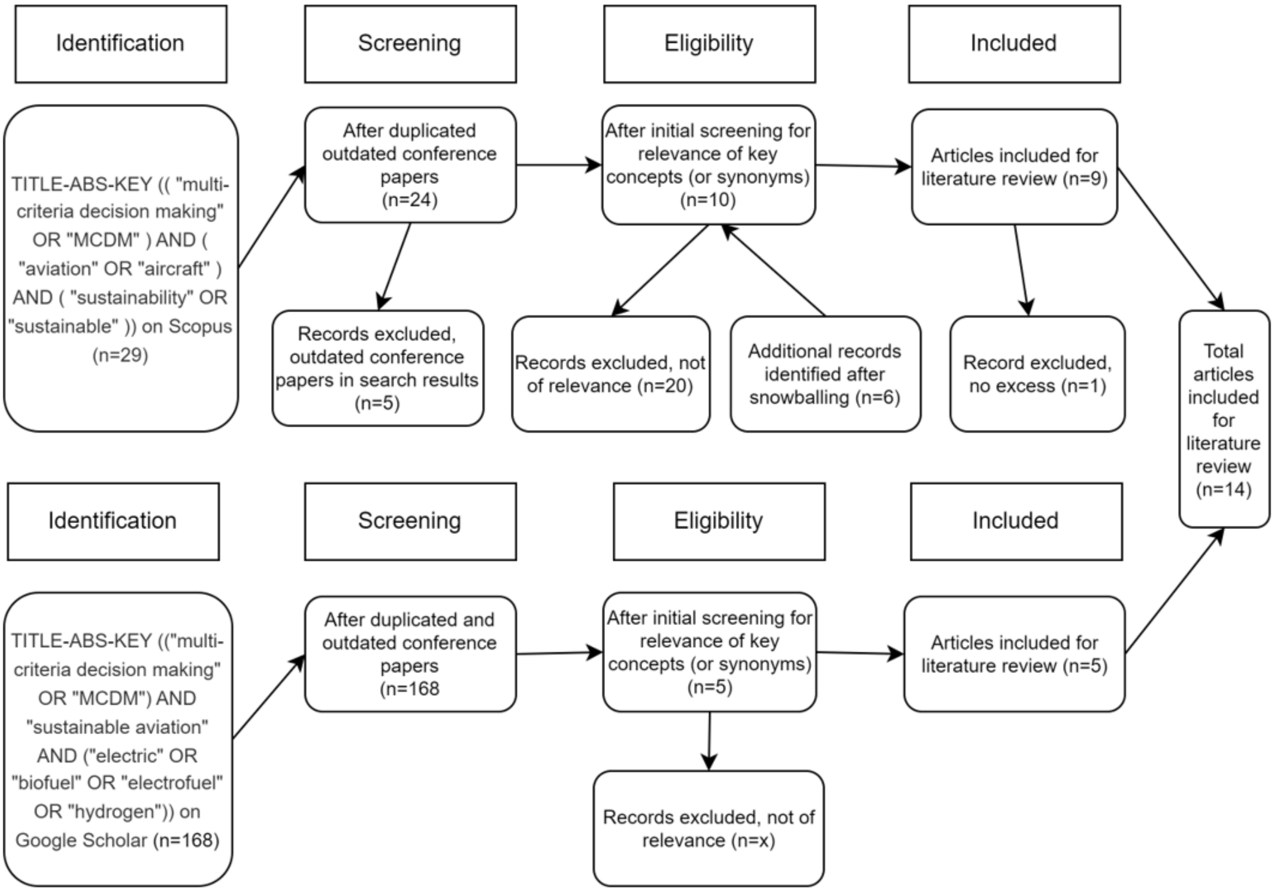

Figure 5.1: PRISMA literature review identifying criteria

Table 5.1 provides an overview of the 14 articles that are included via the use of the PRISMA method (Figure 5.1). The identified studies differ in three main categories: articles that focus on different alternative aviation fuel (pathways) evaluations (Ahmad et al., 2021; Chen & Ren, 2018; Ahmad et al., 2019; Ayar & Karakoc, 2023; Xu et al., 2019; Yang et al., 2023; Acar et al., 2018), and articles that focus on the evaluation of the purchase of different aircraft (Markatos & Pantelakis, 2023; Demircan & Kaplan, 2023; Kiracı & Akan, 2020; Kiracı & Bakır, 2018; Dožić et al., 2018), and more general articles for the adoption of alternative fuel technologies in transport (Tzeng et al., 2005; Yavuz et al., 2015).

The studies listed in the table mainly address the fuel pathways, purchase of aircraft, or the adoption of sustainable transport alternatives in general, as described in the three categories above. This study distinguishes itself by focusing on the preferences of stakeholders towards alternative fuels and associated technologies (aircraft modifications/new aircraft) rather than solely focusing on fuel pathways or the purchase of aircraft. Moreover, the last category pertains to pure MCDM research in the sustainable transport domain and not to the aviation industry in specific.

Table 5.1: LRT criteria identification

No.	Title	Author	Method	Field of study	Key takeaways
1	Implementation of a Holistic MCDM-Based Approach to Assess and Compare Aircraft, under the Prism of Sustainable Aviation	Markatos & Pantelakis (2023)	Analytic Hierarchy Process (AHP) in combination with a Weighted Sum Method (WSM).	Comparing aircraft from the perspective of sustainable aviation.	The article emphasizes the importance of considering environmental criteria in aircraft selection. Furthermore, the article emphasizes the significance of emerging technologies such as sustainable fuels as alternative propulsion systems.
2	A Proposed Method for Aircraft Selection Using Inter-valued Spherical Fuzzy AHP	Demircan & Kaplan (2023)	The method used is an Inter-valued Spherical Fuzzy Analytic Hierarchy Process (IVSFAHP). This is a combination of fuzzy set theory and AHP.	An MCDM is applied to the aviation industry, especially the aircraft selection process for airline companies.	The most important criteria considering the article are financial and technical aspects. The financial aspects concerning the economic viability and technical operational requirements.
3	Aircraft selection by applying AHP and TOPSIS in interval type-2 fuzzy sets	Kiracı & Akan (2020)	The research in this article is conducted via the Interval Type-2 Fuzzy AHP (IT2FAHP) and Interval Type-2 Fuzzy Technique for Order Preference by Similarity to Ideal Solution (IT2FTOPSIS).	The selection process for commercial aircraft (aviation industry). The research focuses on providing a decision support system for the most suitable commercial aircraft.	The research identified and weighted different criteria, enabling a comprehensive evaluation of aircraft alternatives for selection based on multiple dimensions.
4	Application of commercial aircraft selection in the aviation industry through multi-criteria decision-making methods	Kiracı & Bakır (2018)	Three MCDM methods are used: AHP, TOPSIS, and COPRAS & MOORA.	The research focuses on the selection of commercial aircraft for airline companies with an MCDM method (aviation industry).	The article shows consistency across different MCDM methods. Considering the criteria used the cost performance and environmental factors are crucial for airlines and stakeholders in the aviation industry.

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Table 5.1 – continued from previous page

No.	Title	Author	Method	Field of study	Key takeaways
5	Fuzzy AHP approach to passenger aircraft type selection	Dožić et al. (2018)	A hybrid approach of Fuzzy Analytic Hierarchy Process (FAHP) and Logarithmic Fuzzy Preference Programming (LFPP)	The field of study is related to the air transport management. The focus is on the selection of passenger aircraft types for airline operations.	The most important criteria considering this paper are the aircraft characteristics and costs (purchasing and maintenance costs) are key criteria. The right aircraft is not the only important factor: airline policies, competition in the market, and operational efficiency are also important.
6	A stakeholders' participatory approach to multi-criteria assessment of sustainable aviation fuels production pathways	Ahmad et al.(2021)	An MCDM method is used in the form of a fuzzy TOPSIS and the PROMETHEE II method is used to rank	Focuses on SAFs and the evaluation of different pathways for SAF.	The research emphasizes the importance of the environmental and economic impact categories.
7	Multi-attribute sustainability evaluation of alternative aviation fuels based on fuzzy ANP and fuzzy grey relational analysis	Chen & Ren (2018)	A combination of fuzzy Analytic Network Process (ANP) and fuzzy Grey Relational Analysis (FGRA).	Focuses on the evaluation of sustainable alternative aviation fuels.	According to the article are for pathways the capital costs, energy consumption, production cost per unit, environmental impact, and social acceptability really important.
8	Multi-criteria analysis of alternative-fuel buses for public transportation	Tzeng et al. (2005)	A combination of the MCDM method TOPSIS and the VIKOR method are combined.	The research focuses on the evaluation and selection of alternative fuel buses for public transport. E.g. electricity, hydrogen, and methanol.	According to the research, the expert assessment and the raking method are crucial in guiding the development of alternative fuel modes. One of the most important criteria is air pollution.
9	Multi-criteria evaluation of alternative-fuel vehicles via a hierarchical hesitant fuzzy linguistic model	Yavuz et al. (2015)	The approach used is an MCDM on hesitant fuzzy linguistic sets.	In the context of evaluation and selection of alternative-fuel vehicles (AFVs) for commercial fleets.	The article's conclusion highlights the importance of evaluating alternatives on different criteria, from economic/operational efficiency to environmental impact.
10	A Value Tree for Multi-Criteria of Sustainable Aviation Fuels	Ahmad et al. (2019)	MCDM approach with the use of a value tree framework.	Focuses on the evaluation of SAFs.	SAFs are not a major player in the aviation sector due to environmental, economic, and technical complexities. Furthermore, the identification of relevant criteria is crucial.

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Table 5.1 – continued from previous page

No.	Title	Author	Method	Field of study	Key takeaways
11	Decision mechanism between fuel cell types: A case study for small aircraft	Ayar & Karakoc (2023)	AHP (MCDM) to evaluate various fuel cell types for aircraft.	Focuses on the integration of fuel cells into aircraft propulsion systems	The article emphasizes the importance of considering criteria such as safety, efficiency, and cost in the selection of fuel cell types for aircraft applications
12	Performance Evaluation of Alternative Jet Fuels using a hybrid MCDA method	Xu et al. (2019)	A hybrid MCDM analysis framework: a combination of het AHP and the PROMETHEE II methods.	Focuses on the performance evaluation of alternative jet fuels (AJFs). The research aims to assess the feasibility and potential of using AJFs as an alternative for aviation.	Investment cost, GHG, technology maturity, and stakeholder interests are considered most important of the criteria.
13	Evaluating alternative low carbon fuel technologies using a stakeholder participation-based q-rung orthopair linguistic multi-criteria framework	Yang et al. (2023)	A stakeholder participation-based q-rung orthopair linguistic multi-criteria framework.	The article focuses on evaluating alternative low-carbon fuel technologies. The aim is to assess different fuel pathways in terms of different criteria.	The highest-ranked pathways are the e-fuel and e-biofuel pathways. Net water use, contribution to the economy, costs, and process efficiency.
14	Sustainability analysis of different hydrogen production options using hesitant fuzzy AHP	Acar et al. (2018)	An MCDM approach in the form of a Hesitant Fuzzy Analytic Hierarchy Process (HFAHP).	Focus on hydrogen production systems and renewable energy technologies.	The most important criteria for different hydrogen production pathways are the environmental and technical performance, especially regarding water discharge quality, land use, and GHG

5.2 Categorization of criteria: integrating Feitelsons & Salomons framework of and the TBL-theory

The 14 identified studies, as shown in table 5.1, are all MCDM studies where criteria are considered for adopting new technologies. These 14 articles consider relevant criteria for the evaluation of aviation technologies. The criteria identified in the articles are divided into 4 main categories based on the TBL theory and transport innovations feasibility framework by Feitelson & Salomon (2004). In their article, Feitelson & Salomon (2004) state that it gauges the extent of analytical adequacy concerning the adoption of innovation. According to Feitelson & Salomon (2004), new technologies are seldom adopted instantly because many factors play a significant role in the adoption of a technology. The framework of Feitelson & Salomon (2004) focuses on the adoption of transport innovation. Therefore, its relevance to this research is suitable for the transition towards alternative aviation technologies for sustainable aviation. The framework argues that adopting innovation is a societal process of an innovation's technical, economic, social, and political feasibility (Feitelson & Salomon, 2004). In this research, another important factor for adopting innovation is the environment. The framework of Feitelson & Salomon (2004) was conducted in 2004, which makes it not surprising that environment was not a main factor during this time because climate change was less of an important topic those days. However, the environment is included regarding the importance of climate change nowadays, especially regarding this research that emphasizes the importance of a sustainable aviation industry. This category is also emphasized by the Triple Bottom Line (TBL) theory, which claims that sustainable development has three dimensions: a social, an economical, and an environmental dimension (Carter & Rogers, 2008). The TBL perspective argues that intersecting these three dimensions positively affects the environment, society, and long-term economic benefits (Carter & Rogers, 2008). Based on Carter & Rogers (2008) TBL theory and the earlier highlighted importance of the environment for aviation, the category environment is added to the 4 categories of Feitelson & Salomon (2004). For conducting the longlists of criteria in this research, the political category is merged with the social categories. Thus, based on a combination of Feitelson & Salomon (2004) and Carter & Rogers (2008), the 4 main categories include social, economic, technical, and environmental. These criteria have a lot of sub-criteria identified in the 14 articles of the literature review. These sub-criteria are visualized in longlists for each main category in the Tables C.1, C.2, C.3, C.4, allocated in Appendix C. Regarding the practical goal of this study (MCDM in the form of a BWM), not all the identified sub-criteria are used for the research. However, this is explained in detail in the subsequent section.

5.3 Selection of main criteria and sub-criteria

In the figures C.1, C.2, C.3, C.4 in Appendix C, one can see that there are various criteria identified in the 14 articles of the literature review. As stated before in Section 5.1, three categories of identified articles exist. Therefore, the criteria are from three different perspectives, but all MCDM studies identified have criteria related to adopting sustainable aircraft technologies. However, a consensus can be reached over these studies with various criteria. For example, in the environmental category, greenhouse gas emissions are called an important criterion in 13 of the 14 articles. As you can see, there are 4 main criteria, totaling 84 sub-criteria. Regarding the different categories of articles, not all 84 criteria are equally relevant for adopting SATs. Furthermore, the inclusion of too many sub-criteria can make it challenging to comprehend, manage, and assess the information effectively (Choo et al., 1999). However, considering all these criteria would also require a lot of time, with interviewing and conducting the BWM, which is limited regarding the period of this research (Section 3). Therefore, it's not feasible to include every identified sub-criteria in this study to obtain a practical and relevant set of criteria. Due to these considerations, the primary decision is to exclude the social category assessment across alternative SATs. The reason for excluding the social category, and not one of the other categories, is firstly because of the uncertainty of the social impact of SATs. The technologies are relatively, or even still not fully developed, and step-by-step adopted, making measuring the social impact difficult. Secondly, the period of this research for adopting these technologies reaches 2050, which makes it uncertain what the social impact will be regarding potential social value changes. Lastly, the other three categories are assumed to be more important than the social category in adopting technologies. If a technology lacks economic, technological, and environmental performance, assessing its social performance becomes unnecessary because it is not feasible overall.

Besides the exclusion of social performance, the initial 84 criteria are also reduced, not only with the exclusion of the sub-criteria of social performance but also within the economic, technological, and environmental sub-criteria longlists. The overlapping relevant criteria are aggregated from these longlists, and other abundant or irrelevant criteria are removed from the research. In the following subsections, the selection of sub-criteria for the main criteria of economic, environmental, and technological performance are elaborated and substantiated.

5.4 Environmental performance

In this research, the focus is on the evaluation of SATs on the aircraft side (Section 1.3). Nevertheless, environmental performance considers direct and indirect performance on the environment. Direct environmental performance considers the performance of the aircraft with the new SAT - for example, combustion emissions - and indirect environmental performance considers the indirect impact of the use of a certain SAT - for example, hydrogen indirect emissions when produced from fossil fuels. The difference between these direct and indirect performances is further elaborated with the explanation of the sub-criteria of environmental performance in the subsections 5.4.1, 5.4.2, and 5.4.3.

The importance of environmental performance is significant considering the urge to make aviation more sustainable and net zero carbon dioxide emissions argued by (ICAO, 2023) as the necessity of sustainability in aviation is one of the main drivers of this research. The articles Markatos & Pantelakis (2023); Demircan & Kaplan (2023); Kiracı & Akan (2020); Kiracı & Bakır (2018); Ahmad et al. (2021); Chen & Ren (2018); Yavuz et al. (2015); Xu et al. (2019); Yang et al. (2023); Acar et al. (2018) also argue for the importance of the main criteria of the environment due to its necessity. Therefore, environmental performance is an essential main criterion for adopting SATs. The sub-criteria that indicate the direct and indirect environmental performance are elaborated in the following subsections.

5.4.1 Greenhouse gas emissions

As the introduction indicates, aviation must reduce carbon while still growing to pursue the net-zero carbon dioxide emissions goal (ICAO, 2023). This criterion measures the net reduction in greenhouse gas emissions (GHG) compared to traditional jet fuel and aircraft. Almost all 13 of the 14 identified studies from the literature review considered this a criterion (Markatos & Pantelakis, 2023; Demircan & Kaplan, 2023; Kiracı & Akan, 2020; Kiracı & Bakır, 2018; Ahmad et al., 2021; Chen & Ren, 2018; Tzeng et al., 2005; Yavuz et al., 2015; Ahmad et al., 2019; Ayar & Karakoc, 2023; Xu et al., 2019; Yang et al., 2023; Acar et al., 2018). Only the study by Dožić et al. (2018) does not include GHG emissions as an important criterion. If one looks into this study, the study only focuses on the emphasis of aircraft selection based on market conditions and airline requirements, ignoring environmental influences except from noise (Dožić et al., 2018). This study mainly focuses on the technological and economic aspects regarding the selection of aircraft. This study does not see the necessity of including GHG emissions as an essential criterion because they are only focused on the performance of an aircraft to be economically viable and profitable. Besides the studies from the literature review, the ICAO goals of net zero carbon dioxide emissions by 2050 also highlight the importance of GHG emissions as a criterion in the aviation sector (ICAO, 2023). The extent to which the identified SATs influence GHG emissions differs, as indicated in Section 7. For example, the use of hydrogen with renewable energy could be up to almost 100%, and the use of biofuel in the form of HEFA is indicated between 60 and 80%.

As indicated in the description of this subsection, environmental performance has indirect and direct effects. The impact of the GHG emissions emitted by the aircraft is included as direct effects. However, in this study, the full life cycle of SATs environmental performance is included, wherefore the GHG emissions in the production of certain fuels are also included. For example, the utilization of hydrogen has no direct GHG emissions; these will be zero. However, if hydrogen is not produced from renewable energy, the problem shifts from aircraft performance to the production process of certain SATs. Therefore, indirect GHG emissions are also included in this research. The whole life cycle of alternative fuels is considered in this research.

5.4.2 Water consumption

Another essential criterion regarding environmental performance considered is water consumption. This criterion is important because of the shortcomings in water expected over the century (Nations, 2023). In total, 5 of the 14 identified articles argue for using water as an essential criterion (Ahmad et al., 2019, 2021; Yang et al., 2023; Chen & Ren, 2018; Acar et al., 2018). In those studies, the 'water' related criterion differs. The different water-related criteria identified are 'discharge water quality' (Acar et al., 2018), 'water and soil pollution'(Ahmad et al., 2019, 2021), 'net water use' (Yang et al., 2023), and 'water consumption' (Chen & Ren, 2018). These criteria differ in their definition slightly of each other. Therefore, it is chosen to merge these 4 criteria in the most aggregated form: 'water consumption.'

These articles mainly include the SAF production ways (Ahmad et al., 2021, 2019; Chen & Ren, 2018), but water is also consumed by the production of hydrogen (Acar et al., 2018) and electrofuels, such as n-octane (Yang et al., 2023; Dahal et al., 2021; Goldmann et al., 2018). Furthermore, this criterion is validated by 4 experts in the aviation industry during the first interviews. These experts emphasized the importance of water consumption as an indicator of the environmental performance of SATs regarding the prospective of water shortcomings due to climate change. This is asked during the interviews explained in Sections 6.1.1, and 6.1.4. The overarching criterion 'Water consumption' is defined as 'the quality of discharged and used water from the production process of fuel, addressing potential threats to the environment and human health.' Lastly, the 'water consumption' is considered an indirect environmental impact because the water is not directly consumed by the aircraft performance but indirectly by the production of the fuel used for SATs.

5.4.3 Land-use impact

The last sub-criterion considered important for the environmental performance of SATs is land-use impact. The land use impact is used as a criterion in 4 of the 14 selected articles from the literature review (Ahmad et al., 2021, 2019; Yang et al., 2023; Acar et al., 2018). The land-use impact considers the impact of the land used for the production of fuels. Of the 4 articles, 3 consider the impact of the production of biofuels on the land-used (Ahmad et al., 2021, 2019; Yang et al., 2023). In the case of biofuel, the impact of land use is considered, for example, deforestation in producing biomass feedstocks. Furthermore, Acar et al. (2018) focuses on the land use for hydrogen production (e.g., solar panels, wind turbines). Therefore, this research has a broader scope of the land-use impact than the production of biofuels, including the land-use impact for the other SATs: hydrogen and electrofuels. In this research, the aggregate definition of land change impact follows: 'The land area required for production methods, considering the direct and indirect impact on ecosystems and biodiversity.' Lastly, there is a difference between direct and indirect land use changes. For example, in the case of the production of hydrogen, a direct land use impact may arise from the allocation of land for renewable energy sources like solar panels and wind turbines. Moreover, indirect land use changes (ILUC) considers the impact of the increased global demand for hydrogen as fuel, leading to the expansion of renewable electricity sources and potentially impacting entire landscapes and, thereby ecosystems and biodiversity biofuels (Ansell, 2023).

In Table 5.2, the set of sub-criteria of the environmental performance to evaluate SATs.

Table 5.2: Environmental sub-criteria

Main criterion	**Sub-criteria**	**Definition**
Environmental performance	Greenhouse gas emissions (GHG)	The net reduction in direct and indirect greenhouse gas emissions compared to traditional jet fuel and aircraft.
	Water consumption	The quality of discharged and used water from the fuel production process address potential threats to the environment and human health.
	Land use impact	The land area is required for production methods, considering the direct and indirect impacts on ecosystems and biodiversity.

The additional sub-criteria depicted in Figure C.2 (Appendix C) are excluded from consideration. The criteria 'feedstock sustainability' and 'SAF traceability' focus only on biofuels and are therefore excluded from the research (Ahmad et al., 2021, 2019). According to experts in the interviews, other emissions such as NO_x, $PM_{2.5}$, and PM_{10} are excluded because they are considered negligible concerning GHG emissions. Noise is not considered as important as the other criteria selected for this research. This is because the noise has mainly influenced the local residents near an airport, which is regarded as small in impact compared to the selected criteria. Lastly, whereas Markatos & Pantelakis (2023) argues for contrails' importance, other articles did not mention contrails at all. Hence, this is the only article that emphasizes the importance of contrails; they are excluded as a criterion of the research.

5.5 Economical performance

Economic performance refers to all the economic aspects of adopting SATs in this research. As stated before, this research focuses on the aircraft and its possible modifications. Therefore, the potential infrastructure and production plant costs for certain technologies for the airport are left out in this research (Section 1.3).

The aviation industry runs on fossil fuels/oils, there is a lack of competitive SATs for commercial aviation (medium- and long-haul), and on the other hand, there is a lot of competition within the aviation sector (European Commission, 2020). The combination of competition within the aviation sector and lack of competition towards the use of fossil fuels highlights the importance of the potential economic competitiveness of SATs to pursue the goal of net zero CO_2 aviation. However, for adopting technology, the financial costs and benefits are argued as essential factors by Feitelson & Salomon (2004). Additionally, van de Kaa et al. (2011) confirms that during the initial phase, the economic aspects of technology are crucial. Furthermore, all the articles from the literature review identified economic performance as a main criterion. Therefore, the economic performance of SATs is considered an main criterion. The following subsections elaborate on the sub-criteria that indicate economic performance.

5.5.1 Minumum Jet Fuel Selling Price

The first criterion identified considering economic performance is the minimum jet fuel selling price (MJFSP). Ahmad et al. (2021) identifies the economic criterion of minimum fuel price. In other studies, similar criteria are identified, such as: 'fuel price' (Markatos & Pantelakis, 2023), 'production cost per unit' (Chen & Ren, 2018), and 'fuel cost' (Ahmad et al., 2019). These comparable criteria are merged into the aggregated criterion: 'minimum jet fuel selling price (MJFSP).' Next to the identified studies in the literature review for identifying the criteria, the MJFSP is already indicated as a key factor for economic viability in Chapter 4. by Dahal et al. (2021). In this article, the minimum MJFSP is the minimum price a customer could purchase fuel at, such that a zero net present value of profit is achieved. Therefore, the MJFSP equals 'the minimum expected price a customer has to pay for fuel.'

5.5.2 Investments costs

The second sub-criterion for economic performance is the investment costs. These are the costs necessary for modifying existing aircraft or purchasing new aircraft; in other words, they are the financial investments needed to launch flights at a commercial scale. In 6 of the 14 articles, the investment cost is related to the modification or the purchase of an aircraft (Markatos & Pantelakis, 2023; Demircan & Kaplan, 2023; Kiracı & Akan, 2020; Kiracı & Bakır, 2018; Dožić et al., 2018; Yavuz et al., 2015). In 7 other articles, the investment costs are related to the costs of the investment for the production of alternative aviation fuels (Ahmad et al., 2021; Chen & Ren, 2018; Ahmad et al., 2019; Ayar & Karakoc, 2023; Xu et al., 2019; Yang et al., 2023; Acar et al., 2018). According to the scope of this research, these investments for production are outside the scope. In this research, the focus is on the aircraft, wherefore the investment costs are also related to the aircraft and not to the production of the fuels the aircraft runs on. Additionally, the scope considers only the costs associated with the aircraft and fuel systems but not the infrastructure needed for the airport.

5.5.3 Operational costs

The last sub-criterion of the economic performance is the operational costs. These operational costs are an aggregated form of several criteria of the longlist in Figure C.1. In the longlist, there are different criteria for maintenance and operational costs. The articles of Ahmad et al. (2021), Ahmad et al. (2019), Xu et al. (2019), Yang et al. (2023), and Acar et al. (2018) relate the maintenance and operating cost to that of the production of fuels, which is not applicable for this study. On the other hand, it emphasizes the importance of overall operating and maintenance costs for technologies. Besides these articles, the studies of Demircan & Kaplan (2023), Markatos & Pantelakis (2023), Kiracı & Akan (2020), Dožić et al. (2018), and Yavuz et al. (2015) relate the operating and maintenance cost regarding the aircraft. These articles provide the aggregated definition of Direct Operating Costs (DOCs). As earlier explained in Section 4, the DOCs are the direct costs related to flight operation, including costs such as financial cost, total crew cost, total charges and fees, airframe maintenance cost, engine maintenance, and fuel operating cost (Dahal et al., 2021).

As stated in the previous paragraph, maintenance and operation costs are related to the feedstock/powerplant of fuel production in a few of the articles. On the other hand, maintenance and operation costs are also seen as an important factor in aircraft-related articles. Therefore, as experts have emphasized, maintenance and operations costs are important, regardless of the technology. Thus, the criterion of operational costs is considered important in this research based on the literature review articles and verified by stakeholders (Sections 6.1.4).

In the following table 5.3, the sub-criteria taken into account to evaluate SATs from an economic perspective are presented.

Table 5.3: Economic sub-criteria

Main criterion	Sub-criteria	Definition
Economic performance	MJFSP	The "Minimum Jet Fuel Selling Price" of a certain fuel/the minimum expected price a customer has to pay for fuel.
	Investment costs	Investments necessary for modifications in existing aircraft or the purchase of new aircraft needed to launch flights at a commercial scale.
	Operational costs	DOCs are the direct costs related to flight operation including costs such as total financial cost, total crew cost, total charges and fees, aircraft maintenance cost, engine maintenance cost, and fuel operating cost.

5.6 Technological performance

The technical performance relates to all the technical aspects of the adoption of SAT within the scope (Section 1.3). The technological performance is argued as one of the most important by Feitelson & Salomon (2004). They state that one of the most fundamental questions for the adoption of a technology is if the innovation is technologically feasible. If the innovation is technologically not feasible, all the other criteria are pointless. Therefore, technological performance is considered a main criterion in this research. The sub-criteria representing technological performance in this research are elaborated in the next subsections.

5.6.1 Technology readiness level

The first criterion considered for evaluating SATs for technological performance is the technology readiness level (TRL). The TRL differs highly for each technology; the TRL for biofuel via an HEFA pathway is relatively high, and HEFA is already used, but not on a wide scale (Abrantes et al., 2021). On the other hand, the use of hydrogen has a relatively lower TRL for medium- or long-haul commercial passenger aviation. Still, it is considered to have promising development in the coming decades Dahal et al. (2021). The TRL is widely acknowledged as important in the identified articles. Not specific as TRL, but for example, as technological maturity that overlaps TRL (Yavuz et al., 2015; Xu et al., 2019; Yang et al., 2023; Chen & Ren, 2018). In this research, all those narrowly related criteria are merged into the aggregated criterion TRL (Yavuz et al., 2015; Xu et al., 2019; Yang et al., 2023; Chen & Ren, 2018; Ahmad et al., 2019, 2021). In some of these studies, the TRL is related to the production of fuels, but the TRL in this research considers the TRL of the SAT. Nevertheless, the TRL is a general concept for new technologies. Lastly, the TRL is defined as 'the degree of progress and preparedness (maturity) of the technology for real-world application.' The TRL has 9 'degrees' or levels; these levels are expounded in Table A.1 in Appendix A.

5.6.2 Scalability

The second sub-criterion important for the evaluation of SATs is considered scalability. The scalability of sustainable aviation entails two important parts: the scalability of the aircraft technology and the scalability of the fuel production. This criterion is identified in different studies for different aspects, such as the scalability of the feedstocks for certain biofuels (SAFs) by Ahmad et al. (2021, 2019) and next to the literature review Dahal et al. (2021) discusses the scalability of the production of the lithium batteries needed for battery electric aircraft. As can seen in Figure C.4, the scalability only applies to the production process of SAFs. In the scope of this research, the production process of a fuel is excluded (Section 1.3). Thus, the scalability of SATs depends on the aircraft's technology scalability. The criterion of scalability is derived from the literature review but is not related to the aircraft's technology scalability. Therefore, the relevance of this criterion regarding SATs is verified in the interviews with the stakeholders (Sections 6.1.1, and 6.1.4). They emphasized the aircraft's technological scalability, especially with the inclusion of LH_2.

Furthermore, technological scalability influences the feasibility of the widespread adoption of SATs. Therefore, scalability is important because the SAT must be feasible to be widely adopted to make a difference in the total fleet in the aviation industry and pursue net-zero aviation. The specific definition of scalability in this research is 'the capability of the new technology to adjust and function effectively across various scales and conditions on a global scale.'

5.6.3 Efficiency

The last criterion regarding technological performance is the efficiency of the aircraft with adequate fuel. This efficiency is highlighted as an important criterion in different studies of the literature review but with some different perspectives regarding the different nature of the articles. In some of the articles, the efficiency is related to the energy efficiency of the production process of fuels (Tzeng et al., 2005; Acar et al., 2018; Ahmad et al., 2019; Yang et al., 2023). In other articles, the efficiency is more related to the performance of the aircraft (Markatos & Pantelakis, 2023; Demircan & Kaplan, 2023; Kiracı & Akan, 2020; Kiracı & Bakır, 2018; Yavuz et al., 2015). For this criterion, there is an overarching criterion for the aircraft-related efficiency criteria. The aggregated criterion based on the articles that define efficiency regarding aircraft performance is 'the efficiency of fuel consumption concerning the aircraft's performance.'

The criteria for evaluating SATs from a technological perspective are presented in the following Table 5.4.

Table 5.4: Technological sub-criteria

Main criterion	Sub-criteria	Definition
Technological performance	Technology Readiness Level (TRL)	The degree of progress and preparedness (maturity) of the technology for adoption.
	Scalability	The capability of the new technology to adjust and function effectively across various scales and conditions on a global scale.
	Efficiency	The efficiency of fuel consumption concerning the aircraft's performance.

5.7 Overview of selected criteria and stakeholder confirmation

In the previous sections, all the criteria that are identified via the literature reviewed are discussed, and their importance is explained. However, during the stakeholder interviews, the stakeholders agreed upon the selection of all the identified main criteria and their sub-criteria. Sections 6.1.1 & 6.1.4 detail how stakeholders verify the criteria during the interviews. This is because of the need to include all the important criteria and exclude uncertainties about the relevance of the criteria. Thus, the final list of main criteria and sub-criteria is based on the literature review and validated by the interviewed stakeholders. Figure 5.2 presents the main criteria with the corresponding sub-criteria considered in this research.

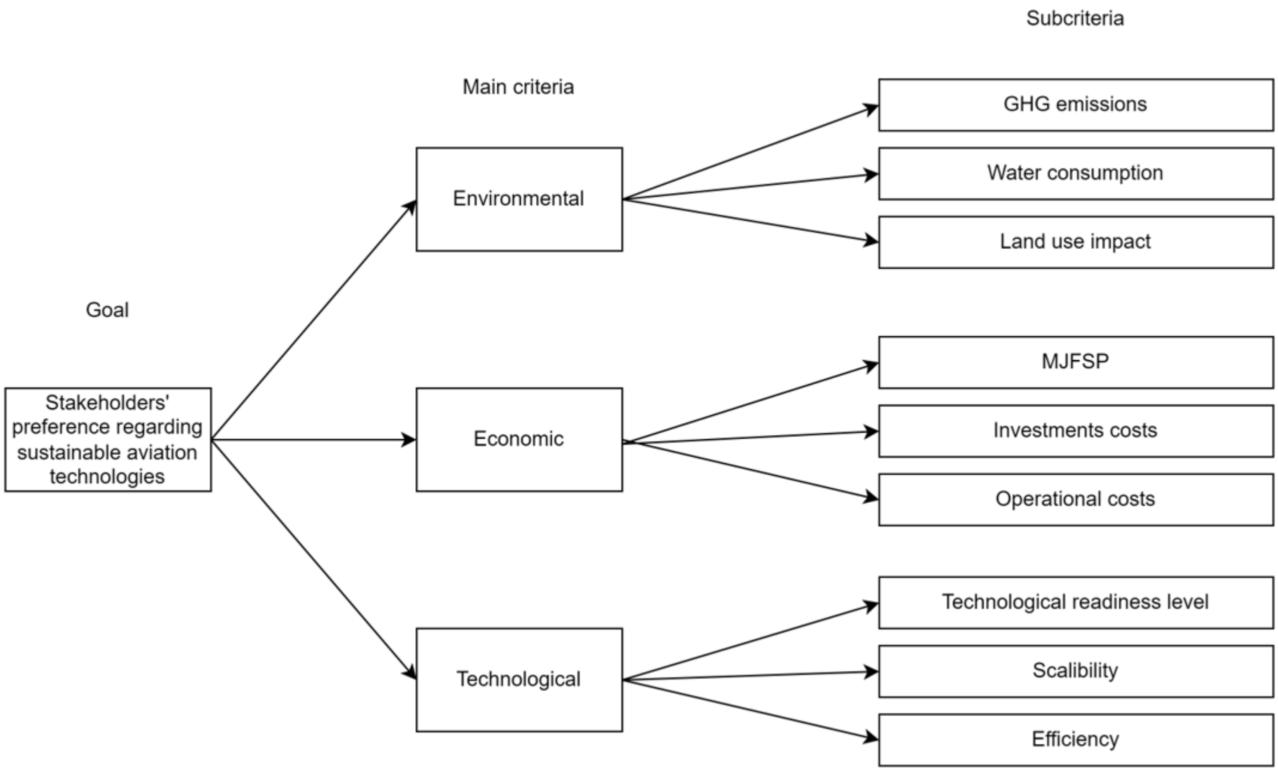


Figure 5.2: Selected main criteria and subsets of sub-criteria for the evaluation of sustainable aviation technologies

6 Obtaining criteria weights

This chapter investigates the sub-question: "What are the weights of the different criteria based on stakeholder perspectives?". The criteria derived from sub-question 2 are subjected to weighting using the Bayesian BWM. The first section delineates the data collection, followed by a subsequent section that presents all the weights obtained by the Bayesian BWM.

6.1 Interviews as data collection tool

To obtain the stakeholder criteria weights, interviews were employed as a data collection tool. These interviews followed a semi-structured format using the imposed structure of the BWM, supplemented by an open discussion/recap. The interviews were conducted through both online platforms like Zoom or Microsoft Teams and in-person settings, ensuring diverse engagement opportunities. Stakeholders were approached via LinkedIn to arrange interviews, resulting in the involvement of eleven stakeholders representing various stakeholder groups (Section 6.1.2).

6.1.1 Description of the interview design

The interview started with a mutual introduction followed by a presentation of the interview structure using Microsoft PowerPoint as a tool to support the remainder of the interview. Subsequently, the context and relevance of the research were explained, along with the goal of the research. Then, the BWM was explained using a simple example to ensure the interviewee's understanding. Furthermore, the interviewee was encouraged to provide pairwise comparisons from their stakeholder perspective, as the aim was to capture stakeholder preferences. After explaining the criteria, the BWM was performed, followed by an open discussion/recap. Detailed information on the interview setup, ensuring reproducibility, is provided in Appendix D.

Furthermore, after the BWM was performed, an open discussion/recap and reflection was held with the interviewee. In the recap, it was queried whether the interviewees concurred with the selected criteria. The stakeholder might raise concerns about certain overlooked sub-criteria or completely support the selection of main and sub-criteria. Moreover, the interviewees were asked if they agreed with the selected SATs for medium- and long-haul commercial passenger aviation. The recap is considered important in the employment of the BWM as it addresses possible limitations and recommendations for further research, as discussed in Sections 8.3 and 8.4. Furthermore, the interviewees were asked if the interview was clear and, if not, how the interview structure could be improved.

Lastly, the interviewee was thanked for his time and participation and asked if they had any recommendations for other stakeholders for participating in an interview. Moreover, the interviewee was asked if they were interested in the final results of the research and if they agreed upon using their answers, emphasizing that they are anonymized.

6.1.2 Stakeholder analysis

Before the stakeholders can be selected, it is important to identify the different stakeholder groups' vested interests or are involved in the implementation of SATs. A brief stakeholder analysis is conducted to obtain these stakeholder groups. The stakeholder groups included in this research are the airline, the expert/advisor, and the producer/manufacturer stakeholder group. The producer/manufacturer stakeholder group because they have an interest in the adoption of SATs regarding fuels and aircraft technologies. The airline stakeholder group has to adopt the SATs to pursue net-zero CO_2 in 2050. Lastly, the expert/advisor stakeholder group is included because this group has expert knowledge in the aviation industry, and it is considered that by their expertise, they know the important criteria for the adoption of SATs from an independent perspective. These different stakeholder groups are used to identify potential interviewees on LinkedIn and ensure sufficient interviewees to represent each stakeholder group. Figure 6.1 below presents the derived stakeholder groups.

Figure 6.1: Identified stakeholder groups

6.1.3 Stakeholders selection

The selected stakeholder needs substantial expertise and working experience to obtain valuable answers in the interview. Therefore, this research aimed to interview stakeholders with know-how and practical experience in aviation. This experience in the aviation industry and level of know-how was derived from LinkedIn profiles. They were not selected if there was any doubt about their level of expertise. Table 6.1 presents the selected stakeholders, stakeholder group, function, experience and expertise. As mentioned in the previous section (Section 6.1.1), the interviewees were anonymized to increase their willingness to participate, resulting in anonymized names and company names. The eleven interviewed stakeholders are shown in Table 6.1 with their corresponding specifications.

Table 6.1: List of interviewed stakeholders

Expert	Stakeholder group	Function	Experience	Expertise
1	Airline	Director	+- 25 years	Strong background in aircraft operation, specialize in fuel efficiency and SAF
2	Expert/ advisor	Sustainable aviation consultant	+ 30 years	aircraft manufacturing and airline industry with focus on sustainability. Currently, consultant.
3	Expert/ advisor	Consultant	+- 3 years	Engineering professional and technical consultant in the aviation industry, focusing on sustainability.
4	Expert/ advisor	Programme officer	+- 5 years	works in a company pursuing sustainable aviation and educational background in aerospace
5	Producer/ manufacturer	Production manager	+ 20 years	Engineering experience in design for manufacturing.
6	Airline	Managing director	+35 years	Various fields in aviation focussing in the last two decades on sustainable aviation
7	Airline	Sustainability director	+ 15 years	Development of sustainable aviation models
8	Producer/ manufacturer	Partnership manager	+- 5 years	In the field of the production and commercialization of SAFs
9	Expert/ advisor	Expert/ consultant	+- 5 years	Educational background in aerospace using expertise to interact between stakeholders
10	Producer/ manufacturer	Head of business development for SAF	+ 15 years	Experienced sustainability leader with regard to aviation
11	Airline	Sustainable aviation fuel manager	+ 10 years	In development of the use of SATs for a large airline company

6.1.4 Stakeholders concurrence on the criteria & exclusion electric

Before obtaining the weights of the different criteria from stakeholder interviews, it is important to ensure that all the stakeholders concurred with the selected main criteria and sub-criteria. Therefore, this is checked in the interviews with the stakeholders, as detailed in Section 6.1.1. This is done to ensure that all important criteria are selected and to exclude uncertainties about the relevance of the criteria. During the interviews, all stakeholders concurred with the selected main criteria and sub-criteria. While they acknowledged the importance and relevance of the selected criteria, some stakeholders suggested an additional criterion. These proposed additions are addressed for further research in Section 8.4.

Furthermore, as mentioned in Section 4.2.1, electric aircraft are excluded from further research due to the lack of promising prospects for electric aircraft regarding medium- & long-haul commercial passenger aircraft. Beyond the exclusion based on the literature from that section, stakeholders were asked regarding their perspective on the different SATs, as detailed in Section 6.1.1. The stakeholders acknowledged the potential of electric aircraft, particularly for short-haul aviation with a few passengers. However, they emphasized that it was not sensible to include electric aircraft in this research regarding the scope of medium- & long-haul commercial passenger aviation, as they did not expect electric aircraft for medium- or long-haul aviation. Therefore, electric aircraft have been formally excluded from the remainder of this study.

6.2 Obtained stakeholder criteria weights

This section details the weights obtained through the Bayesian BWM, determined from stakeholder interviews from various stakeholder groups (Section 6.1.2). This section starts with assessing the inconsistency ratios of these conducted interviews, as elaborated in Section 6.2.1. Subsequently, the obtained weights of the main and sub-criteria for all stakeholders together, along with their corresponding credal ranking, are presented in Sections 6.2.2 and 6.2.3. Lastly, the obtained weights for the separate stakeholder groups are discussed in Section 6.2.4. Additionally, taking into account the transparency of the obtained group weights, the local and global weights assigned to each individual stakeholder are presented in Figure G.1 found within Appendix G.

6.2.1 Consistency ratio

Prior to deriving the criteria weights, it is crucial to ascertain the reliability of stakeholder (decision-maker) responses when making pairwise comparisons. Validation of acceptable inconsistency ratios is important to ensure the rationality of the assessments (Liang et al., 2020). Stakeholders surpassing the inconsistency thresholds, with the pairwise comparisons made, are excluded from further analysis to prevent distortion of results (Liang et al., 2020). Liang et al. (2020) discusses two types of consistency threshold matrices: the input-based and the output-based consistency measurement. This study adopts the thresholds for input-based consistency measurements recommended by Liang et al. (2020) due to their effectiveness and practicality over the output-based consistency ratios. Consequently, this resulted in using the input-based consistency ratio thresholds presented in Table 6.2. This study uses a 9-point scale for both main and sub-criteria. Furthermore, both the main criteria set and the sub-criteria set each consist of 3 criteria. Thus, all the inconsistency ratios have a 9-scale with a 3-criteria threshold of 0.1359 (Table 6.2). This means that any stakeholder surpassing this threshold of 0.1359 is excluded from further analysis.

Table 6.2: Consistency thresholds (Liang et al., 2020)

	Criteria						
Scales	3	4	5	6	7	8	9
3	0.1667	0.1667	0.1667	0.1667	0.1667	0.1667	0.1667
4	0.1121	0.1529	0.1898	0.2206	0.2527	0.2577	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

In Table 6.3, the inconsistency ratios of the stakeholders regarding the main and sub-criteria are presented. The red-colored cells within the table signify consistency ratios surpassing the inconsistency threshold of 0.1359, as derived from Table 6.2. Notably, the consistency ratios that exceed the threshold of 0.1359 have values of 0.1625 and 0.2449. These values were obtained by pairwise comparisons of the environmental sub-criteria and the economic sub-criteria of stakeholder 7. Therefore, stakeholder 7 is excluded from further analysis (Table 6.1). All other consistency ratios remain below the threshold of 0.1359, as can be seen in the table below (Table 6.3).

Table 6.3: Inconsistency ratios of the stakeholders

Stakeholder	1	2	3	4	5	6	7	8	9	10	11
Main criterion	0.1039	0.0417	0.1231	0.0392	0.1222	0.0659	0.0513	0.1231	0.1000	0.1231	0.0278
C1 Environmental	0.191	0.0455	0.1039	0.0000	0.1125	0.1125	0.1625	0.0938	0.1296	0.0317	0.0000
C2 Economic	0.0417	0.0000	0.1259	0.1026	0.0000	0.0364	0.2449	0.0278	0.0000	0.0889	0.0000
C3 Technological	0.0500	0.0769	0.1222	0.0714	0.1122	0.0513	0.1039	0.0463	0.0889	0.0250	0.0889

6.2.2 Obtained weights main criteria for all stakeholders together from the Bayesian BWM

As outlined in Section 3.2.3, this study employs the Bayesian BWM rather than the traditional BWM. The rationale behind this choice lies in the limitations of traditional BWM, which, while capable of deriving optimal weights for a set of criteria based on decision-maker preferences, lacks the capacity to determine optimal weights for aggregate stakeholder groups. To address this limitation and find optimal group decision-making weight with the BWM, the Bayesian BWM has been developed (Mohammadi & Rezaei, 2020). The Bayesian BWM also introduces credal ranking, which entails a weighted directed graph showing interrelations between the criteria. Furthermore, this graph provides insights into the confidence level (CL). This CL signifies the degree of certainty regarding the superiority of one criterion over another. In particular, a CL approaching 1 indicates a stronger certainty in the relationship between two criteria, while a lower CL suggests the opposite

(Mohammadi & Rezaei, 2020).

Applying this Bayesian BWM yielded optimal group weights representing all stakeholders together, as presented in Table 6.4. From the table, it is clear that C1 Environmental performance is considered the highest weighted among the three main criteria, with a weight of 0.445 for all stakeholders together. This indicates that all the stakeholders together prioritize environmental performance over economic and technological performance regarding the adoption of SATs. The ranking of the different main criteria, as determined by the derived weights from all stakeholder groups together, is C1 Environmental performance > C2 Economic performance > C3 Technological performance.

Table 6.4: Stakeholders together optimal group weights per main criterion

Main criterion	**Group weight**	**Ranking**
C1 Environmental	0.445	1
C2 Economic	0.327	2
C3 Technological	0.228	3

Figure 6.2 displays a weighted direct graph illustrating credal rankings and corresponding CLs of the main criteria. The figure shows that the environmental criterion exhibits a high confidence level towards the technological main criterion (0.99) while showing a considerably lower CL towards the economic main criterion (0.87). This lower score is explainable as follows: 7 out of the 10 stakeholders selected environmental as the most important, but 2 chose economic as the most important, resulting in a lower confidence level than 1 (resp. 0.87). Furthermore, the CL of the economic to the technological main criterion is 0.88.

These scores signify a 99% certainty that C1 Environmental performance is more important than C3 Technological performance among all the stakeholders together. Subsequently, there is an 87% certainty that C1 Environmental performance is more important than C2 Economic performance and an 88% certainty that C2 Economic performance surpasses the importance of C3 Technological performance.

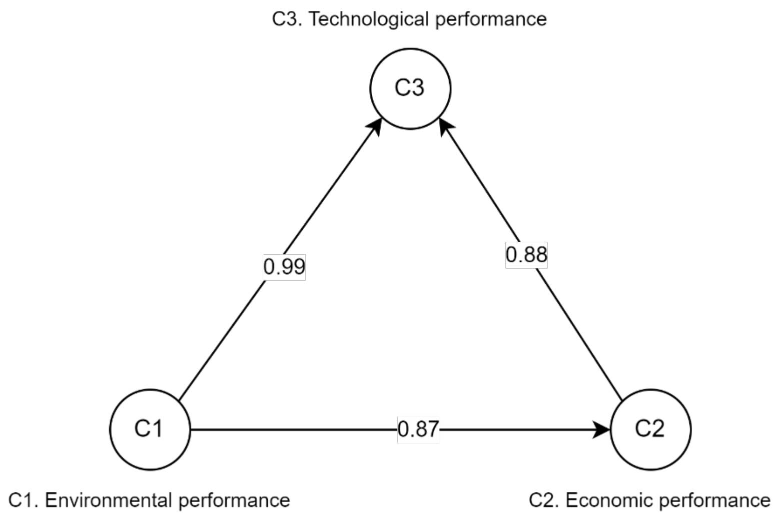


Figure 6.2: Visualizaiton of credal ranking of main criteria for all stakeholders together

6.2.3 Obtained weights sub-criteria for all stakeholders together

By combining the optimal weights assigned to the main criteria with the local weights given to the sub-criteria, the optimal global weights for the sub-criteria can be ascertained. This process involves multiplying the main criteria optimal weights from Table 6.4 by the corresponding local weights of Table 6.5, yielding the global weights as presented in Table 6.5. Additionally, Table 6.5 provides two rankings for the sub-criteria: one within each main criteria category and another encompassing all sub-criteria. While the local weights are ranked within the respective main criteria categories, the global weights are ranked across all sub-criteria.

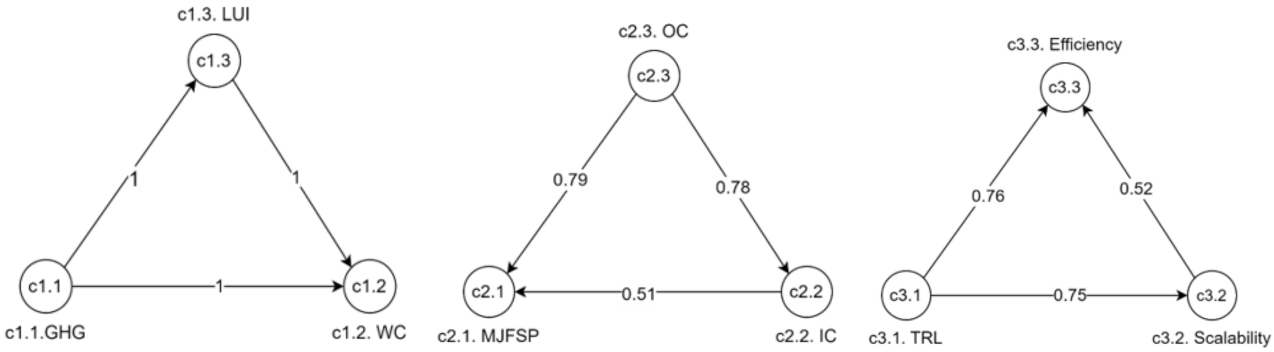
Table 6.5: Stakeholders together optimal group weights per sub-criterion

Main criterion	Sub-criteria	Local weights	Category rank	Global weights	Overall rank
C1 Environmental	c1.1 GHG	0.607	1	0.270	1
	c1.2 WC	0.125	3	0.056	9
	c1.3 LUI	0.267	2	0.119	3
C2 Economic	c2.1 MJFSP	0.307	3	0.100	5
	c2.2 IC	0.308	2	0.101	4
	c2.3 OC	0.385	1	0.126	2
C3 Technological	c3.1 TRL	0.384	1	0.088	6
	c3.2 Scalability	0.310	2	0.071	7
	c3.3 Efficiency	0.306	3	0.070	8

Table 6.5 reveals that among the global optimum weights, the c1.1 GHG emerges as the most important sub-criterion for the adoption of SATs across all stakeholders together, weighting 0.270. Notably, c1.1 GHG aligns with the paramount main criterion of C1 Environmental performance with a weight of 0.455 (Table 6.4). Analysis of the weight-directed graph of the environmental sub-criteria in Figure 6.3a indicates 100% (CL=1) certainty that sub-criterion c1.1 GHG holds greater importance than c1.2 WC and c1.3 LUI. This observation aligns with the expectation, as every interviewed stakeholder, except one, identified the sub-criteria c1.1 GHG as the most important sub-criteria within C1 Environmental performance. The only one that not selected c1.1 GHG as the most important sub-criteria argued that all the environmental sub-criteria are equally important (c1.1=c.1.2=c1.3). Furthermore, the credal ranking in Figure 6.3a presents that c1.3 LUI is with a 100% (CL=1) certainty more important than c1.2 WC. It is also noteworthy that eight out of the ten stakeholders selected c1.2 WC as the least important environmental sub-criterion, while the remaining two stakeholders ranked c1.2 WC equally important to c1.3 LUI. The ranking of c1.3 above c1.2 is emphasized by stakeholders regarding the time scope (2050). Stakeholders highlighted that while 'land use impact' is currently considered of lesser importance, it is expected to become significantly more important with the projected growth in renewable electricity production like windmills and solar panels; this impact will be further researched in Section 7.2.3.

Furthermore, within the main criterion C1 Economic performance, the sub-criterion c2.3 OC is considered the most important (Table 6.5). Among all the optimal global weights, c2.3 OC is ranked second with a score of 0.126, closely followed by c1.3 LUI (0.119). Examining Figure 6.3b, it becomes clear that the CL of c2.3 OC to c.2.1 MJFSP is 0.79 and to c2.2, 0.78. Hence, it can be ascertained with approximately 80% certainty that c2.3 OC holds greater importance than c2.1 MJFSP and c2.2 IC for all stakeholders together. On the other hand, the CL of c2.2 IC to c.2.1 MJFSP is 0.51, indicating a considerably lower certainty level of 51% that c2.2 IC is more important than c2.1 MJFSP. This means that there is almost a fifty-fifty chance, which is not surprising as the weights hardly differ from each other (by 0.001). Therefore, based on these confidence levels, it has to be taken into account that there is just a relatively small certainty that c2.2 IC is more important than c2.1 MJFSP.

Lastly, within the main criterion C3 Technological performance, sub-criterion c3.1 TRL emerges as the most important sub-criterion, with a weight of 0.088, as can be seen in Table 6.5. This is followed by c3.2 Scalability and c3.3 Efficiency, with the respective scores of 0.071 and 0.070. Figure 6.3c presents the credal ranking and the corresponding CLs of the technological sub-criteria. The CLs of c3.1 TRL to c3.2 Scalability and c3.3 Efficiency are 0.75 and 0.76, respectively. This indicates a 75% and 76% certainty that c3.1 TRL is more important than the other technological sub-criteria. However, due to the relatively moderate CLs, the higher importance of c3.1 TRL over the other two technological sub-criteria should be interpreted cautiously. Furthermore, similar to the difference between c2.1 MJFSP and c2.2 IC, the difference between the weights of c3.2 Scalability and c3.3 Efficiency is also minimal, with 0.001. This is illustrated in Figure 6.3c, presenting a CL of 0.52 from c3.2 Scalability to c3.3 Efficiency, suggesting only a 52% certainty that c3.2 Scalability is more important than c3.3 Efficiency. Thus, this ranking should be interpreted with careful consideration. Additionally, it is noteworthy that the sub-criteria of C3 Technological performance rank 6, 7, and 8, respectively, for c3.1, c3.2, and c3.3 in the overall ranking of 9. This implies that for all the stakeholders together, the sub-criteria of the main criterion C3 Technological performance is considered to be the least important, except for c1.2 WC.



(a) Environmental sub-criteria (b) Economic sub-criteria (c) Technological sub-criteria

Figure 6.3: Visualization of credal ranking of sub-criteria for all stakeholders together

6.2.4 Obtained weights per stakeholder group

This section examines the acquired optimal weights attributed to individual stakeholder groups, aiming to provide deeper insight regarding the formation of the optimal weights for all stakeholder groups together. The first subsection presents and expands upon the optimal weights assigned to the main criteria within each stakeholder group. Subsequently, the second subsection discusses the differences among the optimal weights of sub-criteria across the three stakeholder groups.

Obtained weights main criteria per separate stakeholder group

In Table 6.6, the obtained optimal group weights for the airline, expert/advisor, and producer/manufacturer stakeholder groups are presented. An analysis of this table reveals notable distinctions among the stakeholder groups' preferences towards criteria. Particularly, the expert/advisor and producer/manufacturer stakeholder groups assign high weights to the main criterion of environmental performance, with values of 0.519 and 0.496, respectively. Furthermore, the airline stakeholder group attributes a weight of 0.262 to the main criterion of environmental performance, signifying a notable difference in its importance compared to the other two stakeholder groups. Therefore, this difference underscores various perspectives regarding environmental concerns among stakeholder groups.

On the other hand, the airline stakeholder group assigns a weight of 0.565 to the main criterion of economic performance, which is more than four times higher than the weight of the expert/advisor stakeholder group (0.137). Moreover, the expert/advisor stakeholder group assigns twice the weight to technological performance compared to the airline stakeholder group. These variations highlight the different perspectives across all main criteria among the airline and expert/advisor stakeholder groups.

Lastly, credal rankings and corresponding CLs regarding the main criteria for each separate stakeholder group, detailed in the Figures H.1, H.2, and H.3, in Appendix H, do not exhibit qualifications for appointment, with the lowest CL of 0.80.

Table 6.6: Optimal group weights per main criterion of stakeholder groups: airlines, experts/advisors, and producers/manufacturers

	Weights		
Main criterion	**Airline**	**Expert/advisors**	**Producer/manufacturer**
C1 Environmental	0.262	0.519	0.496
C2 Economic	0.565	0.137	0.385
C3 Technological	0.173	0.344	0.119

Obtained weights sub-criteria per separate stakeholder group

This final subsection presents the Tables 6.7, 6.8, and 6.9. These tables present the local and global weights obtained for the sub-criteria per stakeholder group and their respective rankings.

Table 6.7 provides the local and global weights obtained for the airlines' stakeholder group. As can be seen, the three most important criteria for the airlines' stakeholder group are the economic sub-criteria, occupying rank 1 to 3. This is not surprising as C2 economic performance was the most important main criterion of the airline's stakeholder group, as mentioned in the previous subsection (Section 6.2.4). Furthermore, the economic sub-criteria exhibit demonstrates minimal variances among them, with weights ranging from 0.174 to 0.206. This suggests that the airlines' stakeholder group does not have a strong preference between the economic sub-criteria. This is also emphasized by the low CL scores of the economic sub-criteria of the airline stakeholder group in Figure H.1, in Appendix H. Moreover, the technological criteria also show minimal variance ranges, ranging between 0.053 and 0.064, indicating a lack of clear preference. This is emphasized by the airline stakeholder group's low certainty regarding the ranking, as indicated by the CLs presented in Figure H.1 in Appendix H. Additionally, despite the lower main criterion weight assigned to C1 Environmental performance, it is remarkable that the sub-criterion c1.1 GHG retains relatively high-ranked, at number 4.

Table 6.7: Airlines' optimal group weights per sub-criterion

Main criterion	**Sub-criteria**	**Local weights**	**Category rank**	**Global weights**	**Overall rank**
C1 Environmental	c1.1 GHG	0.567	1	0.149	4
	c1.2 WC	0.134	3	0.035	9
	c1.3 LUI	0.299	2	0.078	5
C2 Economic	c2.1 MJFSP	0.309	3	0.174	3
	c2.2 IC	0.365	1	0.206	1
	c2.3 OC	0.327	2	0.185	2
C3 Technological	c3.1 TRL	0.306	3	0.053	8
	c3.2 Scalability	0.370	1	0.064	6
	c3.3 Efficiency	0.324	2	0.056	7

Upon reviewing the local and global weights of the expert/advisor stakeholder group in Table 6.8, it becomes evident that the environmental sub-criteria are the most important, followed by the technological sub-criteria, with relatively lower weights assigned, consistent with the findings outlined in Section 6.2.4. The highest-ranked sub-criterion is the c1.1 GHG, representing a weight of 0.322. This allocation, of almost a third of the total weight, underscores the considerable importance attributed by expert/advisor stakeholder group to the GHG performance of an SAT. Furthermore, the second-ranked sub-criterion for this stakeholder group is c.3.1 TRL, with a weight of 0.176. This is remarkable because this is a significantly higher weight on this sub-criterion (c.3.1 TRL) compared to the other stakeholder groups. It is noteworthy that this is the stakeholder group with by far the lowest scores for the economic sub-criteria.

Table 6.8: Experts/advisors' optimal group weights per sub-criterion

Main criterion	**Sub-criteria**	**Local weights**	**Category rank**	**Global weights**	**Overall rank**
C1 Environmental	c1.1 GHG	0.621	1	0.322	1
	c1.2 WC	0.155	3	0.080	5
	c1.3 LUI	0.224	2	0.117	3
C2 Economic	c2.1 MJFSP	0.521	1	0.071	7
	c2.2 IC	0.224	3	0.031	9
	c2.3 OC	0.255	2	0.035	8
C3 Technological	c3.1 TRL	0.513	1	0.176	2
	c3.2 Scalability	0.228	3	0.078	6
	c3.3 Efficiency	0.260	2	0.089	4

The last Table (6.9) presented below provides insights into the local and global weights assigned by the producer/manufacturer stakeholder group. This stakeholder group assigns the most weight to the main criterion of C1 environmental performance. This is evident from the rankings of c1.1 GHG and c1.3 LUI scores in the overall ranking for the global weights, which hold the first and second positions, respectively, with values of 0.297 and 0.144. The performance of a SAT on these two sub-criteria accounts for nearly half of the total weight. Furthermore, the technological sub-criteria hardly differ from each other, ranging between 0.038 and 0.041. This is also emphasized by the credal ranking in Figure H.3, presenting low CLs values between the sub-criteria (Appendix H). Lastly, it is noteworthy that all the economic sub-criteria receive the lowest weights compared to the other stakeholder groups.

Table 6.9: Producers/manufacturers' optimal group weights per sub-criterion

Main criterion	Sub-criteria	Local weights	Category rank	Global weights	Overall rank
C1 Environmental	c1.1 GHG	0.598	1	0.297	1
	c1.2 WC	0.111	3	0.055	6
	c1.3 LUI	0.291	2	0.144	2
C2 Economic	c2.1 MJFSP	0.329	2	0.127	4
	c2.2 IC	0.348	1	0.134	3
	c2.3 OC	0.324	3	0.125	5
C3 Technological	c3.1 TRL	0.334	2	0.040	8
	c3.2 Scalability	0.347	1	0.041	7
	c3.3 Efficiency	0.319	3	0.038	9

7 Stakeholder preferences on identified SATs

The first sub-question delineates the identification of specific SATs to consider in this research (Chapter 4). In the second sub-question, the relevant main and sub-criteria are defined for the evaluation of the SATs (Chapter 5). This is succeeded by the third sub-question in which the optimal group weights concerning both main and sub-criteria are determined, applying the Bayesian BWM (Rezaei, 2015) (Chapter 6). Findings of the three sub-questions are amalgamated to address the fourth and final sub-question: "How do these alternative sustainable aviation technologies differ concerning stakeholder preferences, considering the criteria and corresponding weights?"

The initial section of this chapter investigates additional literature to ascertain the performance scorecards of the SATs across the 9 sub-criteria of the 3 main criteria. Following this, the subsequent section presents the overall performance scorecards for 2024, 2030, and 2050. Moreover, the subsequent section presents the final scores and rankings of the SATs for each year based on the optimal group decision weights obtained for all the groups, i.e., the stakeholder preferences towards the SATs. Additionally, the concluding section examines the variance in rankings resulting from the utilization of weights from individual stakeholder groups, with this analysis being conducted separately for each stakeholder group.

An additional note is provided to ensure clarity: performance scores or performance scorecards denote performance based solely on criteria, independent of stakeholder preferences, prior to conducting the Weighted Sum Method (WSM). On the other hand, final scores represent the outcomes on SATs/criteria considering stakeholder preferences after the completion of the WSM.

7.1 Literature used for performance scores of SATs on criteria

In addressing the first subquestion, selecting specific SATs (Chapter 4), some performances on the criteria for the SATs are already revealed, e.g., the MJFSP and the operational (Sections 7.3.1 and 7.3.3). However, the performance of most of the criteria remains undisclosed. Hence, literature is examined to precisely determine the performances of the SATs across the 9 sub-criteria to facilitate the conduction of the scorecards, a methodology previously employed in MCDM studies, e.g., Wu et al. (2011).

To ensure consistency in scores across various SATs for each sub-criterion, there is aimed to identify a minimum number of articles, where possible, containing performance data for all SATs within a given sub-criterion. This approach seeks to facilitate valid and reliable comparisons of scores within each sub-criterion.

Lastly, the scores presented in the following sections are based on a comparison of SATS values rather than to conventional aircraft technologies. This comparative approach is adopted due to the study's focus on sustainability. thus disregarding conventional aircraft is as a viable option.

7.2 Environmental performance

This section provides the SAT scores pertaining to the environmental sub-criteria. The following subsections offer detailed substantiation, accompanied by references, to derive the scores for the SATs on the environmental sub-criteria. Table 7.1 below presents a comprehensive analysis of the scores of the SATs concerning the environmental sub-criteria for the years 2024, 2030, and 2050.

Table 7.1: Scorecard environmental performance

Sub-criteria	Year	Performance scores: N-octane	HEFA	LH_2
GHG	2024	3	4	4
	2030	5	5	6
	2050	10	6	10
WC	2024	7	4	9
	2030			
	2050			
LUI	2024	8	10	9
	2030	5		6
	2050	2		3

7.2.1 Greenhouse gases

In this subsection, the three SATs for aviation are discussed concerning greenhouse gas emissions (GHG). Therefore, it is important regarding the greenhouse gas emissions that the production of the electrofuels (n-octane) and hydrogen (LH_2) used for the aircraft is produced from renewable sources to pursue net-zero emissions, as emphasized from the literature reviewed in chapter 4 and 5. This raises the question if that is possible with the current energy mix. The International Energy Agency (IEA) reports that the global share of renewable energy is 29% in 2020, 61% in 2030 and expected to be 88% in 2050 (IEA, 2021). Assuming a linear growth rate between 2020 and 2030, the proportion of renewable electricity is ≈ 42% in 2024, as detailed in Appendix E. This energy mix represents the electricity used to produce hydrogen and electrofuels.

Moreover, none of the reviewed literature sources identified the utilization of renewable electricity as a significant factor influencing GHG emissions in the context of biofuels. Therefore, electricity consumption is assumed to be negligible in producing biofuels compared to electrofuels and hydrogen. This was also confirmed during the interviews by asking the respondents questions in the open discussion (Section 6.1.1).

GHG emissions n-octane
According to the European Commission (2020), electrofuels exhibit the potential to achieve CO_2 emission reductions up to 85 % or more in comparison to conventional fuels. The report of the European Commission (2020) further contends a 100% reduction in CO_2 emissions could be attained if the electrofuels are produced from renewable energy sources and carbon capture from the air. Hence, electrofuels have the potential to approach net-zero emissions, dependent on the extent of renewable electricity (Su-ungkavatin et al., 2023; Dahal et al., 2021; Goldmann et al., 2018) (Section 4.4.3). However, achieving a score of 10/10 is presently not feasible, given the limitations of the current energy mix. Therefore, the scores are conducted based on the energy mix:

- **2024**: the low renewable electricity share (≈ 42%) causes the utilization of electrofuels will not cause net-zero CO_2 emissions. Scoring **3/10**.
- **2030**: the renewable electricity share is increased. Hence, the share of renewable electricity used for n-octane production is also increased. Scoring **5/10**.
- **2050**: almost all the electricity is produced renewable (88%), wherefore the score could be considered **10/10**.

GHG emissions HEFA
The reduction in greenhouse gas emission attributed to HEFA ranges from 50% to 80% (Dahal et al., 2021; Cabrera & de Sousa, 2022; Ansell, 2023; Okolie et al., 2023). However, this study researches the specific HEFA with used cooking oils as feedstock (Section 4.3). According to the European Commission (2021), HEFA-produced biofuel derived from used cooking oils can achieve GHG reduction of up to 69%. Additionally, hydrogeneration enhances the use of hydrogen for producing HEFA-produced fuels (Section 4.3). However, this is considerably small, its significance should not be overlooked, particularly in the context of the current energy mix. Based on this, the following scores are conducted for HEFA utilizing used cooking oils:

- **2024**: emissions are reduced but not near zero, and the hydrogen production is partly green. Scoring **4/10**.

- **2030**: emissions are reduced, but not near zero, and hydrogen production is becoming greener. Scoring **5/10**.
- **2050**: emissions are reduced with the production of green hydrogen but lacking compared to other SATs. Scoring **6/10**.

GHG emissions LH_2
Utilizing liquid hydrogen in aircraft propulsion, with PEM cells to obtain electricity of the LH_2, can reach net-zero emissions, provided that hydrogen production relies on renewable energy sources (Dahal et al., 2021; Ansell, 2023; Cabrera & de Sousa, 2022; Bauen et al., 2020; Yusaf et al., 2022), as previously discussed in Section 4.1.2. Currently, the majority of the hydrogen is produced from natural gas and coal (fossil), emitting tonnes of CO_2 (European Commission, 2022; Yusaf et al., 2022). The challenge in hydrogen production mirrors that of n-octane, with limitations arising from the current energy mix, hindering the realization of 100% CO_2 reductions. However, compared to the electrofuel n-octane, hydrogen production typically entails lower energy requirements (Su-ungkavatin et al., 2023). Hence, the extent of CO_2 emissions reduction resulting from hydrogen utilization is contingent upon the feasibility of green hydrogen production and prevailing electricity mix compositions throughout the decades. Based on these considerations, the ensuing scores for hydrogen are derived::

- **2024**: the energy mix in 2024 of $\approx$ 42%. Scoring a performance of **4/10**.
- **2030**: regarding to the energy mix in 2030 of 61%. Scoring a performance of **6/10**.
- **2050**: regarding to the energy mix in 2050 of 88%. Scoring a performance **10/10**.

7.2.2 Water consumption

This subsection examines water consumption considering the SATs, and concludes with the scores. The water consumption remains consistent for each SAT across the years 2024, 2030, and 2050, as no literature reviewed provided insights into prospective changes in water consumption. Additionally, respondents from interviews did not indicate variations in the future for water consumption.

Water consumption n-octane
As reported by the European Commission (2021), the production of electrofuels is associated with notably lower water consumption compared to biofuel. The specific usage of water for producing n-octane electrofuel is not explicitly provided. However, given the 9 liters of water necessary for 1 liter of hydrogen and the fact that the production of n-octane encompasses additional steps compared to hydrogen production, the water usage is assumed to be higher compared to hydrogen production (Transport & Environment, 2020; Su-ungkavatin et al., 2023). Consequently, the performance score on water consumption for n-octane is estimated at **7/10**.

Water consumption HEFA
The feedstock of used cooking oils is a waste residual. Thus, it does not require water consumption. However, the production of HEFA biofuels necessitates more water compared to electrofuels (European Commission, 2021). The generation of biofuels requires between 33 and 476 liters of water per liter of biofuel (Transport & Environment, 2020). Given the relatively water-scarce nature of used cooking oils as feedstock, it is reasonable to assume that the water usage would be closer to the lower end of this spectrum, around 33 liters per liter of HEFA from used cooking oils. Nonetheless, the processing methods employed in the production still require water (Transport & Environment, 2020). Hence, the overall water consumption remains considerably high, leading to an estimated performance score of **4/10**.

Water consumption LH_2
The water usage for hydrogen is 9 liter per 1 liter of hydrogen (Transport & Environment, 2020). The estimated performance score for hydrogen on water consumption is **9/10**.

7.2.3 Land use impact

This section delves into the exploration of the land use impacts stemming from the use of SATs. Followed up by the derived scores from the literature review.

The land use impact associated with electrofuel and hydrogen production depends on the electricity source. Utilizing wind and solar energy sources typically results in a relatively high land use impact compared to conventional jet fuel (Bicer & Dincer, 2017). On the other hand, energy sources such as hydropower or fossil fuels tend to have a lower land use impact than conventional jet fuel (Bicer & Dincer, 2017). The report of the ICAO (2021) emphasizes that solar PV and wind turbines necessitate significantly more land space than fossil electricity generation. The energy mix, including the proportion of renewable energy, is assumed to be the same as used for the greenhouse gases in Section 7.2.1. Additionally, it is important to determine the share of renewable electricity produced by wind turbines or solar PV to determine the share of solar PV + wind turbines from the total electricity energy mix. These estimations are detailed in Appendix E, and the results are as follows:

- Share of solar PV + wind turbines from total electricity energy mix in 2024 $\approx$ 13%
- Share of solar PV + wind turbines from total electricity energy mix in 2030 $\approx$ 41%
- Share of solar PV + wind turbines from total electricity energy mix in 2050 $\approx$ 68%

Additionally, it should be noted that these results are estimates based on the report by IEA (2021). They provide an indication of the order of magnitude rather than exact values.

Land use impact of n-octane
The production of electrofuel involves energy-intensive processes such as hydrogen electrolysis and additional steps for converting into electrofuels (Su-ungkavatin et al., 2023). Furthermore, the land used for producing electrofuels depends on renewable electricity produced from solar PV and wind turbines, as mentioned in the previous paragraph. Thus, the scores for land use of n-octane as aviation fuel are conducted as follows:

- **2024**: $\approx$ 13% of the electricity used is produced from solar PV or wind with a large amount of land use. Scoring a performance of **8/10**.
- **2030**: $\approx$ 40% of the electricity used is produced from solar PV or wind with a large amount of land use. Scoring a performance of **5/10**.
- **2050**: $\approx$ 68% of the electricity used is produced from solar PV or wind with a large amount of land use. Scoring a performance of **2/10**.

Wherefore, the estimations of the shares of solar PV and wind turbines can be found in Appendix E.

Land use impact of HEFA
The land-use impacts are considered high for the use of HEFA biofuels from palm oils, but for the use of waste materials (i.e., used cooking oils), the impacts are low Dahal et al. (2021). According to the ICAO (2021), the land-use impact of using HEFA with cooking oils is zero. Thus, HEFA with used cooking oils scores **10/10** without any changes over the years.

Land use impact of LH_2
In the case of LH_2 production, the reasoning is similar to that of producing electrofuels. However, hydrogen production encompasses fewer steps than electrofuel production (Su-ungkavatin et al., 2023). Therefore, hydrogen production requires less electricity, resulting in a smaller land use impact compared to electrofuels. Hence, the scores for the land use impact of LH_2 are similar to those for n-octane but considerably smaller:

- **2024**: $\approx$ 13% of the electricity used is produced from solar PV or wind with a large amount of land use. Scoring a performance of **9/10**.
- **2030**: $\approx$ 40% of the electricity used is produced from solar PV or wind with a large amount of land use. Scoring a performance of **6/10**.
- **2050**: $\approx$ 68% of the electricity used is produced from solar PV or wind with a large amount of land use. Scoring a performance of **3/10**.

Wherefore, the estimations of the shares of solar PV and wind turbines can be found in Appendix E.

7.3 Economic performance

Most of the studies in the techno-economic field have very broad ranges of expected costs, as evidenced in literature such as Dahal et al. (2021). Throughout the discussed literature in this section, the costs are predicted to decrease over the years (Dahal et al., 2021; Bauen et al., 2020). Hence, in this study, considering the innovative nature of the SATs, the highest costs are assumed for the scenario of 2024. By 2030, it is assumed that technological advancements will lead to cost reductions, resulting in an average price assumption. In 2050, it is assumed that further technological developments will drive SAT costs to their lowest levels. In the remainder of this section, the scorecard presentation for all the economic sub-criteria considered in this study is provided first, followed by an analysis of the SAT scores regarding the sub-criteria of economic performance based on scientific literature.

Table 7.2: Scorecard economic perfomance

		Performance scores		
Sub-criteria	**Year**	**N-octane**	**HEFA**	**LH_2**
MJFSP	2024	2	1	6
	2030	5	4	7
	2050	8	10	9
IC	2024	7	6	1
	2030	7	6	4
	2050	10	10	10
OC	2024	2	7	4
	2030	3	8	5
	2050	7	10	9

7.3.1 Minimum Jet Fuel Selling Price

This subsection discusses the exploration of the scores on the Minimum Jet Fuel Selling Price (MJFSP) for the SATs from 2024-2050.

MJFSP n-octane

For n-octane, the MJFSP range from 3.53$/kg to 10.20$/kg in the low-cost and high-cost scenarios, respectively (Dahal et al., 2021). In terms of $/GJ, which provides a universal standard for comparing fuels with varying energy densities, the price for n-octane ranges between 80–231 $/GJ with an average of 155 $/GJ. These values are based on assumptions regarding carbon capture costs, electrolysis expenses, and electricity prices (Dahal et al., 2021). These costs are for electrofuel production in general and not for n-octane. However, for purposes in this study, it is assumed that these costs are representative of the production of n-octane. Moreover, it is presumed that the energy mix is inherently integrated into the electrofuel MJFSPs, given the absence of distinction between renewable and fossil electrofuel production, unlike in the case of hydrogen (Dahal et al., 2021). Based on these MJFSPs considerations, the following predictions are madea and corresponding scores are conducted for the years 2024, 2030, and 2050:

- **2024**: in 2024, the high MJFSP scenarios of 231 $/GJ is assumed. Resulting in a performance score of **2/10**.
- **2030**: the average of 155 $/GJ is assumed to be the MJFSP in 2030. Hence, a performance score of **5/10**.
- **2050**: in 2050, the MJFSP is assumed to have the low-cost scenario of 80 $/GJ, concluding in a performance score of **8/10**.

MJFSP HEFA

For HEFA, the MJFSP range from 0.99$/kg to 3.06$/kg in the low-cost and high-cost cases, respectively (Dahal et al., 2021). In terms of $/GJ, the MJFSP is 23–310 $/GJ with an average of 167 $/GJ (Dahal et al., 2021). The MJFSP is very scale-dependent. As Dahal et al. (2021) emphasizes, by increasing the production of HEFA bio-jet fuel by 5 times, the MJFSP will decrease by 34%. Furthermore, the costs are also very dependent on the feedstock used (Dahal et al., 2021). The range of the MJFSP between 23–310 $/GJ is based on the different feedstocks discussed in Dahal et al. (2021). Nevertheless, the high-cost scenario of 310 $/GJ is assumed to be the MJFSP in 2024 because used cooking oils are considered the most expensive feedstock for HEFA (European Commission, 2021). Considering the potentially significant cost reductions associated with increased production of HEFA biofuel, it is assumed that the average of 167 $/GJ could be achievable by 2030, while the low-cost scenario of 23 $/GJ could be achieved by 2050. Resulting in the following scores:

- **2024**: the high-cost scenario of 310 $/GJ is applied according to the high feedstock costs of used cooking oils. Thus, scores a performance of **1/10**.
- **2030**: the average costs of 167 $/GJ are applied due to increasing production benefits. Hence, the performance score is **4/10**.
- **2050**: the low-cost scenario of 23 $/GJ applies due to the assumed maximal benefits of cost reduction from increasing production. Resulting in a performance score of **10/10**.

MJFSP LH_2
For LH_2, the MJFSP ranges from 3.56$/kg to 13.70$/kg in the low-cost case and between 6.80$/kg and 13.70$/kg in the high-cost case, depending on whether the hydrogen is produced from fossil or renewable sources (Dahal et al., 2021). In terms of $/GJ, the MJFSP ranges from 17-72 $/GJ, with an average of 45 $/GJ for fossil hydrogen generation. On the other hand, with renewable resources, the MJFSP for hydrogen ranges between 52-270 $/GJ with an average of 135 $/GJ (Dahal et al., 2021). The costs of renewable energy are decreasing over time (Transport & Environment, 2023). Hence, the MJFSP for hydrogen from renewable sources is presumed to be a high-cost scenario in 2024 (270$/GJ), average in 2030 (135$/GJ), and low in 2050 (52$/GJ). The MJFSP for hydrogen produced from fossil fuel is presumed to have the average MJFSP (45$/GJ), considering it is a widely employed production method (European Commission, 2022). The MJFSPs for 2024, 2030, and 2050 are determined based on the composition of the energy mix (Section 7.2) and the MJFSP for fossil and renewable hydrogen generation, resulting in the following MJFSPs and associated scores:

- **2024**: Based on the following calculation: $270\$/GJ \times 42\% + 45\$/GJ \times 57.5\% = 140.6\$/GJ$. Scoring a performance of **6/10**.
- **2030**: Based on the following calculation: $135\$/GJ \times 61.0\% + 45\$/GJ \times 39.0\% = 99.9\$/GJ$. Scoring a performance of **7/10**.
- **2050**: Based on the following calculation $52\$/GJ \times 88.0\% + 45\$/GJ \times 12.0\% = 51.2\$/GJ$. Scoring a performance of **9/10**.

7.3.2 Investment costs

In this section, the scores for the investment costs are obtained based on the reviewed literature. Furthermore, when considering investment costs in aircraft, it is essential to acknowledge that the depreciation period of passenger aircraft typically spans approximately 20 years (IATA & KPMG, 2015). The remainder of this section discusses the scores for the investment costs for the SATs.

Investment costs n-octane powered aircarft
According to Dahal et al. (2021), modifying and retrofitting existing aircraft is necessary due to their incompatibility with 100% electrofuel. Additionally, Goldmann et al. (2018) underscores the need for aircraft adjustments when utilizing n-octane, although minimal adjustments are required. This is emphasized by the comparable characteristics of n-octane compared to conventional fuel, facilitating a drop-in capability and potential that score 4 and 5 out of 5 of n-octane, respectively (Goldmann et al., 2018). Therefore, the scores are allocated as follows:

- **2024**: minimal modifications are necessary. Scoring a performance of **7/10**.
- **2030**: minimal modifications are necessary. Scoring a performance of **7/10**.
- **2050**: the current fleet is depreciated in 2050 (+ 20 years). It is assumed that the necessary changes to accommodate 100% n-octane fuel in newly produced aircraft will be integrated. Therefore, scores a performance of **10/10**.

Investment costs HEFA powered aircraft
Current engine and propulsion systems face challenges in accommodating 100% bio-jet fuels, necessitating retrofitting and development of new engine propulsion systems (Dahal et al., 2021). An interviewee from an airline company emphasized in the open discussion (Section 6.1.1) that biofuels are missing aromatics, which could influence the engine's gaskets, as also emphasized by Su-ungkavatin et al. (2023); Dahal et al. (2021); Okolie et al. (2023). Consequently, there exists now a blending limit of up to 50% in existing aircraft (Dahal et al., 2021). As a result, the score is estimated to be lower than n-octane due to the need for more significant modifications to enable 100% biofuel aircraft propulsion. This results in the following scores:

- **2024**: modifications are necessary, which enhances investment costs. Scoring a performance of **6/10**.
- **2030**: modifications are necessary, which enhances investment costs. Scoring a performance of **6/10**.
- **2050**: the current fleet is depreciated in 2050 (+ 20 years). The newly produced aircraft are assumed to be compatible with 100% biofuel. Resulting in a peformance score of **10/10**.

Investment costs LH_2 powered aircraft
The costs associated with cryogenic fuel tanks necessary for liquid hydrogen storage, which contribute to additional mass and technology costs, pose challenges for hydrogen aviation (Dahal et al., 2021). Estimating the costs of hydrogen aircraft is difficult due to their ongoing development (Transport & Environment, 2023). Moreover, Transport & Environment (2023) highlights the absence of evidence suggesting that the production of hydrogen aircraft exceeds those of conventional aircraft once hydrogen aircraft are fully developed. Therefore, the costs of hydrogen aircraft are presumed to be high during the initial years of development, and approaching 2050, the costs will be assumed to be comparable to existing aircraft. Resulting in the following scores:

- **2024**: the development of hydrogen aircraft is expensive (Transport & Environment, 2023). Scoring a performance of **1/10**.
- **2030**: developing different hydrogen aircraft types is still expensive but becoming more general. Scoring a performance of **4/10**.
- **2050**: there is no evidence that the production of hydrogen aircraft is higher than conventional aircraft if hydrogen aircraft is fully developed Dahal et al. (2021). Scoring a performance of **10/10**.

7.3.3 Operational costs

The operational costs of conventional technologies range from 3.9 to 4.8 US dollar cents per passenger-kilometer $/PAX/KM for medium and long-haul distances (MH and LH). This range between 3.9 and 4.8 is for MH and LH aircraft combined, which fits the scope of MH to LH commercial aircraft (section 1.3). The operational costs are the same as the earlier Direct Operating Costs (DOCs) (section 4). The DOCs are the direct costs related to flight operation, including costs such as total financial cost, total crew cost, total charges and fees, aircraft maintenance cost, engine maintenance cost, and fuel operating cost (Dahal et al., 2021). The ranges of DOCs, based on Dahal et al. (2021), reflect the uncertainties and variability in factors affecting the DOCs. Hence, the highest costs are assumed for 2024 due to this uncertainty. It is further assumed that through improvements, costs will reach the average of the DOC range by 2030, while assuming that through improvement, 2030 reaches the average of the DOC range by 2030. By 2050, optimized operations are expected to minimize operational costs, approaching the lower end of the DOC range. Resulting in the following scores:

N-ontane operational costs
The operational costs (DOCs) for n-octane fueled aircraft range from 9.2–23.7¢/PAX/km with an average of 16.45¢/PAX/km Dahal et al. (2021).

- **2024**: the operational costs in 2024 for HEFA-biofuel powered aircraft are 23.7¢/PAX/km. Hence, scoring a performance of **2/10**.
- **2030**: the operational costs in 2030 for HEFA-biofuel powered aircraft are 16.45¢/PAX/km. Scoring a performance of **3/10**.
- **2050**: the operational costs in 2050 for HEFA-biofuel powered aircraft are 9.2¢/PAX/km. Results in a performance score of **7/10**.

HEFA operational costs
The operational costs (DOCs) of biofuel utilization range from 5.0-9.2 ¢/PAX/km with an average of 7.1¢ /PAX/km Dahal et al. (2021).

- **2024**: the operational costs in 2024 for HEFA-biofuel powered aircraft are 9.2 ¢/PAX/km. Scoring a performance of **7/10**.
- **2030**: the operational costs in 2030 for HEFA-biofuel powered aircraft are 7.1¢/PAX/km. Scoring a performance of **8/10**.

- **2050**: the operational costs in 2050 for HEFA-biofuel powered aircraft are 5.0 ¢/PAX/km. Resulting in a performance score **10/10**.

LH_2 operational costs
The operational costs (DOCs) associated with hydrogen-powered aircraft are estimated to vary between 8.1 and 23.9 ¢/PAX/km, with an average of 16 ¢/PAX/km for renewable liquid hydrogen, and between 5.9 and 10.1 ¢/PAX/km, with an average of 8 ¢/PAX/km fossil-produced liquid hydrogen Dahal et al. (2021). As for the MJFSP, it is assumed that the price of the fossil-generated hydrogen will be constant. Therefore, the average of 8 ¢/PAX/km is assumed to be the DOCs for fossil-generated hydrogen. On the other hand, the costs of renewable energy are decreasing over time (Transport & Environment, 2023), impacting the DOCs of hydrogen-powered aircraft. Therefore, the DOCs for renewable hydrogen are assumed to peak at 23.9 ¢/PAX/km in 2024. In 2030, the DOCs are assumed to be an average of 16 ¢/PAX/km. Finally, in 2050, the DOCs for renewable are assumed to be the lowest: 8.1 ¢/PAX/km. The DOCs for 2024, 2030, and 2050 are, similarly to the MJFSP, influenced by the global energy mix (IEA, 2021).

- **2024**: the operational costs in 2024 for hydrogen-powered aircraft are:
$23.9\text{¢}/PAX/km \times 42\% + 8\text{¢}/PAX/km \times 57.5\% = 14.8\text{¢}/PAX/km$. Scoring a performance of **4/10**.
- **2030**: the operational costs in 2030 for hydrogen-powered aircraft are:
$16\text{¢}/PAX/km \times 61\% + 8\text{¢}/PAX/km \times 39\% = 12.9/PAX/km$. Scoring a performance of **5/10**.
- **2050**: the operational costs in 2050 for hydrogen-powered aircraft are:
$8.1\text{¢}/PAX/km \times 88\% + 8\text{¢}/PAX/km \times 12\% = 8.1/PAX/km$. Scoring a performance of **9/10**.

7.4 Technological performance

This subsection outlines the SAT scores related to the technological sub-criteria. The remainder of this subsection offers detailed explanations, supported by references, for these technological scores on the SATs. Below in Table 7.3, a comprehensive overview of the SAT scores for the technological sub-criteria for the years 2024, 2030, and 2050 is presented.

Table 7.3: Scorecard technological performance

		Performance scores		
Sub-criteria	**Year**	**N-octane**	**HEFA**	**LH_2**
TRL	2024	6	10	8
	2030	10		10
	2050	10		10
Scalability	2024	4	7	1
	2030	7	8	3
	2050	10	10	7
Efficiency	2024	9	10	6
	2030			
	2050			

7.4.1 Technological readiness level

the technological readiness level (TRL) focuses solely on the current situations of the TRL for the SATs. The inclusion of the three identified SATs is based on their perceived potential, as discussed in Section 4. Therefore, the TRL is assumed to be 9 for all three SATs from 2030 onward, scoring **10/10**. This section delves deeper into the examination of TRLs in the context of the SATs.

Technological readiness level n-octane
For n-octane encompassed as aviation fuel in aircraft, the TRL is between 5-8 (Dahal et al., 2021). Therefore, the TRL will score **6/10**.

Technological readiness level HEFA
The TRL of HEFA with used cooking oils is 9 (Dahal et al., 2021). Scoring **10/10**.

Technological readiness level LH_2
The TRL of liquid hydrogen as SAT ranges from 7-9 (Dahal et al., 2021). Scoring **8/10**.

7.4.2 Scalability

This subsection obtains and substantiates the scalability scores on the SATs. Additionally, with regard to scalability, akin to investment costs, it is important to take into account that the typical depreciation time of passenger aircraft approximates around 20 years (IATA & KPMG, 2015).

Scalability n-octane powered aircraft
The considerable scalability of n-octane within aircraft stems from its performance characteristics during combustion and turbine processes. This is highlighted by its respective scores of 4 out of 5 for drop-in capability (combustion) and 5 out of 5 for the drop-in potential (turbine) (Goldmann et al., 2018). This implies that minimal modifications are necessary for using electrofuels in aircraft, as mentioned regarding investment costs. On the other hand, Dahal et al. (2021) emphasizes that the TRL of electrofuels falls within the range of 5-8, which implies that scalability could be difficult because certification is first necessary (TRL 8, in Figure A.1 in Appendix A). Therefore, the following scores are considered:

- **2024**: the TRL is low between 5-8. TRL 8 is necessary for certification. Therefore scores **4/10**.
- **2030**: the TRL is assumed to be 9 (Section 7.4.1). The drop-in capabilities are high, and minimal modifications are necessary. Scoring **7/10**.
- **2050**: the aircraft are depreciated, and the new aircraft will be compatible with electrofuels. Scoring **10/10**.

Scalability HEFA powered aircraft
The scalability of HEFA as an aircraft fuel is deemed highly feasible. The primary challenge lies in the readiness of existing aircraft, which can only accommodate blends of up to 50% due to the insufficient aromatics content of biofuels for full 100% utilization (Su-ungkavatin et al., 2023). Therefore, modifications are required in existing aircraft, primarily involving the adoption of new sealing materials to address leakage concerns and enhance overall engine performance for full biofuel utilization (Su-ungkavatin et al., 2023). However, scalability remains viable up to 50% blending threshold, with gradual modifications paving the way for eventual 100% biofuel-powered aircraft. Based on this, the scalability is considered as follows:

- **2024**: The technology is partly scalable according to the 50% blending limit and small modifications have to be made for 100% compatibility. Scoring a performance of **7/10**.
- **2030**: Modifications are necessary for 100% biofuel powered aircraft. Scoring a performance of **8/10**.
- **2050**: Aircraft of the current fleet are depreciated; new aircraft are compatible with 100% biofuels. Scoring a performance of **10/10**.

Scalability LH_2 powered aircraft
The scalability of LH_2 is considered relatively limited. Implementation of hydrogen-powered aircraft necessitates the production of new aircraft, rather than modifying existing ones as highlighted in Section 7.3.2. This requirement, combined with the depreciation time of 20 years for a passenger aircraft, hinders scalability. Assuming that the aircraft owner acts from a profit motive, scalability is only gradually possible when the aircraft are depreciated. Therefore, the hydrogen technology scores low in scalability, but it is anticipated to increase towards 2050 as current aircraft are retired and replaced. Additionally, while the development of hydrogen aircraft is ongoing, it is expected to take time, with production projected to commence by 2030 (Transport & Environment, 2023). Resulting in the following scores:

- **2024**: the hydrogen aircraft are not ready for scalability because they are still in the developing phase. Scoring a performance of **1/10**.
- **2030**: the first hydrogen aircraft can be produced, but the current fleet is not depreciated. This means that the aircraft currently working must be replaced, which prevents scalability. Scoring a performance of **3/10**.
- **2050**: the hydrogen aircraft are 20 years in production, and aircraft of the current fleet are depreciated. Emphasizing a favorable climate for the scalability of hydrogen aircraft, but not as good as the other technologies because they could be modified instead of replaced. Scoring a performance of **7/10**.

7.4.3 Efficiency

In this final section of the technological performance sub-criteria, the efficiency scores assigned to the SATs are substantiated. Efficiency scores on the SATs have remained consistent across different years, as the studies in the literature did not find any evidence suggesting noticeable improvement in efficiency over time.

Efficiency n-octane powered aircraft
The fuel efficiency concerning aircraft performance is relatively high. This is because Goldmann et al. (2018) emphasized that the combustion properties score 4 out of 5. Furthermore, the turbine power output for n-octane achieves even 5 out of 5, which implies high energy consumption efficiency. Moreover, Goldmann et al. (2018) emphasizes the similarity of the n-octane electrofuels compared to conventional fuels, wherefore comparable performance is expected. Therefore, the efficiency of n-octane electrofuel-powered aircraft is rated with a performance score of **9/10.**

Efficiency HEFA powered aircraft
As outlined in the study by Dahal et al. (2021), bio-jet fuel is utilized in identical aircraft as conventional fuel (up to 50%), yielding comparable block energy use (MJ/PAX/km). Nevertheless, optimizing aircraft design to align with the specific characteristics of biojet fuel could potentially enhance performance, thereby improving fuel consumption efficiency beyond that of conventional fuels, resulting in a performance score of **10/10**.

Efficiency LH_2 powered aircraft
The block use energy (MJ/PAX/km) associated with LH_2 surpasses that of biofuel and conventional fuels (Dahal et al., 2021). This is caused by the lower volumetric energy density of hydrogen, even in liquid form, which requires larger and heavier cryogenic storage systems necessary for maintaining the liquid hydrogen at low temperatures. Therefore, hydrogen propulsion aircraft are heavier, containing the same amount of energy, wherefore they are less efficient compared to HEFA and n-octane powered aircraft. Scoring a performance of **6/10.**

7.5 Final performance scorecard

Table 7.4 presents a detailed overview of the SATs performances scores across all sub-criteria for the years 2024, 2030, and 2050. This scorecard serves as input to obtain the ranking of the stakeholder's preferences regarding the SATs across the specified years, as elaborated in the subsequent section (7.6).

Table 7.4: Final performance scorecard all criteria

<table>
<tr><th colspan="3"></th><th colspan="3">Performance scores</th></tr>
<tr><th>Main criteria</th><th>Sub-criteria</th><th>Year</th><th>N-octane</th><th>HEFA</th><th>LH$_2$</th></tr>
<tr><td rowspan="9">Environmental</td><td rowspan="3">GHG</td><td>2024</td><td>3</td><td>4</td><td>4</td></tr>
<tr><td>2030</td><td>5</td><td>5</td><td>6</td></tr>
<tr><td>2050</td><td>10</td><td>6</td><td>10</td></tr>
<tr><td rowspan="3">WC</td><td>2024</td><td rowspan="3">7</td><td rowspan="3">4</td><td rowspan="3">9</td></tr>
<tr><td>2030</td></tr>
<tr><td>2050</td></tr>
<tr><td rowspan="3">LUI</td><td>2024</td><td>8</td><td rowspan="3">10</td><td>9</td></tr>
<tr><td>2030</td><td>5</td><td>6</td></tr>
<tr><td>2050</td><td>2</td><td>3</td></tr>
<tr><td rowspan="9">Economic</td><td rowspan="3">MJFSP</td><td>2024</td><td>2</td><td>1</td><td>6</td></tr>
<tr><td>2030</td><td>5</td><td>4</td><td>7</td></tr>
<tr><td>2050</td><td>8</td><td>10</td><td>9</td></tr>
<tr><td rowspan="3">IC</td><td>2024</td><td>7</td><td>6</td><td>1</td></tr>
<tr><td>2030</td><td>7</td><td>6</td><td>4</td></tr>
<tr><td>2050</td><td>10</td><td>10</td><td>10</td></tr>
<tr><td rowspan="3">OC</td><td>2024</td><td>2</td><td>7</td><td>4</td></tr>
<tr><td>2030</td><td>3</td><td>8</td><td>5</td></tr>
<tr><td>2050</td><td>7</td><td>10</td><td>9</td></tr>
<tr><td rowspan="9">Technological</td><td rowspan="3">TRL</td><td>2024</td><td>6</td><td rowspan="3">10</td><td>8</td></tr>
<tr><td>2030</td><td>10</td><td>10</td></tr>
<tr><td>2050</td><td>10</td><td>10</td></tr>
<tr><td rowspan="3">Scalability</td><td>2024</td><td>4</td><td>7</td><td>1</td></tr>
<tr><td>2030</td><td>7</td><td>8</td><td>3</td></tr>
<tr><td>2050</td><td>10</td><td>10</td><td>7</td></tr>
<tr><td rowspan="3">Efficiency</td><td>2024</td><td rowspan="3">9</td><td rowspan="3">10</td><td rowspan="3">6</td></tr>
<tr><td>2030</td></tr>
<tr><td>2050</td></tr>
</table>

7.6 Stakeholder preferences regarding SATs

In the final step of this Bayesian BWM, the SATs are ranked on the criteria weights assigned by the stakeholders and the respective SAT scores established earlier in this chapter. The weighted sum method (WSM) is employed to compute the final scores of the SATs, facilitating the ranking of stakeholder preferences regarding the SATs. The formula for the WSM is expressed as:

$$V_i = \sum_{j=i}^{n} w_j p_{ij}$$

wherefore,

- w_j = the weight for criterion j
- p_{ij} = the score of alternative i with respect to criterion j
- V_i = the overall value of alternative i, determined by multiplying score $p_i j$ with the weight w_j of criterion j (Rezaei, 2015).

The remainder of this section discusses the final scores across all the stakeholder groups together, for the airline stakeholder group, for the expert stakeholder group, and for the producer/manufacturer stakeholder group for the years 2024, 2030, and 2050. The final SAT scores across the separate stakeholder groups are discussed to better understand each group's preferences and how they potentially differ from or align with the scores of all the stakeholder groups together.

7.6.1 Scores regarding all stakeholder groups together preferences

Utilizing the criteria weights derived from the interviews and the SAT performance scores on the sub-criteria sourced from scientific literature, the WSM method is performed (see Table 7.5). The analysis identifies HEFA as the highest-ranking SAT in Table 7.5, implying a preference among all stakeholders together towards HEFA for the year 2024. Following this, LH_2 emerges as the second most favored choice, succeeded by n-octane.

Table 7.5: Ranking and scores of the SATs in 2024

Main criteria	Sub-criteria	Global weights (w_j)	N-octane	HEFA	LH_2
Environmental	GHG	0.270	0.81	1.08	1.08
	WC	0.056	0.39	0.22	0.50
	LUI	0.119	0.95	1.19	1.07
Economic	MJFSP	0.100	0.20	0.10	0.60
	IC	0.101	0.71	0.60	0.10
	OC	0.126	0.25	0.88	0.50
Technological	TRL	0.088	0.53	0.88	0.70
	Scalability	0.071	0.28	0.50	0.07
	Efficiency	0.070	0.63	0.70	0.42
		Total	**4.75**	**6.15**	**5.05**
		Ranking	3	1	2

Table 7.6 shows the ranking of the SATs in 2030. The ranking remains consistent with that of (resp. HEFA > LH_2 > n-octane). However, the final scores for all SATs have increased, indicating an increased preference among stakeholders for the SATs compared to 2024, influenced by changes in SAT scores. Furthermore, it is noteworthy that there is a small difference in scores between n-octane and LH_2. This emphasizes the need for a sensitivity analysis to ascertain the robustness of the ranking results (Section 7.7).

Table 7.6: Ranking and scores of the SATs in 2030

Main criteria	Sub-criteria	Global weights (w_j)	N-octane	HEFA	LH_2
Environmental	GHG	0.270	1.35	1.35	1.62
	WC	0.056	0.39	0.22	0.50
	LUI	0.119	0.59	1.19	0.71
Economic	MJFSP	0.100	0.50	0.40	0.70
	IC	0.101	0.71	0.60	0.40
	OC	0.126	0.38	1.01	0.63
Technological	TRL	0.088	0.88	0.88	0.88
	Scalability	0.071	0.50	0.57	0.21
	Efficiency	0.070	0.63	0.70	0.42
		Total	**5.92**	**6.92**	**6.08**
		Ranking	3	1	2

Lastly, Table 7.7 presents the ranking of the SATs for the year 2050. Initially, the ranking appears consistent with that of the years 2024 and 2025. However, there is a significant difference in the extent to which HEFA is considered superior to the other SATs. Despite this, there is a relatively small difference in the total scores for all SATs, emphasizing again the necessity of conducting a sensitivity analysis (see Section 7.7) Moreover, it is pertinent to observe that HEFA exhibits deficiencies primarily in the sub-criteria related to GHG emissions, and to a lesser extent, in WC while having superiority across all remaining sub-criteria compared to n-octane and LH_2.

Table 7.7: Ranking and scores of the SATs in 2050

Main criteria	Sub-criteria	Global weights (w_j)	N-octane	HEFA	LH_2
Environmental	GHG	0.270	2.70	1.62	2.70
	WC	0.056	0.39	0.22	0.50
	LUI	0.119	0.24	1.19	0.36
Economic	MJFSP	0.100	0.80	1.00	0.90
	IC	0.101	1.01	1.01	1.01
	OC	0.126	0.88	1.26	1.13
Technological	TRL	0.088	0.88	0.88	0.88
	Scalability	0.071	0.71	0.71	0.50
	Efficiency	0.070	0.63	0.70	0.42
		Total	**8.23**	**8.58**	**8.39**
		Ranking	3	1	2

7.6.2 Scores regarding airline stakeholder group preferences

Table 7.8 presents the final scores of SATs by the derived weights from the airline stakeholder group in 2024. The airline stakeholder group prioritizes economic sub-criteria more than all stakeholders together (Section 7.6.1). Furthermore, the largest change in weight is regarding the sub-criterion of GHG emissions, from 0.270 for all the stakeholder groups together to 0.149 for the airline stakeholder groups. The higher importance of the economic subcriteria, in combination with the lower importance of the environmental subcriteria, causes a switch in ranking from HEFA > LH_2 > n-octane to HEFA > n-octane > LH_2.

Table 7.8: Ranking and scores of the SATs in 2024: airlines

Main criteria	Sub-criteria	Global weights (w_j)	N-octane	HEFA	LH_2
Environmental	GHG	0.149	0.45	0.59	0.59
	WC	0.035	0.25	0.14	0.32
	LUI	0.078	0.63	0.78	0.70
Economic	MJFSP	0.174	0.35	0.17	1.05
	IC	0.206	1.44	1.24	0.21
	OC	0.185	0.37	1.29	0.74
Technological	TRL	0.053	0.32	0.53	0.42
	Scalability	0.064	0.26	0.45	0.06
	Efficiency	0.056	0.50	0.56	0.34
		Total	**4.56**	**5.76**	**4.43**
		Ranking	2	1	3

In Table 7.9, the final scores of the SATs in 2030 are presented for the airline stakeholder group. The ranking remains consistent with that of 2024 for this stakeholder group: HEFA > n-octane > LH_2, thus deviating from the ranking of all the stakeholders together. Furthermore, the total scores of n-octane and LH_2 have exhibited greater increases compared to the total score of HEFA.

Table 7.9: Ranking and scores of the SATs in 2030: airlines

Main criteria	Sub-criteria	Global weights (w_j)	N-octane	HEFA	LH_2
Environmental	GHG	0.149	0.74	0.74	0.89
	WC	0.035	0.25	0.14	0.32
	LUI	0.078	0.39	0.78	0.47
Economic	MJFSP	0.174	0.87	0.70	1.22
	IC	0.206	1.44	1.24	0.82
	OC	0.185	0.55	1.48	0.92
Technological	TRL	0.053	0.53	0.53	0.53
	Scalability	0.064	0.45	0.51	0.19
	Efficiency	0.056	0.50	0.56	0.34
		Total	**5.73**	**6.68**	**5.70**
		Ranking	2	1	3

In 2050, HEFA maintains the highest score for the airline stakeholder group (Table 7.10). HEFA scores the highest or equal for all the sub-criteria except for the GHG emissions and WC. Unlike in 2024 and 2030 the ranking sequence is the same as the sequence for all the stakeholder groups together HEFA > LH_2 > n-octane. Furthermore, it is remarkable that LH_2 approaches the score of HEFA closely. This is attributed to a substantial increase in scores of GHG emissions and OC. Additionally, the IC of LH_2 equals that of HEFA in 2050, whereas in 2030, HEFA was scoring significantly better.

Table 7.10: Ranking and scores of the SATs in 2050: airlines

Main criteria	Sub-criteria	Global weights (w_j)	N-octane	HEFA	LH_2
Environmental	GHG	0.149	1.49	0.89	1.49
	WC	0.035	0.25	0.14	0.32
	LUI	0.078	0.16	0.78	0.23
Economic	MJFSP	0.174	1.40	1.74	1.57
	IC	0.206	2.06	2.06	2.06
	OC	0.185	1.29	1.85	1.66
Technological	TRL	0.053	0.53	0.53	0.53
	Scalability	0.064	0.64	0.64	0.45
	Efficiency	0.056	0.50	0.56	0.34
		Total	**8.31**	**9.20**	**8.64**
		Ranking	3	1	2

7.6.3 Scores regarding expert/advisor stakeholder group preferences

For the expert/advisors stakeholder groups, the SAT performance scores and rankings for the years 2024, 2030, and 2050 are presented in Tables 7.11, 7.12, 7.13, respectively. The expert/advisor stakeholder group has a significantly higher weight for the environmental criteria compared to the airline stakeholder group and even higher than for all the groups together. On the other hand, the scores for the economic sub-criteria are relatively lower compared to the airline stakeholder group and all stakeholders together. Furthermore, a notable observation is the relatively high weight of the sub-criteria TRL compared to all the other stakeholder groups, separate and together. Despite these differences in weight, the rankings of the SATs remain consistent with those of all stakeholders together in 2024: HEFA > LH_2 > n-octane.

Table 7.11: Ranking and scores of the SATs in 2024: experts/advisors

Main criteria	Sub-criteria	Global weights (w_j)	N-octane	HEFA	LH_2
Environmental	GHG	0.322	0.97	1.29	1.29
	WC	0.080	0.56	0.32	0.72
	LUI	0.117	0.93	1.17	1.05
Economic	MJFSP	0.071	0.14	0.07	0.43
	IC	0.031	0.21	0.18	0.03
	OC	0.035	0.07	0.24	0.14
Technological	TRL	0.176	1.06	1.76	1.41
	Scalability	0.078	0.31	0.55	0.08
	Efficiency	0.089	0.81	0.89	0.54
		Total	**5.06**	**6.27**	**5.48**
		Ranking	3	1	2

In the table for the experts/advisors stakeholder group in 2030 (Table 7.12), the ranking sequence of the SATs remains the same: HEFA > LH_2 > n-octane. However, it is notable that in comparison with 2024, both n-octane and LH_2 exhibit closer to the score of HEFA. This convergence is attributed to a notable increase in the scores for TRL and GHG for n-octane and LH_2. However, this trend is slightly oppressed by a reduction in the score for LUI for n-octane and LH_2.

Table 7.12: Ranking and scores of the SATs in 2030: experts/advisors

Main criteria	Sub-criteria	Global weights (w_j)	N-octane	HEFA	LH_2
Environmental	GHG	0.322	1.61	1.61	1.93
	WC	0.080	0.56	0.32	0.72
	LUI	0.117	0.58	1.17	0.70
Economic	MJFSP	0.071	0.36	0.28	0.50
	IC	0.031	0.21	0.18	0.12
	OC	0.035	0.10	0.28	0.17
Technological	TRL	0.176	1.76	1.76	1.76
	Scalability	0.078	0.55	0.63	0.24
	Efficiency	0.089	0.81	0.89	0.54
		Total	**6.55**	**7.13**	**6.69**
		Ranking	3	1	2

In 2030, the scores of n-octane and LH_2 had already approached those of HEFA. By 2050, both the scores of n-octane and LH_2 surpassed the total score for HEFA. Consequently, the ranking shifted: n-octane > LH_2 > HEFA. As depicted in Table 7.13, there is minimal difference among the scores, indicating comparable performances among the SATs. This represents change compared to the scores observed in 2030 for the experts/advisors stakeholder group, where the scores exhibited more variation. This is mainly caused by the heavily increased scores of the sub-criteria of GHG emissions for n-octane and LH_2.

Table 7.13: Ranking and scores of the SATs in 2050: experts/advisors

Main criteria	Sub-criteria	Global weights (w_j)	N-octane	HEFA	LH_2
Environmental	GHG	0.322	3.22	1.93	3.22
	WC	0.080	0.56	0.32	0.72
	LUI	0.117	0.23	1.17	0.35
Economic	MJFSP	0.071	0.57	0.71	0.64
	IC	0.031	0.31	0.31	0.31
	OC	0.035	0.24	0.35	0.31
Technological	TRL	0.176	1.76	1.76	1.76
	Scalability	0.078	0.78	0.78	0.55
	Efficiency	0.089	0.81	0.89	0.54
		Total	**8.49**	**8.23**	**8.41**
		Ranking	1	3	2

7.6.4 Scores regarding producer/manufacturer stakeholder group preferences

In Tables 7.14, 7.15, and 7.16, the scores of the SATs are presented regarding the weights of the producer/ manufacturer stakeholder group. Compared to the stakeholder groups of the airlines and the experts/advisors, the weights of the producer/manufacturer group closely resemble those allocated to the environmental sub-criteria of all the stakeholders together (Section 7.6.1). Conversely, The economic sub-criteria receive substantially higher weights compared to all stakeholder groups together, and the technological sub-criteria lower.

The ranking of the SATs regarding the producer/manufacturer stakeholder group is the same as for all the stakeholders together: HEFA > n-octane > LH_2, as can be seen in Table 7.14.

Table 7.14: Ranking and scores of the SATs in 2024: producers/manufacturers

Main criteria	**Sub-criteria**	**Global weights** (w_j)	**N-octane**	**HEFA**	**LH_2**
Environmental	GHG	0.297	0.89	1.19	1.19
	WC	0.055	0.39	0.22	0.50
	LUI	0.144	1.15	1.44	1.30
Economic	MJFSP	0.127	0.25	0.13	0.76
	IC	0.134	0.94	0.80	0.13
	OC	0.125	0.25	0.87	0.50
Technological	TRL	0.040	0.24	0.40	0.32
	Scalability	0.041	0.17	0.29	0.04
	Efficiency	0.038	0.34	0.38	0.23
		Total	**4.61**	**5.61**	**4.85**
		Ranking	3	1	2

In 2030, the ranking of the SATs remains consistent for the stakeholder group of the producers/manufacturers compared to all the stakeholder groups together. Additionally, it can be noted that LH_2 is slightly more approaching the score of HEFA compared to 2024.

Table 7.15: Ranking and scores of the SATs in 2030: producers/manufacturers

Main criteria	**Sub-criteria**	**Global weights** (w_j)	**N-octane**	**HEFA**	**LH_2**
Environmental	GHG	0.297	1.48	1.48	1.78
	WC	0.055	0.39	0.22	0.50
	LUI	0.144	0.72	1.44	0.87
Economic	MJFSP	0.127	0.63	0.51	0.89
	IC	0.134	0.94	0.80	0.54
	OC	0.125	0.37	1.00	0.62
Technological	TRL	0.040	0.40	0.40	0.40
	Scalability	0.041	0.29	0.33	0.12
	Efficiency	0.038	0.34	0.38	0.23
		Total	**5.56**	**6.56**	**5.94**
		Ranking	3	1	2

In 2050, the SAT rankings remain the same, with HEFA retaining its first-ranked position and LH_2 following closely as the second-ranked option. However, the difference in scores between HEFA and LH_2 is notably small, approximately 0.07. This small difference can be attributed to a significant increase in GHG emissions and IC scores for LH_2 compared to 2030. Furthermore, it is remarkable that the stakeholder group of producers/manufacturers have for all the years the same ranking of SATs (resp. HEFA $>$ LH_2 $>$ n-octane) aligning with all the stakeholders together, despite the fact that the difference between HEFA and LH_2 is extremely small in 2050.

Table 7.16: Ranking and scores of the SATs in 2050: producers/manufacturers

Main criteria	**Sub-criteria**	**Global weights** (w_j)	**N-octane**	**HEFA**	**LH_2**
Environmental	GHG	0.297	2.97	1.78	2.97
	WC	0.055	0.39	0.22	0.50
	LUI	0.144	0.29	1.44	0.43
Economic	MJFSP	0.127	1.01	1.27	1.14
	IC	0.134	1.34	1.34	1.34
	OC	0.125	0.87	1.25	1.12
Technological	TRL	0.040	0.40	0.40	0.40
	Scalability	0.041	0.41	0.41	0.29
	Efficiency	0.038	0.34	0.38	0.23
		Total	**8.02**	**8.48**	**8.41**
		Ranking	3	1	2

7.6.5 Final scores and rankings on SATs regarding stakeholder preferences

Table 7.17 presents an overview of the final scores on the SATs regarding stakeholder preferences. The final scores are presented regarding the preferences of all stakeholders together and for each individual stakeholder group, as illustrated in Table 7.17.

Table 7.17: Final scores and rankings on SATs regarding stakeholder preferences

Year	Stakeholder group	N-octane	HEFA	LH_2	Ranking
2024	All together	4.75	**6.15**	5.05	HEFA > LH_2 > N-octane
	Airline	4.56	**5.76**	4.43	HEFA > N-octane > LH_2
	Expert/advisor	5.06	**6.48**	5.68	HEFA > LH_2 > N-octane
	Producer/manufacturer	4.61	**5.72**	4.96	HEFA > LH_2 > N-octane
2030	All together	5.92	**6.92**	6.08	HEFA > LH_2 > N-octane
	Airline	5.73	**6.68**	5.70	HEFA > N-octane > LH_2
	Expert/advisor	6.55	**7.13**	6.69	HEFA > LH_2 > N-octane
	Producer/manufacturer	5.56	**6.56**	5.94	HEFA > LH_2 > N-octane
2050	All together	8.23	**8.58**	8.39	HEFA > LH_2 > N-octane
	Airline	8.31	**9.20**	8.64	HEFA > LH_2 > N-octane
	Expert/advisor	**8.49**	8.23	8.41	N-octane > LH_2 > HEFA
	Producer/manufacturer	8.02	**8.48**	8.41	HEFA > LH_2 > N-octane

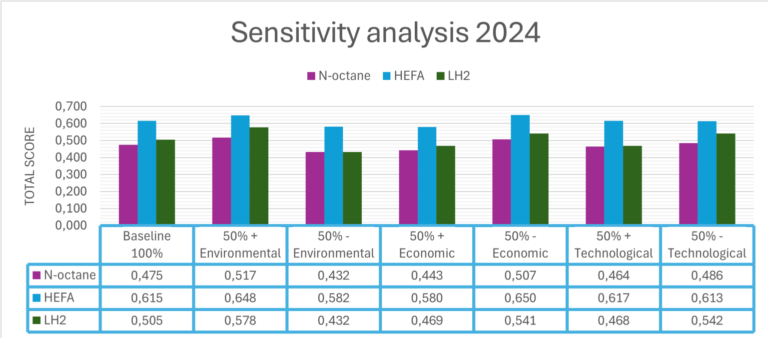
Table 7.17 emphasized the superiority of HEFA across all stakeholder groups together and within each individual stakeholder group, except for the expert/advisor stakeholder group in the year 2050. Notably, in 2050, HEFA is ranked third regarding the expert/advisor stakeholder group, scoring the lowest among the SATs (resp. N-octane > LH_2 > HEFA). Furthermore, deviations compared to all stakeholders together are observed within the airline stakeholder group for 2024 and 2030. In these years, the preferences of the airline stakeholder group follow HEFA > N-octane > LH_2 instead of HEFA > LH_2 > N-octane for all stakeholder groups together. Moreover, Table 7.17 reveals a significant increase in all the scores from 2024 to 2050. Lastly, in the years 2024 and 2030, HEFA scores significantly higher than the other SATs for all the stakeholder groups together and also for each individual stakeholder group. However, by 2050, the scores of the SATs regarding the preferences are approaching each other, except within the airline stakeholder group where HEFA remains distinctly the highest-scoring SAT.

7.7 Sensitivity analysis

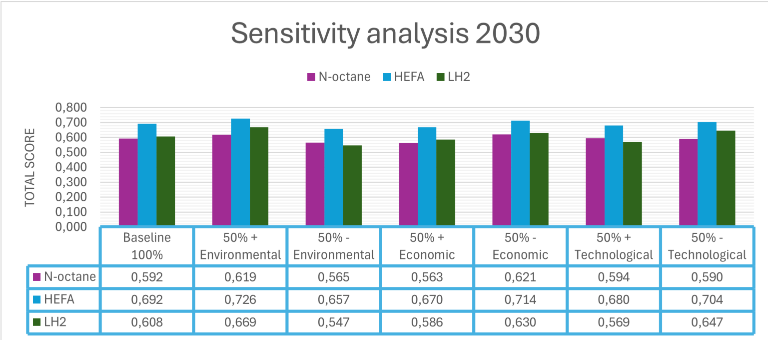
A sensitivity analysis is conducted to investigate how changes in stakeholder preferences might affect rankings. The analysis involves adjusting the weights assigned to the main criteria by $\pm$50%. This sensitivity analysis explores uncertainties in the results derived from the performed Bayesian Best Worst Method. The sensitivity analysis entails 6 different scenarios for each year, resulting in 18 scenarios for sensitivity analysis (Table 7.18). The $\pm$50% adjustment is selected to determine the influence of changes in the different main criteria regarding the SAT rankings. Figure 7.1, located below Table 7.18, presents the final scores of the SATs across the scenario and year.

Table 7.18: Ranking of SATs in different scenarios after the sensitivity analysis

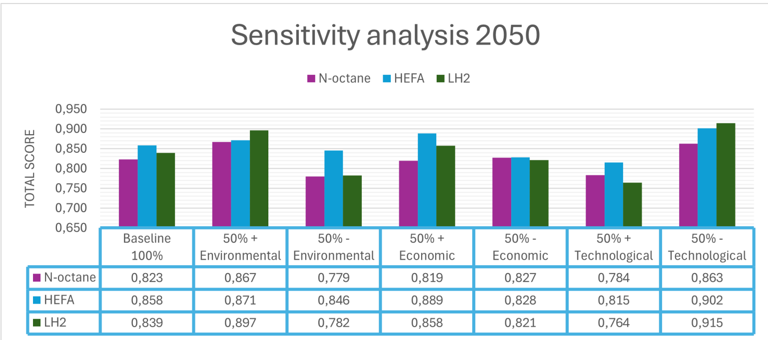
Scenario	**Variation in weights**	**SAT ranking**
2024	Reference scenario	HEFA > LH_2 > n-octane
1	+ 50% Environmental	HEFA > LH_2 > n-octane
2	- 50% Environmental	HEFA > LH_2 > n-octane
3	+ 50% Economic	HEFA > LH_2 > n-octane
4	- 50% Economic	HEFA > LH_2 > n-octane
5	+ 50% Technological	HEFA > LH_2 > n-octane
6	- 50% Technological	HEFA > LH_2 > n-octane
2030	Reference scenario	HEFA > LH_2 > n-octane
1	+ 50% Environmental	HEFA > LH_2 > n-octane
2	- 50% Economic	HEFA > n-octane > LH_2
3	+ 50% Economic	HEFA > LH_2 > n-octane
4	- 50% Economic	HEFA > LH_2 > n-octane
5	+ 50% Technological	HEFA > n-octane > LH_2
6	- 50% Technological	HEFA > LH_2 > n-octane
2050	Reference scenario	HEFA > LH_2 > n-octane
1	+ 50% Environmental	LH_2 > HEFA > n-octane
2	- 50% Environmental	HEFA > LH_2 > n-octane
3	+ 50% Economic	HEFA > LH_2 > n-octane
4	- 50% Economic	HEFA > n-octane > LH_2
5	+ 50% Technological	HEFA > n-octane > LH_2
6	- 50% Technological	LH_2 > HEFA > n-octane



(a) Sensitivity analysis 2024



(b) Sensitivity analysis 2030



(c) Sensitivity analysis 2050

Figure 7.1: Sensitivity analysis final SAT scores

In the reference scenario in 2024, HEFA emerges as the most preferred SAT among all stakeholders together, with a score of 6.15. This primarily arises from overall high scores, scoring the highest on 6 of the 9 sub-criteria. However, HEFA lags behind in the MJFSP, the IC, and the WC compared to other SATs in the reference scenario in 2024. Regarding the overall highest scores of HEFA on almost all the sub-criteria compared to the other SATS (6 out of 9), it can be seen that the influence of varying the weights of the main criteria barely influences the scores. Thus, while the different scenarios influence the magnitude of SAT scores, they do not change the ranking sequence, as shown in Table 7.18.

Furthermore, HEFA maintains the highest-ranked SAT in the reference scenario for 2030. As indicated in Section 7.6, the total scores of n-octane and LH_2 are closer to each other in 2030 (Figure 7.1). The impact of this close scoring is evident in scenarios 2 and 5 for 2030. In these scenarios, the established ranking order is disrupted, with HEFA > n-octane > LH_2 instead of the expected HEFA > LH_2 > n-octane. Thus, it could be stated that when the total scores of n-octane and LH_2 are close to each other, a decrease in environmental weight (scenario 2) or an increase in technological weight (scenario 5) influences the ranking, resulting in n-octane scoring higher than LH_2, contrary to the usual ranking.

Moreover, in 2050, HEFA retains its superiority over the other SATs in the reference scenario. As noted in Section 7.6, the scores for n-octane, HEFA, and LH_2 are extremely close to each other (8.23, 8.58, and 8.39, respectively). This is also noticeable in the changes in ranking results from the scenarios in 2050. Table 7.18 demonstrates that the ranking changes for 4 out of the 6 scenarios. For scenarios 1 and 6, the LH_2 ranks the highest, followed by HEFA and then n-octane. In scenarios 4 and 5, the ranking sequence is HEFA > n-octane > LH_2. However, if one looks closer at the values in Figure 7.1c, it becomes apparent that the ranking sequences are sensitive to changes in the weights of the main criteria. For instance, in scenario 4, the SATs are ranked with values that differ from 'best' to 'worst' at 0.07. Therefore, it could be considered that the total scores in 2050 are so closely aligned that the ranking results are significantly influenced by changes in the weights of the main criteria, indicating a sensitivity to stakeholder preferences. Furthermore, considering the higher the total scores, the impact of a change is larger, considering the scenarios with a percentage change.

In conclusion, the sensitivity analysis reveals that the ranking results are relatively insensitive to changes in the weights of the main criteria in 2024. However, in 2030, the ranking results in the reference scenario have slightly more sensitivity to an increase in technological weight and a decrease in environmental weight. By 2050, the results are remarkably sensitive due to the close total scores of the SATs and the higher overall scores, making the impact of a change in percentage more significant

8 Discussion and conclusion

The aim of this study is to gain a comprehensive understanding of the stakeholders preferences towards sustainable aviation technologies (SATs) for transitioning the aviation industry to net zero CO_2 emissions by 2050. The study specifically focuses on three SATs identified in the technology groups of hydrogen, biofuel, and electrofuel, as detailed in Chapter 4. The primary research goal is to gain insights into the preferred SATs by the stakeholders based on a comprehensive set of main and sub-criteria established for the evaluation of SATs. These criteria are considered relevant for the evaluation of SATs through a literature review (Chapter 5). Subsequently, these criteria were weighted by implementing the BWM during interviews across three different stakeholder groups, as discussed in Chapter 6. Furthermore, performance scorecards obtained based on scientific literature and corresponding obtained weights were utilized in the Weighted Sum Method (WSM) to ascertain the ranking preferences of the stakeholders concerning the three SATs (Chapter 7). In relation to the aim and research goal of this research, the main research question was formulated:

"What are stakeholder preferences towards sustainable aviation technologies (SATs) for transition to net zero CO_2 aviation in 2050?"

To address this main research question, four sub-questions have been developed. The subsequent sections of this chapter will delve into detailed discussions, followed by the conclusions, limitations, and recommendations for further research stemming from this research.

8.1 Discussion

This section delves into detailed discussions of the conducted research and its corresponding findings: representativeness of research, evaluating 2050 SAT scores, land use impact, and addressing subjectivity of stakeholders. It ends with a reflection on societal and academic relevance.

Representativeness of research
The representativeness of this study is debatable. The research is based on 10 interviews to determine the preferences regarding SATs of the entire aviation industry. Although the selection of the stakeholders aimed to obtain a representative group, the limited number of interviewed stakeholders raises concerns about the representativeness. Therefore, the results must be interpreted carefully, as it is uncertain whether they accurately reflect the broader industry preferences.

For instance, from this research, it could be considered with a certain validity that greenhouse gas emissions are seen as the most important sub-criteria within the main criteria of environmental performance, as all the stakeholders pointed this sub-criteria out as the most important environmental sub-criterion. However, among the three stakeholders interviewed from the airline group, one had a significantly different perspective from the other two. This one stakeholder prioritized environmental performance as the most important criterion, while the other two prioritized economic performance. Given that only three stakeholders were interviewed and they assign already significantly different importance to the main criteria, it is questionable whether these findings are representative of the entire airline group.

Thus, the results provide an indication of stakeholder preferences regarding SATs rather than certain outcomes that are representative of the entire aviation industry. Therefore, while the method is considered appropriate, additional interviews are necessary to ensure the results' representativeness for the entire aviation industry, as detailed in Sections 8.3 and 8.4.

Evaluating 2050 SAT scores
The highest ranking of HEFA in 2050 is debatable, given the close scores of n-octane and LH_2. Therefore, considering the assumptions made regarding the SATs performance scores, it is questionable if it could be said with certainty that HEFA is still the highest-ranked SAT in 2050. Except for this, changes in criteria weights in the future could also affect the rankings, as emphasized in the sensitivity analysis (Section 7.7). These uncertainties for the future regarding the assumptions made and potential changing stakeholder perspectives on criteria are further mentioned in Section 8.3.

Land use impact
The land use impact of solar PV and wind turbines oppresses the high scores on greenhouse gas emissions of

n-octane and LH_2 in 2030 and especially 2050. Therefore, HEFA remains the highest-ranked SAT for both 2030 and 2050. This raises a debate regarding the goal of net-zero carbon emissions. While HEFA ranks highest based on stakeholder preferences, policymakers aim for the goal of net-zero emissions by 2050. Therefore, the negative land use impact of renewable electricity from solar PV and wind turbines suppresses the potential preference for the SATs with the potential for the highest carbon emissions reductions, n-octane and LH_2. This raises questions about the use of solar PV and wind turbines as renewable sources as they indirectly lead to the use of HEFA, which has significantly lower carbon emissions reductions compared to n-octane and LH_2 produced from renewable sources.

Addressing subjectivity of stakeholders
One of the criticisms of the BWM was the subjectivity of the decision-makers affecting the results, as emphasized by Annema et al. (2015) mentioned in Section 3.2.3. A stakeholder could obtain advantages from a certain chosen SAT being ranked the highest. This criticism seemed justified during the first interview conducted. After presenting and explaining the evaluated SATs, it became evident that the interviewee - a biofuel producer from the producer/manufacturer stakeholder group - was responding to the pairwise comparisons in a way that would ensure the biofuel HEFA ranked the highest. Therefore, this interview was excluded from the research.

Additionally, to prevent this bias in subsequent interviews, the evaluated SATs were presented only after the pairwise comparisons between the criteria were made. In this way, the stakeholders had to make pairwise comparisons without knowing which SATs were being evaluated. This approach helped to ensure that the comparisons were based on their perspectives regarding the criteria rather than pre-existing preferences for specific SATs. This is a valuable insight for using the BWM in future research to prevent the criticism mentioned by Annema et al. (2015).

Reflection on societal relevance
The introduction of this research emphasizes its societal relevance, as the research aids policymakers and the aviation industry in making informed decisions that reduce the environmental impact of aviation and promote societal well-being. There are two concrete main findings that can help policymakers and the aviation industry to make more informed decisions. Firstly, the insights into the stakeholder preferences for the three discussed SATs are provided, giving them an insight into how the stakeholders perceive the SATs. This holds promise in terms of potential policies, such as subsidization, to accelerate implementation. Secondly, the use of scorecards allows for comparisons between SAT performances relative to the others, independent of stakeholder preferences. For example, if policymakers want to minimize the land use impact, they can consult the scorecards to identify the most favorable SAT in this regard. Thus, reflecting on the findings of this research, it is evident that this study holds societal relevance.

However, the representativeness of this study can not be ascertained, as noted earlier in the discussion. Hence, it is not recommended to formulate definitive policies based on the findings of this research but to use the findings as indications. To ensure the validity of the research for policy-making purposes, it is recommended to expand the number of interviewed stakeholders, as detailed in Section 8.4.

Reflection on academic relevance
The academic or scientific relevance of this research would mainly be aimed at providing insight into the stakeholder preferences regarding SATs, addressing the knowledge gap, and the ensuing main research question. Reflecting on the conducted research and outcomes, it can be concluded that the research aims have been met and reduced the identified knowledge gap, thereby contributing to the scientific literature as discussed in Chapter 2.2. The utilized Bayesian Best-Worst Method, in combination with the Weighted Sum Method, provided the stakeholder preferences regarding the SATs. Additionally, the criteria weights obtained from the interviews and the performance scorecards of the selected SATs derived from the literature have provided insights into how these preferences were established. Lastly, this research holds scientific value in defining relevant criteria for the evaluation of SATs and their corresponding weights, laying the groundwork for future multi-criteria analysis assessments on SATs.

8.2 Conclusion

This research aimed to identify the preferences of aviation industry stakeholders regarding SATs for transition to net zero CO_2 emissions in 2050 regarding the aspirational long-term goals of the International Civil Aviation Organization (ICAO) (ICAO, 2023). Therefore, the research question to be answered is:

"What are stakeholders preferences towards sustainable aviation technologies (SATs) for transition to net zero CO_2 aviation in 2050?"

The primary conclusion to this research question is: **HEFA consistently emerges as the most preferred SAT** across the years for all the stakeholders together and for the separate stakeholder groups, with the exception of the expert/advisor group in 2050 where n-octane ranks highest, as illustrated in Table 7.17.

Table 7.17: Final scores and rankings on SATs regarding stakeholder preferences (from Chapter 7)

Year	Stakeholder group	N-octane	HEFA	LH_2	Ranking
2024	All together	4.75	**6.15**	5.05	HEFA > LH_2 > N-octane
	Airline	4.56	**5.76**	4.43	HEFA > N-octane > LH_2
	Expert/advisor	5.06	**6.48**	5.68	HEFA > LH_2 > N-octane
	Producer/manufacturer	4.61	**5.72**	4.96	HEFA > LH_2 > N-octane
2030	All together	5.92	**6.92**	6.08	HEFA > LH_2 > N-octane
	Airline	5.73	**6.68**	5.70	HEFA > N-octane > LH_2
	Expert/advisor	6.55	**7.13**	6.69	HEFA > LH_2 > N-octane
	Producer/manufacturer	5.56	**6.56**	5.94	HEFA > LH_2 > N-octane
2050	All together	8.23	**8.58**	8.39	HEFA > LH_2 > N-octane
	Airline	8.31	**9.20**	8.64	HEFA > LH_2 > N-octane
	Expert/advisor	**8.49**	8.23	8.41	N-octane > LH_2 > HEFA
	Producer/manufacturer	8.02	**8.48**	8.41	HEFA > LH_2 > N-octane

To answer the main research question, the following steps were taken: through an analysis of scientific literature, the specific SATs with promising potential for adoption are identified within the technology groups of hydrogen, biofuel, and electrofuel. Furthermore, through a comprehensive literature review, criteria deemed relevant for the evaluation of SATs were identified. Subsequently, the weights of these criteria were determined through interviews and the application of the Bayesian BWM. Lastly, performance scorecards of the SATs on the criteria were determined, succeeded by the application of the Weighted Sum Method to obtain the final scores and rankings of the SATs regarding the stakeholder preferences. Additional key findings identified in the process of addressing the main research question are outlined as follows:

- **The evaluated SATs are electrofuel n-octane powered aircraft, LH_2 with PEM fuel cells powered aircraft, and HEFA biofuel from used cooking oils powered aircraft.** These SATs are considered most promising within the technology groups of electrofuel-powered, hydrogen-powered, electric-powered, and biofuel-powered aircraft. Concerning the research scope on medium- and long-haul commercial passenger aircraft, the electric-powered technology group has been excluded from further research based on literature findings and stakeholder feedback.
- **The evaluation of SATs is based on three main criteria, each with three sub-criteria.** The main criteria are "Environmental performance," "Economic performance," and "Technological performance."
  - The environmental criterion includes the sub-criteria of "Greenhouse gas emissions," "Water consumption," and "Land use impact."
  - The economic criterion entails the sub-criteria of "Minimum jet fuel selling price," "Investment costs," and "Operational costs."
  - The technological criterion is defined by the sub-criteria of "Technological readiness level," "Scalability," and "Efficiency."
- Considering the **obtained weights** on the main criteria and respective sub-criteria, **all stakeholders together perceive "Environmental performance" as the paramount main criterion** for evaluating SATs, with a weight of 0.445 out of 1. "Environmental performance" is followed by "Economic performance"

weighting 0.327, and "Technological performance" weighting 0.228. Among all sub-criteria, **"Greenhouse gas emissions" is the most significant sub-criterion**, weighting 0.270. The second-ranked sub-criterion is "Operational costs" (0.126), followed by "Land use impact," (0.119). Hence, while "Greenhouse gas emissions" hold extraordinary weight, "Operational costs" and "Land use impact" also merit extra consideration in the evaluation of SATs.

- While **n-octane and LH_2** have a high potential for reducing greenhouse gas emissions, their **scores are suppressed by negative land use impacts.** From 2024 to 2030 and 2050, all final scores increase and the scores of n-octane and LH_2 trend towards HEFA final score. This is due to their increased "Greenhouse gas emissions" scores, the top-ranked criterion. However, their "Land use impact" scores, the third-ranked criterion, decrease over time due to renewable electricity from solar PV and wind turbines. Consequently, **HEFA maintains the highest SAT scores** due to its significant greenhouse gas reductions and lack of land use requirements, as it utilizes waste residuals.
- HEFA remains the preferred SAT across almost all years for the **separate stakeholder groups** (Table 7.17), while they have **varying perspectives regarding the criteria.** The airline stakeholder group is the only stakeholder group that assigned the highest weight to "Economic performance" instead of "Environmental performance". The expert/advisor stakeholder group assigns lower weights to "Economic performance" in favor of "Technological performance." The producers/manufacturers stakeholder group aligns with the ranking of the main criteria of all stakeholder groups together, with slight variations in weighting.

8.3 Limitations

The first limitation to address is the small sample size of stakeholder interviews (10) used to gather perspectives on the criteria. While the selection process aimed to represent the aviation industry, it is uncertain if this was achieved. Therefore, the weights derived from these stakeholder perspectives could be biased compared to the entire stakeholder field of the aviation industry if the interviewed stakeholders are not a representative group.

The second limitation that must be addressed concerns the actual technological feasibility of the SATs. The LH_2 and n-octane SATs are not currently used commercially for medium- and long-haul aircraft. Literature suggests these two SATs hold promise for near-future applicability, but their feasibility is not guaranteed. Additionally, it is assumed, according to scientific literature, that aircraft modified for HEFA can operate on 100% biofuel, yet this is not practiced on a commercial scale for medium- or long-haul passenger aircraft. In conclusion, despite the high scores on the SATs, it must be recognized that these scores do not necessarily reflect the technological feasibility of medium- and long-haul commercial passenger aircraft. Thus, the future has yet to deliver on the promise of technological feasibility. This uncertainty is a crucial limitation as if a technology is not feasible, all other criteria become irrelevant, as emphasized earlier in this research by Feitelson & Salomon (2004).

Thirdly, the SAT performance scorecards on the criteria rely heavily on assumptions due to the novelty of the SATs. These assumptions inherently limit the accuracy of the scores. While efforts are made to ensure these assumptions are well substantiated, it remains impossible to guarantee the scores with certainty. The years 2024 and 2030 are current and relatively near, which suggests that the assumptions for these years might be more accurate compared to the year 2050. Given that 2050 is far away, it is presumed that the degree of uncertainty is higher due to the more speculative assumptions involved. Therefore, the uncertainties from assumptions embedded in the scorecards make it difficult to accurately predict the preferred SAT in 2050, especially since the scores are expected to converge closely in 2050.

Furthemore, the forecast for 2030 and 2050 faces another limitation: the uncertainty of stakeholder preferences. These preferences are shaped by current stakeholder perspectives on the criteria, and it is uncertain if these perspectives will remain the same in 2030 and 2050. This uncertainty is underscored by the sensitivity analysis, which shows that variances in criteria weights can shift rankings of preferred SATs (Section 7.7).

Moreover, a few stakeholders highlighted the dependency and overlap among certain criteria. They mentioned the overlap between "Minimum jet fuel selling price" and the "Operational costs", noting that the fuel costs are inherently part of "Operational costs". Additionally, they suggested that "Scalability" might fall under "Technological readiness level", and that "Efficiency" could be dependent on "Technological readiness level" as well. Despite agreeing upon the relevance of the criteria set, some stakeholders struggled to compare them due to their interconnectedness.

Lastly, the research left out of scope the infrastructure for fuels, production plants for fuels, and manufacturer fabrics for aircraft. Therefore, it is assumed that these are not constraining factors. However, it is not ascertained that these components will not actually be constraining factors and if the characteristics regarding these components will influence the perspectives of the stakeholders towards SATs in a broader picture.

8.4 Recommendations for further research

Firstly, due to the limited conducted stakeholder interviews, as mentioned in the limitations (Section 8.3), further research is recommended to conduct a larger number of interviews to ensure a representative stakeholder group, reducing the chance of a potential bias in the weights.

Secondly, while all the stakeholders unanimously agreed on the criteria identified in the literature review as relevant for the evaluation of SATs, almost all stakeholders from expert/advisor and producer/manufacturer groups argued for the inclusion of contrails. Contrails, or condensation trials, are long, thin clouds formed by aircraft engine exhaust when water vapor condenses and freezes at high altitudes. Only one article in the literature review, by Markatos & Pantelakis (2023), addressed contrails. Therefore, this criterion was excluded because it was perceived as less important compared to the included criteria.
However, these stakeholders from expert/advisor and producer/manufacturer groups emphasized the importance of the inclusion of contrails due to their impact on the greenhouse effect, particularly emphasizing the potential increase in contrails from LH_2 usage resulting in higher vapor production. On the other hand, two of the three stakeholders from the airline stakeholder group argued that the inclusion of contrails is unnecessary, given the lack of scientific evidence regarding their environmental impact. Given this uncertainty around the importance and impact of contrails, it is evident that further research is warranted. Hence, further research is recommended to ascertain the impact of contrails and, if included in further research, their potential influence on SAT preferences.

Thirdly, based on the corresponding identified limitation, further research is recommended on the infrastructure, fuel production plants, and fabrics for aircraft/modifications concerning the adoption of SATs. Where these aspects were not included within the scope of this study, researching them would be complementary to the potential of SATs in a broader picture. The infrastructure, fuel production process/plant and the manufacture of fabrics are crucial for the feasibility of the wide adoption of corresponding SATs, as highlighted by the stakeholders during the interviews. Therefore, further research is recommended in these areas to explore the potential of the SATs in a broader picture.

Furthermore, further research is recommended to ensure that the fuel of an SAT has the feedstock capacity to fulfill the needs of the aviation industry with regard to the demand of other sectors. For example, are there enough used cooking oils to produce enough HEFA biofuel for the whole aviation industry? These types of questions are recommended for further research to reveal the potential of the fuels for widescale adoption of the SATs.

Additionally, this study delves into individual SATs rather than exploring a combination of SATs aimed at achieving net-zero CO_2 emissions. Stakeholders emphasized the potential viability of utilizing complementary SATs instead of focusing on one individual SAT in the future. For instance, biofuel-powered aircraft could be employed for long-haul aircraft operations and hydrogen for medium-haul aircraft operations. Hence, further research is recommended to investigate the potential of complementary use of SATs for different types of aircraft operations.

Lastly, this research does not include policy measures regarding the aviation industry. Therefore recommendations are made to explore the impact of policy measures on the preferences regarding SATs. For example, the SAT HEFA exhibits high greenhouse gas emissions compared to LH_2 and n-octane; what impact would the implementation of carbon taxes have on the ranking and scores of SATS? Would this change the ranking, or would it have no effect? Therefore, further research is recommended regarding the influence of policy measures on the preferences for SATs.

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A Technological Readiness Level

Table A.1 presents the TRL levels used by the European Union derived from European Commission (2014).

Table A.1: Technological Readiness Levels

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

B Likert scale

Table B.1: Likert scale used during BWM

Rating	Definition
1	Equally important
2	Slightly more important
3	Moderately more important
4	Significantly more important
5	Strongly more important
6	Between strongly and very strongly more important
7	Very strongly more important
8	Extremely more important
9	Absolutely more important

C Longlists criteria per category

In this Appendix, all the identified criteria in the literature review of sub-question 2 are presented in the Tables C.1, C.2, C.3, and C.4. The criteria are divided into four tables corresponding to their category.

Table C.1: Longlist Economical

Category	Criteria	Description	Study
Economical	DOC/operating cost	Represents the direct costs related to flight operation including costs such as total financial cost, total crew cost, total charges and fees, airframe maintenance cost, engine maintenance cost, and fuel operating cost.	Demircan & Kaplan (2023), Markatos & Pantelakis (2023), Kiracı & Akan (2020), Yavuz et al. (2015)
	Aircraft purchase/ investment costs	Signifies the initial investment required to acquire the aircraft.	Markatos & Pantelakis (2023), Demircan & Kaplan (2023), Kiracı & Akan (2020), Kiracı & Bakır (2018), Dožić et al. (2018), Yavuz et al. (2015)
	Delivery time	The time that aerospace manufacturing companies can deliver the aircraft.	Demircan & Kaplan (2023)
	Maintenance cost	The maintenance costs of the aircraft.	Demircan & Kaplan (2023), Kiracı & Akan (2020), Dožić et al. (2018)
	Salvage cost	The salvage costs for aircraft if not in operation.	Kiracı & Akan (2020)
	c/ASM	Cost Per Available Seat Mile.	Dožić et al. (2018)
	Feedstock alternative use	Explores the potential alternative uses of feedstock aside from sustainable aviation fuel production.	Ahmad et al. (2021), Ahmad et al. (2019)
	Feedstock profitability	Feedstock profitability: Evaluates the financial benefits associated with producing a specific feedstock.	Ahmad et al. (2021), Ahmad et al. (2019)
	MJFSP	Represents the expected minimum selling price of sustainable aviation fuels, a significant factor impacting the overall economic competitiveness of the aircraft.	Ahmad et al. (2021), Chen & Ren (2018), Ahmad et al. (2019), Markatos & Pantelakis (2023)
	Operations & maintenance cost	Relates to the operational and maintenance expenses of the production facility.	Ahmad et al. (2021), Ahmad et al. (2019), Yang et al. (2023)
	Feedstock cost	Represents the expenses incurred in procuring the primary feedstock material.	Ahmad et al. (2021), Ahmad et al. (2019)
	Capital cost	The costs for facilities and factories building to produce aviation fuels/hydrogen.	Ahmad et al. (2021), Chen & Ren (2018), Ahmad et al. (2019), Acar et al. (2018)
	Industrial relationship	The relationship of each alternative to other industrial production is taken as the criterion.	Tzeng et al. (2005)
	Employment cost	Refers to the costs of production and implementation of alternative vehicles.	Tzeng et al. (2005)
	Market penetration	Commonness of vehicle technology.	Yavuz et al. (2015)
	Competitive advantage	Plays a crucial role in assessing the strategic positioning, market.	Ahmad et al. (2019)
	Cost	Represents the economic feasibility of implementing and maintaining the fuel cell system, including initial investment, operational costs, and maintenance expenses.	Ayar & Karakoc (2023)
	Investment costs	Refers to the capital expenditure required to establish a commercial-level production facility.	Xu et al. (2019), Yang et al. (2023)
	Running costs	Operational and maintenance costs associated with the production of alternative jet fuels.	Xu et al. (2019), Acar et al. (2018)
	Revenue	Potential income generated from the sale of alternative jet fuel products.	Xu et al. (2019)
	Market maturity	Indicates the readiness of the market in terms of availability, competitiveness, and compatibility with the economic system.	Yang et al. (2023)

Table C.2: Longlist Environmental

Category	Criteria	Description	Study
Environmental	GHG emissions	Measures the net reduction in greenhouse gas emissions compared to traditional jet fuel and aircraft.	Markatos & Pantelakis (2023), Demircan & Kaplan (2023), Kiracı & Akan (2020), Kiracı & Bakır (2018), Chen & Ren (2018), Tzeng et al. (2005), Yavuz et al. (2015), Ayar & Karakoc (2023), Xu et al. (2019), Yang et al. (2023), Acar et al. (2018), Ahmad et al. (2021), Ahmad et al. (2019)
	NOx emissions	Quantifies the nitrogen oxide emissions released by the aircraft, contributing to air pollution.	Markatos & Pantelakis (2023)
	Contrails	Represents the formation of condensation trailsbehind the aircraft, affecting atmospheric conditions.	Markatos & Pantelakis (2023)
	Noise	Reflects the level of noise generated by the aircraft during operation.	Demircan & Kaplan (2023), Kiracı & Akan (2020), Tzeng et al. (2005), Ayar & Karakoc (2023)
	Feedstock sustainability	Focuses on the sustainability of the feedstock supply for sustainable aviation fuel production.	Ahmad et al. (2021), Ahmad et al. (2019)
	Land-use impact	Describes the direct and indirect changes in land use resulting from the introduction of sustainable fuel production. Evaluates the land area required for the hydrogen production methods, considering the impact on ecosystems and biodiversity.	Ahmad et al. (2021), Ahmad et al. (2019), Yang et al. (2023), Acar et al. (2018)
	Water consumption	The total water consumption during the whole lifecycle of aviation fuels	Ahmad et al. (2021), Chen & Ren (2018), Yang et al. (2023), Acar et al. (2018), Ahmad et al. (2019)
	PM2.5 & PM10	PM emissions during the whole life cycle of aviation fuels.	Chen & Ren (2018)
	SAF traceability	Refers to the ability to trace the origin and the production process of sustainable aviation fuels.	Ahmad et al. (2021), Ahmad et al. (2019)

Table C.3: Longlist Social

Category	Criteria	Description	Study
Scoial	Contribution to economy	Reflects the impact on wealth creation and economic activities, such as job creation and new enterprise establishments.	Ahmad et al. (2021), Yang et al. (2023)
	Food security	Relates to the impact of the production pathway on food security and avialability.	Ahmad et al. (2021)
	Social acceptability	The social acceptance of the fuel and/or technology.	Ahmad et al. (2021), Chen & Ren (2018), Yang et al. (2023), Acar et al. (2018)
	Innovation on technology	The innovation compared to tranditional aviation heavy oils.	Chen & Ren (2018)
	Wealth and job creation	Potential for generating wealth and creating job opportunities.	Yavuz et al. (2015), Xu et al. (2019), Yang et al. (2023), Acar et al. (2018)
	Staheholders' interest	Views and opinions of various stakeholders regarding specific alternative jet fuel technologies.	Xu et al. (2019)
	Training opportunities	Indicates the importance of providing training programs to enhance knowledge and skills in the hydrogen production industry.	Acar et al. (2018)
	Impact on public health	Considers the effects of hydrogen production on public health, emphasizing the importance of producing hydrogen in a way that does not pose risks to human well-being.	Acar et al. (2018)
	Traceability	Refers to the ability to trace the origin and production process of sustainable aviation fuels.	Ahmad et al. (2021), Ahmad et al. (2019)

Table C.4: Longlist Technological

,	Criteria	Description	Study
Technological	Maximum payload	Indicates the maximum weight of passengers and cargo that the aircraft can carry, influencing its operational efficiency.	Markatos & Pantelakis (2023), Kiracı & Bakır (2018)
	Fuel intensity /Fuel consumption / fuel efficiency	Refers to the efficiency of fuel consumption in relation to the aircraft's performance.	Markatos & Pantelakis (2023), Demircan & Kaplan (2023), Kiracı & Akan (2020), Kiracı & Bakır (2018), Yavuz et al. (2015)
	Seat capacity	Capacity of seats in the aircraft.	Demircan & Kaplan (2023), Kiracı & Akan (2020), Kiracı & Bakır (2018), Dožić et al. (2018)
	Belly capacity	The capacity for luggage and freight in a passanger aircraft.	Demircan & Kaplan (2023), Dožić et al. (2018), Kiracı & Akan (2020)
	Range	The maximum distance an aircraft can fly from departure to arrival.	Demircan & Kaplan (2023), Kiracı & Akan (2020), Kiracı & Bakır (2018), Dožić et al. (2018), Yavuz et al. (2015)
	Reliability	Is the property of an aircraft stated by the probability that it will perform a necessary function in a given environment for a certain period.	Demircan & Kaplan (2023)
	Durability	Indicates the longevity and robustness of the technology under operational conditions, considering factors such as maintenance requirements and lfiespan.	Demircan & Kaplan (2023), Kiracı & Akan (2020), Ayar & Karakoc (2023)
	Speed	-	Kiracı & Akan (2020), Kiracı & Bakır (2018)
	Landing and take-off distance	The distance necessary to take-off or for landing of an aircraft.	Kiracı & Akan (2020)
	Blending limit	Indicates the maximum blending ratio of sustainable aviation fuel with conventional jet fuel.	Ahmad et al. (2021), Ahmad et al. (2019)
	Conventional jet fuel compatibility	Assesses the compatibility of sustainable aviation fuel with traditional jet fuel.	Ahmad et al. (2021), Ahmad et al. (2019)
	Domestic technological compatibility	Reflects the capability of domestic technology to support the production pathway.	Ahmad et al. (2021), Ahmad et al. (2019)
	Process integration	Considers the level of integration within the production process.	Ahmad et al. (2021), Ahmad et al. (2019)
	Process technical maturity	Evaluates the technical maturity level of the production process.	Ahmad et al. (2021), Ahmad et al. (2019)
	Production scalability	Examines the ability of the production pathway to scale up production volume.	Ahmad et al. (2021), Ahmad et al. (2019)
	Quality and composition of feedstock	Considers the quality and composition of the feedstock used in production.	Ahmad et al. (2021), Ahmad et al. (2019)
	Energy supply	Based on the yearly amount of energy that can be supplied, on the reliability of energy supply, the reliability of energy storage, and on the cost of energy supply.	Tzeng et al. (2005)
	Energy efficiency	Represents the efficiency of fuel energy.	Tzeng et al. (2005), Acar et al. (2018)
	Sense of comfort	The particular issue regarding sense of comfort.	Tzeng et al. (2005)
	Perceived quality	Public opionion.	Yavuz et al. (2015)
	Filling time	Time to fill tank or depot to full capacity.	Yavuz et al. (2015)
	Safety	Refers to the level of safety provided by the new technology/fuel during operation, considering factors such as risk of malfunction, leakage, and potential hazards.	Yavuz et al. (2015), Ahmad et al. (2019), Ayar & Karakoc (2023)
	Energetic content	Represents the energy content or efficiency of the production process in converting inputs to outputs.	Ahmad et al. (2019), Yang et al. (2023)
	Combustion efficiency	Refers to the ability of the fuel cell system to convert input energy into usable power efficiently.	Ahmad et al. (2019)
	SAF viscosity	Refers to the thickness or flow characteristics of sustainable aviaiton fuel, which can impact their handling, storage, and combustion properties.	Ahmad et al. (2019)
	SAF flash point	Indicates the flash point of sustainable aviation fuels, which is crucial for safety considerations during storage, handling, and transportation.	Ahmad et al. (2019)
	SAF density	Refers to the energy density of sustainable aviation fuels, which impacts their performance and efficiency in aircraft engines, influencing range and fuel consumption.	Ahmad et al. (2019)
	Fuel handling infrastructure modification	The modifications required in fuel handling infrastructure, including storage tanks, pipelines, and refueling equipment.	Ahmad et al. (2019)
	Ease of transportation	The logistical aspects of transporting alternative fuels.	Ahmad et al. (2019)
	Land productivity	Addresses the efficiency of land use for feedstock production, aiming to maximize productivity.	Ahmad et al. (2019)
	Temperature	Considers the operating temperature range of the fuell cell system, which can affect performance efficiency and thermal management requirements.	Ayar & Karakoc (2023)
	Startup time	-	Ayar & Karakoc (2023)
	Specific power	Represents the power output per unit weight of the fuel cell. Higher specific power values indicate a more lightweight and power-efficient system.	Ayar & Karakoc (2023)
	Power density	Refers to the amount of power output per unit volume or weight of the fuel cell. Higher power density indicates a more compact and efficient fuel cell.	Ayar & Karakoc (2023)
	Power capacity	Indicates the total amount of power that can be generated by the fuel cell system. It is a crucial factor in determining the performance capabilities of he fuel cell.	Ayar & Karakoc (2023)
	Energy efficiency	Focuses on the efficiency of energy utilization in the hydrogen production process, aiming to minimize energy waste and enhance overall efficiency.	Ahmad et al. (2019), Yang et al. (2023), Acar et al. (2018), Chen & Ren (2018)
	Efficiency	Refers to the ability of the fuel cell system to convert input energy into usable power efficiently. Higher efficiency values indicate better energy utilization.	Ayar & Karakoc (2023)
	Fuel varity	Reflects the flexibility of the fuel cell system to utilize different types of fuels, which can impact availability, cost, and sustainability.	Ayar & Karakoc (2023)
	Pathway efficiency	Production rate of jet fuel relative to the required resources.	Xu et al. (2019)
	Technology maturity	Level of technological readiness of the production process, assessed based on the Technology Readiness Level (TRL).	Yavuz et al. (2015), Xu et al. (2019), Yang et al. (2023), Chen & Ren (2018)
	Transferability	The extent to which a specific alternative jet fuel technology can be transferred and applied in different environments.	Xu et al. (2019)
	Fuel production complexity	Describes the complexity of the system required for fuel production.	Yang et al. (2023)
	Exergy efficiency - water consumption	Evaluates the efficiency of resource utilization and waste minimization, emphasizing the importance of using resources effectively with minimal waste.	Acar et al. (2018)
	Process control	Considers the level of control and optimization in the production process, enabling adjustments based on demand, supply, and market conditions.	Acar et al. (2018)
	Raw material input - water consumption	Assesses the amount of raw materials required for hydrogen production, highlighting the importance of resource efficiency and sustainable sourcing.	Acar et al. (2018)

D Detailed structure stakeholder interviews

This Appendix delineates the detailed structure followed during stakeholder interviews to determine the criteria weights through the BWM. The PowerPoint slides utilized during these interviews are provided in the next appendix (Appendix F).

Introduction + interview structure

The interview starts with a mutual introduction, wherein my educational background is explained. Additionally, assurance is provided to the stakeholder regarding the anonymization of the derived information from the interview, followed by a request for consent for research use. Furthermore, the stakeholder share their expertise and experience in the aviation industry, especially regarding sustainability. Subsequently, the interview structure is presented to the stakeholders. The presented structure is as follows: context and research goal, followed by the methodology of the BWM, execution of the BWM, and finally, a small recap/evaluation of the conducted interview.

Context & research goal

The research context is explained based on the ICAO goal of achieving net zero CO_2 emissions in 2050. Furthermore, the identified knowledge gap emphasizes the relevance of the research. Moreover, the research goal is presented, and a link has been established to the relevance of utilizing the BWM.

Explanation of BWM on the basis of a simple example

After the link has been established to the relevance of the BWM regarding the goal of the research, the BWM is explained using a simple example. After presenting this simple example, the stakeholder is queried regarding 100% complete comprehension. Furthermore, in this example, the Likert scale utilized within the BWM is presented, as detailed in Table B.1 in Appendix B.

Explanation criteria

Before conducting the BWM, the interviewee is provided with a figure encompassing all the main and sub-criteria considered important according to the literature for the evaluation of SATs. The main criteria and their corresponding sub-criteria are explained to the interviewee. Lastly, the interviewee is asked if all the criteria are understood to prevent misunderstanding in the definitions of the criteria.

Performing the BWM

Once the criteria have been clarified, the BWM is conducted with the stakeholder. The BWM is divided into four different comparisons: one for the main criteria and three for the corresponding sub-criteria. In each BWM comparison, the Likert scale and the definitions of the corresponding criteria are presented to ensure the understanding of the interviewee. The BWM begins with the main criteria: environmental, economic, and technological. Subsequently, BWM comparisons are conducted for environmental, economic and technological sub-criteria. During each BWM comparison, the interviewee was requested to identify the criteria they perceived as the most and least important, followed by the comparisons between criteria using the Likert scale. Detailed steps of the BWM pairwise comparisons with stakeholders are expounded in detail in Section 3.2.3 and visualized in Appendix F.

SATs

Following the BWM execution, the considered SATs were presented and explained to the stakeholders.

Evaluation

During this evaluation, the stakeholders were asked for feedback on the identified criteria and suggestions for any potentially missing criteria. This question was similarly asked regarding the SATs, as emphasized by the exclusion of the battery-electric SAT (Section 6.1.4). Additionally, the experts were requested for additional stakeholder suggestions to interview and asked if they were interested in the final analysis/research.

E Estimations on energy mix

According to IEA (2021), the shares of renewable energy are projected to be 29%, 61%, and 88% for the years 2020, 2030, and 2050, respectively. For this research, it is necessary to estimate the share for the year 2024, as this is the current situation. It is assumed that the growth in the renewable electricity share is linear between 2020 and 2030, resulting in the following calculation:

$$\text{Share renewable electricity in 2024} = (\%\ 2030 - \%\ 2020) \div \Delta\ \text{years} \times \Delta\ \text{years to 2024} = 61\% - 29\% \div 10 \times 4 \approx 42\%$$

Furthermore, the shares of renewable electricity produced by the solar PVs and wind turbines are calculated to consider the land use impact of LH_2 and n-octane. These results in the following calculations, based on data derived from the study of IEA (2021):

- 2024:

$$\text{Share Solar PV + Wind of renewable electricity} = \frac{(\text{Solar PV} + \text{Wind})}{\text{Total Renewables}} = \frac{2413\text{TWh}}{7660\text{TWh}} \approx 32\%$$

- 2030:

$$\text{Share Solar PV + Wind of renewable electricity} = \frac{(\text{Solar PV} + \text{Wind})}{\text{Total Renewables}} = \frac{14978\text{TWh}}{22817\text{TWh}} \approx 66\%$$

- 2050:

$$\text{Share Solar PV + Wind of renewable electricity} = \frac{(\text{Solar PV} + \text{Wind})}{\text{Total Renewables}} = \frac{48244\text{TWh}}{62333\text{TWh}} \approx 77\%$$

Using these approximate shares of solar PV and wind turbine of renewable electricity production, combined with the total renewable electricity shares, the shares of solar PV and wind turbines can be determined in relation to the total electricity produced. This leads to the following calculations:

- 2024:

$$\begin{aligned}\text{Share solar PV + Wind of total electricity} &= \text{Share solar PV + Wind of renewable electricity}\\ &\times \text{share renewable electricity of total electricity} = 32\% \times 42\% \approx 13\%\end{aligned}$$

- 2030:

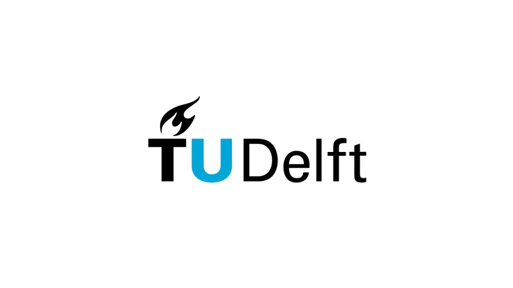
$$\begin{aligned}\text{Share solar PV + Wind of total electricity} &= \text{Share solar PV + Wind of renewable electricity}\\ &\times \text{share renewable electricity of total electricity} = 65\% \times 61\% \approx 40\%\end{aligned}$$

- 2050:

$$\begin{aligned}\text{Share solar PV + Wind of total electricity} &= \text{Share solar PV + Wind of renewable electricity}\\ &\times \text{share renewable electricity of total electricity} = 77\% \times 88\% \approx 68\%\end{aligned}$$

Additionally, it should be noted that these results are estimates based on the report by IEA (2021). They provide an indication of the order of magnitude rather than exact values.

F PowerPoint slides utilized in interview proceedings



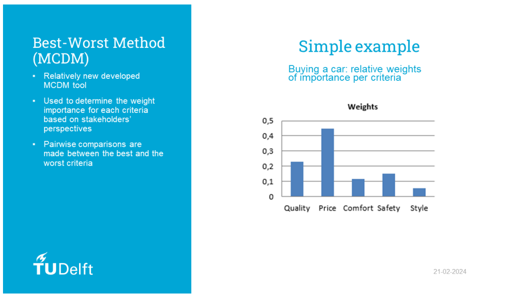
(a)

(b)

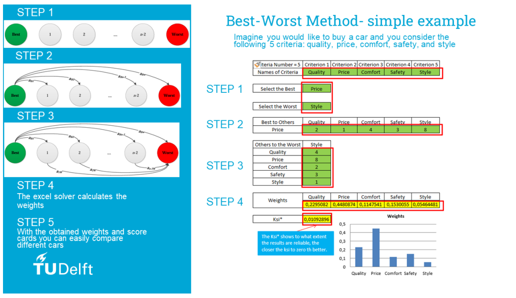
(c)

(d)

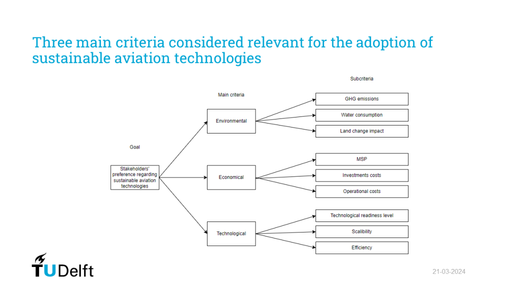
(e)



(f)



(g)



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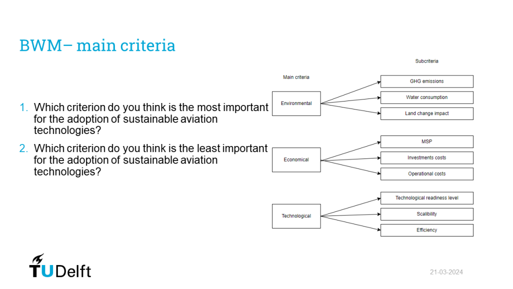
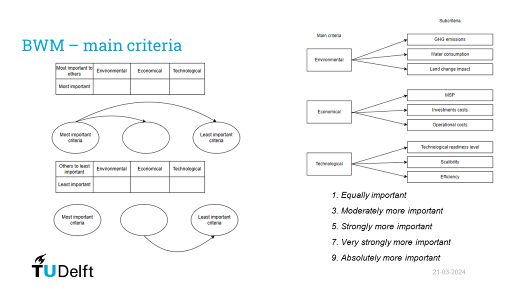
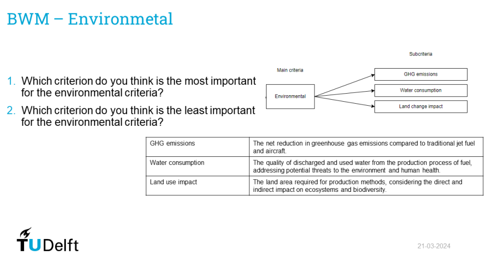


(i)



(j)



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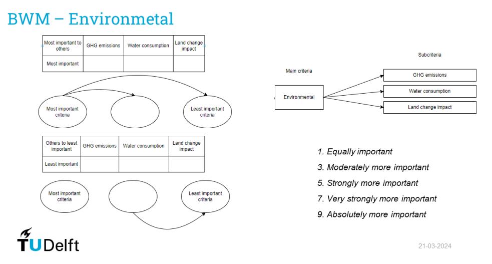
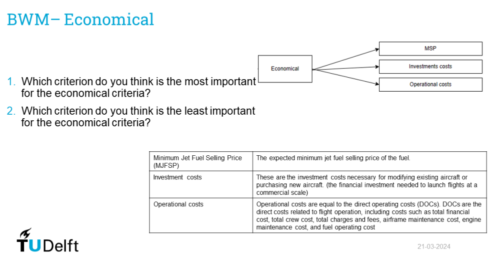
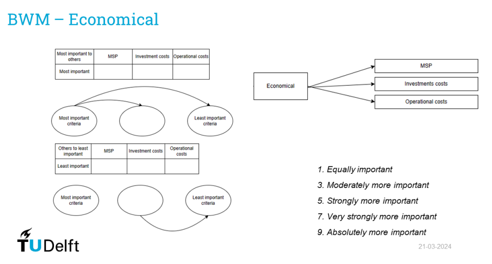


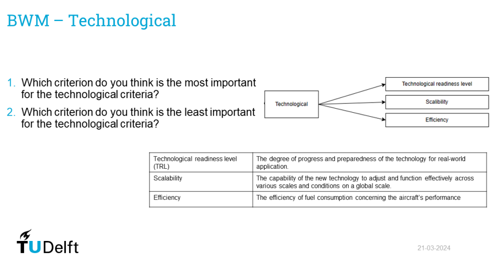
(b)



(c)



(d)



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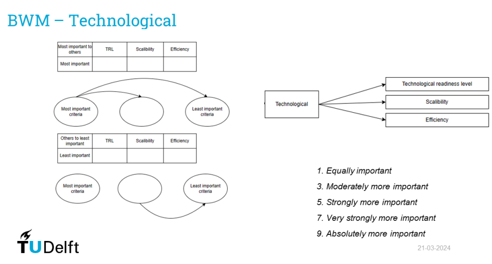
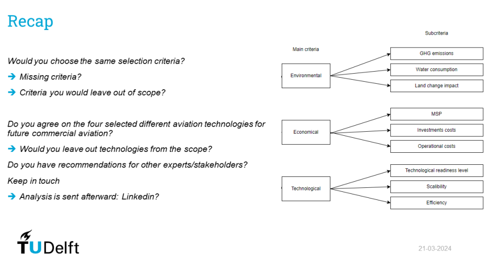
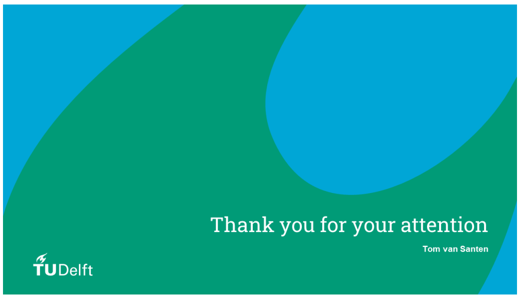


(f)

(g)



(h)



(i)

Figure F.2: PowerPoint slides utilized in interview proceedings

G Local and global weights per individual stakeholder

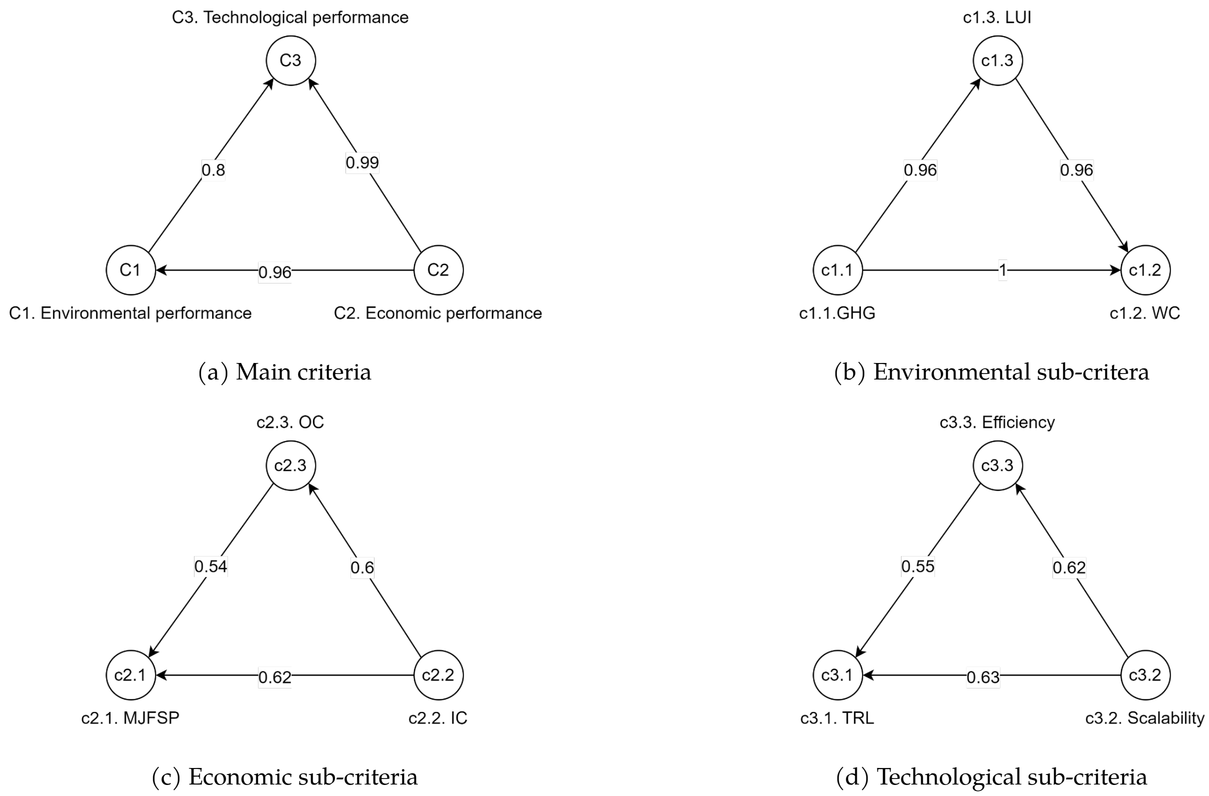
BWM per stakeholder local sub-criteria weights	Environmental	Economic	Technological	GHG	WC	LUI	MJFSP	IC	OC	TRL	Scalability	Efficiency
Airline	0,091	0,740	0,169	0,655	0,091	0,255	0,125	0,167	0,708	0,200	0,250	0,550
Expert	0,542	0,167	0,292	0,773	0,091	0,136	0,143	0,286	0,571	0,385	0,462	0,154
Expert	0,662	0,077	0,262	0,740	0,091	0,169	0,105	0,818	0,077	0,722	0,211	0,067
Expert	0,490	0,059	0,451	0,333	0,333	0,333	0,077	0,718	0,205	0,429	0,071	0,500
Producer/manufacturer	0,722	0,211	0,067	0,675	0,063	0,263	0,143	0,429	0,429	0,173	0,071	0,755
Airline	0,165	0,758	0,077	0,675	0,063	0,263	0,673	0,091	0,236	0,487	0,436	0,077
Producer/manufacturer	0,662	0,262	0,077	0,594	0,063	0,344	0,583	0,111	0,306	0,083	0,796	0,120
Expert	0,500	0,300	0,200	0,685	0,111	0,204	0,333	0,333	0,333	0,644	0,111	0,244
Producer/manufacturer	0,262	0,662	0,077	0,746	0,111	0,143	0,244	0,111	0,644	0,650	0,225	0,125
Airline	0,583	0,306	0,111	0,600	0,200	0,200	0,714	0,143	0,143	0,111	0,244	0,644

BWM per stakeholder global sub-criteria weights	Environmental	Economic	Technological	GHG	WC	LUI	MJFSP	IC	OC	TRL	Scalability	Efficiency
Airline	0,091	0,169	0,740	0,060	0,008	0,023	0,093	0,123	0,524	0,034	0,042	0,093
Expert	0,542	0,167	0,292	0,419	0,049	0,074	0,024	0,048	0,095	0,112	0,135	0,045
Expert	0,662	0,077	0,262	0,490	0,060	0,112	0,008	0,063	0,006	0,189	0,055	0,017
Expert	0,490	0,059	0,451	0,163	0,163	0,163	0,005	0,042	0,012	0,193	0,032	0,225
Producer/manufacturer	0,722	0,211	0,067	0,488	0,045	0,190	0,030	0,090	0,090	0,012	0,005	0,050
Airline	0,165	0,758	0,077	0,111	0,010	0,043	0,510	0,069	0,179	0,037	0,034	0,006
Producer/manufacturer	0,662	0,262	0,077	0,393	0,041	0,227	0,153	0,029	0,080	0,006	0,061	0,009
Expert	0,500	0,300	0,200	0,343	0,056	0,102	0,100	0,100	0,100	0,129	0,022	0,049
Producer/manufacturer	0,262	0,662	0,077	0,343	0,056	0,102	0,100	0,100	0,100	0,129	0,022	0,049
Airline	0,583	0,306	0,111	0,350	0,117	0,117	0,218	0,044	0,044	0,012	0,027	0,072

Figure G.1: Local and global weights per individual stakeholder

H Visualization of credal rankings per stakeholder group

This appendix presents the visualizations of the weighted directed graphs for the main and sub-criteria per stakeholder. These graphs display the credal ranking of the main and sub-criteria and the confidence levels associated with them for each stakeholder group.



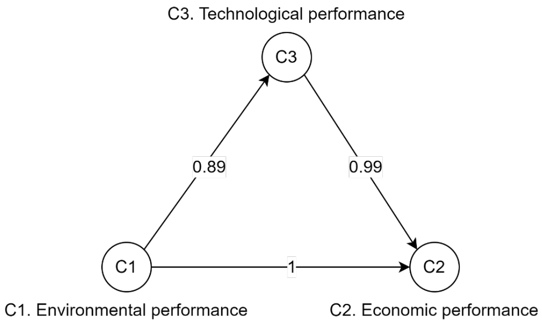
(a) Main criteria

(b) Environmental sub-critera

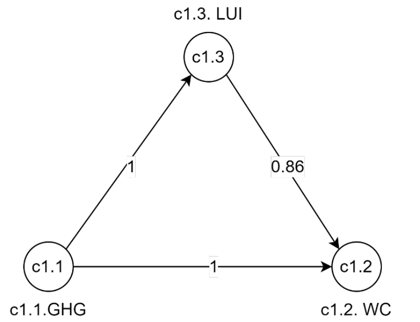
(c) Economic sub-criteria

(d) Technological sub-criteria

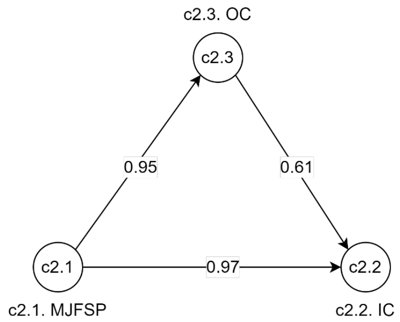
Figure H.1: Visualization of credal ranking: airline stakeholder group



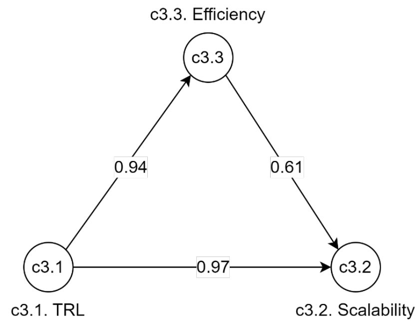
(a) Main criteria



(b) Environmental sub-criteria

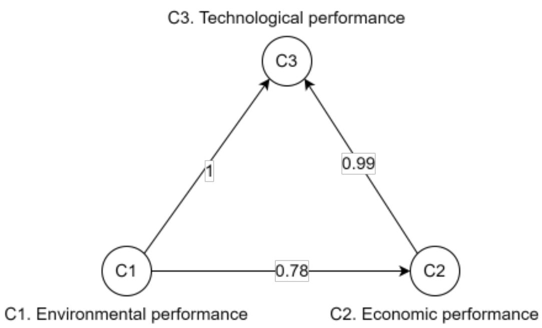


(c) Economic sub-criteria

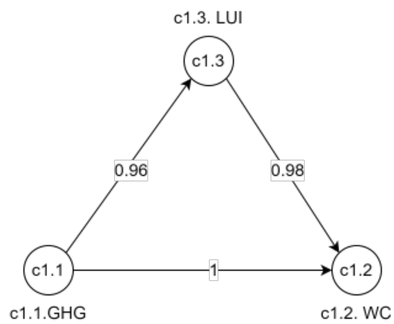


(d) Technological sub-criteria

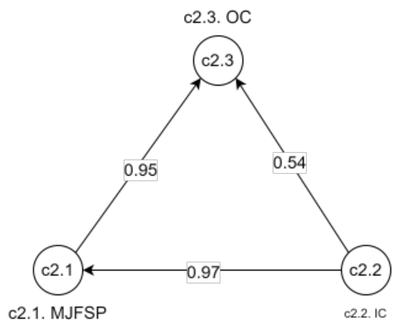
Figure H.2: Visualization of credal ranking: expert/advisor stakeholder group



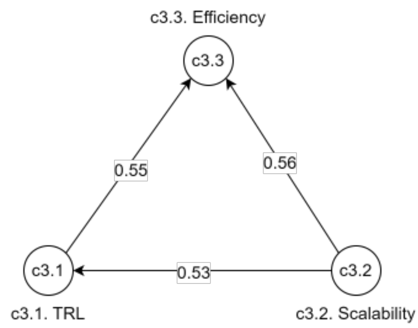
(a) Main criteria



(b) Environmental sub-criteria



(c) Economic sub-criteria



(d) Technological sub-criteria

Figure H.3: Visualization of credal ranking: producer/manufacturer stakeholder group