

IBN HALDUN UNIVERSITY
SCHOOL OF GRADUATE STUDIES
DEPARTMENT OF AIR TRANSPORT MANAGEMENT

MASTER THESIS

**SUSTAINABLE AVIATION FUEL PRODUCTION AND
AVIATION SECTOR**

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THESIS SUPERVISOR
ASSOC. PROF. ALİ OSMAN KUŞAKCI

ISTANBUL, 2023

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MASTER THESIS

**SUSTAINABLE AVIATION FUEL PRODUCTION AND
AVIATION SECTOR**

By

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**A thesis submitted to the School of Graduate Studies in partial
fulfillment of the requirements for the degree of Master of Science in
Air Transport Management**

**THESIS SUPERVISOR
ASSOC. PROF. ALİ OSMAN KUŞAKCI**

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APPROVAL PAGE

This is to certify that we have read this thesis and that, in our opinion, it is fully adequate, in scope and quality, as a thesis for the degree of Master of Science in Air Transport Management.

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I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

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ÖZ

SÜRDÜRÜLEBİLİR HAVACILIK YAKIT ÜRETİMİ VE
HAVACILIK SEKTÖRÜ

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Sürdürülebilir havacılık yakıtları (SAF), modern havacılığı karbondan arındırmak için uygulanabilir bir çözüm sunar. Geleneksel jet yakıtlarının aksine, SAF'ler çeşitli şekillerde üretilir ve dolayısıyla bu süreçlerden birinin seçimi, birbiri ile çelişen öncelikleri içeren karmaşık bir Çok Kriterli Karar Verme problemidir. Bu çalışma, çok kriterli bir metodoloji olan PROMETHEE-2'yi kullanarak SAF üretim süreçlerini değerlendirmektedir. SAF teknolojisinin henüz ilk aşamalarında olması ve bunlarla ilgili veri eksikliği nedeniyle, verilerin ve tercihlerin toplanmasına yardımcı olması için havacılık sektöründeki birkaç paydaş çalışmaya dahil edilmiştir. Önerilen çerçevenin gücü, çeşitli paydaşların subjektif görüşlerine uyacak şekilde uyarlanabilirliğinde, sıralama sisteminin seçiminde ve sonuçların sağlamlığında yatmaktadır. Bu araştırma, sosyal, çevresel, ekonomik ve teknolojik değerlendirme kriterlerine göre kategorize edilmiş 24 parametreye dayalı olarak 11 (A1'den A11'e) SAF üretim yolunu sıralamak için bir dizi paydaştan katılımcı bir şekilde yararlanmıştır. Sektör profesyonellerine SAF üretim yöntemlerini belirlenen kriterine göre derecelendirmeleri için bir form verilmiştir. Veriler, profesyonellerin yargılayıcı kişisel önyargılarını azaltmak için bulanık TOPSIS ve bulanık VIKOR ve PROMETHEE kullanılarak doğrulanmıştır. Çalışma, SAF üretimi için en uygun hammaddenin, gazlaştırma veya Fischer-T sentez grubunda CO₂'nin SAF'a (A11) doğrudan geçiş süreci olduğunu göstermektedir.

Anahtar Kelimeler: Havacılık, Havacılık Yakıtı, PROMETHEE-2, Sürdürülebilir, Yeşil Yakıt.

ABSTRACT

SUSTAINABLE AVIATION FUEL PRODUCTION AND AVIATION SECTOR

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Sustainable aviation fuels (SAF) present a feasible solution to decarbonize modern aviation. In contrast to traditional jet fuels, SAFs are produced in a variety of ways, thereby making the choice of one of these processes a complicated Multi-Criteria Decision challenge that involves conflicting priorities. This study evaluates SAF production processes using a multicriteria methodology, PROMETHEE-2. Due to the initial phase of SAF technology advancement and the lack of data on these, several stakeholders in the aviation sector were enlisted to assist in the collection of data and preferences. The suggested framework's strength lies in its adaptability to suit the subjective opinions of diverse stakeholders, selection of ranking system, and robustness of outcomes. This research utilizes a set of stakeholders in a participative manner to rank 11 (A1 to A11) SAF production paths based on 24 parameters categorized into social, environmental, economic, and technological evaluation criteria. Industry professionals were given a form to rate SAF production methods according to a performance criterion. Data is validated using fuzzy TOPSIS and fuzzy VIKOR and PROMETHEE to reduce professionals' judgmental personal prejudice. The study shows that the optimal feedstock for SAF production is the direct transition process of CO₂ to SAF (A11) in the gasification or Fischer-T synthesis group.

Keywords: Aviation, Green fuel, Sustainable Aviation Fuel, PROMETHEE-2.

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LIST OF ABBREVIATIONS AND SYMBOLS

ASTM	American Society for Testing and Materials
ATJ	Alcohols to Jet
CO ₂	Carbon Dioxide
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
C ₄ H ₁₀ O	N-butanol
CPIS	Crisp Positive Ideal Solution
DCI	Degree of Consensus Index
DSHC	Direct Sugars to Hydro-Carbon
DII	Degree of Importance Index
EROI	Energy Return on Investment
EU	European Union
EtOH	Ethanol
FNIS	Fuzzy Negative Ideal Solution
F-T	Fischer Tropsch
FPIS	Fuzzy Positive Ideal Solution
GHG	Greenhouse Gases
HTL	Hydrothermal Liquefaction
HEFA	Hydro processed Esters and Fatty Acids
ICAO	International Civil Aviation Organization
LCA	Life Cycle Analysis
MeOH	Methanol
MSW	Municipal Solid Wastes
MSP	Minimum Selling Price
MCDM	Multi-criteria Decision Making
RPK	Revenue Passenger Kilometers
SAF	Sustainable Aviation Fuel
SO _x	Sulphur Oxides
SPK	Synthetic Paraffinic Kerosene
UN	United Nations
UFP	Ultrafine Particles

CHAPTER I

INTRODUCTION

The sector of air transportation has recorded a significant increase over the past decades. In 2019, governments are projected to gain USD129 billion in revenue from taxes and 70 million employees in the supply chain globally (IATA, 2019). Commercial aviation has positive economic and social consequences, but it also has negative environmental consequences due to greenhouse gas emissions as well as other negative impacts. Even though greenhouse gases (GHG) are made up of more than just carbon dioxide (CO₂), the fact that CO₂ is accountable for a substantial amount (about 53%) of the overall Greenhouse gas effect is what gives it its significance.

Despite accounting for only a small percentage (2%-2.6) of annual worldwide Emissions of carbon dioxide (ICAO, 2016), the effects of these emissions are much more severe on the environment than those of other emission sources (Kivits, Charles, and Ryan, 2010). According to the IATA, an international trade association for the airlines sector, predicts that the number of international travel passengers will multiply by 2035 when compared to the year 2016. The airline industry is expected to grow by 4.5–4.8% per year. By 2050, it is anticipated that the airline industry's contribution to world fossil fuel Carbon dioxide emissions will range from 4.6% - to 20.2% (O'Connell et al., 2019).

Innovations in technology and operational advancements can be crucial in decarbonization within the industry. Specifically, innovations in aviation structural designs and enhanced propulsion systems have the potential to enhance technical effectiveness. new study, for example, evaluates the viability of electrification for long-distance airplanes (Schäfer, 2018). Nevertheless, electrical airplanes may not be accessible commercially until 2050.

Planned optimal flight routes and the usage of Sustainable Aviation Fuels are additional methods for decarbonizing aviation (Michailos, 2017). Given the lack of technical preparedness in alternative options, liquid fuels will remain to serve a central role in flight operations. Therefore, the utilization of Sustainable aviation fuels (SAF) is viewed as a moderate strategic plan for controlling emissions and lowering reliance on fossil fuels (Royal Society, 2019).

SAF manufacturing methods confront considerable sustainability concerns despite their potential to decarbonize the aviation industry (Wang et al., 2019). These difficulties stem from technological uncertainties, societal perceptions, the impact on the environment from manufacturing and distribution, as well as economic factors (Bann et al., 2017). Due to the industry's high degree of unpredictability, the decision-making environment becomes increasingly complex. Most of the research analyzes the efficacy of sustainable aviation fuel production pathways using techno-economic assessment (Li, Mupondwa, and Tabil, 2018). The increasing complexity of the situation necessitates the consideration of multi-criteria decisions to enable making decisions concerning the context of many, frequently contradicting criteria.

The literature review on multi-criteria decision-making on SAF production reveals a shortage of research on SAF production methods, which is validated by the most recent review conducted by Dožić, S. (2019). This research intends to bridge that gap by offering a participative model relying on the multi-criteria decision framework that includes the opinions of airline industry experts regarding low-carbon aviation fuel manufacturing pathways.

By combining a literature review with the insights of industry professionals, the study was able to establish a set of performing criteria and related indicators that form the basis of this framework's operationalization. These factors are categorized under social, environmental, economic, and technological effects. In addition, the research collected opinions from industry professionals to obtain data on the comparative significance of the criteria that were under evaluation, and rankings for each alternative or sustainable aviation fuel production method on every one of the parameters. The study simulates professionals' preferences and ranks potential routes for producing

sustainable aviation fuels using this data. Furthermore, this study compared the multicriteria ranking outcomes using a variety of MCDM techniques.

The chapters of this study are structured as follows: Initially, Chapter 2 summarizes previous sustainable aviation fuels-related studies. Chapter 3 presents a comprehensive assessment approach for sustainable aviation fuel production methods, examining the multiple production options currently available. The Multi-criteria decision methodology for prioritizing sustainable aviation fuel production paths and related implementation considerations are presented in Chapter 5. Chapter 5 presents the numerical findings and analyzes it with the sensitivity assessment, whereas the conclusion summarizes and concludes the study.



CHAPTER II

LITERATURE REVIEW

The literature review is structured according to research examining societal, environmental, economic, and technological aspects. To ensure sustainability in producing low-carbon fuel sources, it is necessary to reflect the viewpoints of diverse and sometimes competing stakeholder groups who collectively frame a strategic component of the energy generation matrix (Neves et al., 2020; Kim, Lee, and Ahn, 2019). This section discusses every one of the four different viewpoints on airplane fuels. There is much research considering the social standpoint on public opinions and the acceptability of eco-friendly fuels in road transportation systems. These research papers clearly indicate that the general population is conscious of the environmental and economic advantages of using economically efficient fuels; nevertheless, the socio-environmental effect of energy production is not yet completely acknowledged (Amin et al., 2017). It has also been discovered that the “food versus fuel” issue continues to influence popular notions of green gases.

Many research attempts examine farmers’ readiness for crop cultivation concerning environmentally friendly fuel creation and agriculture advisors’ behavior towards promoting environmentally friendly fuels. This research aimed to determine whether farmers were willing to dedicate land, labor, and resources to the cultivation of biomass feedstocks. According to these studies, the readiness of farmers to cultivate fuel crops is a complex interplay of economic, societal, and biophysical elements (Yaghoubi et al., 2019).

Farmers’ readiness to cultivate differ by location, crop variety and profit, their level of education, and available technological and fiscal resources. Less emphasis has been placed on the aviation industry. For instance, perceptions of tourists regarding the utilization of jet biofuel in Poland were surveyed (Filimonau, et al., 2018). They examined views of advantages and safety measures and proposed the necessity for a

public awareness initiative to promote green aviation fuel usage. In the United Kingdom, a second exploratory analysis of the environmental implications of airline and sustainable fuel usage was conducted. This research indicated that the public has a limited knowledge of the environmental advantages of sustainable fuels.

Chiaramonti (2019) underlined the challenges and prospects for sustainable fuel adoption, whereas Kivits et al. (2010) studied the significance of airports in aiding cleaner aviation. The study utilizing a macro-economic framework focused on Input to Output evaluation examined the production impacts of airline fuels in a Brazilian economic system. The study uncovered favorable socioeconomic outcomes for employment and Gross domestic product on balance (Wang et al., 2019). Numerous research has centered on the environmental implications of sustainable aviation fuel production (Kolosz, 2020).

O'Connell et al., (2019) prioritized energy efficiency and reduced greenhouse gas (GHG) emissions as the two important factors. The study found that some Sustainable aviation fuel conversion methods are more energy-intensive than others, excluding those that utilize trash and leftovers as feedstock. Research by Staples et al. (2018) examined emission reductions resulting from the manufacture of SAF from non-food² feedstocks via several conversion methods across their whole life cycle. The estimate revealed that annual investments of approximately 12 billion USD will be required to reduce greenhouse emissions by a minimum of 50% by 2050.

In addition to considering several feedstocks and transformation methods, additional articles assessed a singular feedstock and its procedure. Ganguly et al., (2018) performed a Life Cycle Assessment (LCA) on a wood-related feedstock for sustainable aviation fuel manufacturing. It was discovered that this type of SAF can reduce global warming by 78% as compared to traditional aviation fuel. Likewise, the HTL for micro-algae feedstock was evaluated by Fortier et al., (2014) for two distinct manufacturing facilities. According to their findings, compared to fuels generated in a traditional refinery, sustainable aviation fuel produced at a wastewater treatment facility has a lower life cycle GHG intensity.

Similarly, Seber et al. (2014) utilized LCA to determine the GHG discharge reductions and manufacturing expenses related to HEFA. It was discovered that LCA of green fuel derived from yellow grease created fewer greenhouse gas emissions than sustainable aviation fuel derived from tallow when compared with aviation fuel derived from petroleum. Additionally, sustainable aviation fuel produced from yellow grease provides a reduced Minimal Selling Price than sustainable aviation fuel produced from tallow. There is unanimity across LCA that sustainable aviation fuel can cut aviation's GHG emissions. Because of variability in the environment and the adoption of very own conclusions on the structure boundaries, the results of this research are not similar.

Another study evaluated the effect of long-standing policy initiatives and measures on reducing Carbon dioxide emissions through global air travel in a policy viewpoint using a continual time model indicated that a carbon pricing system, in conjunction with the use of low carbon fuel, might help achieve the desired emission reductions (Sgouridis et al., 2011). Bann et al. (2017) used a financial technique to determine the most suited SAF production process from an economic standpoint. They employed stochastic modeling focused on a net current value computation for six alternative approaches to defining the minimal selling price of sustainable aviation fuels.

Six sustainable aviation fuel manufacturing paths were subjected to a thorough pioneer plant techno-economic assessment. Depending on hypotheses, none of the evaluated paths could achieve cost competition through fossil-formed aviation fuels till 2020, indicating that producing sustainable aviation fuels with current infrastructure and services can be a preferable strategic approach to connect price differential and sustainable aviation fuels production to commercial-level (De Jong et al., 2015).

Another study compared the minimum selling price of aviation fuel derived from food crops with non-food feedstocks, which differs from the focus of other techno-economic assessments (Diederichs et al., 2016). Consideration is given to HEFA, gasification or Fischer Tropsch synthesis, hybrid gasification, and syngas fermenting approach. Each manufacturing approach yielded a fuel with a minimum selling price that was two to four times greater than conventional aviation fuels manufactured from fossil sources.

In addition, they found that SAF produced using vegetable oil-based feedstocks is more comparable in price to standard aviation fuel than SAF derived from non-food feedstocks.

The gasification or Fischer Tropsch production method is more financially feasible when compared to the hybrid method. A study was conducted focusing on energy investment return analysis intended for Fischer Tropsch, hydro-processed ester, and fatty acids, as well as improved fermentation procedures utilizing various feedstocks (Trivedi et al., 2015).

The Fischer Tropsch procedure with switchgrass yielded the highest energy return on investment (EROI) at 9.8%. A techno-economic assessment, including environmental factors for sustainable aviation fuel production paths, concluded that such operations use the mass and energy balance method (Neuling & Kaltschmitt, 2018). According to their findings, achieving technological, economic, and environmental objectives concurrently for a single method is not possible.

Li et al. (2018) produced sustainable aviation fuel using camelina oil through hydro process. Under the production parameters analyzed, the MSP of sustainable aviation fuel ranged from \$0.40 to \$0.17 per liter, with feedstock expenditure being the most sensitive factor. Michailos (2018) also conducted a thorough production design and cost evaluation of sustainable aviation fuel from sugar cane residual (bagasse). It was discovered that one kilogram of dry bagasse may create 0.121 kilograms of sustainable aviation fuel at a rate of \$2.78 per liter.

A study on a combined environmental approach with techno-economic evaluation for the establishment of an SAF production facility alongside Brazil's preexisting sugarcane processing sector discovered that the HEFA manufacturing path might result in maximum productivity. At the same time, the gasification or Fischer Tropsch pathway offers the best financial performance. The ATJ production path is the lowest desired due to its poor aviation fuel output (Klein et al., 2018). Chuck and Donnelly (2014) evaluated the energy viscosity and cloud point temperatures of sustainable fuel to conventional aviation fuel from a technological standpoint. Sustainable aviation

fuels derived through oil feedstocks are similar to standard aviation fuel rather than sustainable aviation fuels derived from other source materials.

Silva et al. (2016) conducted research examining the functional characteristics of behavior in response, atmosphere, the existence of stirring, and the employment of catalysts. Their primary focus was on the technical properties of biomass resources derived from oil, specifically the macauba palm tree. Oil produced from such trees might serve as a substrate for SAFs. In addition, the analysis revealed that a combination of 5% sustainable and standard aviation fuels is feasible.

Similarly, research based on a model that explored the effects of sustainable aviation fuel hydrocarbon composition, thermodynamic characteristics, as well as fuel combustion on airplane performances studied three alternative SAFs and compared them to standard aviation fuel, including camelina, jatropha, as well as microalgae (Lokesh et al., 2015). It was determined that sustainable aviation fuels are superior to standard aviation fuels in terms of fuel efficiency and pollution.

A comparative study focusing on many criteria to evaluate the viability of various sources of fuels for the airline industry showed that the fuels obtained from the Fischer Tropsh & HEFA procedures were shown to be practical for supplementing the existing aviation fuel supplies. However, hydrogen is deemed impracticable because of airplanes' existing engine technology (Hileman & Stratton, 2014). It was discovered that alcohol, biofuel, and biokerosene are more acceptable for road transport.

None of the aforementioned investigations employ the multi-criteria decision-making conceptual approach, which is gradually being introduced into the Life cycle assessment or techno-economic assessment toolbox as a definitive endpoint approach, notwithstanding the issue reasoning reflecting a multi-criteria dilemma. Some of this research shows that the parameters under discussion are contradictory, necessitating an examination of MCDM techniques. This research intends to address this disparity by presenting an investors' participative multi-criteria decision structure that addresses the opinions of airline-experienced professionals on lower-carbon aviation energy production approaches.

CHAPTER III

SUSTAINABLE AVIATION FUEL PRODUCTION PATHWAYS

3.1. Aviation Industry at Present

Concerning the battle over climate crisis, aviation occupies a dire state. According to statistics from 2018, industry contributed to 3.5% of global warming when non-CO₂ emissions are considered and approximately 2.5% of global CO₂ emissions (Ritchie, 2020). Aviation is commonly considered an industry that is hard to decarbonize technologically or even economically. In 2019, emission levels from jet fuel combustion recorded a higher point of 1027 Metric tons of CO₂, even though these values only account for 12% of CO₂ emissions for the unified transportation industry (IEA, 2022; Air Transport Action Group, 2020).

The Climate Accord from the UN Climate Change Conference declared the target of reducing the average rise in global temperature to far less than 2°C over prior industrial values and intends for 1.5°C (UN, 2015). Since then, governments have improved their attempts to develop unique strategies for contributing to the common goal, even though most existing goals are rarely if ever accomplished.

The transportation sector is still behind other industries which are making faster progress in their decarbonization initiatives, with European Union numbers indicating that it is particularly off track in attaining the planned climate goals. Due to the current climate crisis, several of the aviation sector's short-term projected carbon footprint reduction plans are under harsh criticism for being much too insufficient (Reuters, 2021).

The ICAO member nations also endorsed CORSIA, a market-related framework created in 2016 to achieve net-zero growth in global aviation starting in 2020.

Although the necessity for both short and the long carbon footprint lessening is widely agreed upon, the majority of such plans and initiatives were developed depending on a model that expected a significant rise in corporate air traffic flow, and which failed to take into account the sudden halt in airplanes imposed on by the current COVID-19 outbreak (Scheelhaase et al., 2019), which resulted in the largest decline in global aviation passengers ever, as shown in Figure 3.1.

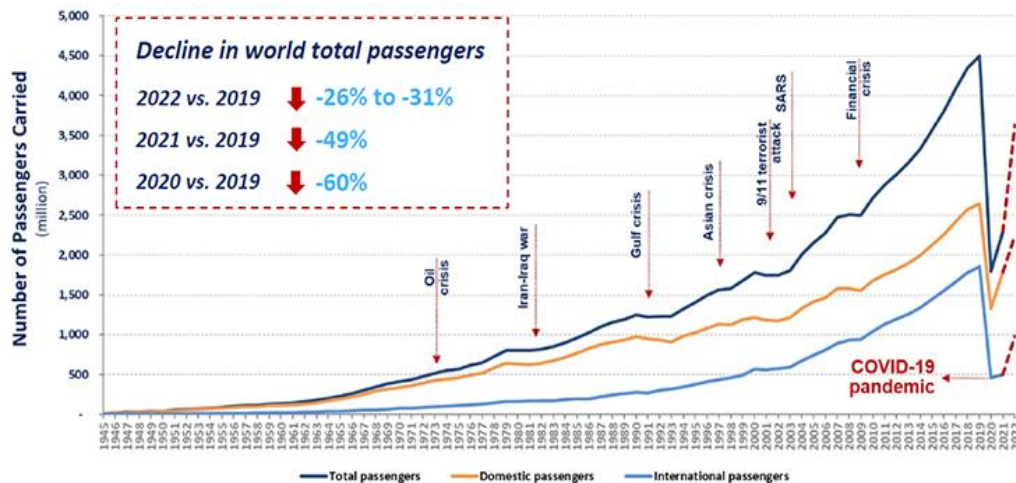


Figure 3.1. History of Global Passengers Carried (1945-2022)

Source: (International Civil Aviation Organization, 2021)

In the most severe phase of lockdown throughout 2020, 2/3 of the international industrial aviation fleet was inactive, and despite a considerable increase in flight numbers in 2021, fueled mostly by the air freight business, RPKs remained lower than 50 percent of 2019 estimates (Aviation Benefits, 2021). The drop in aviation traffic is still thought to be only transitory, notwithstanding the slower-than-anticipated recovery (Figure 1.2).

Even though it is not anticipated that the total number of passengers in 2022 will exceed as fast as in 2019, and current long-term estimates suggest that passenger traffic will be 8% lower in 2050 in comparison to similar research conducted before the pandemic, this is not sufficient to get rid of the requirement for mitigation strategies, although the effects of the pandemic caused some present carbon strategies to change their goals (International Civil Aviation Organization, 2022).

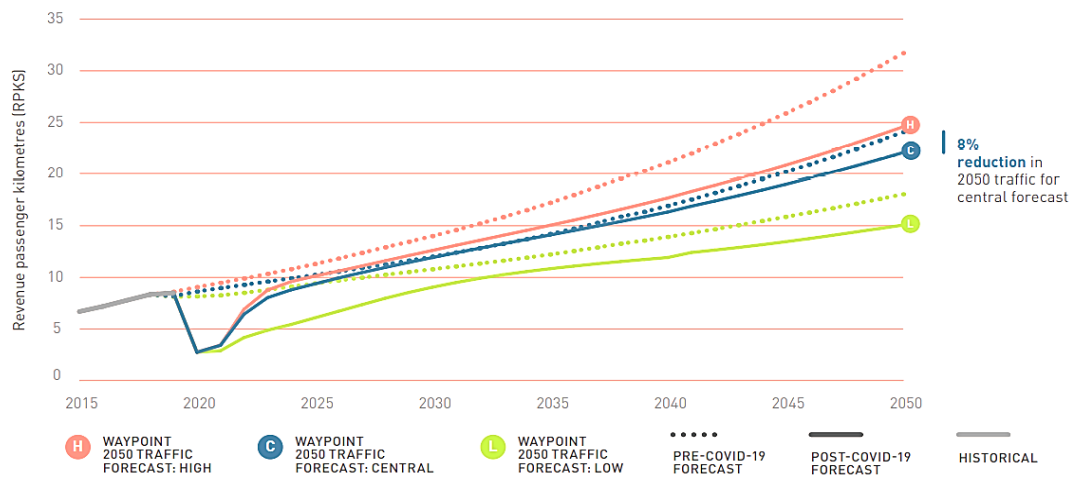


Figure 3.2. Pre and Post-Coronavirus Estimates for RPKs Through 2050

Source: (Air Transport Action Group, 2021)

There are varying focus areas that can lower the sector’s GHG emissions, but each has varying levels of capability at present. Maximizing flight routes for minimal level emissions instead of cost, enhancing maintenance work schedule as well as other operational initiatives, and bringing new additional developments in weight management resources and associated technology contribute significantly to reducing emissions and must not be ignored, however, they are simply inadequate (Timperley, 2021).

The present generation of airplanes is 20% more energy-intensive than the prior generation and 85% more economical than airplanes from the 1960s; this is the most substantial gain in recent years. As shown in Figure 3, the development rate is gradually reducing, while continued developments are not likely to equal the expected growth in aviation traffic, therefore it will be inadequate (International Civil Aviation Organization, 2019).

Additionally, studies have been conducted on reducing emissions at various stages. Obviously, aviation emissions are highest during the takeoff and climbing phases, but ignition and warm-up emission levels are also crucial since the inefficiency related to cold starting results in higher energy and emission losses. In addition, the decrease in greenhouse gas emissions since the initial stages of the flu outbreak has bolstered movements arguing that the wisest action to take is to halt the expansion of the business

instead of relying solely on future scientific discoveries (Roberts et al., 2014; Alkema, 2021). Nonetheless, considering the competition in the industry, this choice seems impractical. It is evident that to achieve the desired outcomes, commercial aviation must reduce and eliminate its dependence on fossil fuels.

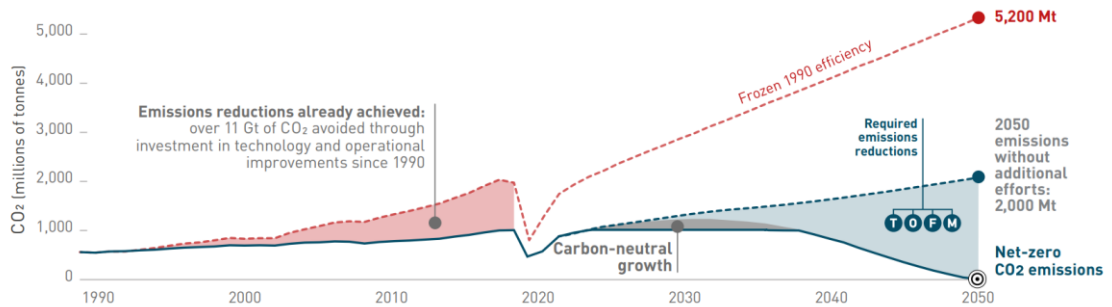


Figure 3.3. Projected CO2 Emissions From 1990 to 2050

Note: without any significant effort, in comparison to the net-zero objective of 2050 and productivity trend since 1990. Technology innovations (T), operations and infrastructural enhancements (O), usage of SAF (F), as well as offsets and other carbon reduction alternatives (C), are used to achieve the necessary reduction in emissions (M); Source: (Air Transport Action Group, 2021)

Hydrogen-powered and battery-powered airplanes are alternatives, primarily based on future advancements that can transcend the current technological limitations, but these alternatives will need substantial changes to the design in airplanes and due to the slower fleet renewal cycle, yet new airplane deliveries are delayed in previous 2 years and short-term execution level demanded is too expensive for businesses. Therefore, these innovations are only feasible as options for the future (Scheelhaase, 2019).

The best option for short and medium ranges is a "drop-in" alternative for traditional jet kerosene, as many routes to producing SAF have already been licensed for commercial usage up to particular composition levels. Bioactive feedstocks are currently the most common, but sustainability is a key challenge for larger operations; therefore, power-to-liquid choices may provide a better answer. However, the latter is very costly in contrast to the earlier, and other alternatives, like solar energy, remain in the early testing stages.

3.2. Green Fuels Used in the Aviation Industry

Even though there is no standard meaning for sustainable aviation fuels (SAF), the term generally refers to a varying drop-in kerosene alternative solution that is created from a wide range of feedstocks, whereas the ICAO (2022) defines sustainable aviation fuels as alternative fuels that meet specified sustainability requirements.

Before the climate crisis established itself as this century's defining issue, research activities were mostly motivated by economic & supply concerns. Ever since, the first sustainable aviation fuels have been licensed for industrial usage, by 2019, over 45 airlines had flown more than a quarter million sustainable aviation fuel flights, but modern usage represents less than 0.1% of jet fuel utilization (IEA, 2022).

Another difficulty is prevailing restrictions on mandatory combination tiers. Research shows that sustainable aviation fuels can reduce life cycle CO₂ emissions by as much as 80%, even while reducing the emissions of many other contaminants like soot, SO_x, and UFPs, and moderating the impact on climate change of contrails (BP, 2021; Narciso and DeSousa, 2021). Nevertheless, mixing ratios for recognized methods are limited to 5 to 50 percent, based on the transformation procedure. Because nitrile O-rings' usage necessitates a minimal level of 8 percent aromatic component in fuels to operate efficiently, initial pure sustainable aviation fuels did not fulfill this requirement.

Recent advancements in sustainable aviation fuel transfer techniques and novel O-rings manufactured from fluoro-carbons that do not necessitate the same aromatic concentration in fuels may result in imminent regulatory modifications. United Airlines conducted an effective demo aircraft utilizing 100% SAF in one of its engines in 2021 (Palmer, 2021).

3.2.1. Outline of Certification Procedure

SAF must possess the same characteristics as conventional jet fuel, which is termed "drop-in ready." ASTM D1655 is the global standard commonly referred to classify kerosene fuel in industrial air travel. It is a mandatory requirement for airline turbine

fuel and creates the prerequisites that both Jet A and A-1 must meet. Due to its low maximal freezing point, Jet A-1 is preferable for long-distance aircraft that use arctic paths, yet the production cost is high (Chevron, 2007).

Figure 3.4 depicts the three-stage, four-tiered testing method established by ASTM D4054, which is a mandatory procedure for qualifying and Certification of new airline turbine fuels and extracts, which is required for a novel aircraft fuel to be licensed for business use.

After a SAF passes all the necessary tests, it is included in the relevant standard for aircraft turbine fuel including synthetic hydrocarbons (ASTM D7566), which controls the requirements for drop-in fuels and could be utilized in industrial airlines at permitted combining ratios. The exhaustive and thorough approach outlined by D4054 necessitates various fuel amounts at each level, as well as the 3–5-year procedure imposes a minimum cost of \$5M on prospective fuel manufacturers (Heyne et al., 2021). To solve this problem, stimulate and speed up the study, ASTM authorized a fast-track annex for D4054 in January 2020; however, innovative fuels certified with this method are constrained to a blending ratio of 10% (Office of Energy Efficiency and Renewable Energy, 2020).

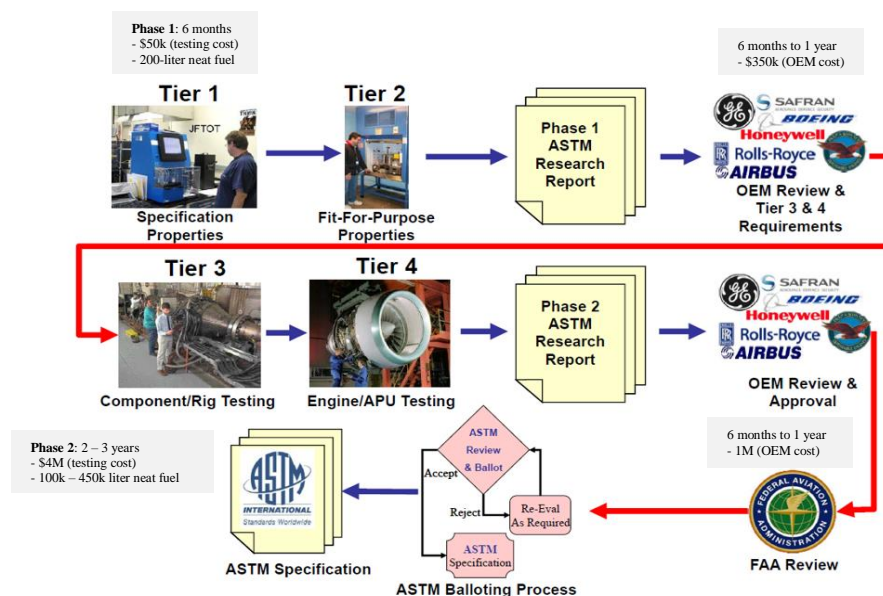


Figure 3.4. Fuel and Cost Needs for a Notional ASTM D4054 Evaluation Method, Excluding Fuel Cost Production
Source: (Heyne, Rauch, Le Clercq, and Colket, 2021)

3.2.2. Biofuels Utilized in the Aviation Sector

Any carbon-based material, or feedstock, which can be renewed is a potential source for biofuels. When producing biofuels from plants, some of the carbon dioxide (CO₂) released during the procedure is reabsorbed by the following crop generation, greatly lowering the related carbon life-cycle emissions. Carbon life-cycle emissions are compared in Figure 3.5 for fossil-based aviation fuel and bio SAF.

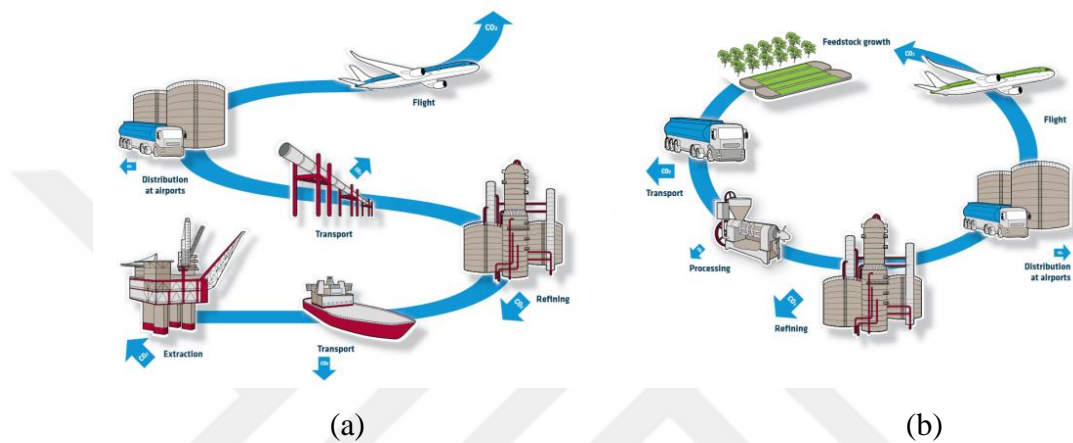


Figure 3.5. (a) LCA of Carbon for Fossil Aviation Fuels (b) Sustainable Biofuels

Source: (Air Transport Action Group., 2017)

The biofuel production process involves a series of processes. Once the appropriate feedstock has been created and gathered, several pretreatment processes may be needed before the conversion procedure can begin, and these steps vary based on the feedstock kind. The fuel is only ready for shipment and use once the conversion procedure has been completed.

3.2.2.1. Renewable Feedstocks

Not all biofuels are suitable for use in the airline industry. Bio-diesel fuel, for instance, doesn't match the performances for use in airplanes, mostly because of its greater freezing point and poorer energy density compared to Jet fuels. However, trials on internal combustion engines have shown possibilities towards certain bioalcohols; for example, bioethanol was employed to diminish diesel releases throughout the initial

and warm-up stages. Combinations of normal diesel, biodiesel, and n-butanol revealed a greater reduction in emissions (Adin et al., 2021). To be classed as a sustainable aviation fuel, a biofuel must meet additional sustainable and emission standards. In contrast, biofuels derived from food crops aren't feasible options for future deployment (Altun et al., 2011).

Four feedstocks acceptable for sustainable aviation fuel are oils, sugars, starches, and lignocellulosic renewable sources (PtX Hub, 2022). Every category necessitates distinct pretreatment methods and is suited to distinct conversion procedures. Occasionally, waste from human activity, particularly commercial by-products, might also be regarded as a distinct feedstock class. A comprehensive overview of potential biofuel feedstocks is beyond the scope of this research, however, a number of the most potential materials for sustainable aviation fuel synthesis are provided below.

Camelina: In the past, palm oil and soybeans were the most common first-generation resources used to create biofuels using oil, however, these substances have been associated with a variety of sustainability problems, including increased food costs and environmental concerns. Second-generation biofuels are more likely to achieve the necessary sustainable goals because they are made from non-food crop varieties or other alternate material materials that do not aim to contend with consumable biomass resources for land management. This includes *Camelina sativa*. Due to its high fatty oil content, this non-edible fuel crop is mostly utilized as raw material in biofuel production; however, the byproduct of oil extraction can be utilized as supplemental feed for cattle (Air Transport Action Group, 2017). Furthermore, *Camelina* is utilized as a cover crop, similar to field pennycress and Ethiopian mustard.

Cover crops are produced during seasons when cereal-cropped land is normally left unused. The sustainable advantages of this method are not yet fully evident and require further investigation, as it can generate other difficulties such as limiting livestock fodder, but it can also increase soil quality compared to mono-crop, as it decreases erosion and increases infiltration of water and carbon absorption (World Economic Forum, 2020).

Jatropha: *Jatropha*, also known as *Jatropha curcas*, is another plant that has the potential to be a source of lipid oil because it can produce oil from 2.5 t /ha to 3 t /ha. Unlike *Camelina*, the byproducts of its extracting oil cannot be fed to livestock since it is toxic to both people and animals (Farm Energy, 2019). One of the key benefits of employing this plant as a fuel raw material is that it can be cultivated in marginal or unproductive environments, such as dry regions. The existing SAF productivity numbers could be increased by using just a small amount of these soil conditions, without interfering with agricultural crops or even being reliant on their rotational schedules (Hari et al., 2015). However, it is still not a practical alternative until persistent production difficulties are resolved. Low seed production, vulnerability to viral diseases and insects, and the complication and expense of effective oil extraction methods all contribute to these problems (Moniruzzaman et al., 2017).

Halophyte: This is a salt-tolerant plant that thrives in harsh environments. These exhibit considerable potential as oil as well as lignocellulosic feedstocks. However, some species, including castor bean and sunflower, have presented to produce exceptionally prominent levels of oil (approximately 50% of overall dried seed mass) (Sharma et al., 2016). While soil salination can reduce crop yields, modern genetic engineering and synthetic biology promise to alleviate this problem and even improve future harvests. Etihad Airways has flown with Halophyte-based gasoline (CAAFI, 2019). The fact that Halophytes can be employed to produce fuel while also accomplishing other goals, such as desalinizing arable land, is another illustration of their adaptability and potential.

Algae: Third-generation biofuels are frequently referred to as “algae fuels”. Algae have higher growth rates than second-generation fuels and require less land (Lee and Lavoie, 2013). During progressive growth, microalgae can frequently quadruple their biomass in less than 24 hours, and sometimes as quickly as 3.5 hours. Algae’s carbon-absorbing characteristics make them ideal for carbon sequestration. Algae may survive in a range of wastewaters, accumulating nutrients like nitrogen and phosphorus, enhancing their economic and environmental advantages. Algae can be farmed in marginal sites like desert borders and may be the best alternative for future biofuel generation (Chisti, 2007).

Waste Oil: A variety of conversion procedures can be used to turn various waste products and materials into SAF (Hari et al., 2015). Although the long-term viability of a few of these substances is still up for question, residual cooking oil, livestock fats, tall and fish oils, as well as other leftover lipids can contribute around 20M tons of sustainable aviation fuels and 20M tons of renewable fuels. Forest and agricultural leftovers are eco-friendly fuel sources. Food crop remnants, such as leaves and stems wheat husks as well as other processed wastes, and logging wastes, such as branches and other material, all fall into this category (O'Malley et al., 2021).

Wood wastes have an inexpensive lignocellulosic potential as well as a high lignocellulosic yield. The EU alone can produce around 150Mt of sustainable forestry and agriculture residues, while worldwide feedstock availability in 2030 can provide 135 million metric tons of sustainable aviation fuels each year. Solid waste from municipalities also has enormous potential, with 2 billion metric tons generated a year globally, half of which is biogenic. Grass clippings, old furniture, food scraps, discarded clothing, newspapers, and unopened packages are all part of it (Searle and Malins, 2016).

Using MSW for biofuel production also helps reduce emissions by diverting garbage from landfills, where it would decompose anaerobically and release CO₂, methane, as well as other pollutants into the air. Plastic waste-to-energy conversion can be a potential possibility for aviation fuel generation since research shows encouraging outcomes in emissions and efficiency by up to 40% mixing proportions (Mariappan et al., 2021).

3.2.2.2. Accredited Paths

Currently, ASTM has validated eight technological systems or conversion methods to produce SAFs, and these are outlined in a similar number of annexes to the standards, most notably D7566. Maximal blending proportions for Fischer-Tropsch containing Synthetic Paraffinic Kerosene and incorporating Aromatics vary depending on the feedstocks used to create them. In 2009, the Fischer-Tropsch procedure became the first to be authorized by ASTM, and it is now included in Annex A1 of D7566. The maximum allowable mix percentage is 50%. Liquid hydrocarbons can be extracted

from coal using the FT formulation, which was created in 1920 by Hans Tropsch and Franz Fischer (Schmidt et al., 2018; Kolosz et al., 2020).

The method involves a reactor using a cobalt/iron compound to catalyze a thermochemical reaction that transforms a refined gas combination of carbon monoxide plus hydrogen into a gaseous and liquid mixture of hydrocarbon chains at varying lengths. After undergoing hydrocracking and isomerization during the refining process, the product is distilled to produce a variety of byproducts, one of which is a synthetic paraffinic kerosene (SPK) that is functionally equivalent to conventional aviation fuel. It is possible to create syngas by gasifying carbon-based feedstocks at high temperatures (1200-1600 degrees Celsius). This includes biomass in addition to fossil fuels like coal and natural gas (Schmidt et al., 2018).

Waste from cities, farms, and forests, algae, and trees can all be used as sustainable feedstocks. While FT fuels exhibit a decrease in Nitrogen oxides, the further pretreatment processes required by biomass mitigate considerably the overall drop in life cycle carbon emissions. In 2015, Annex A4 of Document D7566 approved a second variant of the FT path. Fischer-Tropsch synthesized paraffinic kerosene comprising aromatics (FT-SPK/A) is formed via a similar FT formulation method as regular FT-SPK, however when adding benzene to increase the aromatic material of the final hydrocarbon and improve its compatibility with modern engines by reducing fuel leakage. Currently, this method can be utilized only in combinations equal to 50 percent and it holds the greatest ability to have its future value raised, and there is a good chance that it will eventually be approved for 100% traditional fuel substitution (SkyNRG, 2020; CAAFI, 2022b).

3.3. Challenges Faced

The insufficient maturity of certain or most of the fuel approaches; the shortage of sufficient quantities of raw material; and, in the situation of bio-sustainable aviation fuels, sustainability issues related to the growth in feedstock generation; and a total absence of support from international bodies and governments to boost and ease the fossil fuel transition are all factors slowing down the range and development of the fuel alternatives market. All these challenges have a detrimental impact on the cost-

efficiency of SAFs. If left unanswered, and when the economic feasibility of these fuels stays in dispute it may result in a slowdown in emissions reduction efforts, consequently limiting the industry from attaining its goals for the next several decades.

Despite the growing fleet of aircraft equipped with SAFs, especially those using Hydro processed Esters and Fatty Acids Synthetic Paraffinic Kerosine (HEFA-SPK), no approach has so far reached the ultimate technical ease on requirement (Ricardo Energy and Environment, 2020). However, biofuels are nearer to widespread adoption than other options (If co-processing is abandoned due to environmental concerns and the fact that it allows for the lowest possible blending limits). All H₂-using processes will benefit from developments in green hydrogen production that reduce the cost gap between green hydrogen and fossil fuel production.

While power-to-liquid technologies are currently not cost-competitive with biofuels, it is projected that this approach will become the most financially competitive in the future. These processes rely on new advances in both elevated temperature and co-electrolysis. Throughout this research, it is shown how important it is to meet feedstock sustainability standards when producing biofuels. This is accomplished by comparing life cycle evaluations to specified restrictions and ensuring that no issues over food security and land utilization/conservation occur (World Economic Forum, 2020).

Biogenic feedstocks' potential to meet future expected fuel demands without jeopardizing these commitments has been called into question (Schmidt et al., 2018). Land utilized for infrastructures and transportation must also be subjected to sustainability reviews when generating economies of scale, independent of the alternative energy source produced. Even if production is streamlined to acquire aviation fuel, co-product valorization must not be ignored because most fuel production routes also yield other goods (Wulf et al., 2020).

The policies governing sustainable aviation fuels must operate as catalysts to motivate corporations to shift their focus from fossil fuels to the usage of renewable energy. Obviously, financial assistance systems are of the utmost importance, as they might affect a project's financial feasibility. These include newly authorized tax breaks in the US and direct project finance (Gordon et al., 2021). SAF use can also be

encouraged by legislation, like the European Commission’s Refuel EU Aviation directive, which establishes individual objectives for sustainable aviation fuel integration in European Union airports, ranging from 2% by 2025 and 63% in 2050 for biofuels as well as from 0.7% by 2030 for e-fuels (Dyk, 2021). Hydrogen and battery-powered technologies are two examples of those still under the RandD phase. Increasing the speed of the certification process (ASTM) and reevaluating the max. allowable blending rate is notably contributing to the alternate fuel development.

3.4. Approaches to Producing SAF

Sustainable aviation fuels are generated in numerous methods, and each manufacturing route includes its own technological (like fuel composition), economical (like cost), societal (like public acceptance), and environmental (like GHG) features. SAF methods of production can be roughly broken down into two groups, biochemical and thermo-chemical. Figure 3.6 depicts a summary of SAF production paths. The subsequent subsections provide a summary of these approaches. Shahabuddin et al. (2020) provide a comprehensive overview of these processes (Shahabuddin et al., 2020).

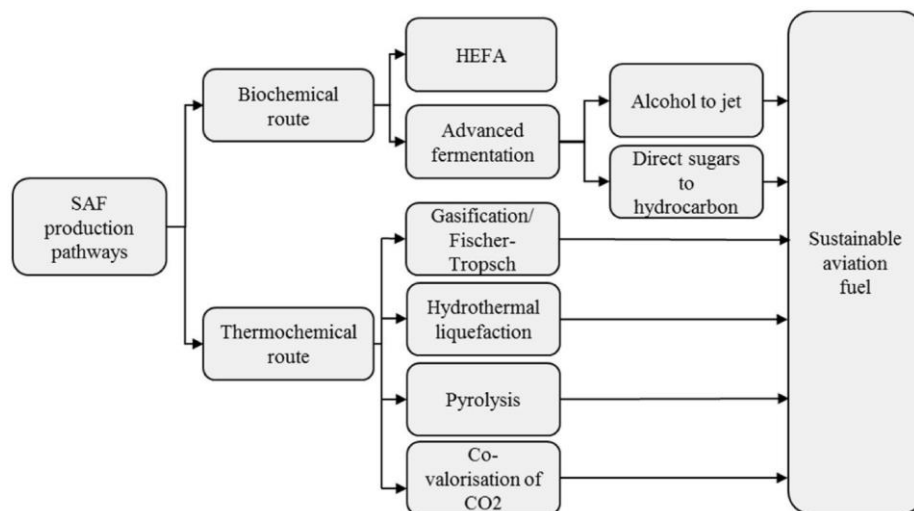


Figure 3.6. Process Classification on SAF Production Paths

Source: (Shahabuddin et al., 2020)

3.4.1. HEFA

The Hydro-processed esters and fatty acids metabolic procedure produces long-chain hydrocarbons. Long-chain hydrocarbons are produced via hydrogenation and isomerization from any oil, including animal fat, residual grease, vegetable oil, as well as algae oil, while aviation fuel is produced using a separate chosen cracking method (Dayton and Foust, 2020). Because of their hydroprocessing, SAFs have a high energy content, good thermal stability, and lower emission of tailpipe (Gawron et al., 2020). As a result of these qualities, ASTM has approved HEFA fuels for usage in mixtures with regular aviation fuel at a 50% blending limit. Many airline companies, notably KLM, Lufthansa, and Etihad, have undertaken effective test launches utilizing mixtures of standard and Hydro-processed esters and fatty acid aviation.

3.4.2. Improved Fermentation

The modern fermentation route includes two processes:

- i. Alcohols To Jet (ATJ)
- ii. Direct Sugars to Hydro-Carbon (DSHC).

This category is based on the concept that both ATJ and DSHC have fermenting as their fundamental procedure. Long-chain Hydro-Carbon with properties like traditional Jet-A1 fuel can be produced by the ATJ method from alcohols like ethanol (EtOH), methanol (MeOH), or n-butanol (C₄H₁₀O). Alcohol can be produced either by sugar fermentation, the catalytic transformation of biomasses, or the direct carbohydrates conversion to hydrocarbon, making it the primary raw material (Hari et al., 2015). The ATJ procedure consists of four steps regardless of the alcohol source.

To obtain the desired product, dehydration, and oligomerization are the first two processes, proceeded by hydrogenation and distillation (Geleynse et al., 2020). The procedure involved in this route has reached an advanced stage of development, which is one of its key benefits. The ATJ procedure incurs greater infrastructure expenses than the Fischer-Tropsch process. When performing either the F-T or ATJ process, the catalyst selection is crucial. In contrast, the DSHC procedure does not require alcohol generation. Utilizing anaerobic fermentation, concentrated carbohydrates are changed

into hydrocarbons (Zhang et al., 2020). The next step is phase separation, which is used to produce aviation.

3.4.3. Fischer-Tropsch Production

Syngas, mostly composed of carbon monoxide and hydrogen, is produced via this thermochemical conversion from carbon-rich biomass. Through a catalytic process, the syngas is converted into a liquid fuel. Carbon-free aviation fuel can be derived from a range of biomass resources, like wood wastes from the forestry and timber industries, poplar, and willow, as well as Agri wastes including corn stover and wheat straws. To create SAF, however, the use of an F-T catalyst is necessary; this is a costly process because of the high temperatures and pressures involved (Dayton and Foust, 2020).

3.4.4. Pyrolysis

Products of pyrolysis include gas, charcoal, and oil. Bio-oil has a wide variety of organic molecules, from C1 - C21+ in the carbon chain. The increased oxygen concentration of bio-oil is another drawback that must be overcome before the fuel may be used. Chemical interactions in the existence of high-pressure hydrogen, known as hydrotreating, are used to eliminate oxygen molecules. After this purification step, hydrotreating is used to create a wide range of hydrocarbons, like aviation fuels (Chen et al., 2020).

3.4.5. HTL

Thermochemically, Hydrothermal liquefaction uses high temperatures between 250°C-375°C and pressured water at 4 Mpa - 22Mpa to transform biomass into liquid fuel sources (Gollakota et al., 2018). Algae, composts, wastewater sludge, and lignocellulosic-like corn stover biomasses are common examples of feedstocks employed in the HTL process (Castello et al., 2019). For the process of molecular breaking to take place, enough time must be allowed. Bio-crude, the resulting oil, has a high oxygen concentration that is eliminated during the hydrotreating process.

Distillation is used to separate the refined hydrocarbons into aviation fuel, diesel, as well as other byproducts.

3.4.6. Co-Valorization of Carbon Dioxide and Waste Biomass

Syngas high in carbon monoxide (CO) are created by the gasification of waste biomass, while syngas rich in hydrogen (H₂) are produced through the co-electrolysis of CO₂ and water in this path of development, providing a dual feedstock for F-T procedures (Zang et al., 2020).



4.1. Performance Criterion Selection, SAF Production Methods and Measures

The initial phase of the methodology entails identifying performance standards and their respective measurements for analyzing SAF production techniques. They are termed as alternatives under the multi-criteria decision-making problem. A summary of the 15 different production paths for SAF that the study found in the literature review is given (see Appendix - Table A1). Furthermore, an initial list of 45 performance indicators was found after reviewing scholarly articles on the social, economic, environmental, and technological elements of sustainable liquefied transport fuels (see Table A3 in Appendix).

According to the research of Markevicius et al. (2010), some rating factors are less important than others. Accordingly, the initial 45 criterion and 15 SAF production paths were reduced to 24 and 11. The research employs the approach presented by Kassem et al. (2016) using an online survey with biofuel/ airline fuel specialists adopting a value tree approach integrated into the Delphi technique, which constitutes a systematic multi-set procedure in response to generate better rates of acceptance among engaged participants (i.e., specialists and stakeholders) as well as a solidity measure related eliminated criterion (Kassem et al., 2016).

The value tree technique is enhanced with every cycle by utilizing a hybrid penalty-reward system that relies on selected aggregate metrics' cut-offs, including degree of importance and Degree of consensus index for all criteria. The degree of consensus index clusters participants' ratings into three groups expressing the levels of agreement amongst participants on the important rating, but the degree of significance index is simply a total of weighted participant assessments that considers the significance of every criterion by applying a five-point scale (Table 4.1).

Table 4.1. Consensus Level for Categories

Group	Description
A	No. of responses indicating important and extremely important
B	No. of responses indicating moderate
C	No. of responses indicating unimportant and avoidable

To elaborate, there is not any universally accepted cutoff for the Degree of consensus index and degree of importance index; nonetheless, after reviewing the available literature, the study settled on a 50% cutoff to refine the criterion for Sustainable aviation fuel production paths. The result was a list of 15 possible options to take and 39 criteria to meet. Moreover, professionals from bio-airline fuel manufacturers, airlines, academic institutions, regulatory agencies, and airline industry international organizations reviewed each criterion and method of production. Thus, the overall evaluation model included a total of 24 criteria, with 11 alternate paths to SAF production. Tables 4.2 and 4.3 outline the evaluable performance indicators associated with SAF production paths.

Table 4.2. Final Evaluation of Criterion and Codes

Category	Code	Criterion	Description
Social	Soc11	Traceability	Transparency of the whole manufacturing procedure from the raw materials to finished products.
	Soc12	Economical contribution	This signifies the establishment of new businesses, industrial areas, rural growth, etc.
	Soc13	Food safety	The effect of feedstock utilized to produce green fuel on food availability.
	Soc14	Social acceptance	Public opinion towards SAF production and utilization.
Environmental	Env1	Sustainability on feedstock	It signifies the continued availability of feedstock for green fuel production.
	Env2	Savings on GHG emissions	CO ₂ discharge levels compared to jet fuels.
	Env3	The impact caused by a change in land usage	SAF production changes land use directly and indirectly.
	Env4	Water and Soil pollution	Impact of using fertilizers and pesticides to produce biomass.

Table 4.2. (cont.)

Economic	Econ1	Alternative uses with feedstock	Other potential feedstock applications besides SAF production like electricity and biomethane.
	Econ2	Profitability of feedstock	Monetary benefits in generating a particular feedstock.
	Econ3	Minimal price for selling	Minimum selling price estimated for the SAF.
	Econ4	Input energy usage	Energy consumption during SAF manufacture.
	Econ5	Productivity of Land	Incorporation of short crop rotations or intensive farming methods.
	Econ6	Operational and maintenance costs	Operational and maintenance costs related to the SAF production plant.
	Econ7	Cost on feedstock	Costs of acquiring raw materials required for manufacturing of fuel.
	Econ8	Cost of plant capital	Construction-related costs of production and associated services.
Technical	Tech1	Blending limits	Amount of authorized alternative fuel that can be blended with standard jet fuels.
	Tech2	Compatibility with Standard jet fuels	Fuel characteristics, such as flashpoint, viscosity, density, and energy content, closely resemble those of conventional jet fuel.
	Tech3	Local technical capability	The availability of locally accessible production technologies.
	Tech4	Integration process	The capability of a production method to be integrated with established jet-fuel refinery infrastructures.
	Tech5	Maturity of process technology	The current stage of development for a workflow is either initial, demo, or else commercialized.
	Tech6	Method yield	Quantity of sustainable aviation fuel acquired via conversion method.
	Tech7	Scalability on production volume	Capability for future expansion of sustainable aviation fuel processing facilities
	Tech8	Composition and quality of feedstock	Quality of SAF batch

Table 4.3. Sustainable Aviation Fuel Production Paths Evaluated in This Research

Production method	Feedstocks	Code
Hydro processed Esters and Fatty Acids (HEFA)	Algae and microalgae	A 1
	Used cooking oils and animal fats	A 2
	Oilseeds	A 3
Fischer-Tropsch synthesis or gasification	Municipal solid wastes	A 4
	Wood residues and agricultural wastes	A 5
Devolatilization or Pyrolysis	Algae and microalgae	A 6
	Wood residues and agricultural wastes	A 7
Hydrothermal liquefaction (HTL)	Algae and microalgae	A 8
	Wood residues and agricultural wastes	A 9
Advanced fermentation	Wood residues and agricultural wastes	A 10
CO ₂ co-valorization and biomass waste	Combination of industrial waste gases CO ₂ and wood residues	A 11

4.2. Selection and Application of Expert Preference Data Extraction Approaches

To simulate experts' choices, this research had an interview with European aviation fuel supply chain experts to learn the relative significance they attach to different criteria. 22 experts were considered with more than 5 years of expertise in the field (Table A4). Research requires experts' assistance to make a logical decision on the selection of appropriate qualitative data collection procedure to implement (Lienert, et al., 2016; Ouenniche and Pérez-Gladish, 2018). Special consideration was given to experts' ranking or point distribution, as well as the analytical processes, respectively.

Four impactful criteria (social, environmental, economic, and technological) were ranked in relation to one another and given a total score out of 100. This was done because it was the most user-friendly option and could accurately indicate the weight each criterion had in relation to the overall objective and the preferences of the persons involved.

4.3. Selection of Ranking Structure for SAF Production Path and Its Application

Airline industry professionals used a simple ranking system to rate SAF manufacturing paths on every criterion. Due to the newness of this framework and the lack of data on these parameters, this study surveyed airline industry professionals to obtain data and decided to discrete values for each criterion except 1, which is evaluated on a continual range.

To improve the discriminatory power of ranking techniques, a numerical scale from 1 to 9 at a consideration of extremely poor, poor, average, good to excellent was proposed in a form respectively and then converted to a score out of 100 (see Table A2). The lack of SAF-specific data resulted in the use of a Likert-type scale to reduce the cognitive load on professionals while maintaining data availability.

4.4. Selection and Application of Ranking System on SAF Production Paths

This research aims to apply the PROMETHEE-2 approach, which was first introduced by Brans and Vincke (1985). Our selection of PROMETHEE-2 is focused on its capacity to utilize both qualitative and quantitative data for alternate assessment and its capacity to manage ambiguity in experts' opinions and grades depending on pairwise assessments of alternatives.

PROMETHEE-2 can be conceptualized as a modeling and key paradigm for MCDA difficulties in which the difficulty in deciding is modeled as a fully connected system where nodes are alternative and the arc reflects preferences relations among node pairs or alternatives (a, b) , like $\pi(a, b)$.

PROMETHEE-2 approach is especially useful when there are conflicting objectives and trade-offs to consider, making it applicable to a wide range of decision problems, These visuals can help decision-makers better understand the relationships between criteria and alternatives, This means that subjective judgments and expert opinions can be integrated into the model.

The alternative or node's strength a , which is called the net outranking flow, is written as $\phi(a)$ or $\phi_{net}(a)$, and it is calculated by deducting outward outranking flow $\phi^+(a)$ from inward outranking flow $\phi^-(a)$ i.e., $\phi_{net}(a) = \phi^+(a) - \phi^-(a)$. The answer to the question of rating a group of alternatives according to the MCDM approach is provided by arranging alternatives as per their strength in descending order as calculated through net outranking flows, ϕ_s . Following is a breakdown of the method in detail.

Input: Weighting scheme and the decision matrix

In PROMETHEE-2, the data is integrated into a decision matrix as depicted in Eq. 4.1 below.

$$DM = [c_1(a_1) \cdots c_n(a_1) \quad \vdots \quad c_1(a_m) \cdots c_n(a_m)] \quad (4.1)$$

where alternative set is denoted as $A = \{a_1, a_2, \dots, a_i, \dots, a_m\}$, and performance criteria set is considered as $C = \{c_1, c_2, \dots, c_j, \dots, c_n\}$. The alternative a_i 's performance on criterion j is indicated by $c_j(a_i)$ where; $i = 1, \dots, m$, and $j = 1, \dots, n$. After that, we obtain the comparative importance weight (w_j), of n^{th} performance criterion. $w_j = (w_1, w_2, \dots, w_n)$, where $j = 1, \dots, n$, it includes non-negative weights with $\sum_{j=1}^n w_j = 1$.

Step 1: For every alternative pair (a, b) on a criteria j , we calculate the difference of opinion in criterion j performance with respect to alternative a and b , represented as $D_j(a, b)$, (Eq. 4.2):

$$D_j(a, b) = c_j(a) - c_j(b), \quad j = 1, \dots, n \forall a, b \in A \quad (4.2)$$

Step 2: To find every alternative pair (a, b) for criterion j , the method calculates a local preference index $P_j(a, b)$, that considers the difference of opinion in performance of criterion j concerning alternative a and b that is calculated previously using step 1.

Brans and Vince (1985) highlighted the different preference index functions. This study adopts the type 1 general preference as given in Eq. 4.3.

$$P(D) = \begin{cases} 0, & D \leq 0 \\ 1, & D > 0 \end{cases} \quad (4.3)$$

Output: The concluding rating of each of the alternatives is determined based on the net ranking, $\emptyset_{net}(\cdot)$. That is, the higher the net ranking, the more desirable the alternative is.



CHAPTER V

RESEARCH FINDINGS AND ANALYSIS

This Chapter discusses the findings of the empirical study. Specifically, criteria weights derived from the proposed methodology are presented. Furthermore, the ranks of wider implications by category are shown, and these paths' local and global PROMETHEE-II ratings are given.

5.1. Weights of the Performance Criterion

Collected experts' opinions considering the criterion weights. The evaluations use the geometric means of all professionals' perceptions to avoid outliers. According to the findings, the economic and environmental classifications are the most crucial, with 31% and 28% of the total weight, respectively. The classification of technological criterion is the 3rd most significant, carrying 25% of the weight, while the classification of social criteria is the least significant, carrying 16% of relative weight. Local weights distinguish a criterion's significance in each input parameter. Food security is given the most weight (29.8%) in the societal impact category, followed by social acceptance (26.9%), economic contribution (23.3%), and traceability (20%).

Similarly, among environmental concerns, reduced greenhouse gas emissions are most prioritized by 36.6% of respondents, while reducing pollution to soil and water is ranked lowest by 17.5%. Professionals agree that MSP is the most significant criterion (17.8%). Regarding technical criteria, compatibility with standard aviation fuel is the most highly valued (18.7%), followed by domestic technical capability (8.6%). After that, the study calculates the overall weights of every criterion.

The relative weight of each impact category is multiplied by the local weight of the corresponding criterion to generate the final score. Examples include food security, which has a global weight of 4.8%, calculated by multiplying the local weights (0.298)

with the impact category's relative weight (0.16). Figure 5.1 summarizes global sets of criteria weights.

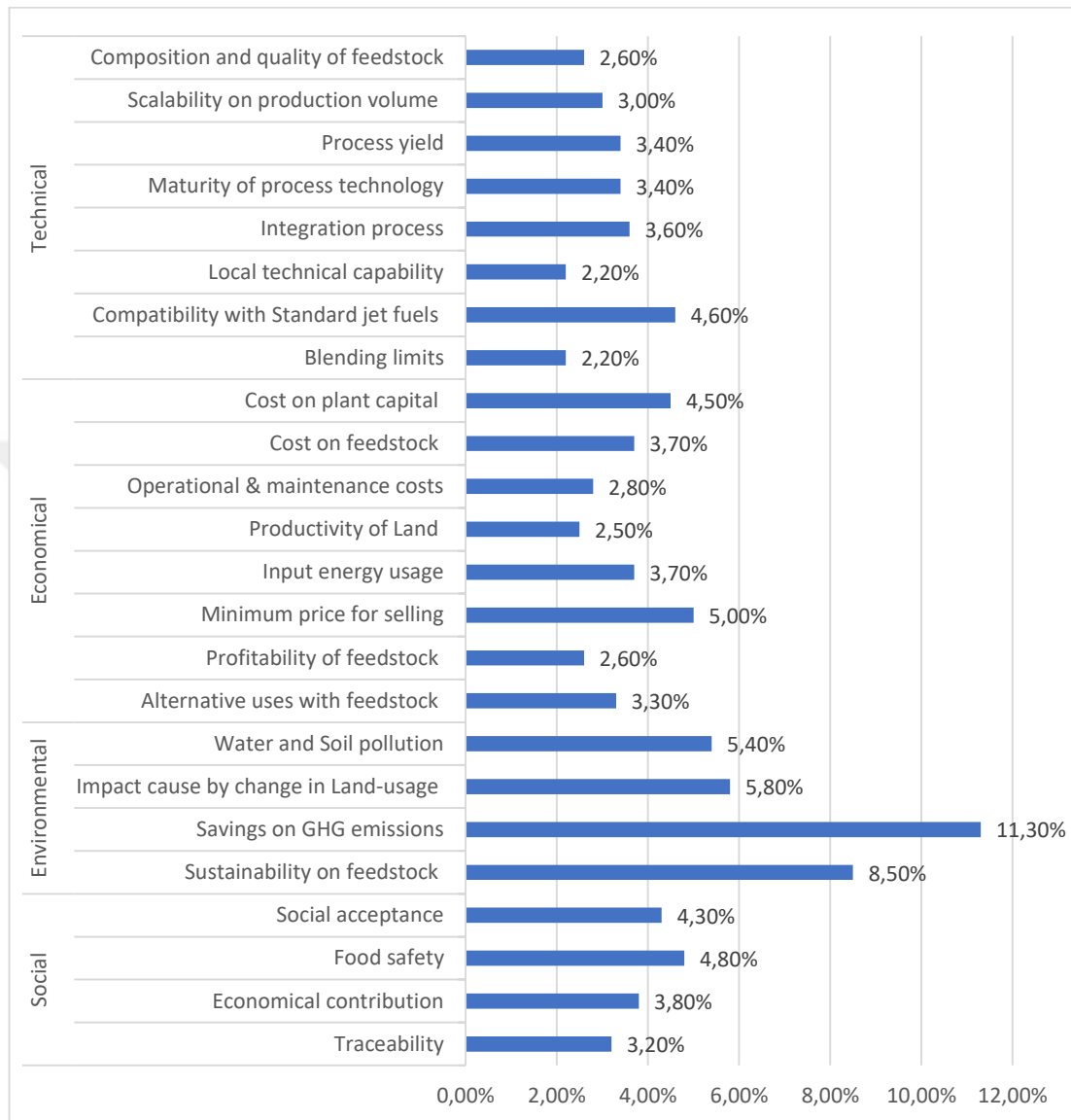


Figure 5.1. Global Weight of Selected Criteria

Reduction of greenhouse gas emissions is the crucial global criterion with 11.3%, backed with sustainable feedstock practices of 8.5% and change in land usage effect (5.8%). The highest 3 global criterion originates from environmental influence. This high priority from professionals makes sense, given that sustainable aviation fuels are promoted as a greener alternative to traditional aviation. The most significant criterion within the economic impact classification is the MSP weighted at 5%.

The global criterion weight values for food security and standard aviation fuel suitability show up at 4.8% and 4.6%, respectively, reflecting the importance placed on these factors concerning social and technical impacts.

The Principal Components Analysis (PCA) outcome is plotted on a 2D plan called “GAIA”. Utilizing the GAIA model, disagreement, commonalities, and interdependencies between criteria are evaluated. As the length of a criterion vector increases, it becomes more discriminatory. In this instance, a 24-D criterion is predicted, with 67.1 percent (Figure 5.2).

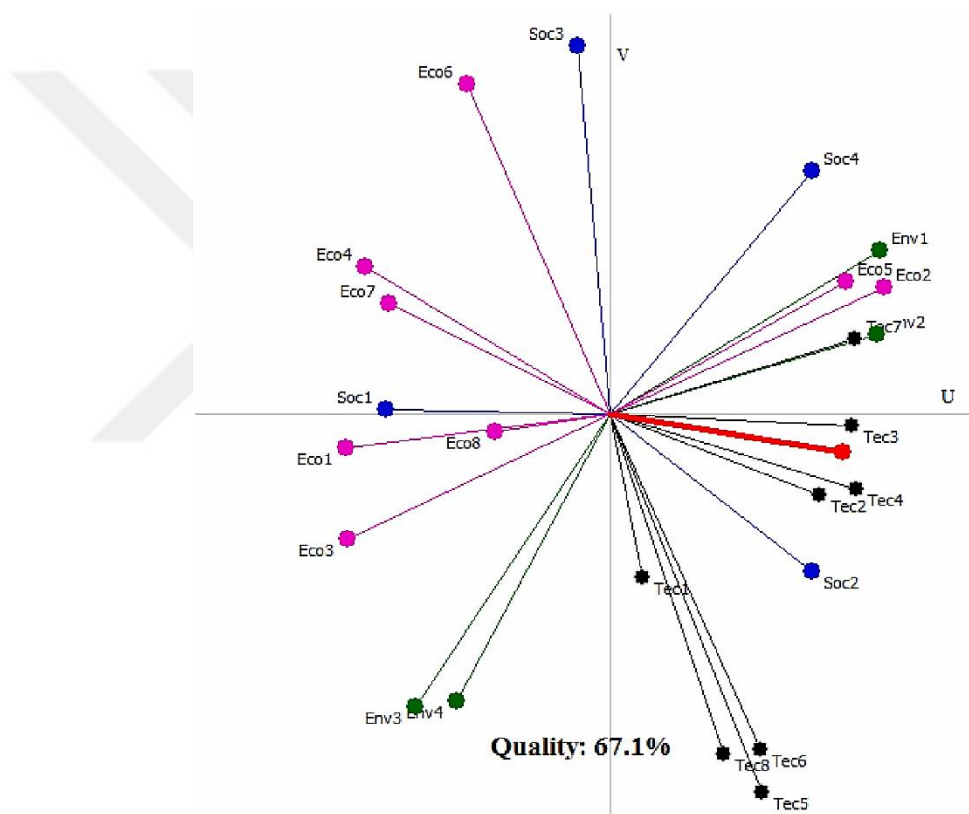


Figure 5.2. Graphical Representation of GAIA Plan for Selected Criteria

This shows that the information offered by the group of professionals is reliable. Criteria indicating competing values can be seen in the above graph (Figure 5.2). For instance, the profitability of feedstock (Econ2) and productivity of land (Econ5) are incompatible with alternate feedstock usage (Econ1), Minimum selling price (Econ3), and capital costs of the plant (Econ8). Identical preferences are indicated by vectors pointing toward the same direction.

Sustainability of feedstock (Env1) and Greenhouse gas emission saving (Env2) from environmental effect, whereas standard aviation fuel compatibility (Tech2), local technical capabilities (Tech3), and integration process (Tech4) have similar views. The most important factors to consider are food security (Soc13), the effect of land use changes (Env3), the operating costs and maintenance (Econ6), as well as the level of technological maturation in the procedure (Tech5). Tech5 is the only differentiating criterion on the decision axis along the vector line (Red).

The decision axis leads towards desired sustainable aviation fuel production paths not illustrated in Figure 3.6. Ultimately, standard aviation fuel adaptability (Tech2), and scalability of production volume (Tech7) are independent within the social, environmental, economic, and technological effect criteria as well as contributions to the economy (Soc12), public acceptance (Soc14), reductions in GHGs (Env2), the change in land usage effects (Env3), the operating costs and maintenance (Econ6) and productivity of land (Econ5). Due to competing requirements, selecting a suitable sustainable aviation fuel production path would be difficult.

5.2. A Single-Criterion Evaluation of Production Method

The best and worst sustainable aviation fuel production paths following a single criterion are summarized in Table 5.1. Using mono-criterion ratings allows one to evaluate how well a sustainable aviation fuel production path does concerning a specific performance measure. Furthermore, this research discusses the findings about the most crucial performance metric across every impact criteria category.

Food security is a key criterion for social effect. HEFA method using Algae and Microalgae (A1) is excellent, and HEFA using Oilseeds (A3) is the poorest. Even though paths A1 and A3 utilize HEFA as their primary transition method, their relative rankings are determined by the feedstock employed. Path A1 utilizes algae or microalgae as raw material which doesn't conflict with agricultural land and freshwater. Instead, it might be farmed offshore or using urban wastewater treatment plants.

A3 competes directly with the production of food as well as the utilization of cropland because it relies on oilseeds for feedstocks. Therefore, this production method is the lowest preferred option. When considering the environmental impact, A11 reduces the most GHGs, whereas A3 saves the lowest. Because of its superior emission reductions compared to A3, A11 is favored. This is because it uses direct CO₂ and CO from waste operations. The utilization of wood waste is a preferable feedstock over oilseeds for reducing lifecycle GHG emissions.

Considering the cost of SAF, which is two to three times higher than the regular HEFA production method using Algae and Microalgae (A1), the pricing becomes an important aspect. Analysis based on a single criterion indicates that manufacturing path A3 achieves the lowest Minimum selling price like A2; however, A11 tends to be the least preferred option. HEFA manufacturing paths typically result in a lower Minimum selling price when compared to gasification or F-T synthesizing. Regarding technological impact, A5 is the best SAF production path for compatibility with standard aviation fuel, whereas A1 is the most undesirable SAF production path.

Both A1 and A3 produce sustainable aviation fuels as alternatives for jet A. However, professionals prefer gasification or F-T synthesizing (A1 approach) to HEFA (conversion method utilized in the A3 path). Municipal solid wastes may be a better feedstock for sustainable aviation fuels than algae and microalgae. Contradictory ranks across criteria are a shortcoming of Uni-dimensional or mono-criterion ratings.

A11 provides the greatest GHG emission savings but is the most expensive option, as seen by its low minimum selling price. In contrast, A3 gives the least greenhouse gas emission savings and the best minimum selling price value among production paths. This scenario is a challenge for decision-makers. When all criteria are considered at once, they would not be capable of making a well-informed decision about which sustainable aviation fuel production path performs best. Additionally, ties can occur between alternatives when using a Uni-dimensional rating system. A8-A9 and A1-A2 are identical in blended limit criteria and feedstock sustainable development. Many sustainable aviation fuel production paths have common societal, environmental, economic, and technological considerations. The study evaluates different criteria in every impact area to avoid mixed performance outcomes and identical rankings or ties.

In the below section, the study discusses the summary of sustainable aviation fuel production methods in terms of societal, environmental, economic, and technological impacts.

Table 5.1. Criterion-Based Ratings of Sustainable Aviation Fuel Production Methods

Criterion	Rank order (worst to best)										
<i>Social criteria</i>											
Traceability	A4	A10 A5		A8	A 7	A11 A6		A3 A2		A9	A1
Economical contribution	A9	A6	A1	A8	A 7	A3	A1	A2	A11	A5	A4
Food safety	A3	A8 A7		A10 A5		A6	A2	A11 A9 A4			A1
Social acceptance	A3 A1		A2	A6	A10 A5		A7	A9 A8		A4	A11
<i>Environmental criteria</i>											
Sustainability on feedstock	A3	A2	A1	A9 A6		A10	A7	A8	A4	A5	A11
Savings on GHG emissions	A3	A9	A6 A1		A2	A10 A8		A7	A4	A5	A11
Impact via the change in land usage	A4	A11	A5	A6	A7	A9	A8 A2		A1	A1 0	A3
Water and Soil pollution	A3	A1 A2		A10 A8		A4 A7		A6	A5	A11	A9
<i>Economic criteria</i>											
Alternative uses with feedstock	A5	A11	A8	A7	A 4	A2	A1 0	A9	A6	A1	A3
Profitability of feedstock	A3	A1	A2	A9	A 6	A17	A1 0	A8	A5	A4	A1 1

Table 5.1. (cont.)

Minimal price for selling	A11	A5	A4	A10 A8	A7	A6 A1	A9	A2	A3		
Input energy usage	A5	A8	A11	A10 A7	A4 A3	A9	A6	A2	A1		
Productivity of Land	A3	A1 0	A1	A9	A6 A2	A7	A4	A8	A1 1	A5	
Operational and maintenance costs	A5	A11 A3	A2	A 8	A7	A9	A4	A10 A6	A1		
Cost on feedstock	A5	A7	A11	A1 0	A 2	A6	A4	A8	A3	A9	A1
Cost of plant capital	A1 1	A1 0	A9	A6	A 5	A8	A3	A4	A7 A1	A2	
Technical criteria											
Blending limits	A9 A8 A7 A6			A 10	A11 A5 A4 A3 A2 A1						
Compatibility with Standard jet fuels	A1	A7	A9 A3	A 8	A6	A2	A11	A4	A1 0	A5	
Local technical capability	A1	A9	A3	A2	A 6	A8	A7	A11 A5	A4	A1 0	
Integration process	A1	A9	A10	A2	A 6	A3	A7	A8	A11 A4	A5	
Maturity of process technology	A1	A9	A6	A8	A7 A2	A4	A1 1	A5	A10 A3		
Method yield	A1	A4	A6	A9	A10 A7	A8 A3	A5 A2	A1	A1		
Scalability on production volume	A3	A2	A6	A1	A 9	A4	A8	A7	A10	A5	A11
Composition and quality of feedstock	A4	A1	A2 A6 A7	A9	A8	A1 0	A5	A3	A1 1		

5.3. Evaluation of Sustainable Aviation Fuel Production Methods Based on Impacting Criteria

Initially, utilizing weight vectors of 0.200, 0.233, 0.289, and 0.269 for social criterion, the study ranked SAF production methods as illustrated in Figure 5.3 from the public standpoint representing social-oriented stakeholders – for example, govt. entities and non-profit organizations reflect public welfare. Relying on production paths, gasification, or Fischer Tropsch synthesizing procedures, i.e., A4 and A11 ranked higher when compared to HEFA methods, A1 and A2.

The usage of wood residue as a feedstock is favored over the use of algae or microalgae. This is reasonable, considering that the wood residue and municipal solid waste supply chain and marketplace are mature and accepted by the public. Nevertheless, a lack of data on potential customers and familiarity with ideal cultivation techniques, among other obstacles, have been recognized as impediments to the social adoption of algae and oil seeds.

However, most airlines worldwide have utilized or are employing HEFA, and discarded cooking oil and animal fats-derived sustainable aviation fuel, making A2's 5th place in the social effect category seem even more surprising. This demonstrates the absence of public participation on the part of airlines and SAF producers regarding their projects, which would lead to the higher social acceptability of SAFs. Using the weight vector 0.273, 0.366, 0.187, and 0.175 for environmentally oriented stakeholders - for example, climate advocacy parties, global regulatory bodies, etc.), the study ranked SAF production paths as illustrated in Figure 5.3.

A11 has the best environmental performance due to its use of confined CO₂, preceded by methods A5 and A8, whereas A6, A3, and A9 show the poorest environmental performances, especially in comparison to oily biomass, gasification, or F-T synthesis-related production methods utilizing collected CO₂ and wood residues or agricultural wastes demonstrating greater environmental benefits. This is because of the extensive use of fertilizers and emissions from cultivation processes in the production of algae as well as microalgae and oilseeds.

Both A8 and A9 utilize HTL as a transition method, yet their respective feedstocks are algae, microalgae wood residues, or agricultural wastes. This preference for algae and microalgae is owing to their faster rates of growth, which result in greater Carbon sequestration, greater yield per landmass, and fewer requirements for fertile ground. Therefore, HTL from algae or microalgae is more environmentally friendly than HTL from other terrestrial feedstock choices.

Economic preferences offer the viewpoint of commercially driven stakeholders (for example, SAF producers, commercial airlines, as well as feedstock suppliers). These parties are involved in analyzing the fiscal benefits of generating SAF through a certain route. Figure 5.3 summarizes the ratings according to the economic criteria weight vector 0.117, 0.092, 0.178, 0.132, 0.090, 0.098, 0.132, and 0.159.



Figure 5.3. Impact of Category-Wise SAF Production Method Ranking

The best 3 Sustainable aviation fuel production paths are revealed to involve chemical mixing procedures for fuel generation. Nevertheless, gasification or Fischer Tropsch synthesis, i.e., A4, A5, and A11, predominates the rest. This circumstance demonstrates a chemical procedure and utilizes feedstock. The relative cost rating SAF production methods A2 and A3 both utilize the HEFA method with distinct feedstocks,

which supports this conclusion. MSW and wood residue or agricultural waste are favored over oily biomass because of their considerably lower cost (A3).

The A6 and A7 Sustainable aviation fuel production paths are roughly similarly regarded. Compared to HEFA-based procedures, the preference for gasification or F-T synthesis contradicts the Minimum selling price's most critical economic effect criterion. Sustainable aviation fuel price is calculated to be \$0.67 - \$1.25 per liter for HEFA produced from waste oilseeds, \$0.78 - \$1.43 per liter for HEFA produced from animal fats, and \$0.96 - \$1.38 per liter for gasification or Fischer Tropsch synthesizing of municipal solid waste (Bann et al., 2017).

The economic performance of HEFA-related fuel production methods is higher when compared with gasification or Fischer-T synthesis-based alternatives (Chu et al., 2017; Janic, 2018). The economic performance derived from the net present value of HTL-based methods is rated lower by Bann et al. (2017). However, this study ranks production method A8 higher than HEFA and Fischer-T synthesis or gasification apart from production method A4. HTL-based techniques can be utilized for SAF generation in the future. Regarding technical analysis, the sustainable aviation fuel production methods are ranked using the following weight matrix; 0.086, 0.186, 0.086, 0.143, 0.137, 0.134, 0.121, 0.104. The figure below presents the rating of sustainable aviation fuel production methods; A5, A10, and A11 are the 3 highest-ranked production options. Production method A5 is developed on gasification or F-T synthesis; it has a high Sustainable aviation fuel yield and is more developed than method A10, whereas method A11 is less developed and has a lower technical readiness status.

However, regarding technological ability, A1 is the least desirable of the production routes, following A9 and A6. Because of the elevated water and oxygen concentration in the biocrude oil generated, A1 and A6 with algae or microalgae have a reduced sustainable aviation fuel yield. According to research data, A6 has a superior production method than A9. This result contradicts earlier studies that showed HTL (A9) is superior to pyrolysis (A6) for most biomass materials, including wood residues. Moreover, biomass pyrolysis and gasification technologies are currently available on the market, although biomass HTL remains in the early stages.

5.4. SAF Production Methods and Global MCDA Ratings

The study utilizes the PROMTHEE-II to evaluate the eleven sustainable aviation fuel production methods considering 24 criteria in depth. Table 5.2 lists every production process's outgoing and incoming flows, whereas Figure 5.4 depicts the net flows and ranks. Only SAF production methods with favorable outranking flow are discussed here. These production paths provide a compelling commercial basis for investment activities in the future and regulatory improvements.

Table 5.2. Inflow and Outflow in Sustainable Aviation Fuel Production Methods

Production method	Code	Feedstocks	Inflow	Outflow	Net Phi
Hydro processed	A 1	Algae and Microalgae	0.442	0.518	-0.077
Esters and Fatty Acids (HEFA)	A 2	Animal fats or Used cooking oils	0.487	0.465	0.023
	A 3	Oilseeds	0.423	0.534	-0.112
F-T synthesis or gasification	A 4	Municipal solid wastes	0.583	0.386	0.198
	A 5	Wood residues and Agri wastes	0.552	0.423	0.130
Devolatilization or Pyrolysis	A 6	Algae and Microalgae	0.375	0.582	-0.208
	A 7	Wood residues and Agri wastes	0.446	0.517	-0.072
Hydrothermal liquefaction (HTL)	A 8	Algae and Microalgae	0.483	0.464	0.020
	A 9	Wood residues and Agri wastes	0.380	0.584	-0.205
Advanced fermentation	A 10	Wood residues and Agri wastes	0.509	0.447	0.063
CO ₂ co-valorization and biomass waste	A 11	Combination of Industrial waste gases CO ₂ and wood residues	0.605	0.365	0.25

Figure 5.3 shows that Method A6 has the lowest outranking flow of all Sustainable aviation fuel production methods, with a value of 0.207, and A9 and A3 are the next two extremes, with values of 0.2045 and 0.111 accordingly. The A11 production method has a total outranking flow of 0.240, greater than all other methods. The fact that the highest-ranked production methods, A4, A5, and A11, are gasification or

Fischer-T synthesis procedures demonstrates that professionals acknowledge that they are the most appropriate methods for Sustainable aviation fuel production. Syngas, the primary constituent of gasify or Fischer Tropsch synthesis, is produced from Municipal Solid wastes, wood residues, and Agri wastes, all of which are inexpensive feedstock. This offers gasification or Fischer-T synthesis-related production methods a strategic benefit by offsetting its higher capital costs and smaller production scale in comparison to HEFA methods (Neuling and Kaltschmitt, 2018).

Besides gasification or Fischer-T synthesis, the study indicates that A10, which is advanced fermenting, is the second-best method. In contrast to the existing research, which claims that advanced fermenting (DSHC and ATJ) related methods are constrained in feedstock sustainability and incapable of reaching the commercial development stage, the results presented here appear plausible. Nevertheless, it might be challenging to scale up the advanced fermented production process. Figure 5.5 illustrates that A10 ranks comparatively higher because of its superior overall technical and environmental attributes.

Although A8 (HTL methods with algae or microalgae) scored higher than A2 (HEFA using waste cooking oils or animal fat), this production method's possible capacity expansion is constrained by the availability of inputs. Eventually, other options outperform A6 and A9 (production method using pyrolysis and HTL, respectively). These outcomes are constant with relevant research on biofuel generation technologies (Fiorese et al., 2013). According to their study of industry professionals, gasification or Fischer-T synthesis and oil-based methods, including HEFA, Pyrolysis, and HTL, were the most common production methods.

The optimal feedstock for SAF production is the direct transition process of CO₂ to SAF (A11) in the gasification or Fischer-T synthesis group. This might be the case since experts believe that CO₂ extraction from industrial technologies is a more direct way than employing MSW (A4), wood residues, and agricultural waste (A5). The reduction in Greenhouse gas emission by using landfill gas to counterbalance the use of fossil fuels has been dropped even though converting MSW into biofuel prevents Greenhouse gas emission that derives waste in landfills and incinerating processes (Suresh et al., 2018).



Figure 5.4. MCDM Ranks Sustainable Aviation Fuel Production Methods

According to a feedstock evaluation, agricultural waste and wood byproducts are favored above algae or microalgae due to their lack of familiarity as a viable feedstock as well as the increased pre- and post-procedure requirement can be one probable factor (IRENA, 2016). Likewise, research data implies that agriculturalists are still considering oilseeds as an unfeasible option, and they appear to be involved in the food vs. fuel war.

5.5. A Ranking of SAF Production Methods Using PROMETHEE Group's Decision Support System

The overall rating of sustainable aviation fuel production methods was described in the prior section. The analysis is furthered by comparing each professional's 8 preferences to identify inconsistencies. This is done by doing a separate PROMETHEE-GAIA study for every professional to identify any possibility of conflicts. After that, the research combines all to get a worldwide ranking and utilizes the GAIA plan to analyze the various expert viewpoints.

The differing opinions of experts regarding the rank of SAF production methods are depicted in Figure 5.5. Notably, each SAF production method is displayed as points, whereas each professional's preference is shown as an 'E'-labeled vector. The red arrow represents the decision axis, which indicates the optimal production method's direction (A11, A4, and A5) and is distant from the lowest possibilities (A6, A9, and A3). When it comes to the decision axis, not every possible production method succeeds from every potential professional's perspective. There is a clustering of

inclination toward several production methods. Nine professionals E5, E8, E11, E13, E17, E19, E20, E21 prefer A1 and A2 for Sustainable aviation fuel production methods, whereas A11, A4, and A5 are favored by the others. This differentiation can be due to the unique experience of the experts.

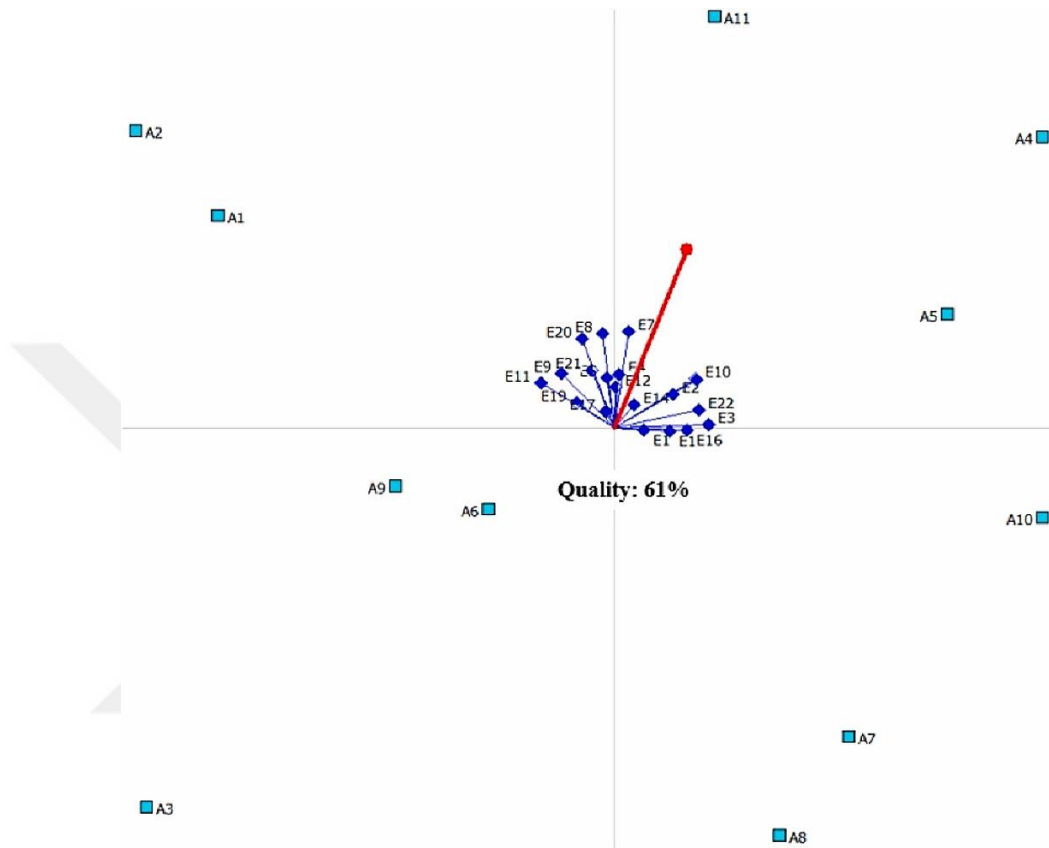


Figure 5.5. GAIA Graph on Global Ranking of Sustainable Fuel Production Method

5.6. Analysis of Sensitivity

To confirm the validity of the chosen alternates, it is crucial to evaluate the result's reliability. To do this, a sensitivity study is carried out and the initial rankings of the alternative solutions are verified. Two different strategies were used to achieve this goal:

- i. Modify the weight of the criterion, use PROMETHEE to verify the rank, and
- ii. Compare and confirm the SAF production method ranking using two additional MCDM techniques.

5.6.1. Tests on Criteria Weights

To evaluate the impacts of varying criteria weights on alternative rankings, this research considers four scenarios:

- i. Pessimistic (considering the weights assigned to each stakeholder's least criteria)
- ii. Likely (based upon the average weights of criteria),
- iii. Optimistic (considers the highest weight of criteria obtained at the interview)
- iv. Neutral (assuming all criteria are equally weighted).

To determine the amount to which decision-makers' preferences will influence the previously stated results, this study assumes that every criterion has equal value and assigns every one of the 24 criteria a weighted sum of 4.2%. This research has been designated as neutral. In all studies reviewed, SAF method A11 obtains the highest rating in all four tests, accompanied by A4 at 2nd position 3 times and A5 at 3rd position 3 times, according to the findings of the sensitivity assessment shown in Figure 5.6.

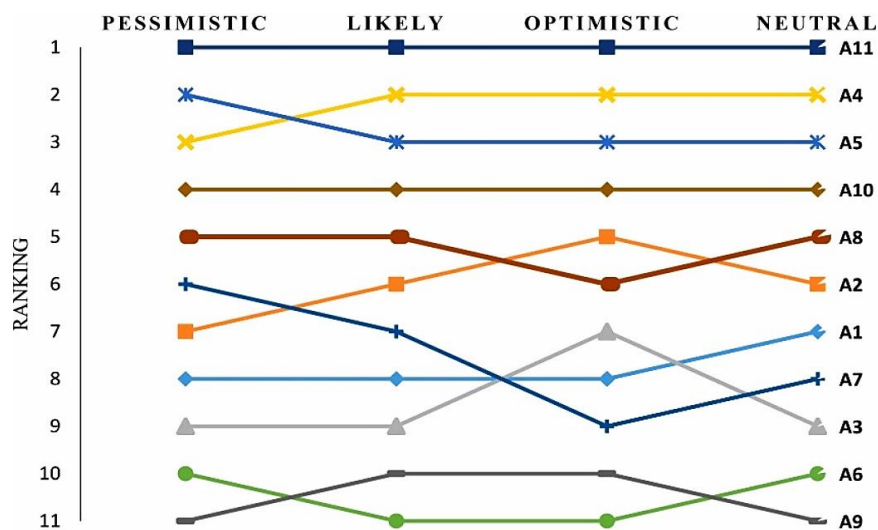


Figure 5.6. Sensitivity Analysis Results

According to the research, the best and poorest-performing production method's ranks did not significantly shift after the weights were changed to an equivalent weighting factor. This indicates that the results are reliable and resistant to changes in the weight of the input criteria. Thereby, the SAF production methods rankings can be trusted.

5.6.2. Comparison of MCDM Methodologies

To compare the results of the ranking, this study utilized two alternative MCDM methodologies: TOPSIS and VIKOR. To account for the unpredictability of professional preferences, the research adopts the fuzzy version of the TOPSIS and VIKOR approaches, as shown in Figure 5.7 (Awasthi et al., 2018).

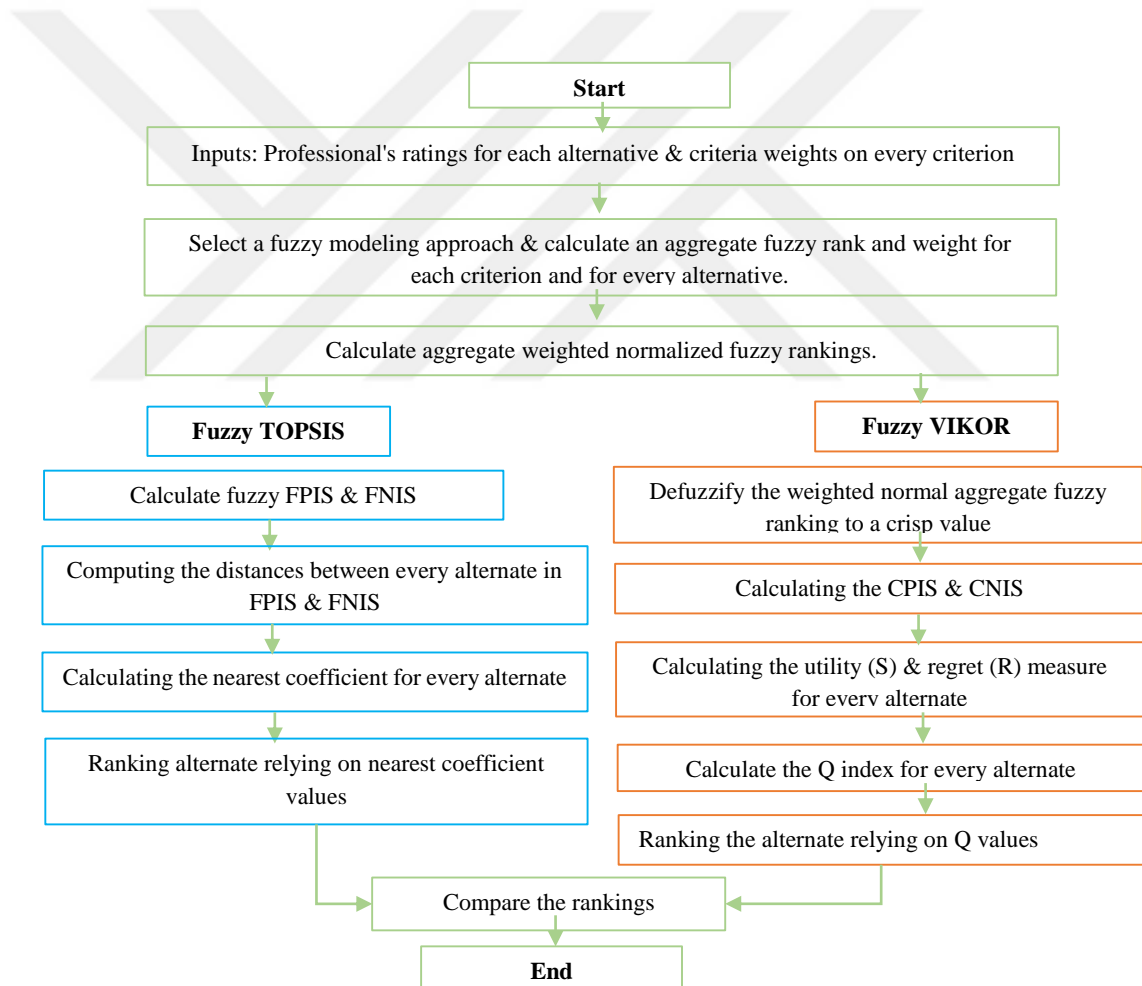


Figure 5.7. The Flowchart on Fuzzy Multicriteria Decision Method

A summary of detailed implementation information for the formulations of fuzzy TOPSIS and VIKOR analysis is shown below:

Inputs: The ranking done by the K professionals of m alternatives with n criteria is denoted with x_{ij}^k ; where $i = 1, \dots, m$, and $j = 1, \dots, n$, and $k = 1, \dots, K$ and every professional's given weight for every criterion is w_j^k ; where $j = 1, \dots, n$, and $k = 1, \dots, K$.

Step 1: Choosing a proper modeling context and computing the aggregated fuzzy rankings for every alternative and weights on every criterion. Utilizing fuzzy triangular numbers to develop the fuzzy data is easier and more common, whereas this study relates to the rankings. Hence, for every alternative " i " ($i = 1, \dots, m$) and criteria " j " ($j = 1, \dots, n$), the rankings by K professionals are combined to singular triangle fuzzy rankings, assume $\tilde{x}_{ij} = (a_{ij}, b_{ij}, c_{ij})$, like:

$$a_{ij} = \min_k \{x_{ij}^k\}; b_{ij} = \frac{1}{K} \sum_k x_{ij}^k; c_{ij} = \max_k \{x_{ij}^k\}$$

Likewise, compute the aggregated fuzzy weights for all criteria j ($j = 1, \dots, n$), assume $\tilde{w}_{j,1} = w_{j,1}, w_{j,2}, w_{j,3}$, like:

$$w_{i,1} = \min_k \{w_j^k\}; w_{j,2} = \frac{1}{K} \sum_k w_j^k; w_{j,3} = \max_k \{w_j^k\}$$

Summarize aggregate fuzzy rankings as a decision matrix and fuzzy weight as vector criterion.

Step 2: Computing weighted normal aggregate fuzzy rankings, assume \tilde{n}_{ij} where $i = 1, \dots, m$ and $j = 1, \dots, n$, like:

$$\tilde{n}_{ij} = \tilde{w}_j \otimes \left(\frac{a_{ij}}{\max_i}, \frac{b_{ij}}{\max_i}, \frac{c_{ij}}{\max_i} \right) = \left(w_{i,1} \frac{a_{ij}}{\max_i}, w_{i,2} \frac{b_{ij}}{\max_i}, w_{i,3} \frac{c_{ij}}{\max_i} \right); \text{ where, } i = 1, \dots, m \text{ and } j \in C^+$$

$$\tilde{n}_{ij} = \tilde{w}_j \otimes \left(\frac{\min_i}{a_{ij}}, \frac{\min_i}{b_{ij}}, \frac{\min_i}{c_{ij}} \right) = \left(w_{i,1} \frac{\min_i}{a_{ij}}, w_{i,2} \frac{\min_i}{b_{ij}}, w_{i,3} \frac{\min_i}{c_{ij}} \right); \text{ where, } i = 1, \dots, m \text{ and } j \in C^-$$

where C^- (respective C^+) indicates cost criterion set (respective benefit criterion) in which low values (respective high values) is better.

Based on the values obtained at this step, fuzzy TOPSIS follows the steps below.

Step 3: Computing the Fuzzy positive and Negative ideal solutions (FPIS and FNIS) accordingly assuming \tilde{n}^+ and \tilde{n}^- , like:

$$\tilde{n}_j^+ = \left\{ \begin{array}{l} \min_{i=1, \dots, m} \tilde{n}_{ij} \text{ IF } j \in C^- \\ \max_{i=1, \dots, m} \tilde{n}_{ij} \text{ IF } j \in C^+ \end{array} ; j = 1, \dots, n \right.$$

$$\tilde{n}_j^- = \left\{ \begin{array}{l} \max_{i=1, \dots, m} \tilde{n}_{ij} \text{ IF } j \in C^- \\ \min_{i=1, \dots, m} \tilde{n}_{ij} \text{ IF } j \in C^+ \end{array} ; j = 1, \dots, n \right.$$

Step 4: Computing the distances i.e., $d(i, \tilde{n}^+)$ and $d(i, \tilde{n}^-)$ between every alternate i in FPIS (\tilde{n}^+) and FNIS (\tilde{n}^-). Where, $i = 1, \dots, m$:

$$d_i^+ = \left\{ \frac{1}{n} \sum_j (\tilde{n}_{ij} - \tilde{n}_j^+)^2 \right\}^{\frac{1}{2}}$$

$$d_i^- = \left\{ \frac{1}{n} \sum_j (\tilde{n}_{ij} - \tilde{n}_j^-)^2 \right\}^{\frac{1}{2}}$$

Step 5: Choosing the similar scores, which is also known to be the closest coefficient for every alternate i ($i = 1, \dots, m$) as shown below:

$$S_i^- = d(i, \tilde{n}^-) / (d(i, \tilde{n}^-) + d(i, \tilde{n}^+))$$

Step 6: Ranking the alternate in ascending order concerning their similarities in the ranks. Hence, the effective alternate method is distanced from FNIS and nearest to the FPIS.

Alternatively, fuzzy VIKOR determines the optimal ranking based on the following procedure.

Step 3: Defuzzification of the weighted normal aggregate fuzzy rankings, i.e., \tilde{n}_{ij} ($i = 1, \dots, m; j = 1, \dots, n$) as crisp value by considering n_{ij} , as shown below:

$$n_{ij} = \frac{1}{6} \left(w_{j,1} \frac{a_{ij}}{\max_i}, 4w_{j,2} \frac{b_{ij}}{\max_i}, w_{j,3} \frac{c_{ij}}{\max_i} \right); \text{ where, } i = 1, \dots, m; \text{ and } j \in C^+$$

$$n_{ij} = \frac{1}{6} \left(w_{j,1} \frac{\min_i}{a_{ij}}, w_{j,2} \frac{\min_i}{b_{ij}}, w_{j,3} \frac{\min_i}{c_{ij}} \right); \text{ where, } i = 1, \dots, m \text{ and } j \in C^-$$

Step 4: Computing the CPIS considering n^+ Moreover, calculating the rating as shown below:

$$n_j^+ = \left\{ \min_{i=1, \dots, m} n_{ij} \text{ IF } j \in C^- \quad \max_{i=1, \dots, m} n_{ij} \text{ IF } j \in C^+ \right\}; \text{ where, } j = 1, \dots, n$$

Step 5: Calculate the performance marks i.e., Q_i for every alternate i , where; ($i = 1, \dots, m$):

$$Q_i = \alpha \left(\frac{S_i^- - S^+}{S^- - S^+} \right) + (1 - \alpha) \left(\frac{R_i^- - R^+}{R^- - R^+} \right); 0 \leq \alpha \leq 1$$

Where,

$$S_i = \sum_{j=1}^m (n_j^+ - n_{ij}); R_i = \max_j \{(n_j^+ - n_{ij})\}$$

$$S^+ = \min_i S_i; S^- = \max_i S_i; R^+ = \min_i R_i; R^- = \max_i R_i$$

Consider $\alpha = 0.5$

Step 6: Ranking the alternate methods according to their performance in descending order. Hence, the superior alternate method holds the lowest value.

The rank order produced with TOPSIS and VIKOR using fuzzy methodologies is shown in Table 5.3. Here, A4 and A5 were consistently placed in the highest 3 by both techniques. However, A6 and A9 were consistently ranked in the lowest three.

Nevertheless, due to variations in the theoretical basis of both methods, the rank given to A3 and A11 in both methodologies are distinct.

Table 5.3. Fuzzy VIKOR and TOPSIS for Sustainable Fuel Production Method Ranking

		Alternate rank order										
		▼Poor						Strong				
	VIKOR	A3	A9	A6	A8	A7	A11	A10	A1	A2	A5	A4
	TOPSIS	A9	A6	A7	A8	A3	A10	A2	A1	A5	A4	A11

In addition, this research investigates the correlation between the rankings produced by the three MCDM methodologies utilized for this research.

Table 5.4. Correlation Coefficients of Ranking Method

		PROMETHEE-II	Fuzzy	
			T	V
PROMETHEE-II		1		
Fuzzy	T	0.928	1	
	V	0.674	0.746	1

* Correlation coefficients are statistically significant on 0.01.

A correlation study of Spearman's rho shows a strong positive relationship at 0.928 between the PROMETHEE ranking and fuzzy TOPSIS and a minimal but still significant relationship at 0.674 between the PROMETHEE ranking and fuzzy VIKOR (Table 5.4). Overall, it can be concluded that the rankings are trustworthy and solid.

CHAPTER VI

CONCLUSION

The airline industry's efforts to reduce CO₂ emissions and find new sources of jet fuel have the chance to benefit significantly when using sustainable fuels in aviation. SAF could be produced in various methods, making choosing a particular route a challenging strategic choice. Utilizing TEA or LCA research, the existing literature compares the effectiveness of one or more methods. This study proposed a comprehensive assessment approach for the SAF selection problem.

6.1. Theoretical Implications

To close this gap, this research used a stakeholder engagement strategy to collaborate with professionals to create a comprehensive structure based on evaluation criteria including societal, environmental, economic, and technological factors. To determine the most important factors for investment/production/purchase/usage of SAF, this study created a questionnaire to obtain stakeholders' opinions. In-depth conversations with industry professionals confirmed the criterion. Industry professionals were given another form to rate SAF production methods according to a performance criterion. Data is validated using fuzzy TOPSIS and fuzzy VIKOR and PROMETHEE to reduce professionals' judgmental personal prejudice.

6.2. Practical Implications

The analysis concluded that economic and environmental considerations outweigh technological and social considerations. The focus on these two groups is logical given that SAFs are marketed as having less harmful environmental consequences than normal Jet-A fuel yet serve as a more expensive alternative. Greenhouse gas reductions, sustainability on feedstocks, minimum selling price, compatibility of jet fuel, and traceability of sustainable aviation fuel are the essential performance factors

for rating their production methods. A comparison of sustainable production methods based solely on one criterion reveals that no single production method dominates the 24 assessment criteria. In addition, various results are observed when examining each effect category separately in mono-criteria rankings. HEFA-based output scores highest in economic effects. This conclusion should be interpreted cautiously, as HEFA appears to be a viable opportunity among the remaining 3 impact categories. According to global rankings, gasification or Fischer-T synthesis, advanced fermentation, and hydrothermal liquefaction are the top conversion processes for SAFs. Although technologically developed and frequently used commercially, HEFA-based procedures are less desirable. It is noticeable that collected waste from gas, wood, and farms is superior feedstock when compared to algae or microalgae and purpose-grown seeds that are non-edible for oil extraction.

Animal fats or used cooking oil varieties are additional enticing options, but their restricted availability prevents them from increasing SAF production. The findings suggest integrating/designing/modifying the waste gases and leftovers supply chain for Sustainable aviation fuel production. The SAF production method analysis and ranking approach aid policymaking. A nation's technical, feedstock, and economic conditions must guide SAF production methods.

Some countries, like Brazil, make SAF from sugarcane, whereas the United Kingdom has found that municipal solid waste and agricultural waste make the best feedstock for making SAF. To secure a consistent supply of raw materials to produce SAF, feedstock suppliers might receive monetary benefits. An improved feedstock supply chain will assist in minimizing the unpredictability in the production of SAF and ensure commercial stability for both feedstock providers and the SAF production companies. Technology-wise, strengthening SAF production paths and RandD capacities will boost economic competitiveness and the bio-economy. These competencies would be sold to other countries.

In addition, as indicated in the research, the plant capital investment of the SAF production method is a critical factor. In this regard, it is recommended to simplify and underwrite debt or equity funding by state governments. This scenario will increase the trust of private capitalists, allowing new investors and establishing refineries

providing biofuel for road transportation to incorporate SAF into their business models. The results of this research may also be used to develop policy choices such as production or buying quotas from a particular SAF production method, taxes on standard jet fuel (creating a comparable environment for that SAF production method), including subsidies for sustainable production of aviation fuels.

In addition, as indicated by Larsson et al. (2019), SAF production can be regarded as a catalyst for creating national climate change policies. In conclusion, it is anticipated that policymakers and decision-makers will consider the research results when investing or making a policy decision about SAF production methods. These findings raise new research questions. For instance, it could be intriguing to examine conflicts across all the societal, economic, technological, and environmental criteria. It is also intended to integrate more synthetic methods for SAF production and a range-based technique to investigate ranking distribution.

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APPENDICES

APPENDIX A

List of Sustainable Aviation Fuel Production Methods

Production Methods	Feedstock (Non-food)
Hydro processed Esters and Fatty Acids	Algae or Micro-algae
	Yellow grease
	Animal fat - Tallow
	Soybean
Gasification or Fischer-Tropsch Synthesis	Municipal solid wastes
	Wood residues or Agri waste
Pyrolysis	Algae or Micro-algae
	Corn stover
	Wood residues or Agri waste
HTL	Algae or Micro-algae
	Wood residues
Alcohols to Jet	Wood residues
	Wheat straws
Direct Sugars to Hydro-Carbon	Wheat straws
Co-valorization of carbon dioxide and biomass wastes	Industrial waste CO ₂ gases and Wood residues

Ranking form for production methods

Production methods		Ranking					
		1	2	3	4	5	6
HEFA with used cooking oils and Animal fats	A2					✓✓	✓✓✓
F-T synthesis or gasification with MSW	A4		✓✓ ✓	✓			
F-T-synthesis/gasification with Wood residues and Agricultural wastes	A5		✓	✓✓ ✓			
HTL with Algae and Microalgae	A8					✓✓	

Advanced fermentation with wood residues and Agri wastes	A10					✓✓✓ ✓	
CO2 co-valorization and biomass waste with Industrial waste gases CO2 and wood residues	A11	✓✓✓ ✓					



APPENDIX B

Selection Criteria

Social	Environmental	Economic	Technical
<ul style="list-style-type: none"> ● Price of the food ● Green marketing ● Employment creation ● Technological Collaboration ● Traceability ● Economical contribution ● Food safety ● Social acceptance 	<ul style="list-style-type: none"> ● Water usage ● Sustainability on feedstock ● Savings on GHG emissions ● Impact via the change in land usage ● Water and Soil pollution 	<ul style="list-style-type: none"> ● Availability of Sustainable jet fuels ● Cost of transport and storing of feedstock. ● Lasting off-take contracts ● Incentives on production ● Subsidies on Infrastructure Expansion ● Capital cost involved ● Alternate use of feedstocks ● Profitability of feedstock ● Minimal price for selling ● Input energy usage ● Productivity of Land ● Operational and maintenance costs ● Cost on feedstock ● Cost of plant capital 	<ul style="list-style-type: none"> ● Energetic contents ● The efficiency of the process ● The flexibility of the process ● Fuel yield ● The comfort of SAF transport and storing ● Efficacy on Combustion ● Boiling level of SAF ● The freezing temperature of SAF ● Temperature (Flash) ● The viscosity of SAF at -20°C ● Blending limits ● Compatibility with Standard jet fuels ● Local technical capability ● Integration process ● Maturity of process technology ● Method yield ● Scalability on production volume ● Composition and quality of feedstock

APPENDIX C

Respondents

Participants	Years of Expertise	Department	Job Role	Company
Participant 1	5+	Supply chain	Supply Chain Executive	Shell Aviation
Participant 2	5+	Supply chain	Supply Chain Assistant	BP Aviation
Participant 3	10+	Supply chain	Supply Chain Operations Manager	Total Energies
Participant 4	6	Supply chain	Supply Chain Coordinator	Lufthansa Aviation Fuel
Participant 5	8	Supply chain	Supply Chain Assistant	Sky tanking
Participant 6	5	Supply chain	Supply Chain Administrator	Air BP
Participant 7	6	Supply chain	Supply Chain Specialist	World Fuel Services
Participant 8	5	Supply chain	Downstream Purchasing Assistant	CEPSA
Participant 9	12	Supply chain	Supply Chain Manager	ExxonMobil Aviation
Participant 10	7	Supply chain	Supply Chain Executive	Gazpromneft-Aero.
Participant 11	6	Supply chain	Supply Chain Analyst	Shell Aviation
Participant 12	9	Supply chain	Supply Chain Coordinator	BP Aviation

Participant 13	14	Supply chain	Supply Chain Assistant Manager	TotalEnergies
Participant 14	10+	Supply chain	Supply Chain Manager	Lufthansa Aviation Fuel
Participant 15	8+	Supply chain	Supply Chain Operations Coordinator	Sky tanking
Participant 16	6	Supply chain	Supply Chain Specialist	Air BP
Participant 17	7	Supply chain	Fuel Supply Coordinator	ExxonMobil Aviation
Participant 18	5	Supply chain	Supply Chain Coordinator	ExxonMobil Aviation
Participant 19	17	Supply chain	Supply Chain Manager	Gazpromneft- Aero
Participant 20	8+	Supply chain	Downstream Procurement Manager	CEPSA
Participant 21	7+	Supply chain	Supply Chain Coordinator	Air BP
Participant 22	12+	Supply chain	Fuel Supply Executive	World Fuel Services

APPENDIX D

Criterion Source

Category	Selected Criterion	Citation
Social	Traceability	(Testa, Lanzini, & Iraldo, 2016).
	Economical contribution	(Wang, Kamali, Osseweijer, and Posada, (2019).
	Food safety	(Zhao, Sikarwar, Fennell, Shah, and Anthony, 2017).
	Social acceptance	(Gegg and Wells, 2017)
Environmental	Sustainability on feedstock	(Chiaramonti, 2019)
	Savings on GHG emissions	(Zemanek, Champagne, and Mabee, 2020)
	The impact caused by a change in land usage	(Testa, Lanzini, & Iraldo, 2016).
	Water and Soil pollution	(Dale, Efroymson, & Langholtz, (2016).
Economic	Alternative uses with feedstock	(Hileman and Stratton, 2014)
	Profitability of feedstock	(Chagas, Klein, Junqueira, Rezende, Cardoso, Cavalett, and Bonomi, 2018)
	Minimal price for selling	(Ribeiro, Silva, Ribeiro, and Dotti, (2017).
	Input energy usage	(Baudry, Macharis, and Vallée, 2018),
	Productivity of Land	(Li, Mupondwa, and Tabil, 2018)
	Operational and maintenance costs	(Ali-Mandegari, Farzad, Diederichs, & Görgens, 2016),
	Cost on feedstock	(Hoefnagels, De-Jong, Faaij, Slade, Mawhood, and Junginger, 2015)
	Cost of plant capital	(Thornhill et al., 2017)
Technical	Blending limits	(Cheng and Brewer, 2017)
	Compatibility with Standard jet fuels	(Hileman & Stratton, 2014)
	Local technical capability	(Neuling & Kaltschmitt, 2018)
	Integration process	(Akhanova, Ahmad, Nadeem, Houghton, & Muhammad-Sukki, 2017)
	Maturity of process technology	(Bann, Malina, Staples, Suresh, Pearson, Tyner, Hileman, and Barrett, 2017)
	Method yield	(Schillo, Isabelle, and Shakiba, 2017)
	Scalability on production volume	Atsonios, Kougioumtzis, Panopoulos, & Kakaras, 2015)
	Composition and quality of feedstock	Fiorese, Catenacci, Verdolini, and Bosetti, 2012)

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