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Masterthesis

Opportunities for the increase of production and market-uptake of sustainable aviation fuels

Selena Hamers

Scriptie ingediend tot het behalen van de graad van master handelsingenieur, afstudeerrichting technologie in business

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Preface

This thesis, titled 'Opportunities for the increase of production and market uptake of Sustainable Aviation Fuels,' marks the final part of my studies in Business Engineering at Hasselt University.

Ever since the beginning of this thesis, I have been motivated by the fact that my goal is to bring new insights to the field of sustainable aviation. This determination has never wavered, as the topic intrigued me and even ignited a small passion for it. Nevertheless, it was sometimes challenging and occasionally felt lost amidst the 'forest' of extensive aspects and complex interactions of SAF. Nevertheless, I hope my efforts over the last year have borne fruit.

I am deeply grateful to my co-promotor, Elisabeth Woeldgen, for her prompt and insightful feedback throughout this process. Her contributions were crucial in refining my work, providing clarity and direction whenever I faced challenges. Likewise, Professor Dr. Malina's guidance was invaluable. His expertise helped guide my research to a conclusion, integrating a broad range of topics into a cohesive narrative.

Looking to the future, I am excited about the opportunities that SAF can bring to the aviation industry. Embracing SAF's potential will pave the way for a more sustainable and resilient future.

I wish you an enlightening and educational journey through my thesis,

Selena Hamers

Inhoudsopgave

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Table of abbreviations

1-G	First generation
2-G	Second generation
3-G	Third generation
4-G	Fourth generation
ASTM	American Society for Testing and Materials
ATJ-SPK	Alcohol-to-Jet Synthetic Paraffinic Kerosene
CH	Catalytic Hydrothermolysis Synthesized Kerosene
CO_2	Carbon Dioxide
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
ECE	Energy conersion efficiency
EU	European Union
FOG	Fats, oils and greases
FOG Co-Processing	Fats, Oils, and Greases Co-Processing
FT Co-Processing	Fisher-Tropsch Co-hydroprocessing’
FT-HP-SPK	Fischer-Tropsch Hydroprocessed Synthesized Paraffinic Kerosene
FT-SPK/A	Fischer-Tropsch Synthesized Paraffinic Kerosene with Aromatics
GHG	Greenhouse Gas
HEFA-SPK	Synthesized Paraffinic Kerosene from Hydroprocessed Esters and Fatty Acids
HFS-SIP	Hydroprocessed Fermented Sugars to Synthetic Isoparaffins
IATA	International Air Transport Association
ICAO	International Civil Aviation Organisation
iLUC	Indirect Land Use Changes
iLUC	Indirect land use changes (explain(!))
LCE	Life Cycle Emissions
MSP	Minimum selling price
MSW	Municipal Solid Waste
OFMSW	Organic fraction of municipal solid waste
OPR	Open Raceway Pond
PBR	Closed photobioreactor
PtL	Power-to-Liquid
R&D	Research and development
RDD&D	Research, design, development and deployment
SABA	Sustainable Airlines Buyers Alliance
SAF	Sustainable Aviation Fuel
SCOPE	The Scientific Committee On Problems of the Environment
SDG	Sustainable Development goal
SPK-HC-HEFA	Hydrocarbon-Hydroprocessed Esters and Fatty Acids
TEA	Techno-Economic Assessment

TRL	Technology readiness level
U.S.	United States
UCO	Used Cooking Oil
UN	United Nations

Introduction

Global warming, extreme weather events, and rising seas are among the severe consequences faced due to high carbon dioxide (CO_2) emissions. The implications of these emissions harm both humans and nature. In response, the International Civil Aviation Organization (ICAO) aims for the **aviation** industry to achieve **climate neutrality** by **2050**, setting an interim target to cut emissions by 55 % by 2030.

Key to achieving these ambitious targets is the widespread adoption and scale-up of **Sustainable Aviation Fuels** (SAF). SAF, derived from biomass and renewable resources such as residual streams or waste, offer a viable 'drop-in' solution compatible with existing aviation infrastructure and aircraft. Unlike traditional fossil fuels, which release carbon sequestered millions of years ago and disrupt the long-term carbon balance, SAF utilises recently captured carbon, maintaining a balanced carbon cycle (ICAO, n.d.).
Despite their critical role in decarbonising aviation, SAF fuels were only **0.1% of the total aviation fuels** in 2023 (International Energy Agency, 2023). This low adoption rate of SAF indicates a significant gap in achieving meaningful decarbonization. Addressing this issue is imperative to meet ambitious climate targets set for the aviation sector. This thesis aims to tackle this issue by examining the dynamics of SAF adoption, identifying barriers hindering its scale-up, and proposing viable strategies to overcome these obstacles. Through comprehensive research and analysis, this thesis seeks to provide actionable insights to accelerate the uptake of SAF and drive the aviation industry towards a more sustainable future.

This research involves an extensive review of the academic literature on SAF, using databases such as UHasselt Discovery, Web of Science, Google Scholar, and Ebscohost. Publications from 1990 onwards have been consulted to ensure a comprehensive coverage of the development within the field. The geographical area is not restricted, considering the aviation industry's global scope and the SAF's universal relevance.

In conclusion, this thesis represents a contribution to the field by offering a comprehensive analysis of the dynamics surrounding SAF scale-up. By synthesizing existing knowledge and proposing actionable strategies, the developed taxonomy provides a roadmap for overcoming barriers to adoption. Ultimately, the aim is to gain insights into opportunities for the increase of production and market uptake of SAF, contributing to a greener and more resilient future.

Part A: The aviation sector and sustainable aviation fuels

With more than 100 thousand flights per day, the **aviation sector** plays a significant role in transporting passengers and goods (Clark C., 2016). According to Carbon Brief, the aviation sector will grow by 5 % annually. This growth has also been shown throughout the past decades as there were 1990, on average, 640 million passengers, and by 2017, there were more than 4 billion passengers (Moss, 2019). The International Air Transport Association (IATA) predicts that the number of passengers will double by 2037 and reach 8.2 billion yearly. This immense growth of the aviation sector also comes with increased emissions. Since 2013, aviation emissions have increased by 26 % (Pidcock R. and Yeo S., 2016).

The ICAO stated that aviation accounts for around **two % of global CO_2 emissions** (Ritchie H., 2020). The 'two %' claim has been used since the early 1990s, and the aviation sector stressed that aviation is a small slice of a large pie of carbon emissions. However, Dr Joeri Rogelj, an expert on carbon budgets, sheds a different light on the aviation sector's emissions. He has projected that if the aviation sector does not step in, it will consume **27 % of the carbon budget** regarding the '1.5°C by 2050' goal. The carbon budget from 2015 till 2050 should not be exceeded if we want to keep the global temperature rise under control. The extensiveness of the share of aviation emissions can be attributed to the earlier-mentioned annual growth of the aviation sector. Besides, people have a growing desire to fly, and the aviation sector needs to reduce their emissions. However, the aviation sector also impacts the climate with **other emissions,** such as nitrogen oxides and vapour trails, that change the atmosphere's composition and amplify the CO_2 effect (Pidcock R. and Yeo S., 2016). According to the European Federation for Transport and Environment, these emissions were responsible for more than 65 % of aviation's impact on the climate in 2018 (Transport & Environment, n.d.).

Emissions have serious **implications** for both humans and nature, leading to global warming, extreme weather events, shifts in wildlife populations, and rising sea levels (European Commission, n.d.). These changes underscore the urgent need for global actions to mitigate their impact and ensure a sustainable future. In response, the ICAO, an agency of the UN dedicated to regulating international air travel, has set the goal of **aviation** being **climate-neutral by 2050**. To reach this goal, emissions should be reduced by 55 % by 2030 (ICAO, 2022).

To operationalise these targets, the ICAO created the 'Carbon Offsetting and Reduction Scheme for International Aviation', also known as **CORSIA**. Participation in this program is voluntary until 2027, after which it becomes mandatory for most UN countries. Within CORSIA, airlines that perform international flights must monitor and report their emissions. If these emissions exceed their 2019 levels, an airline must purchase **carbon credits** from the carbon market. These credits are generated by projects that are reducing the emission of CO_2, leading to a stabilisation of the total CO_2 emissions. However, these carbon credits are a temporary measure of CORSIA, only set to continue for a few more years, as this is not a sustainable solution to declining emissions in the longer term (Pidcock R. and Yeo S., 2016).

To achieve a **sustained reduction** in emissions and simultaneously encourage the growth of the aviation sector, there is a so-called **'basked of measures'** (ICAO, 2019). It consists of aircraft technology improvements, such as applying new airplane-type designs. Furthermore, there should be improvements in air traffic management and infrastructure. Only drastic improvements in technology and infrastructure would make the aviation industry use less CO_2 to reduce the carbon budget from 27 to 20 % (Pidcock R. and Yeo S., 2016).

Sustainable Aviation Fuels (SAF) are introduced to achieve an even more significant decline in emissions. This fuel is derived from biomass such as plants, or renewable sources from residues or waste. According to IATA, when SAF is produced from biomass, the carbon dioxide absorbed by the plants during their growth generally offsets the emissions produced when the fuel is burned, making SAF nearly carbon neutral. In comparison to conventional jet fuel (CJF), pure SAF has the potential to reduce greenhouse gas emissions by up to 94% (WEF, 2023). SAF is, therefore, a crucial element in achieving net-zero emissions in aviation, estimating that 450 billion litres of SAF will be necessary by 2050 (Igini M., 2022).

The expansion of the SAF market will depend on its **supply chain dynamics**, which can be divided into three parts: upstream, midstream and downstream (Martinez-Valencia et al., 2021). The upstream stage involves producing, collecting, transporting, and pre-processing feedstocks. This stage serves as the foundation for SAF. In the midstream stage, conversion techniques convert the biomass into fuel. Finally, in the downstream stage, the fuel is delivered to end-users. These stages are presented in Figure 1.

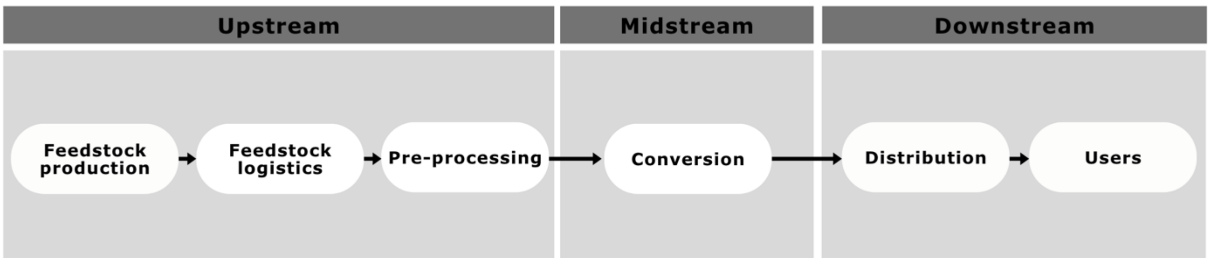


Figure 1: The supply chain structure of SAF

The up and midstream part, forming the supply side of SAF, will be discussed in part B. The downstream part of SAF, forming the demand side of SAF, will be discussed in part C.

Part B: The supply side of SAF

This chapter delves into the supply side of SAF, starting with an exploration of the diverse feedstocks utilized in SAF production and their potential viability for increased adoption, as outlined in section 1. Subsequently, attention turns to the array of conversion techniques and pathways employed in SAF production, detailed in section 2. Section 3 evaluates the economic feasibility and environmental implications of SAF production on a broader scale. Finally, section 4 delves into the SAF production market, examining the industry's evolution, projections, key producers, and the factors influencing their growth and obstacles they face.

1. Feedstocks used in SAF production

The production of SAF starts with the production of feedstocks. As highlighted by Shehab et al., these feedstocks are crucial in the uptake of SAF production since they are important determinants of the highest possible SAF production (2023). While traditional SAF feedstocks typically involve biomass, innovative approaches use non-biomass, as illustrated in Figure 2.

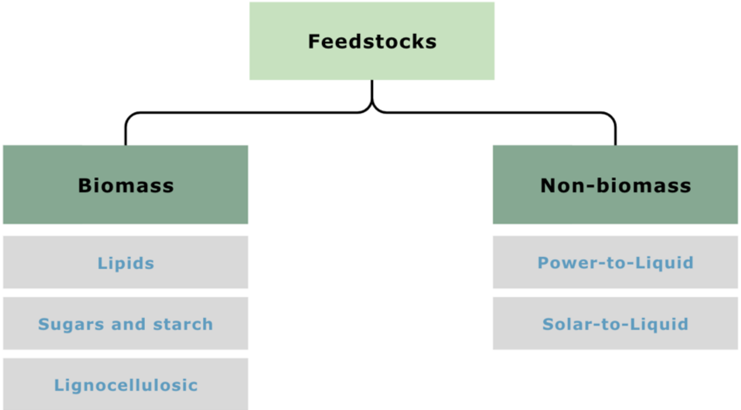


Figure 2: Types of feedstocks for SAF production

1.1. Biomass feedstocks

Biomass is a term used to describe organic materials from plants and animals. In the context of SAF, three component categories of biomass, namely lipids and fatty acids, sugars and starches, and lignocellulosic compounds, can be converted into SAF, as shown in Figure 2.

The first category, **lipids,** is currently the most used component for producing SAFs. These compounds can be obtained from various sources, including oils and fats derived from triglycerides and fatty acids. The second type of biomass compounds is **sugar and starch**. Sugars are simple carbohydrates, while starches are complex carbohydrates. However, they fall under the same component category as they are both rich in disaccharides and polysaccharides and can be easily converted into each other. The third category, **lignocellulosic** compounds, refers to non-edible plant materials mainly consisting of cellulose, hemicellulose and lignin components (Alonso et al., 2010; Pasa et al., 2022).

Within these biomass categories, the options have diverse characteristics, such as maturity levels (U.S. Department of Energy, 2022). To address these differences, the concept of **biomass generation** will be used to distinguish the current state-of-the-art feedstocks from those still under development. This can be classified into **four generations**, as illustrated in Figure 3, which showcases the development stages of each biomass.

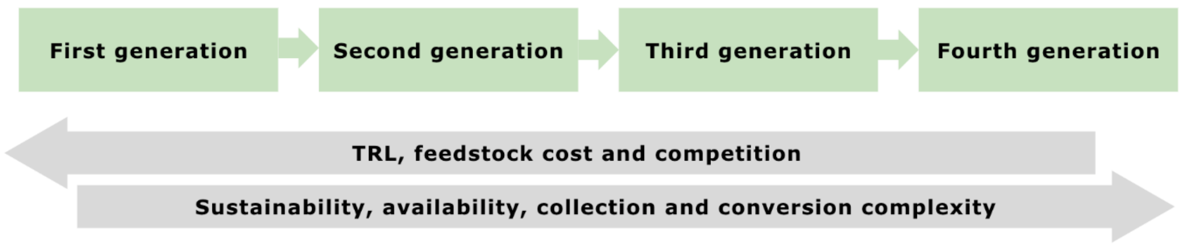


Figure 3: Feedstock generations

According to UNCTAD, the **first-generation** (1-G) feedstocks come from edible crops and plants, such as seeds, grains, or sugar. Next, the **second generation** (2-G) focuses on non-edible biomass, including energy crops, waste, and residues (2008). The **third-generation** (3-G) centres on microalgae, a highly sustainable feedstock grown in water and thus does not require farmland. Finally, **fourth-generation** (4-G) biomass is produced from non-biological resources, such as genetically modified microalgae (Pasa et al., 2022). An overview of the feedstock options within each generation is presented in Figure 4. Sections 1.1.1. to 1.1.4. will further explore each generation. Section 1.6 systematically reviews the determinants determining each feedstock generation's economic, social, and sustainable viability.

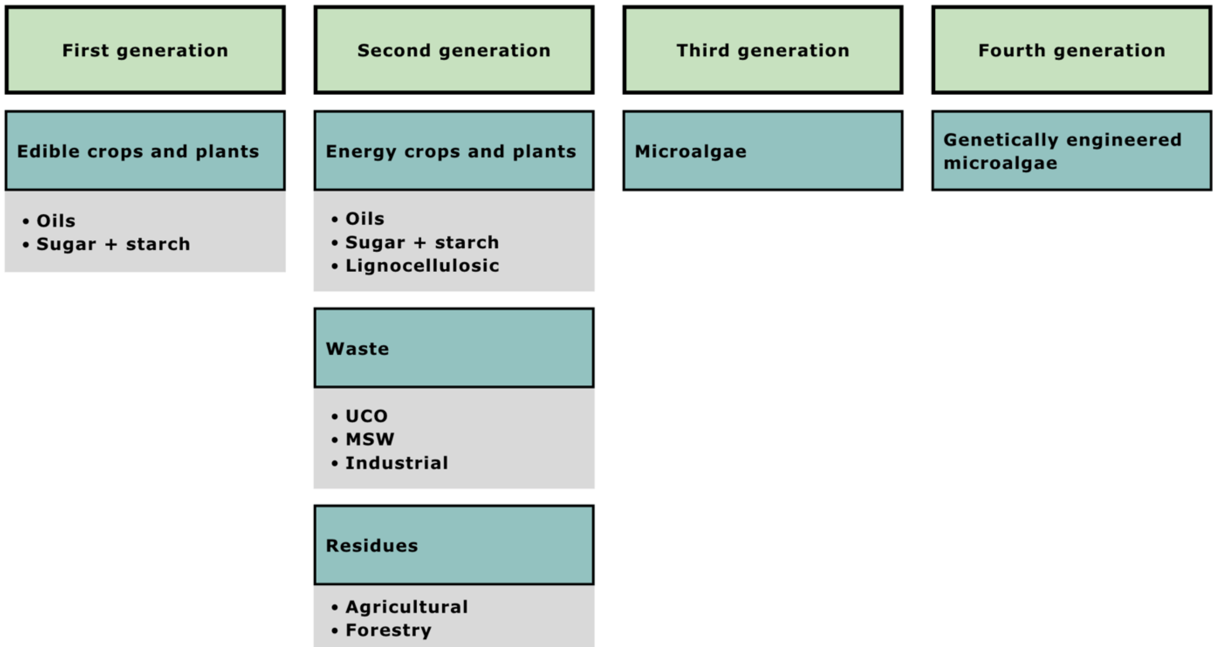


Figure 4: Feedstock options within each generation

1.1.1.First-generation feedstocks

The 1-G feedstocks refer to the most established and convenient biomass types: edible crops and plants. The focus will be on the most used 1-G options, as there are many options. Notably, only feedstocks with lipids or sugar and starch compounds will be discussed, as lignocellulosic feedstocks lack 1-G options (Shehab et al., 2023).

Vegetable oils are an essential source of lipids feedstocks. Within this category, **palm oil** is currently a dominant feedstock as it has the highest oil yield per area. However, palm oil for SAF production competes with the food industry, is geographically limited, and has led to deforestation, biodiversity loss and human rights. Therefore, the EU banned palm oil as feedstock for SAF (Pasa et al., 2022; Shehab et al., 2023). Similarly, **soy oil**, the second most prominent SAF 1-G oil feedstock, encounters the same environmental concerns tied to its cultivation (Pasa et al., 2022).

The most commonly used 1-G **sugar and starch crops** for biofuel include sugarcane, sugar beet, sweet sorghum, and corn. **Sugarcane** is vital for Brazil's bioethanol output due to its low production costs and significant GHG reductions, though it demands considerable water and land resources (Pasa et al., 2022; Adoyele et al., 2020). **Sugar beets** are noted for their high sucrose content and land-use efficiency, making them effective SAF feedstocks (Alexiades et al., 2018). Conversely, the environmental impact of sugarcane varies by region, especially concerning land use changes (de Crom et al., 2020). **Corn** is favoured for its high starch content and efficiency in ethanol conversion, yet its cultivation affects food prices and requires substantial energy for cultivation and processing (University of Nebraska, n.d.).

1.1.2.Second-generation feedstocks

The 2-G feedstocks are produced using **non-edible** feedstocks such as energy crops, wastes and residues, which will be discussed in 1.1.2.1. to 1.1.2.3.

1.1.2.1. Energy crops

Energy crops can be utilised as SAF feedstock and possess specific characteristics, such as a short life cycle, a higher growth rate, and the ability to grow on marginal lands. The primary advantage over 1-G feedstocks is that they do not compete with food crops. The energy crops for lipids, sugar, starch, and lignocellulosic materials will be discussed. However, since each type has several promising options, only one option will be discussed to provide insight into the potential of energy crops.

More than 350 **oil-bearing plants** have been identified, with thousands of subspecies that could be used to produce biofuels (Pasa et al., 2022). **Macauba**, identified as one of the most promising in terms of availability and sustainability, will be discussed as an example to indicate the potential of lipids energy crops. Macauba is a non-edible palm tree, typically found in South America, that is highly adaptable and productive. For instance, it produces up to ten times more oil per hectare than soybeans. Besides, this palm tree has low water requirements (Silva et al., 2016). Multiple countries are also trying to scale up the production of Macauba as it is considered a promising feedstock alternative (Pasa et al., 2022)

Sweet sorghum is identified as a highly promising **sugar energy crop**, as it is an adaptable crop that requires minimal water resources and can grow in low-fertility soils. Moreover, it has a high percentage of fermentable sugars, resulting in yields even higher than those of corn and sugarcane (Umakanth et al., 2020). Prasad et al. consider sweet sorghum a crucial step in increasing biofuel production and reducing carbon emissions (2019).

Native plants are energy crops with **lignocellulosic compounds**. They have great availability as the total amount of native plants is estimated to be around 740 million tons (Pasa et al., 2022). Compared to other crops, these plants are relatively easy to grow, harvest, and process. They can thrive in various geographies, climates, and soil types, including marginal lands unsuitable for conventional crop production. Furthermore, grasses are among the world's highest-yielding biomasses and require low levels of fertilisers and pesticides (Tye et al., 2016). One of the most promising native plants is **Switchgrass**, cultivated in various regions, including North America and Africa (Pasa et al., 2022). It produces around 283 million tons of biomass yearly, resulting in cellulose availability of 85 to 144 million tons (Tye et al. 2016; Larnaudie et al., 2022).

Generally, non-edible energy crops and plants have economic and environmental advantages over 1-G feedstocks. Moreover, there are great opportunities in terms of biomass availability. However, R&D are needed to develop large-scale production of these plants.

1.1.2.2. Waste

Using waste as a potential feedstock for 2-G production is an area of growing interest within the SAF research. This part of the discussion will focus on the most crucial waste feedstocks: used cooking oils (UCO), municipal solid waste (MSW), and industrial waste.

1.1.2.2.1. Used cooking oils

UCO presents the first waste feedstock for SAF production and has two primary **sources**: the **professional sector** and **households**. The professional sector comprises food-processing companies, restaurants, and other catering companies. The **UCO collection** can be categorised into three **systems**: decentralised, centralised, and combined. Decentralised involves collection per house, while centralised collection requires bringing UCO to a public collection point. The combined collection is a combination of both systems. Centralised collection is the most common household system because of its lower operating costs. The collection of UCOs from the professional sector is mostly decentralised since it is obtainable in larger quantities at fewer locations than households. UCO collection from the professional industry is currently more developed and executed than a household collection (Greenea, 2016; Van Grinsven et al., 2020).

UCO is the first type of waste feedstock for SAF production, sourced primarily from the professional sector, including food-processing companies, restaurants, and catering companies. Collection systems vary, with decentralized systems predominating in the professional sector due to the concentrated nature of UCO sources and centralized systems being more common in households due to lower operating costs (Greenea, 2016; Van Grinsven et al., 2020)
In 2016, the **European professional sector** contributed 675 thousand tonnes of UCO. However, there is still substantial untapped potential, particularly in Eastern Europe. The **EU households' total** UCO supply **potential** in 2015 was 854 thousand tonnes, but only 50 thousand tonnes, equivalent to 6 %, were collected from households that year as estimated by Greenia (2016). **Global estimates** of UCO supply are varied, with the ICAO estimating around 25 million tonnes per year, while others suggest only 5 million tonnes (Van Grinsven et al., 2020; Sze Ki Lin et al., 2013). The

variability in UCO collection is influenced by factors such as the profitability of UCO collection and regulatory environments, which can encourage or discourage collection practices (Van Grinsven et al., 2020).

However, the use of UCO as SAF feedstock faces **challenges** such as quality variability and the risk of fraud in sustainability certifications (Van Grinsven et al., 2020). The European Court of Auditors has highlighted risks associated with UCO fraud, where virgin oils are mixed with UCO to claim unsustainable sustainability credits (Van Grinsven et al., 2020; ISCC, 2019b). A fundamental limitation is that the potential volume of SAF production from UCO is inherently capped by the stable level of global UCO production, which cannot be expected to increase significantly. This limitation restricts the long-term scalability of UCO as a primary feedstock for SAF (Shebab et al., 2023).

1.1.2.2.2. Municipal solid waste

Municipal Solid Waste (MSW) includes materials such as paper, plastic, food scraps, and construction debris generated by households, schools, and businesses (Goffin M., 2022). Globally, two billion tonnes of MSW are produced annually, with Europe contributing 240 million tonnes. This number is expected to rise, particularly in urban areas, where a 70% increase is projected by 2025. The organic fraction of MSW (OFMSW) can be utilised for SAF production. MSW comprises for 60 to 70% of OFMSW, which includes food, yard, and paper products (World Bank, n.d.). Utilising OFMSW for SAF production supports circular economy concepts by improving waste management and reducing landfill-associated GHG like methane and CO2 (Shebab et al., 2023; Kowalski et al., 2022).

However, there are also some **challenges** to using OFMSW, as technologies for converting lignocellulose biomass, and thus OFMSW, are not yet technologically mature or cost-competitive. Furthermore, the heterogeneous composition of OFMSW can constrain the feasibility of this pathway (Kowalski et al., 2022)

An example of this approach is the **Nevada waste-to-fuel plant**, the first facility globally to convert MSW to SAF, operated by Fulcrum Bioenergy. It planned to transform 175 thousand tonnes of MSW into 42 million litres of renewable fuel (Fulcrum Bioenergy, n.d.). However, reports state the plant is facing potential collapse as it paused most operations. The plant has struggled since it began operations in 2022 with numerous technical setbacks and financial challenges. This highlights the challenges facing the emerging waste-to-fuel industry and raises concerns about the feasibility of scaling (Elgin B., 2024).

1.1.2.2.3. Industrial waste

Industrial waste offers another route for SAF production. This section examines potential waste sources from industries like food, animal processing, paper and pulp, wood processing, and agriculture.

For instance, the **food industry** produces waste that is rich in organic compounds such as lignocellulose, sugars, and lipids, useable as SAF feedstock. Notably, cheese-whey and high-sugar beverages are stand out due to their high lactose and sugar content, respectively. Above, **animal fat waste from industries** can generate approximately five million tons annually, useable as cost-effective SAF feedstock. It includes various fats like beef tallow and chicken fat, which are advantageous for biofuel due to their fatty acid content but pose challenges like solidification and impurities (Pasa et al., 2022). The **paper and pulp industries** can also contribute with substantial cellulose-rich by-products. Bioethanol production from these by-products is economically viable, integrating smoothly with existing industrial processes and enhancing profitability. Similarly, **wood processing industries** produce usable by-products such as sawdust and trimmings, characterised by their low moisture content and uniformity, ideal for SAF production. Finally, the **agricultural industry** can provide waste that is a rich source of sugar, starch, and lignocellulose, varying with the crop origin, presenting another abundant feedstock for SAF (Jayamuthunagaia et al., 2021).

1.1.2.3. Residues

The third category of biomass is **residues**, which refer to organic materials left over from various activities, such as harvesting, processing, or consuming plants. Both agricultural and forestry residues will be discussed.

1.1.2.3.1. Agricultural

Agricultural residues refer to the by-products that are obtained during the harvesting and processing of crops. **Primary residues**, such as maise stalks, are received from the fields at the time of harvest. These residues are mainly from corn, sugarcane, rice, and wheat. In general, residues from agriculture are not readily available to use as SAF, as they are often used as animal feed or fertiliser. However, rice straw is an exception as it is not used for soil fertilisation and is available in large quantities, going up to 309 million tons per year. **Secondary residues**, such as sawdust co-produced during processing, are generally more abundantly available. These residues are generated at the processing site, which is more centralised, thus lowering the transportation and handling costs. **Bagasse** is a significant residue obtained from processing sugarcane in the agro-industry sector. It is estimated that about 0.6 kilo of sugarcane bagasse is produced for every kilo of it, resulting in a global yield of approximately a billion tons annually (Tye et al., 2016; Sánchez et al., 2009; Pasa et al., 2022)

1.1.2.3.2. Forestry residues

Forestry residues are by-products from activities like forest harvesting or land clearing, which yield usable branches and tops for bioenergy. These residues primarily comprise dense, structurally strong lignocellulosic wood, containing more lignin than non-wood biomass sources like agricultural residues (Zabed et al., 2016; Tye et al., 2016). Forest residues are categorised into primary and secondary types. Primary residues from untouched forests are of higher quality with significant bioenergy potential due to their rich lignocellulosic content but are often limited by conservation regulations. Conversely, secondary residues are derived from regrown forests and are more accessible for commercial use (Shehab et al., 2023).

1.1.3.Third-generation feedstocks

The 3-G feedstocks are primarily defined as **microalgae**, which are single-celled microscopic organisms that can be grown in various types of water without requiring arable land (Sayre R., 2010) Microalgae are found in fresh- and saltwater across all of Earth's ecosystems, with around one million strains estimated to exist, of which approximately four thousand strains are identified (Sajjadi et al., 2018; Anto et al., 2020).

Microalgae are a **productive** source as they can double their weight in one day (Chisti Y., 2003). This is due to rapid photosynthetic growth rates and the ability to harvest year-round. (Chisti Y., 2007). Compared to the highest-yielding vegetable oil crop, palm, the area productivity of microalgae is sixteen times higher (Wang and Tao, 2016).

Moreover, microalgae contain valuable components like lipids, antioxidants, pigments, and proteins (Chisti Y., 2003). Those **lipids** can be converted into SAF. Numerous microalgae species exist, each with distinct traits (Muhammad et al., 2021; Khan et al., 2022). However, not all microalgae species are suitable for producing SAF, highlighting the importance of **selecting the right species**. Research has indicated that **lipid productivity** is the primary indicator of a microalgae species' suitability for biofuel generation (Shanmugam et al., 2020). The lipid quantities between microalgae species range from twenty to 77 % (Mathimani T. and Mallick N.). Species like Chlorella, Scenedesmus, Nannochloropsis sp., and Dunaliella especially have high lipid-generating capabilities among various microalgae types (Griffiths et al., 2012). A new approach to increasing lipids is genetically modifying the microalgae species (Bwapwa et al., 2017; Mofijur et al., 2022). However, since this is considered a 4-G feedstock, it will be discussed later. On the other hand, **lipid quality** is influenced by the composition of fatty acids, which varies from species to species (Volkman et al., 1989). Research by Mofijur et al. indicated that Chlorella sp. was the best microalgae strain for SAF production based on lipid production and quality (2022).

The **cultivation** of microalgae depends on various factors, including nutrient availability (N, P, K), temperature, pH, salinity, inorganic carbon, oxygen, light intensity, and CO_2 levels (Mata et al., 2010). Microalgae cultivation can be executed in open raceway ponds (OPRs) or closed photobioreactors (PBRs). While OPRs are more cost-effective, they are susceptible to environmental contaminants. PBRs provide controlled conditions that optimise growth but are more expensive (Kumar et al., 2020; Banerjee & Ramaswamy, 2017; Mantovani et al., 2020).

Despite the advantages, the commercial use of microalgae for SAF is constrained by multiple **challenges**. An important practical obstacle is the freezing point, which does not yet meet international jet fuel standards (Rony et al., 2023). Moreover, the European Commission report from December 2020 highlights several obstacles restricting the microalgae sector's expansion, including regulatory discrepancies, market limitations due to inadequate scale-up and restricted algae biomass supply (European Commission, n.d.).

1.1.4.Fourth-generation feedstocks

The last generation, 4-G feedstocks, are sourced from **genetically engineered microalgae** to improve fuel production. Genetic modification of microalgae could involve expanding their spectrum range to enhance photosynthetic efficiency (Wolf et al., 2018). Another strategy is to reduce the size of the chlorophyll antenna to improve light penetration (Lee et al., 2002). Metabolic engineering can also significantly increase lipid and carbohydrate levels in microalgae (Hsieh et al., 2009). According to Chen et al., maximising these levels is one of the most interesting strategies to improve the overall yield efficiency of microalgae (2011). An example of a 4-G feedstock is *Chlamydomonas reinhardtii*, a microorganism that has undergone genetic modifications which improved its lipid and carbohydrate content (Sajjadi et al., 2018).

While 4-G feedstocks show potential in addressing challenges faced by other feedstock generations, the commercial-scale implementation of 4-G feedstocks is still far away (Fu et al., 2019; Kumar et al., 2020).

1.2. Determinants of feedstock viability for SAF production

This section systematically analyses each feedstock generation's viability. Based on research by Abdullah et al., **eight determinants** will be discussed (2019), as shown in Figure 5.

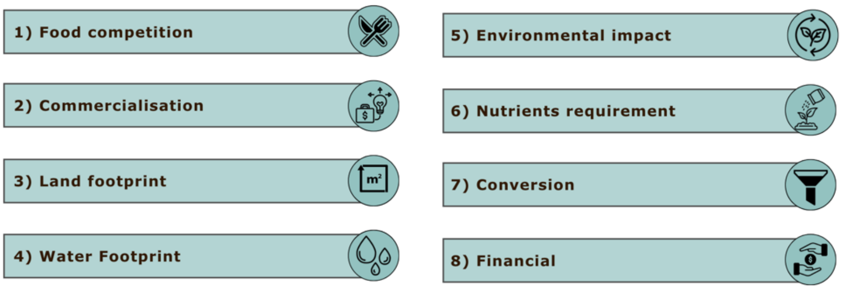


Figure 5: Eight determinants of feedstock viability

The first criterion is the food competition, where the 1-G feedstocks raise the issue known as the **food-versus-fuel dilemma**. These feedstocks directly compete with food production, potentially impacting food security and affecting global SDGs to reduce poverty and hunger. By 2050, the world's population will be near ten billion, influencing market prices of these feedstocks (Mat Aron et al., 2020). However, 2-G, 3-G, and 4-G feedstocks do not pose this conflict, presenting a more sustainable alternative (Naik et al., 2010; Leong et al., 2018).

The second factor to consider is the stage of **commercialisation** of the feedstock production. The 1-G feedstocks have matured and are commercially produced (Abdullah et al., 2019). Regarding 2-G energy crops, several countries are trying to increase the production scale (Pasa et al., 2022). The potential collapse of the waste-to-fuel pioneering company Fulcrum Bioenergy illustrates there are considerable difficulties in achieving large-scale production of 2-G waste feedstocks (Elgin B., 2024). Regarding 3-G production, only a few plants for culturing microalgae biomass have been established. Multiple challenges must be overcome to achieve the commercial production of SAF from microalgae, such as the earlier-mentioned freezing point (Rony et al., 2023). Moreover, there is limited regulation for marine cultivation of 3-G feedstocks (Leong et al., 2018). The widespread adoption of 4-G feedstocks would require political acceptance and support (Malode et al., 2021). Controversies surrounding genetic engineering in agriculture and medicine may extend to biofuel production (Villareal et al., 2020).

The third factor for evaluation is **land footprint**, which is the type of land involved in feedstock cultivation. The cultivation of 1-G feedstock requires significant amounts of arable land (UNCTAD, 2016). Moreover, the expansion of 1-G feedstock cultivation often leads to land competition and significant land use changes, with substantial direct and indirect impacts (Pasa et al., 2022; Shehab et al., 2023). 2-G energy crops can be grown on marginal lands with undesirable characteristics for agricultural cultivation (Pasa et al., 2022). Algae can be cultivated in a variety of environments including freshwater, brackish, or marine systems, which allows for production systems that do not compete with agricultural land. This makes 3-G and 4-G feedstocks sustainable in terms of land use efficiency (Naik et al., 2010).

The fourth determining factor is the **water footprint**. 1-G crops and plants require potable water for cultivation, and the same is true for 2-G energy crops (Abdullah et al., 2019). However, most energy crops have lower water requirements than conventional crops (source). Conventionally, 3-G and 4-G feedstocks require freshwater for cultivation (Khan et al., 2022).

The fifth determinant, the **environmental impact** of feedstocks, varies significantly across generations. The 1-G feedstocks may in negatively impact to the biodiversity and soil quality due to intensive agricultural demands and the use of pesticides and fertilizers (Mat Aron et al., 2020; Abdullah et al., 2019). Their cultivation of 2-G energy crops can contribute to biodiversity by utilizing lands that are otherwise left barren. Moreover, 2-G waste feedstocks contribute to a circular economy by enhancing waste management and reducing landfill emissions like methane and CO_2 (Kowalksi et al., 2022; Shebab et al., 2023). The 3-G feedstock microalgae is noted for its efficient CO_2 sequestration, surpassing terrestrial plants in photosynthetic yield and CO_2 absorption (Van Den Hende et al., 2011; Benedetti et al., 2018; Passel, 2024). They convert carbon into biomass effectively (Mitra et al., 2012), with over 50% of algae's weight being carbon (Algae Biomass Organisation, 2022). Advanced 4-G microalgae can potentially offer greater environmental benefits through enhanced photosynthetic efficiency and light penetration (Chisti Y., 2003).

The sixth topic to evaluate is the **requirement for nutrients**. The 1-G feedstock cultivation involves considerable amounts of pesticides and fertilisers (the University of Nebraska, n.d.) The 2-G energy crops have lower nutrient requirements than other generations (Pasa et al., 2022). The waste and residual feedstocks do not need any fertiliser treatment. Regarding 3-G and 4-G feedstocks, microalgae cultivation depends on multiple nutrients (Abdullah et al., 2019).

The seventh topic is the **conversion** of the feedstocks to SBC. 1-G feedstocks are relatively easy to convert to neat SAF. The conversion techniques of 2-G lignocellulose biomass feedstocks, such as MSW, still need to be technologically mature or cost-competitive. Most projects are under research and development at various TRLs. The microalgae conversion technique (HC-HEFA-SPK) is only at

TRL 5 (ICAO, n.d.). Moreover, the freezing point does not yet meet international jet fuel standards (Rony et al., 2023).

The last determinant is the **financial aspect** of the feedstock cultivation, including the capital and operational costs. The 1-G feedstocks typically have established cultivation and processing methods. However, their capital costs can be higher due to the need for high-quality land and intensive inputs like fertilisers and pesticides. Additionally, their operational costs are elevated due to regular agricultural activities. Conversely, 2-G energy crops that grow on marginal lands generally have lower initial capital costs. However, waste or residue feedstocks generally have capital and operation costs (Abdullah et al., 2019). According to Leong et al., the capital cost for large-scale cultivation of 3-G and 4-G feedstock needs to be lowered (2018).

Table 1: Overview determinants of feedstock generations

Determinant	1-G Feedstocks	2-G Feedstocks	3-G Feedstocks	4-G Feedstocks
Food competition	Compete with food production, impacting food security and SDGs (Laursen W., 2006; Mat Aron et al., 2020)	Do not pose food competition (Naik et al., 2010; Leong et al., 2018)	Do not pose food competition (Naik et al., 2010; Leong et al., 2018)	Do not pose food competition (Naik et al., 2010; Leong et al., 2018)
Commercialisation	Mature and commercially produced (Abdullah et al., 2019)	Increasing production scale Difficulties in large-scale production (Pasa et al., 2022; The Japan Times, 2024)	Few plants established Challenges in commercial production Limited regulation (Debowski et al., 2023; Leong et al., 2018)	Requires political acceptance Controversies in genetic engineering (Malode et al., 2021; Villareal et al., 2020)
Land footprint	Requires significant arable land, leading to land competition and use changes (UNCTAD, 2016; Pasa et al., 2022; Shehab et al., 2023)	Can be grown on marginal lands Sustainable land use (Pasa et al., 2022)	Can be cultivated in various environments Sustainable land use (Naik et al., 2010)	Can be cultivated in various environments Sustainable land use (Naik et al., 2010)
Water footprint	Requires potable water (Abdullah et al., 2019)	Relatively lower water requirements (Abdullah et al., 2019)	Freshwater for cultivation (Khan et al., 2022)	Freshwater for cultivation (Khan et al., 2022)
Environmental impact	Negative impacts on biodiversity and soil quality (Mat Aron et al., 2020; Abdullah et al., 2019)	Enhances waste management Contributes to circular economy (Kowalksi et al., 2022; Shebab et al., 2023)	Efficient CO2 sequestration High photosynthetic yield (Van Den Hende et al., 2011; Benedetti et al., 2018; Passel, 2024)	Greater environmental benefits e.g. enhanced photosynthetic efficiency (Chisti Y., 2003)
Nutrient requirements	High pesticide and fertilizer use (University of Nebraska, n.d.)	Lower nutrient requirements No fertiliser treatment needed (Pasa et al., 2022; Abdullah et al., 2019)	Dependent on multiple nutrients (Mata et al., 2010)	Dependent on multiple nutrients (Mata et al., 2010)
Conversion process	Relatively easy to convert to SAF (Abdullah et al., 2019)	Needs technological maturity and cost-competitiveness (Benetti, 2018; Kowalski et al., 2022)	Conversion techniques at TRL 5 Freezing point issue (ICAO; Rony et al., 2023)	Conversion techniques at TRL 5 Freezing point issue (ICAO; Rony et al., 2023)
Financial aspects	Established methods, high capital and operational costs (Abdullah et al., 2019)	Lower initial capital costs Operational costs higher for waste/residue (Abdullah et al., 2019)	High capital costs (Leong et al., 2018; Nair and Paulose, 2014)	High capital costs (Leong et al., 2018; Nair and Paulose, 2014)

1.3. Non-biomass feedstocks

While biomass-based feedstocks are central to current SAF production, their viability is often constrained as discussed in 1.2. These challenges underscore the need for exploring alternative feedstock sources that do not rely on biomass.

Power-to-liquids (PtL) have emerged as the first alternative to using biomass as feedstock for SAF. The input for PtL SAF is exclusively from renewable energy sources and has unlimited potential. The process captures carbon from atmospheric or industrial flue gases in the form of CO_2 and converts it to CO. Then, it combines CO with electrically produced hydrogen to produce a hydrocarbon fuel. The scalability of PtL is theoretically unlimited, however, commercial-scale PtL is estimated to only gradually enter the market past 2030 (Fontaine et al., 2022). Substantial investments in renewable energy infrastructure will be necessary to expand the production of PtL. This includes increasing solar, wind, and potentially nuclear power generation (Air Transport Action Group, 2021).

Another emerging alternative is **Solar-to-Liquid** (StL), which captures energy from solar heat by concentrating sunlight into a chemical reactor. This process converts CO_2 and water into CO and hydrogen to produce a hydrocarbon fuel similar to PtL. While a pioneering demonstration plant has been successfully tested in Spain, this technique is not ready for large-scale production. Nonetheless, its potential remains considerable, especially since it can achieve self-sustained operation from solar energy by storing the generated heat in a tank for nighttime use (Air Transport Action Group, 2021)

To facilitate the large-scale adoption of PtL and StL, substantial investments are necessary in renewable energy, including solar, wind, and potentially nuclear power. These investments will enable the expansion of non-biomass production capabilities and contribute to the broader goal of achieving net-zero carbon emissions by 2050 (Fontaine et al., 2022).

2. Conversion techniques for SAF production

The focus shifts from exploring the SAF feedstocks to the midstream phase of SAF production. This phase involves using conversion technologies to transform biomass feedstocks into neat SAF. This section outlines the conversion techniques and various pathways as well as the challenges associated with these processes in section 2.1. Additionally, section 2.2. briefly discusses emerging conversion techniques. A detailed discussion of technical aspects will not be covered.

2.1. Certified production pathways

To produce SAF, raw feedstocks must first be **converted** into a Synthetic Blend Component (SBC), commonly referred to as neat SAF. This SBC is subsequently blended with CJF to produce the final SAF product (ICAO, n.d.).

There are three overarching conversion techniques used in this process. First, the **oleochemical conversion** technique uses physicochemical methods to convert biomass into neat SAF. The second technique is **biochemical conversion**, which uses microorganisms to convert biomass into fuels. Lastly, **thermochemical conversion**, which turns biomass into gases through chemical processes at high temperatures (Ammanagi et al., 2021). Within each category of conversion techniques, multiple **production pathways** exist. As shown in Figure 6, a pathway consists of a specific feedstock type in terms of biomass compound, which might require pre-treatment. This is followed by a distinct conversion method (ICAO, n.d.).

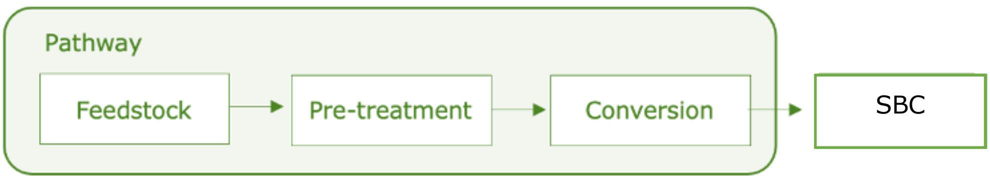


Figure 6: Pathway of neat SAF

Pathways are constantly being evaluated and must meet **sustainability criteria** to be approved as a certified conversion process by the American Society for Testing and Materials (ASTM)

International. According to the ICAO, as of April 2023, ASTM International has certified **eleven pathways** for producing SBC, and eight more conversion techniques are currently being evaluated and considered (ICAO, 2023; U.S. Department of Energy – Energy Efficiency and Renewable Energy, n.d.). The certified pathways are shown in Table 2 in the chronological year of approval.

Table 2: ASTM-certified production pathways

Pathway	**Certification name**	**Feedstock**	**Conversion technique**	**Blend limit**	**TRL**
Fischer-Tropsch Hydroprocessed Synthesized Paraffinic Kerosene	FT-HP-SPK	Energy crops Lignocellulosic biomass Solid waste	Thermochemical	50%	7-8
Synthesized Paraffinic Kerosene from Hydroprocessed Esters and Fatty Acids	HEFA-SPK	Vegetable oil Animal fat	Oleochemical	50%	8-9
Hydroprocessed Fermented Sugars to Synthetic Isoparaffins	SIP-HFS	Conventional sugars Lignocellulosic sugars*	Biochemical	10%	7-8 5*
Synthesized kerosene with aromatics derived by alkylation of light aromatics from non-petroleum sources	FT-SKA	Coals Natural gas Biomass	Thermochemical	50%	6-7
Alcohol-to-Jet Synthetic Paraffinic Kerosene	ATJ-SPK	Sugar and starch crops Lignocellulosic biomass	Biochemical	50%	7-8
Catalytic Hydrothermolysis Synthesized Jet Fuel	CHJ	Vegetable oils Animal fat	Oleochemical	50%	6
Hydrocarbon-Hydroprocessed Esters and Fatty Acids	HC-HEFA-SPK	Microalgae	Oleochemical	10%	5
Synthetic Paraffinic Kerosene with Aromatics	ATJ-SKA	Alcohols from biomass			-
Fats, Oils, and Greases Co-Processing	FOG Co-Processing	Fats, Oils and Greases	Biochemical /co-processing	5%	-
Fisher-Tropsch Co-hydroprocessing	FT Co-processing	Fischer-tropsch biocrude	Thermochemical /co-processing	5%	-
Co-Processing of HEFA	HEFA co-processing	Hydroprocessed esters/fatty acids from biomass’	Oleochemical /co-processing	10%	-

The table above shows the approved pathways have a **maximum blending ratio** of 5 and 50 %. These limits are necessary to meet the required aromatic content, which must fall within 8 to 25 %. Presently, the certified pathways do not meet the minimum amount of aromatics. Furthermore, pure SBC does not contain paraffin and has a lower density and lubrication ability. Therefore, they are incompatible with aircraft and existing aviation fuel infrastructure in their pure state (ICAO, n.d.). The ‘EU Aviation Safety Agency’ (EASA) pointed out that this constrains the use of large amounts of SAF (EASA, n.d.).

The next sections will address some of the challenges of the conversion techniques; however, they are not comprehensive, and other significant issues may also impact the field.

2.1.1.Thermochemical conversion

The FT-HP-SPK, FT-SKA and FT-coprocessing pathways all use the thermochemical conversion technique Fischer-Tropsch. **Challenges** of **FT conversion** include process complexity involving multiple stages. Moreover, there are concerns regarding feedstock quality and consistency as this could affecting efficiency. This could also lead to scale limitations as the heterogeneous feedstock require a small-scale operation. Not being able to operate on a large scale intensify the impact of the high capital costs of conversion facilities (Wang and Wu, 2023). More specifically, it is important to note that the FT-SKA enables the conversion of PtL (ICAO,2023).

2.1.2.Oleochemical conversion

HEFA-SPK, CHJ and HC-HEFA-SPK are the pathways that use oleochemical conversion techniques. The **HEFA-SPK** conversion involves catalytic deoxygenation and hydroprocessing, which is a relatively simple process. This pathway has the highest energy conversion efficiency, and it is the most mature pathway (Bauen et al., 2020; ICAO, n.d.). Challenges associated with SPK-HEFA are relatively limited. However, there is need for strict process control due to heat generation and the fuel's low aromatics content, which makes it considered lower quality. The **HC-HEFA-SPK** uses microalgae oils as a feedstock and, therefore, has an additional challenge of feedstock supply logistics (Usman et al., 2023). The **CHJ** converts feedstocks under high temperatures and pressures with water exposure. Challenges include improving the conversion yield for economic viability and reducing capital expenditures such as catalyst costs (Eswaran et al., 2021)

2.1.3.Biochemical conversion

Three pathways, SIP-HFS, ATJ-SPK and FOG Co-processing, use the biochemical conversion process. Specific challenges for **SIP-HFS** challenges encompass process complexity and improving energy efficiency for enhanced cost-effectiveness (Detsios et al., 2023; Usman et al., 2023). Challenges associated with **ATJ-SPK** include lower SBC quality due to high oxygenate levels and low kerosene content. Moreover, there are economic challenges related to high feedstock, operational production costs and high capital costs with currently low potential for reduction (Pasa et al., 2022; Detsios et al., 2023).

2.1.4.Co-processing

The **FOG, FT and HEFA co-processing** pathways refine raw oils and petroleum during production. These pathways differ from those discussed earlier, as they mix SBC with CJF after refining. Challenges include low blending limits, the need for more available information on co-processing, feedstock variety and process defaults affecting fuel quality (Usman et al., 2023; Detsios et al., 2023).

2.2. Emerging conversion techniques

Of the eleven ASTM-approved pathways, the overall challenge is the dependence on finite feedstock sources, such as fats, oils, and greases, is expected to limit scalability to less than ten % of the total jet fuel supply by 2050. As a result, there is a growing investment trend towards emerging conversion technologies (Boylens H.B., 2022).

An emerging approach is the development of **combined conversion pathways**, merging processes such as ATJ and FT. Such combinations of processes enable the use of more plentiful feedstocks like agricultural residues and MSW, which are often simpler to gather than the fats, oils, and greases that now dominate the market. With multiple airline offtake agreements recently announced, the commercial-scale deployment of those fuel types is just beyond the horizon (Fontaine et al., 2022).

3. Economic and environmental assessment of SAF

SAF production's economic viability and environmental impact are essential for widespread adoption. This section delves into the financial assessment of SAF production, considering feedstock prices, minimum selling prices, and production capacities across various conversion techniques. Additionally, it explores the environmental implications of SAF production, focusing on life cycle emissions and abatement costs associated with different feedstocks and conversion methods. Through a comprehensive analysis, this chapter aims to provide insights into the economic feasibility in section 3.1 and the sustainability of SAF productionin section 3.2.

3.1. Economic assessment of neat SAF production

To commercialise SAF, it is crucial to consider the total cost of producing it. However, determining this cost can be complicated because it depends on various factors, such as the type of conversion techniques used, the feedstock utilised, and the scale of production, among other things. To address this issue, **"Rules of Thumb"** for neat costs were developed by Washington State University and endorsed by the University of Hasselt. These rules provide an estimate of the neat SAF cost and can help in assessing its commercial feasibility.

ICAO assessed four conversion techniques: FT, HEFA, ATJ, and pyrolysis. Pyrolysis is not discussed in this thesis, so only the cost of FT, HEFA, and ATJ will be addressed for multiple possible feedstocks. Two TRLs, n^{th} and pioneer, were considered. The following calculations are based on Techno-Economic Assessment (TEA) models. The following tables will focus on the ICAO summary tables and contain essential information on the four conversion techniques and their feedstocks to view the cost of neat SAF production. A short interpretation of the numbers follows each table.

Table 3: Fisher-Tropsch conversion cost

Fischer Tropsch Conversion					
Feedstock	Feedstock price (dollar per tonne)	Minimum Selling Price (dollar per litre)		Neat SAF production (million litre/year)	
		n^{th}	Pioneer	n^{th}	Pioneer
Municipal Solid Waste	30	0.9	2.1	200	40
Forest Residues	125	1.7	3.3	160	40
Agricultural Residues	110	2.0	3.8	120	40

Based on these numbers from the ICAO, the MSW is the relatively best option within the **FT conversion** for multiple reasons. To start, it has the lowest feedstock price. The feedstock must be processed before it is used with the FT. Further, it has the lowest Minimum Selling Price (MSP). Moreover, it has the highest possible neat SAF production. Furthermore, additional numbers of the ICAO show that MSW has the highest conversion yield since from one tonne of MSW feedstock, approximately 0.31 tonne of distillate neat SAF fuel can be made. The yield is 0.18 and 0.14 tonne distillate per tonne feedstock for forest and agricultural residues, respectively.

Table 4: Alcohol-to-jet conversion cost

Alcohol-To-Jet Conversion					
Feedstock	Feedstock price (dollar per litres)	Minimum Selling Price (dollar per litres)		Neat SAF production (Million L/year)	
		n^{th}	Pioneer	n^{th}	Pioneer
Ethanol (Corn based)	0.41	0.9	1.1	700	70
Isobutanol-low (Corn based)	0.89	1.3	1.5	700	70
Isobutanol-high (Corn based)	1.20	1.7	1.9	700	70

Continuing with the comparison of the **ATJ conversion**, calculations show that the feedstock price of Ethanol is the lowest at 0.41 dollars per litre. Also, the MSP of ethanol is the lowest, at 1.1 at the pioneer level and 0.9 dollars per litre after the n^{th} year. The neat SAF production is the same for Ethanol, Isobutanol-low and Isobutanol-high. The number of litres of neat SAF production with the ATJ conversion is higher than the FT conversion options. Based on the MSP and the neat SAF production, the ATJ conversion with ethanol is more favourable than the FT conversion with MSW.

Table 5: HEFA conversion cost

HEFA Conversion					
Feedstock	Feedstock price (dollar per ton)	Minimum Selling Price (dollar per litres)		Neat SAF production (million L/year)	
		n^{th}	Pioneer	n^{th}	Pioneer
FOGs	580	0.8	-	550	-
Soybean oil	809	1.0	-	550	-

For the **HEFA Conversion,** the feedstock options FOGs and soybean oil have been assessed. Calculations show that FOGs, has the relatively lowest feedstock of 580 dollars per ton and it also has the lowest MSP of 0.8 dollars per litre. The MSP is 20 % higher at 1.0 dollars per litre. The neat SAF production for both feedstocks can reach 550 million litres annually in the n^{th} year.

The following figure **compare the 'neat' MSP** in the n^{th} year of the above-discussed SAF pathways. This diagram also compares the MSP of SAF to the price of CJF in January 2022.

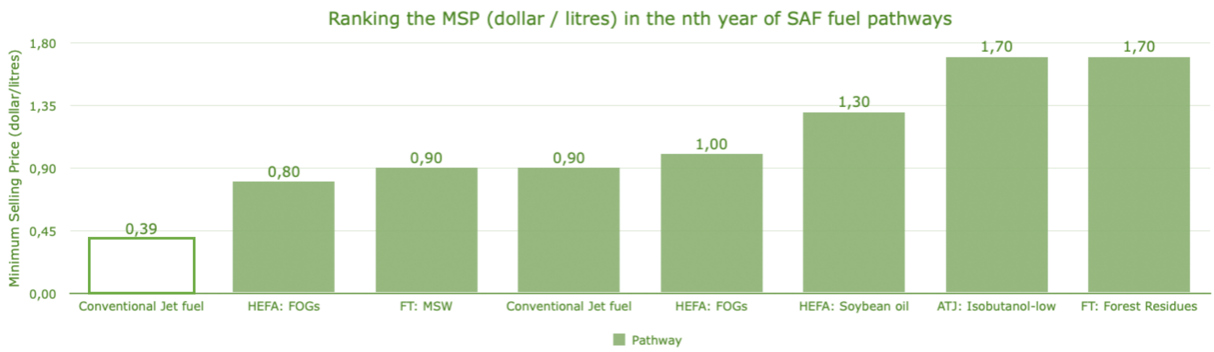


Figure 7: Ranking of the MSP (dollar/litres) in the nth year of neat SAF fuel pathways

Ranking the calculations from the ICAO on the MSP in the n^{th} year shows that the neat SAF production made from FOGs with the HEFA conversion technique has the lowest MSP in the n^{th} year. The neat SAF made from Ethanol with the ATJ conversion technique and MSW with the FT conversion technique have a slightly higher MSP per litre. Ethanol is especially interesting as it has a yearly neat SAF production capacity of around 27 % higher in the n^{th} year than the HEFA conversion with FOGs. Nevertheless, CJF per litre was 39 cents in January 2022 (ICAO, n.d.), significantly lower than the lowest calculated MSP of neat SAF fuel.

In these calculations, no incentives were included. Besides, the calculations are based on assumptions, and the costs are based on 'U.S. costs', so they may differ in other regions. Given these conditions, the calculated prices are possibly not plausible.

3.2. Environmental impact and abatement costs of neat SAF production

Whether a conversion technique combined with a particular feedstock is a favourable neat SAF fuel depends not only on the MSP. The goal of the neat SAF is to decline CO_2 emissions. Subsequently, it is also essential to consider the cost that must be paid to avoid one tonne of CO_2 emissions. However, as these costs also depend on the cost of production of neat SAF, which is yet uncertain, the same 'Rules of Thumb' as discussed above will be applied. The FT, ATJ and HEFA conversion techniques are discussed for the same feedstock options used in the last section. The following table is based on numbers of the ICAO and the 'CORSIA Default **Life Cycle Emission (LCE)** values for CORSIA Eligible Fuels and gives an insight into the **'Abatement costs'** of CO_2 for each pathway at the pioneer and n^{th} levels.

Table 6: LCE and abatement cost Fischer-Tropsch conversion

Fischer-Tropsch Conversion			
Feedstock	Life Cycle Emissions (gCO_2e/MJ)	Abatement costs (Dollar per tonne CO_2)	
		n^{th}	Pioneer
MSW	32.5	210	840
Forest residues	8.3	420	990
Agricultural residue	7.7	520	1170

The **FT conversion** technique combined with the MSW feedstock has the lowest abatement costs. This could partially be because this feedstock has the relatively lowest MSP compared to forest and agricultural residues. This reasoning is supported by the fact that MSW's actual LCE values are the highest of the three feedstocks. The forest and agricultural residues have higher abatement costs; however, their LCEs are more than three times lower.

Table 7: LCE and abatement cost Alcohol-To-Jet conversion

Alcohol-To-Jet Conversion			
Feedstock	Life Cycle Emissions (gCO_2e/MJ)	Abatement costs (dollar per tonne CO_2) n^{th}	Pioneer
Ethanol (corn based)	90.8	No abatement	No abatement
Isobutanol-low (corn based)	77.9	2100	2510
Isobutanol-high (corn based)	77.9	3220	3680

Regarding the **ATJ conversion** technique, the numbers show that the feedstock Ethanol has no abatement costs as it does not diminish CO_2. The Isobutanol-low and -high feedstock does abate CO_2; however, this cost is relatively high compared to the FT conversion feedstocks. These results align with the relatively high LCEs of these three ATJ-conversion feedstocks. The fact that the LCEs of these neat SAF fuels are relatively very high raises the question of whether these pathways are a suitable solution for reaching 'net-zero flying by 2050'.

Table 8: LCE and abatement cost of HEFA conversion

HEFA Conversion			
Feedstock	Life Cycle Emissions (gCO_2e/MJ)	Abatement costs (Dollar per tonne CO_2) n^{th}	Pioneer
FOGs	18.2	130	-
Soybean oil	64.9	640	-

The ICAO numbers on the **HEFA Conversion** show that the feedstocks FOGs and soybean oil are very different. For instance, the abatement costs of soybean oil in the nth year are almost five times higher than those of FOGs. Also, the LCEs of FOGs are more than three times lower than those of soybean oil. The abatement costs at the pioneer level are not available for these HEFA conversions.

Based on the **comparison of the LCEs** of the FT, ATJ, and HEFA conversion techniques, a ranking of the most favourable 'neat' SAF fuel pathway based on the emission of CO_2 can be made. This ranking is shown in the following diagram, which includes the LCEs of CJF with a global average of 88.7 gCO_2e per MJ (Jing et al., 2022).

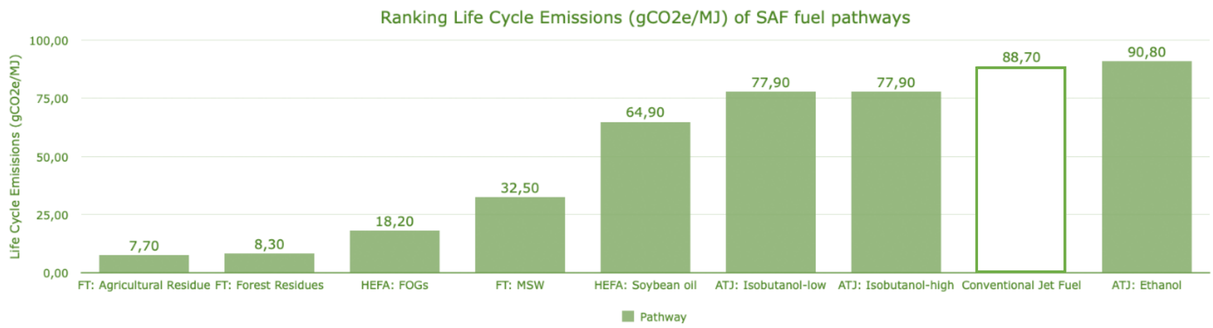


Figure 8: Ranking LCE of SAF fuel pathways

The LCEs ranking (Figure 8) shows that neat SAF made from agricultural and forest residues take the first and second place, respectively, as they have relatively low CO_2 emissions. Their emissions are more than ten times lower than CJF. The neat SAF fuel made from FOGs with HEFA stands in third place as favourable SAF fuel even though it has more than twice as many LCEs compared to the agricultural and forest residues SAF. Next in the ranking is MSW from FT, followed by soybean oil from HEFA, continued with ATJ isobutanol-low and -high, followed by the non-SAF, CJF. Lastly comes ethanol, made by ATJ, which has the highest CO_2 emissions through its life cycle.

Besides ranking CO_2 emissions during the life cycle, it is also important to rank the cost of abating a ton of CO_2. The next diagram compares the dollars it takes to abate a ton of CO_2. The abatement costs of this ranked diagram are based on the n^{th} year.

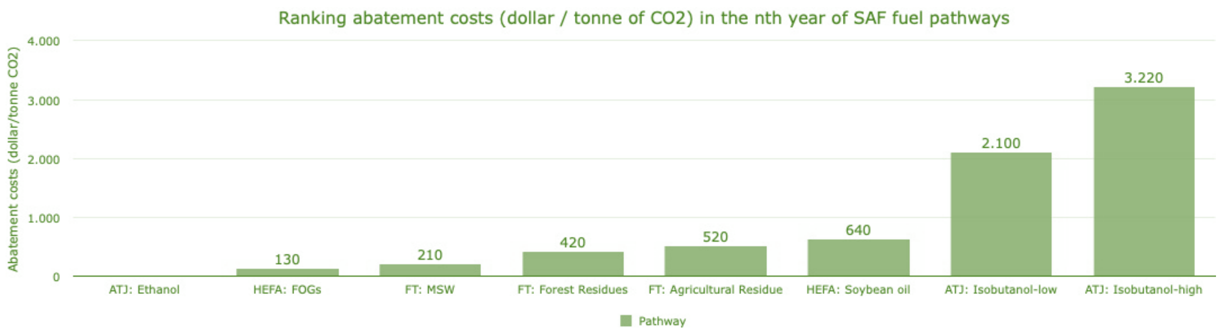


Figure 9: Ranking abatement costs in the nth year of neat SAF fuel pathways

The ranking of the abatement costs (Figure 9) is slightly different from the LCE ranking. The FOGs-based SAF has the lowest cost in avoiding one tonne of CO_2 that would have been emitted by CJF. Next comes the FT with MSW feedstock, and in third place stands the FT Forest Residues, which has a doubled cost of reduction compared to FT MSW. The fourth and fifth in the ranking are, respectively, the FT conversion with agricultural residue and the HEFA process with Soybean oil. The two SAF fuels with the highest abatement costs are ATJ isobutanol-low and -high. These two fuels have significantly higher abatement costs than the other SAF fuels. The SAF fuel made with ATJ conversion with Ethanol is falling out of this ranking, as it emits more CO_2 than CJF. So, there is no reduction of CO_2 with this fuel, and thus, there are no abatement costs.

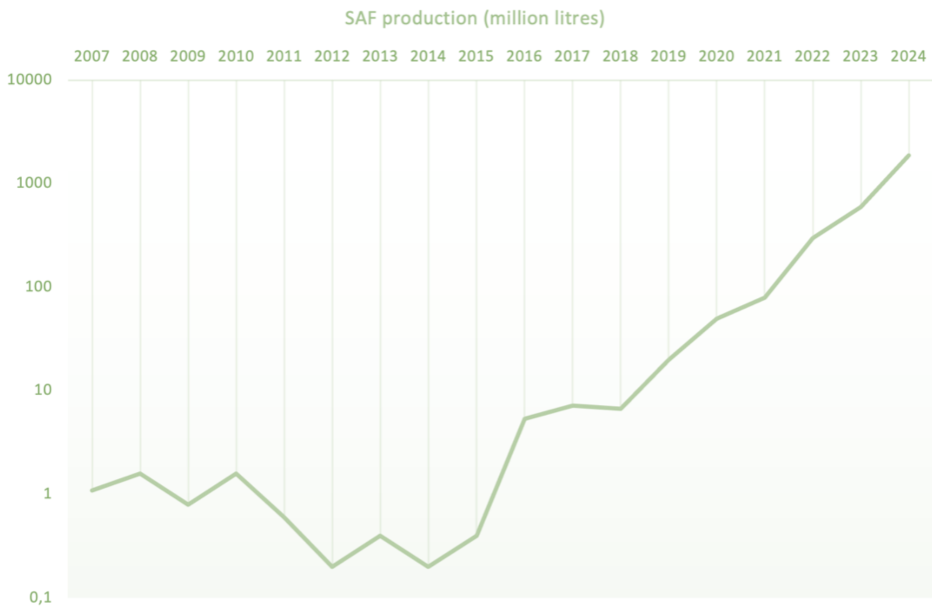
Comparing the rankings of the abatement costs and life cycle emissions can be helpful to the supply side as well as the policy side. Given that SAF fuels are created to go towards net-zero flying, it is essential to look beyond the production costs and capacity. It is crucial to notice that these calculations are prospects based on assumptions. Also, no incentives were included in the calculated abatement costs and these costs are based on conditions from the U.S. (ICAO, n.d.) Given these conditions, the calculated LCEs and abated costs are possibly invalid.

4. The SAF production market

This section explores the evolving landscape of the SAF production market. Section 4.1 outlines the evolution of the SAF market, followed by projections in section 4.2. Lastly, section 4.3 discusses SAF producers, as well as their drivers and barriers.

4.1. Evolution of SAF production

Figure 10 illustrates the historical growth of SAF production from 2007 to the projected figures for 2024, indicating rapid recent increases. Production is expected to triple in 2024 to 1875 million litres, yet this will only constitute 0.53% of total aviation fuel, underscoring the emerging but still limited role of SAF in the broader aviation fuel market (IATA, 2023).



Year	Million litre
2007	1,1
2008	1,6
2009	0,8
2010	1,6
2011	0,6
2012	0,2
2013	0,4
2014	0,2
2015	0,4
2016	5,4
2017	7,2
2018	6,7
2019	20
2020	50
2021	80
2022	300
2023	600
2024e	1875

Figure 10: Historic SAF production, expressed in logarithmic million litres from 2007-2024e (IATA, 2023; ICAO, n.d.)

4.2. Projections of SAF production

Projections indicate that SAF production will need to significantly increase to meet aviation's net-zero goals by 2050. The IATA expects SAF production to grow to 8 billion litres by 2025. Five years later, in 2030, it is supposed to have almost tripled to 23 billion litres. In 2035, it is required to produce 90 billion litres, and by 2040, the yearly production should reach 229 million litres. This means that between 2030 and 2040, there is an anticipated nearly tenfold rise in SAF production. This is expected to further rise to 346 billion litres by 2045. Eventually, to meet the required SAF for the Net Zero 2050, 449 billion litres must be produced yearly. These numbers are visualised in Figure 11, based on the IATA Fly Net Zero report (IATA, 2023). This timeline illustrates the expected increase in SAF production needed to achieve the 'Net Zero 2050' goal.

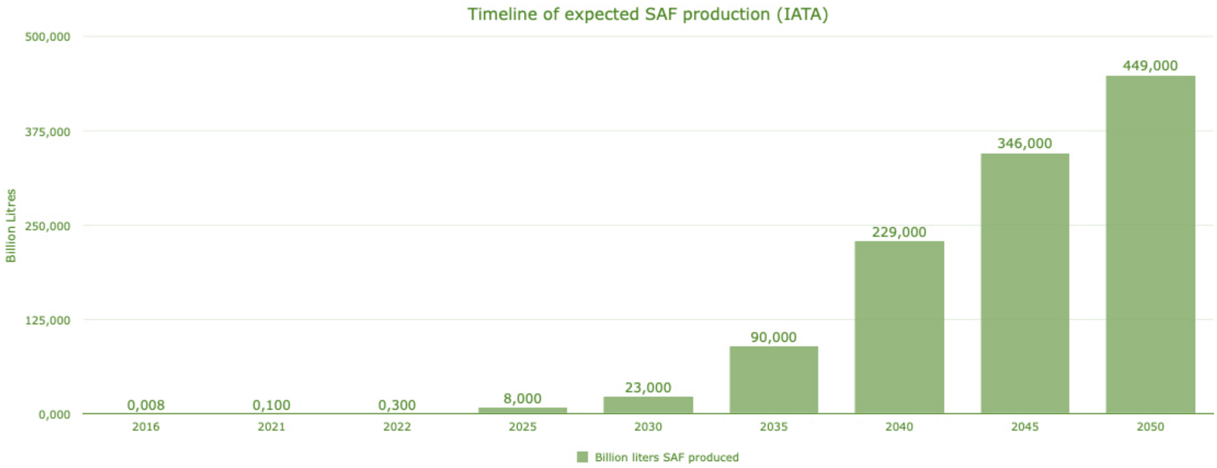


Figure 11: Timeline of expected SAF production in terms of billion litres

4.3. The SAF producers

Based on the offtake SAF volume numbers provided by the ICAO, this section discusses the **top five producers of SAF**. An overview of their production volumes, share of total production volume and utilised conversion technology is provided in table x. These numbers relate to the year 2023.

Table 9: Top five producers SAF 2023 (ICAO, 2023)

Company	Production volume (Million litres)	Share of total production volume	Conversion technology
Gevo	9.550	22 %	ATJ-SPK
Fulcrum	6.719	16 %	FT-HP-SPK
Alder Fuels	5.678	13 %	Pyrolysis oil (APOTM) technology
Shell	2.792	7 %	SPK-HEFA and FT-HP-SPK
Neste	2.452	6 %	SPK HEFA

The largest SAF fuel producer currently is **Gevo**, an American company. They use the ATJ-SPK pathway and produce 9.550 million SAF litres. As the total offtake volume was 42.506 million litres, Gevo produces approximately 22% of the total offtake volume (ICAO, 2023). Gevo expects to expand quickly and plans to sell more than 3.7 billion litres of SAF by 2030 (BBC research, 2022). The second largest producer is **Fulcrum**, which produces 6.719 million litres using the FT-HP-SPK conversion method. Third in line stands **Alder Fuels,** with an offtake volume of 5.678 million litres through their patented process 'prylosis oil technology'. Fourth comes **Shell**, with a relatively much lower volume of 2.792 million litres through SPK-HEFA and FT-HP-SPK. **Neste** is the fifth SAF fuel producer, with a total offtake volume of 2.452 million litres with the SPK-HEFA pathway (ICAO, 2023). According to Neste, they are ‘the largest producer of renewable diesel and jet fuel in the world’; however, this does not make Neste the largest SAF producer since renewable diesel is not always considered an SAF (Neste, n.d.). These five leading firms in offtake numbers account for almost 60% of the total offtake volume (ICAO, 2023).

Besides these leading firms, some organisations are still considered **start-ups**; however, their growth is fast. **LanzaJet** was created in 2020 and has already secured place in the SAF industry. They have already gained powerful partnerships with companies such as British Airways, Shell, etc. They use the ATJ-SPK technology to produce SBC. **SkyNRG** is another start-up producing SBC through SPK-HEFA. They have important partnerships with KLM Royal Dutch, World Energy, and Shell Aviation. With their expansion plans, they are projected to be on the list of leading companies by 2030 with a supply of 1,25 billion metric litres of SAF (BBC research, 2022).

According to the IATA, the foremost **driver** for becoming a SAF supplier starts with the fact that SAF could become a necessity for airlines as there is a need to reduce carbon emissions (2015). Another driver is the lack of alternative technology to fuel as many airplanes as SAF. As regulations will require the airlines to emit less CO_2, an enormous SAF demand is expected (IATA, 2015). Subsequently, revenues could eventually turn high, as it is still possible to achieve a significant share of the relatively new SAF market, which has a lot of growth potential. Gegg et al.'s study emphasises the SAF market's new business opportunities. Besides the short-term losses that might occur, the long-term benefits could be substantial (2014).

Despite various drivers for SAF development, several **constraints** significantly impede industry growth. High entry barriers characterise the SAF market, with challenges arising from complex technologies, substantial capital requirements, social acceptance, environmental concerns, and a diverse regulatory landscape (Ahmad and Xu, 2021). Additionally, economies of scale further restrict the entry of new suppliers. Production costs remain a major hurdle, complicated by quality control and logistics issues, making scaling up SAF production challenging (Gegg et al., 2014). Policy inconsistency also poses significant barriers, with stakeholders noting a lack of sufficient government funding and support (Gegg et al., 2014; Korkut et al., 2021). Insufficient feedstock supply and limited refinery capacity further constrain the market (Gegg et al., 2014). Moreover, integrating SAF into existing conventional fuel supply lines is costly and time-consuming, especially for smaller producers (Souza et al., 2015; RSB, 2023).

Part C: The demand side of SAF

This part examines the complex interplay of factors driving SAF demand and market penetration. It starts by exploring the overall market demand in section 1. This is followed by section 2, which evaluates individual demand. Additionally, the economic and political players will be discussed in sections 3 and 4, and collaborative networks will also be indicated in section 5.

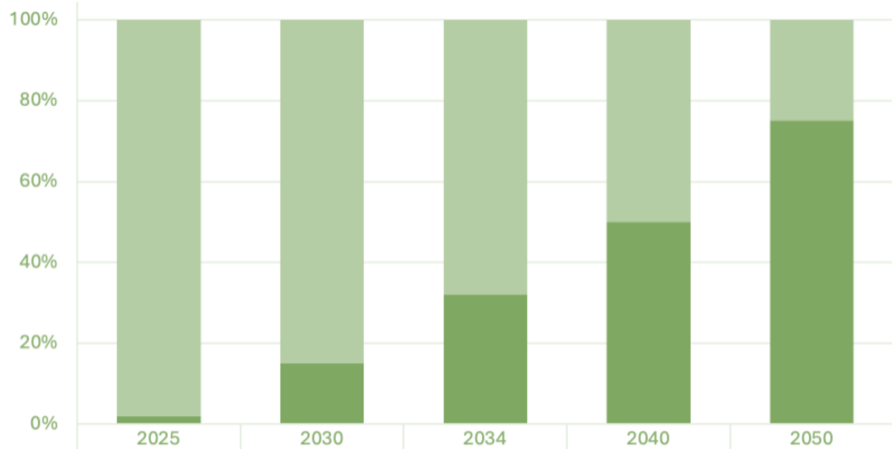
1. Analysis of SAF demand

This section analyses the SAF demand, covering its evolution and forecasts (section 1.1), types of demand (section 1.2), and the dynamics of the SAF demand (section 1.3).

1.1. Evolution and prospects of SAF demand

The **adoption of SAF** has undergone an evolution marked by **milestones**, starting in 2008, when Virgin Atlantic conducted its first test flight with SAF. Following this, from 2011 to 2015, over 2500 commercial passenger flights were performed by 22 airlines. Commercial SAF flights surpassed 250 thousand in 2019. Between 2022 and 2023, SAF consumption tripled to 600 million litres, representing substantial growth (IATA, 2023). In 2024; over 419 thousand commercial flights have been conducted using SAF since 2011 (Qasem et al., 2024).

Yet, this is only a small share of the total aviation fuel compared to the CFJ share. PwC's research used the IAE Net Zero Pathway numbers to **forecast global SAF demand** (PwC, 2022). Figure 12 shows the projected SAF share compared to CJF.



	2025	2030	2034	2040	2050
Jet Fuel share	98%	85%	68%	50%	25%
SAF share	2%	15%	32%	50%	75%

Figure 12: SAF share and jet fuel share (CJF) of the total aviation share

1.2. Types and segmentation of SAF demand

The total aviation demand consists of the demand for fossil jet fuel and SAF. The demand for SAF can be further categorised into **two major types**: mandated and voluntary demand (figure 13).

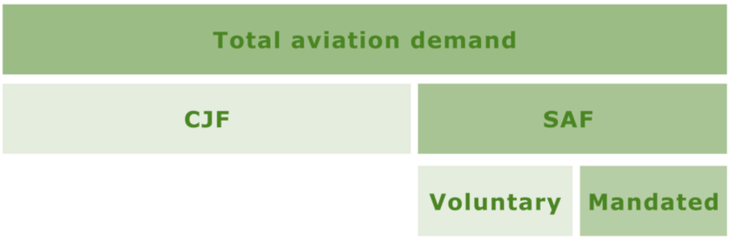


Figure 13: Visualisation of total aviation fuel demand

The mandated demand is driven by **compliance** with national, regional, or global mandates, policies, and rules that require emissions reductions. The parties who must adhere to the government regulations are generally fuel manufacturers, fuel providers, and airlines. The regulatory actions promote demand and offer long-term certainty for financial investments and the expansion of SAF. On the other hand, **voluntary demand** goes beyond the mandated demand. This is solely driven by the voluntary desire to purchase offsets and, thus, not by obligations to do things that lead to emission reduction. As there is no law enforcement in the voluntary system, it will only be done up to a certain degree. This is supported by the fact that trading volumes in the voluntary market are far lower than those in the compliance market (Hathwar, 2022).

The SAF market operates primarily in a **business-to-business (B2B)** model, where 'airlines' represent the demand side of the SAF. B2B transactions typically involve large quantities, long sales cycles, complex pricing structures, and strategic partnerships for mutual benefit (Chen et al., 2022). While the focus lies on B2B interactions, it is important to consider the **business-to-consumer (B2C)** segment, which involves the end-users of SAF. This perspective is relevant as airlines strive to meet individual passenger needs and preferences. This **end-user market** can further be segmented by type into commercial aviation, general, and military aviation. **Commercial** aviation is further segmented by leisure and corporate passengers and cargo transportation. **General** aviation is further segmented into public services, private flights for business purposes, and private flights. General flights are not conducted by scheduled airlines. **Military** aviation is further segmented by combat and non-combat aircraft. (Mordor Intelligence, n.d.). An overview of the SAF demand is visualised in figure 14.

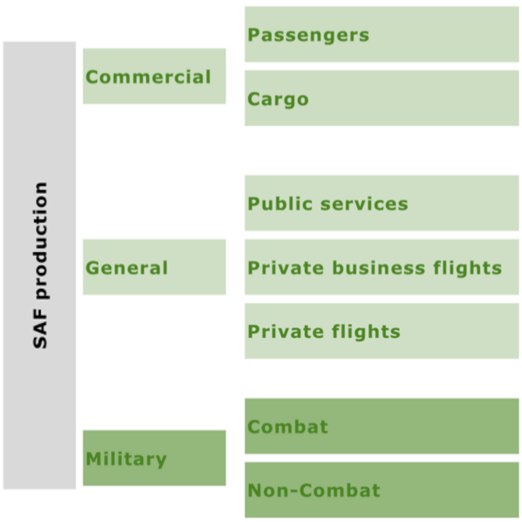


Figure 14: Overview of SAF end-user SAF market

1.3. The dynamics of SAF demand

Various driving forces influence the demand for SAF. The agentic and structuralist perspectives, visualised in Figure 15, will be applied to gain a detailed understanding of these driving forces.

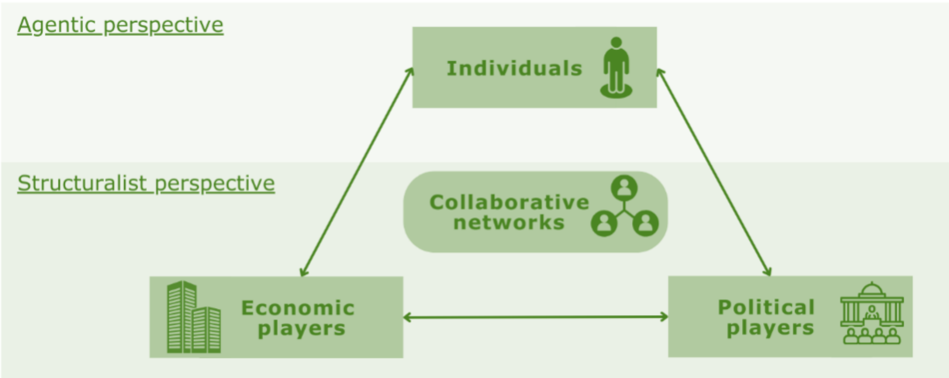


Figure 15: Perspectives on reducing aviation emissions

The **agentic perspective** focuses on the pivotal role of individuals in driving the reduction of aviation emissions. It posits that individuals can make environmentally conscious choices, including opting for low-emission air travel and advocating for policy reforms. Conversely, the **structuralist perspective** underscores the need for action at the governmental and industry levels to address aviation emissions. It focuses on the influence of regulatory frameworks, industry practices, and business advertising in shaping consumer behaviours. Structuralists argue that individual actions alone are insufficient to achieve meaningful emissions reductions and advocate for high-level policies and actions to realise systemic transformations within the aviation sector (Dolsak and Prakash, 2022).

2. The SAF demand of individuals

As noted by Korba et al., conducting an examination of the direct and indirect factors influencing individuals' choice of SAF can offer valuable insights into the underlying drivers of SAF demand (2023). Therefore, This chapter will examine the individuals' voluntary demand for SAF from a social science perspective using the **Theory of Planned Behaviour** (TPB). TPB is a widely used framework that explains the psychological factors affecting individuals' intentions and behaviours (Azjen I., 2011). This framework has gained attention in environmental studies (Yuriev et al., 2020), and will therefore be used to identify and categorise the factors influencing individuals' demand for SAF.

Central to the TPB is the idea that **behaviours** are influenced by individual intentions. These **intentions** are influenced by attitudes, subjective norms, and perceived behavioural control (PBC). **Attitudes** reflect personal evaluations of the behaviour; **subjective norms** involve perceived social pressures; and **PBC** relates to one's perception of the ease or difficulty of performing the behavior (Fiorello A.P., 1999, Ajzen I., 2011).

In the case of SAF, **behaviour** is reflected in individuals' SAF use, which is represented by their actions in the market. As SAF is more expensive than CJF, airlines might have to charge more for tickets, making the consumers' WTP an important factor. Therefore, **WTP** will be considered the **intention** component. The intention of WTP for SAF is also influenced by demographic variables (Ahmad and Xu, 2021) and will therefore be added to the framework. Figure 16 shows an overview of the TPB applied to the individual voluntary demand of SAF. Each component will be discussed in sections 2.1 to 2.6

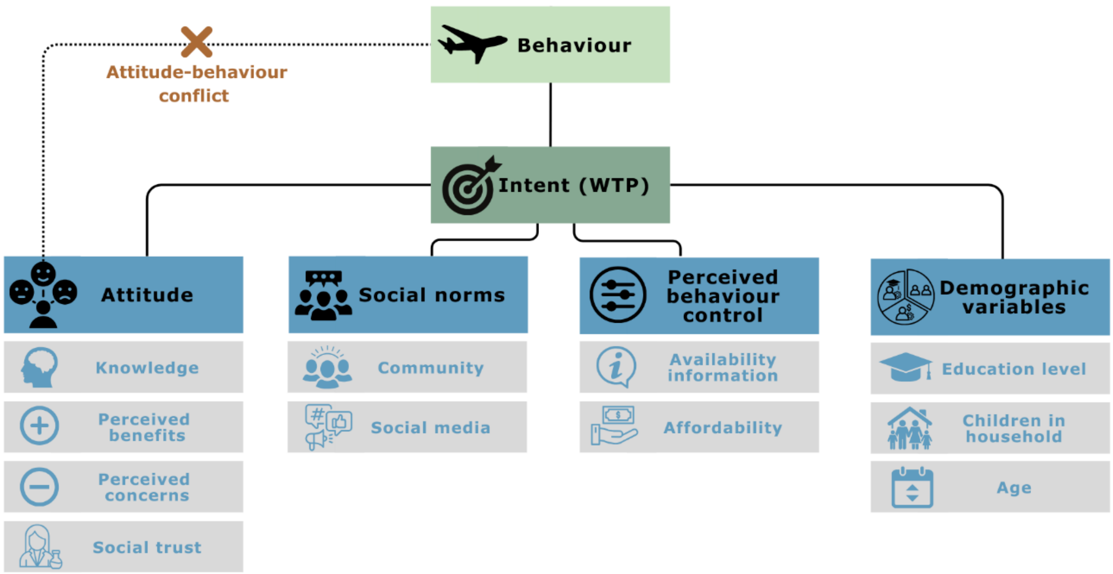


Figure 16: Individual demand SAF

2.1. Attitude

According to the TPB framework, achieving a positive attitude towards SAF predicts an individual's intention to use SAF (Azjen et al., 2011; Korba et al., 2023). **Attitude** comprises the public's views regarding the usefulness of SAF, which can be categorised into the following statements: support the idea of using SAF, negative about the idea of using SAF, prefer airlines using SAF, and encourage others to use SAF. Ahmad et al.'s survey showed that 71 % of their participants support the idea of using SAF, which can be interpreted as a favourable attitude toward using SAF. In addition, 91% of the participants expressed their disagreement with the idea that using SAF is not a good practice. Additionally, 71% prefer airlines that use SAF, while the remaining 29% remain undecided. All participants agreed to encourage others to choose flights using SAF. These attitudes are determined by multiple dimensions: knowledge, perceived benefits, perceived concerns and social trust (Ahmad et al., 2019).

2.1.1.Knowledge of SAF

Based on research by Ahmed et al., four topics will be analysed to gain insight into an **individual's knowledge** of **SAF**. The first aspect is the **recognition** of **aviation** as a significant **contributor** to **GHG emissions**. The survey by Ahmed et al. revealed that almost 75% of their participants acknowledged aviation as a primary contributor to GHG emissions, whereas only 10% opposed this idea. However, a survey initiated by EASA, which gathered insights across 18 European countries, underscores the public’s desire for greater environmental transparency. Only 5% of respondents were aware of the CO_2 impact of their air travel, and 80% expressed a desire to access environmental information about their flights (EASA, n.d.).

The second facet involves the **concerns** of individuals about **GHG emissions** from aviation (Ahmad et al., 2019). Santos and Delina note the rising environmental consciousness, particularly among Millennials (2021). Moreover, according to a 2019 McKinsey survey, approximately 40 % of Millennials plan to reduce air travel due to concerns about aviation's contribution to climate change (Dichter et al., 2020). However, Higham et al. suggest that individuals only have limited agency regarding their aviation emissions (2019).

The third area assesses **awareness** of **SAF utilisation in aviation**. Ahmad et al. found a moderate degree of this awareness, with 55% of the respondents aware of its usage in aviation (2019). Filimonau et al.'s study revealed a general recognition of biofuels' potential but a lack of awareness regarding their specific application in air travel (2018).

The fourth dimension delves into an **individual’s knowledge** regarding **SAF**. According to Ahmed et al., approximately 60% of participants exhibited insufficient knowledge of SAF (2019). For instance, Xu et al. showed that their participants lacked information about the SAF production process and its technical characteristics (2022). Additionally, Filimonau and Högström highlighted the limited public understanding of the environmental advantages of SAF (2017). Moreover, the public expressed uncertainty regarding whether SAFs lead to reduced GHG emissions while maintaining affordable flight prices (Anderson et al., 2022). Additionally, there was a lack of understanding regarding the challenges associated with SAF adoption in aviation (Filimonau et al., 2018).

2.1.2.Perceived benefits

According to Ahmad et al., the **perceived benefits** can be assessed through the following criteria: the diminished reliance on traditional jet fuel, decreased reliance of a country on foreign oil, anticipated environmental benefits, offering better advantages compared to other measures for reducing GHG in aviation, and economic and societal benefits. Over 70 % of the participants expressed the perception that SAF has the potential to decrease reliance on CJF. Similarly, 70% agreed that SAF usage could reduce a country's oil dependence. Moreover, approximately 74% of the participants agreed it could significantly aid in safeguarding the environment. However, opinions were divided when comparing SAF to other measures for reducing GHG emissions, with 54% of participants undecided. Nevertheless, there was unanimous agreement among participants that investments in SAF would yield benefits for both the economy and society (2019)

2.1.3.Perceived concerns

A third factor is **perceived concerns**, which negatively impact attitudes towards SAF. These concerns encompass various aspects, including worries about the safety implications, potential competition for agricultural land, harm to ecosystems, the energy balance, and insufficient supply (Ahmad et al., 2019).

Xu et al. found that the biggest concern regarding SAF use was the lack of ability to **meet demands** (2022). Ahmad et al. found that nearly 60% of participants expressed concerns about their inability to meet demands (2019). Moreover, Xu et al. point to the **'food versus fuel' dilemma** as the second largest and most common concern, with more than 50% of the participants believing that SAF production would compete for cropland (2022). Besides, Ahmad et al. found that the perceived **environmental concerns** of the production are diverse, with some disagreeing (44%), others agreeing (30%), and a notable percentage undecided (26%) (2019). For instance, while SAF is considered beneficial for the environment, its production is perceived as environmentally harmful due to concerns about soil and water pollution (Xu et al., 2022). Additionally, around 31% of respondents perceive that SAF production consumes more **energy** than it generates, while approximately 22.73% hold the opposite view. The research also showed that only a small percentage (4.7%) of participants expressed **safety concerns** about SAF (Ahmad et al., 2019).

2.1.4.Social trust

Social trust is pivotal in shaping public attitudes toward accepting technology, including SAF (Adnan et al., 2018). It encompasses the public's confidence in various stakeholders involved in technology or innovation, such as experts, government, industry, and scientists (Amin et al., 2017). Ahmad et al. indicate distinct levels of trust in entities involved in SAF development. Their assessment of social trust included three specific items: the role of the scientific community in SAF development, the societal impact of SAF producers, and the contributions of policymakers in SAF initiatives. The **SAF producers** are especially highly trusted, with 76% of participants expressing agreement with their contributions, followed by the **scientific community**, which is recognised by approximately 40% of respondents. However, there is uncertainty among 30% of participants regarding the scientific community's contributions, possibly due to limited public engagement efforts by scientists. Trust in **policymakers** is notably lower, with 40% of participants undecided and 35% disagreeing with their contributions. This highlights the need to enhance trust in policymakers to foster support for SAF initiatives (Ahmad et al., 2019).

2.1.5.Attitude-behaviour conflict

Despite having positive attitudes toward the environment and its protection, many frequent flyers are reluctant to change their travelling behaviour (Alcock et al., 2017). Filimonau et al. also pointed out this conflict between attitudes and behaviours, hindering voluntary efforts. This conflict arises when individuals acknowledge that their flying habits could contribute to reducing GHG emissions but fail to act accordingly (2018; Xu et al., 2022). The inconsistency can be attributed to **cognitive dissonance**, as this phenomenon occurs when an individual experiences mental unease due to a clash between their values or beliefs and their behavior. This discomfort prompts people to reduce the dissonance by either changing their attitudes, values, or beliefs or by adjusting their behavior (McDonald et al., 2015).

2.2. Subjective norms

Subjective or social norms play a role in influencing people's behaviour. They are caused by perceived social pressure from others to engage in specific actions. When a social group promotes pro-environmental attitudes, individuals may feel obligated to conform to gain in-group identity (Laroche et al., 2001). To increase individual demand for SAF, it's important to create a positive social norm where those surrounding the individual also support SAF (Korba et al., 2023).

The **social learning theory** offers insights into how individuals are influenced by the behaviours and attitudes of their **community** toward green initiatives, here SAF (Reed et al., 2010). The theory suggests that individuals are more likely to adopt pro-environmental behaviours if they perceive that others are doing the same (Korba et al., 2023). Social learning involves transforming knowledge and perception that extends beyond individual boundaries (Reed et al., 2010). As the theory suggests that passenger attitudes can be positively influenced by observing the behaviour of other passengers and stakeholders, someone's community plays an important role in individual decision-making and action (Allen et al., 2002). Assisting in social learning can increase the likelihood of individuals or groups actively addressing challenges (Wals A., 2009).

While traditionally, air travel is seen as beneficial to the community, an alternative perspective is emerging. More people see flying as socially devaluing, leading to feelings of shame and a loss of status (Korba et al., 2023). **Social media platforms** have become increasingly influential as they facilitate these discussions and allow users to share their perspectives (Roxburgh et al., 2019). It serve as an 'arena' for ideological discussion and digital activism, offering valuable insights into how people exchange views (Becken et al., 2020). For instance, the concept of 'feeling ashamed of flying' has gained significant attention. The term "flygskam" (Swedish for flight shame) emerged to describe this phenomenon. It describes the feeling that, for some individuals, shame arises regarding their flying behaviour regardless of their environmental concerns (Gössling et al., 2020). A growing number of travellers experience "flight shame," a social media trend prompting individuals to reduce their carbon footprint or explore more eco-friendly travel options (Korba et al., 2023).

2.3. Perceived behavioural control

Perceived behavioural control refers to an individual's ability to choose a certain behaviour (Dijst et al., 2008). It can, therefore, increase or decrease the intention to buy SAF. An individual's ability to choose SAF is affected by the **availability** of clear and comprehensive **information** about its environmental benefits and availability. The more informed individuals are, the more likely they are to perceive that they have control over their choice to use SAF. However, gaps in information dissemination can diminish perceived control, making it less likely that individuals will see SAF as a viable option (Filimonau et al., 2018).

Affordability is another critical aspect of PBC. The cost difference between SAF and CJF can deter or encourage individuals from choosing SAF. Studies suggest that individuals with lower fare expenditures are more willing to pay a premium for SAF (Hui et al., 2024).

2.4. Demographic variables

Demographic variables, such as education level, household composition, age, and education, also influence the intention to choose SAF.

Xu et al.'s study found that **education level** is significantly related to WTP for SAF. Individuals with a higher level of education may have increased social trust or decreased perceived risks, leading to a higher WTP (2020). Above, the presence of **children in households** has also been found to be a significant factor in determining the WTP for SAF (Hui et al., 2024). Parents are often concerned about the impact that environmental degradation could have on future generations, emphasising the role of family dynamics in environmental decisions (Biswas A., 2016). **Age** was also found to be a significant predictor, although its contribution to WTP is small (Xu et al., 2020). According to Hui et al., younger passengers tend to have a higher WTP for SAF (2024). Older passengers may have a lower WTP due to limited exposure to aviation-specific environmental initiatives (Korba et al., 2023). Moreover, younger persons are generally more proficient in seeking information online, which could influence their knowledge and, consequently, their WTP for SAF (van Deursen et al., 2011; Hui et al., 2024).

2.5. Willingness to pay

The **WTP** measures the intention to choose SAF. As the production of SBC is more expensive than CJF, airlines might have to charge more for tickets, making the WTP an important factor in the SAF uptake (Ahmad and Xu, 2021). According to Hinnen et al., consumers are generally willing to pay more for sustainable practices in aviation. For instance, they found that in Switzerland, 20% of travellers are willing to pay extra for environmentally friendly airline services (Hinnen et al., 2017).

A study conducted by Hui et al. demonstrated that only **attitude** significantly impacts WTP for SAF surcharges. Subjective norms and perceived behavioural control did not have a significant effect (2024). Moreover, the **demographic variables** education level, household children, and age significantly impact WTP for SAF (Xu et al., 2020).

3. Political players

Political players in the SFA sector can primarily be divided into international regulatory bodies and national governments.

International regulatory bodies include the EU, ICAO, and IATA. Table 10 summarises three organisations and their roles in fostering the development and widespread adoption of SAF. Each organisation has launched distinct programs and policies aimed at integrating SAF into the aviation sector, to achieve environmental targets and mitigate GHG emissions. These initiatives demonstrate a comprehensive and strategic approach at the international level (Shariar and Khanal, 2022).

Table 10: International regulatory bodies

Organisation	Initiatives & Roles	Source
EU (European Union)	• Emissions Trading Scheme for aviation via Directive 2008/101/EC in 2008, requiring payments for carbon emissions from aircraft entering EU airspace starting 2012. • EU Biofuels Flightpath in 2011 targeting a 3-4% SAF contribution by 2020. • LaunchedReFuelEU in 2021 to increase SAF usage to 2% by 2025 and 63% by 2050.	(European Union, 2008) (Wei et al., 2019) (IATA, 2013) (ICAO, 2023)
ICAO (International Civil Aviation Organization)	• Coordinates international air navigation standards and promotes SAF development. • Launched CORSIA in 2018 to reduce GHG emissions by encouraging the use of SAF. • Established the Third ICAO Conference on Aviation and Alternative Fuels (CAAF/3) to agree on a global framework for reducing CO2 emissions by 5% by 2030. • Adopted a long-term goal for net-zero carbon emissions by 2050.	(ICAO, 2021) (IATA, 2016) (EU Aviation Safety Agency, 2022)
IATA (International Air Transport Association)	• Represents and serves the global airline industry, with a membership comprising 83% of total air traffic. • Committed to reducing the aviation industry's carbon footprint through various programs supporting SAF development and adoption.	(IATA, n.d.)

Additionally, **national governments** play a crucial role in advancing the development and adoption of SAF through various strategic initiatives tailored to their specific economic and environmental contexts. The initiatives by national governments across various regions, based on research by Shahriar and Khanal (2022), are summarised in Table 11. These efforts include a mix of regulatory frameworks, financial incentives, and international collaborations.

Table 11: National initiatives for SAF development

Region	Initiative	Year	Objective/Details	Source
United States	Energy Independence and Security Act (EISA)	2007	Targets 37 billion liters of SAF by 2022, supports SAF incorporation into national supply with Renewable Fuel Standard 2.	(U.S. Congress, 2007) (Tao et al., 2017)
	Sustainable Aviation Fuel Act	2021	Introduced by President Biden to provide financial support to boost SAF production and usage.	(Reuters, 2021)
Asia	Qatar Biofuels Project	2010	Collaborative project for SAF production from microalgae.	(Atmowidjojo et al., 2021)
	Aviation Biofuels and Renewable Energy Task Force (ABRETF)	2013	Formed in Indonesia to increase biofuels production capacity.	(Shariar et al., 2022)
	Initiatives for Next-generation Aviation Fuels (INAF)	2014	Japanese initiative to establish SAF supply chains, including use for 2020 Olympics.	(ICAO, 2020)
South America	Brazilian National Biofuel Policy (RenovaBio)	2019	Supports the decarbonization of aviation fuels through a carbon credit market.	(Shariar and Khanal, 2022)
Europe	Renewable Transport Fuel Obligation (RTFO)	2018	UK's financial incentive mechanism to encourage SAF production.	(ICAO, 2021)
	Climate Change Law	2020	Enacted in Spain and France to increase SAF supply by 2025 and 2030, respectively.	(Department of Transport, 2021)
	Fossil-free Sweden Initiative	2020	Swedish goal to achieve a 30% SAF blend ratio by 2030.	(C. Velarde, 2020) (Shariar and Khanal, 2022)

It's important to note that these tables do not encompass all global and national initiatives but focuses on key examples to illustrate the range of approaches. There is a clear diversity of policies, from regulatory frameworks and financial incentives to international collaborations. The taxonomy (part E section 3) will further explain the potential policy strategies.

4. Economic players

This section will discuss the economic players involved in the demand of SAF, presented in figure 17: airlines, producers and corporate travel.

Figure 17: Economic players SAF market

Airlines are important economic players in the demand for SAF, especially as they are the purchasers of SAF and the 'providers' of SAF to individual consumers. SAF presents an opportunity to enhance brand favorability by supporting sustainable practices. However, airlines face significant hurdles in embracing SAF due to concerns about the **price premium** associated with these fuels. Moreover, airlines are hesitant to absorb the additional costs of SAF while striving to maintain competitive ticket prices (Dichter et al., 2020).

Airports are situated at the convergence of numerous stakeholders in the aviation sector, including fuel producers, airlines, governments, and end customers. This strategic position enables airports to play an increasing role in implementing SAFs (RSB, 2023). Strong airport leadership can drive industry sustainability and the adoption of SAF (Klauber et al., 2017). Research conducted by the Airports Council International and RSB revealed that in 2022, almost one-third of the world's 32 busiest airports have incorporated SAF into their strategic frameworks. Distributing SAF at airports brings multiple **benefits**, such as lowering particulate emissions and enhancing local air quality. It also supports airports in reaching their decarbonisation goals. However, implementing SAF distribution faces **obstacles**, moreover 'Sustainable Airports Platform' survey revealed that 89% of respondents consider the implementation of SAF to be a challenge. For instance, the limited SAF availability complicates distribution. Additionally, the roles of airports in SAF implementation is not clear (RSB, 2023).

Corporate travellers are defined as employees of businesses who regularly travel by air for work using commercial airlines (WEF, 2023). Business travel plays a significant role in driving aviation demand. Despite the decline of corporate flights after COVID-19, business travel still comprises about 30% of all air travel in Europe. According to the Travel Smart Campaign, 83% of global companies have not established ambitious goals to decrease their corporate travel emissions (TE org, n.d.). The World Economic Forum highlights the critical **role of executive leadership** in adopting SAF initiatives. The commitment of the CEO and the executive team significantly influences the prioritisation of sustainability measures such as SAF. Additionally, ESG accounting further increases the shift towards SAF in major firms (Kotsantonis et al., 2016; WEF, 2023). Several **barriers** can impede its adoption for corporations, such as the financial aspect, since the costs of SAF can deter its broader implementation if not balanced within the company's financial planning and carbon accounting strategies. Moreover, a lack of awareness and education about the benefits of SAF can hinder its adoption (WEF, 2023).

5. Collaborative networks

Multiple **collaborative networks** function at the intersection of both political advocacy and economic activity. They collaborate with political entities to shape policies and create standards that align with sustainability goals. Economically, they mobilise resources, influence investment decisions, and support the development and commercialisation of SAF by creating markets and ensuring supply chain sustainability (RSB, 2023). Some important collaborative networks are summarised in Table 12.

Table 12: Collaborative networks

Initiative	Focus	Main Actions	Source
Sustainable Aviation Buyers Alliance (SABA)	Drive SAF investment and adoption	• Introduce certification systems • Group SAF certificate procurements • Educate members • Support technological innovation in SAF production	(SABA, n.d.)
Roundtable on Sustainable Biomaterials (RSB)	Ensure sustainable SAF production	• Provide a certification system covering the full supply chain • Offer strategic advice • Collaboration platforms for sustainability	(RSB, n.d.)
Smart Freight Centre (SFC)	Freight transport	• Increase transparency and operational efficiencies • Increase adoption SAF • Engage in sustainable aviation through collaborative platforms like GLEC and Clean Cargo	(SFC, n.d.)
Clean Skies for Tomorrow Coalition (CST)	Coalition of stakeholders	• Brings together leaders from industry, government, and civil society in a public-private partnership • Involves a diverse group of stakeholders, including major airlines, airports, fuel suppliers, and various non-aviation businesses dependent on air transport	(CST, n.d.) (WEF, n.d.)
First Movers Coalition (FMC)	Collective buying power	• Combines the individual commitments of their members (nations and corporations) together into a powerful and credible market demand	(FMC, n.d.) (WEF, n.d.)

Part D: Taxonomy

After delving into the complex dynamics of SAF production and market adoption, it becomes crucial to understand the multifaceted strategies that can facilitate this transition. This part will systematically categorise a wide spectrum of strategies into coherent themes, thereby illustrating how various aspects of supply, demand, and policy collectively influence the SAF landscape. Figure 18 functions as a roadmap for the discussions in this part. The insights compiled in taxonomy are derived from an analysis of current practices, potential innovations, and evolving policy frameworks.

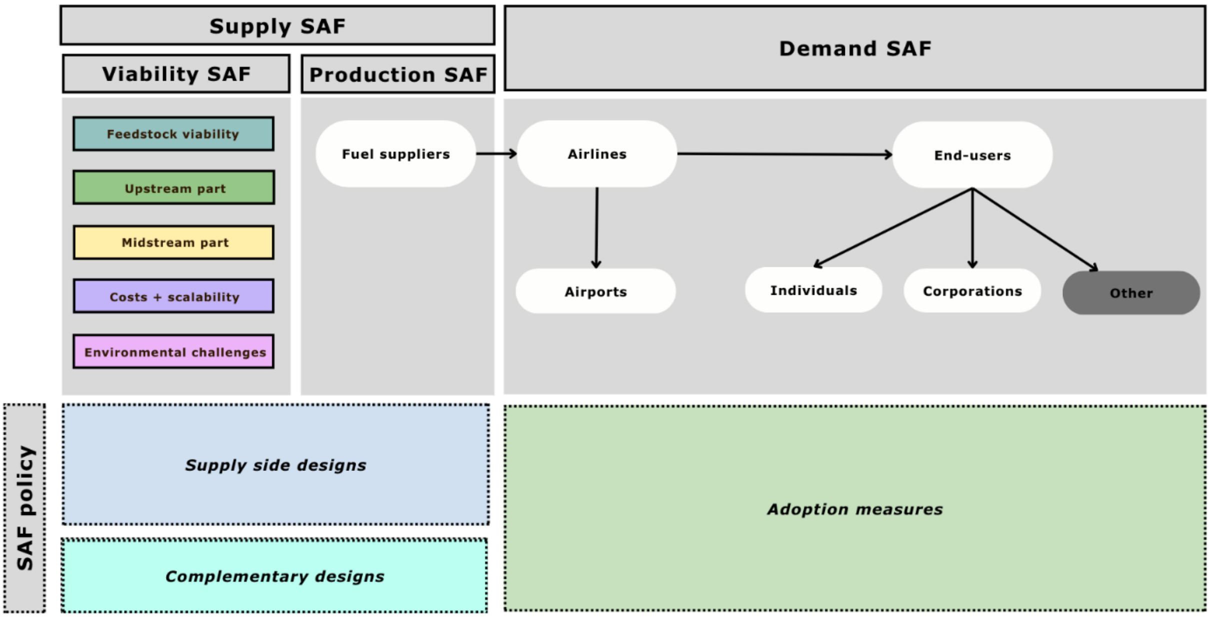


Figure 18: Integrated figure of SAF uptake strategies

1. The supply side

1.1. Enhancing feedstock viability

The feedstock section of the supply side in this taxonomy delves into the foundational elements necessary for SAF production. This part examines the diverse range of feedstocks available for SAF manufacturing, from 1-G to 4-G. It addresses the challenges discussed in 'part B section 1.6' such as feedstock availability and sustainability, while exploring strategic solutions to enhance feedstock viability and efficiency. The goal is to outline actionable strategies that can mitigate existing barriers and scale up the production of SAF.

1.1.1.Competition with food industry

One significant challenge in using **1-G feedstocks** is their **competition with food crops**. An effective strategy to mitigate these concerns is to only use **byproducts** from 1-G feedstocks, which are unsuitable for food production. Such byproducts, including pulp and molasses, present valuable alternatives for SAF production without competing with food resources (UNCTD, 2016).

1.1.2.Commercialisation

The stage of **commercialisation** of **2-G feedstocks** cultivation is a challenge faced by several countries that are trying to **scale up the production** (Pasa et al., 2022). In this context, **non-OECD countries** possess significant opportunities to produce non-edible 2-G feedstocks such as lignocellulosic energy crops, MSW and residues (Malina et al., 2022). Dina Bacovsky from IEA Bioenergy highlights this as it could create income in rural areas while facilitating a transition to sustainable energy sources (IAE Bioenergy, 2023).

Egypt and India provide examples of opportunities to collect large amounts of **residues**. Egypt has approximately 5.2 million tonnes of dry crop residues available annually, priced between 40 to 60 euros per ton. In India, approximately 500 million tons of crop residues are produced every year. Wheat straw and rice straw are the most common residues, and as discussed in Part B 1.3.3, these can both be used for SAF production. However, the interval between the two cropping seasons is only 20 days, providing limited time to manage these residues. Therefore, establishing a supply chain is challenging as the time to collect, transport, and store is restricted.

Additionally, **waste** represents a significantly untapped resource in numerous developing countries (IAE Bioenergy, 2023). Moreover, the World Bank predicted that by 2050, the amount of **MSW** generated in developing countries will be doubled due to the projected increase in population and gross domestic product. However, many of these countries lack MSW collection and landfilling systems, leading to environmental and health problems (Hoornweg and Bhada-Tata, 2012; Troschinetz and Mihelcic, 2009). Using MSW as a feedstock for SAF production can incentivise increasing MSW collection in developing countries and, therefore, lead to better waste management practices that can improve the environmental and health conditions (Malina et al., 2022).

However, **barriers** hinder SAF production in these regions. The first obstacle is acquiring **finance** and the associated **high-risk premium**. Investing in developing countries is a higher risk compared to OECD countries, which increases the SAF production costs by 15 to 40% (IAE Bioenergy, 2023). Minimising this risk premium requires collaborative approaches such as financial agreements with international development banks, off-take agreements from global airlines, corporate purchases, and robust government support through expertise and regulatory frameworks. An example of a collaboration is the 'Global Facility to Decarbonize Transport (GFDT),' through which the World Bank funds 185 million euros over ten years to projects that enhance low-carbon mobility. However, specific aviation-related funding not yet organized (IAE Bioenergy, 2023).

Moreover, support from the international community is required to establish the **technology transfer** to the developing countries. An example of this is the **LEAP-RE initiative**, backed by the EU, which focuses on enhancing renewable energy technologies across Africa by fostering innovation in R&D and education. The initiative currently oversees 31 projects and collaborates with over 220 partners from more than 30 nations. The main objective of LEAP-RE is to empower communities, organisations, and individuals to make sustainable energy choices. One of the key focus points of the program is to promote sustainable methods of biomass collection (IAE Bioenergy, 2023). A project under LEAP-RE is PyroBioFuel, which aims to develop a cost-effective, standalone system of sustainable feedstock production in rural and remote areas across Africa. This will be done by establishing a knowledge base of the feedstocks. These vary greatly by region and season, going from virgin biomass to energy crops and agricultural residues. The anticipated result of this project is the creation of technological innovations as well as energy solutions in both the EU and Africa. (Leap-re, n.d.).

The commercialisation of **3-G microalgae** biomass production is still in its early stages, with only a few established large-scale plants for culturing microalgal biomass (Debowski et al., 2023). Rony et al. add that multiple challenges must be overcome to achieve a large-scale commercial production of environmental aviation fuels from microalgae (2023). In 2023, the EU-funded initiative FuelGae was established to improve the potential of microalgae as a fuel for aviation and shipment industries. It involves a consortium of 13 partners from 6 countries coordinated by the Spanish National Research Council. This five-million-euro project spans four years and plans to establish microalgae pilot plants and a biorefinery. The aim is to enhance the production of lipids from microalgae as well as achieving lower environmental impacts and higher resource efficiency (Cordis C., 2023; GreenAir news, 2024).

Moreover, there is no regulation for marine cultivation of 3-G and 4-G feedstocks (Leong et al., 2018). Additionally, the **4-G feedstocks** need political support and public acceptance regarding the involved genetic engineering (Malode et al., 2021). A European study suggests that consumer acceptance could be secured if the production systems used to guarantee safety, favoring closed production systems (Villareal et al., 2020; Cavelius et al., 2023).

1.1.3.Land footprint

The third evaluation factor in SAF feedstock production is the **land footprint**. Cultivating **1-G feedstock** often requires large areas of arable land, leading to direct and indirect land use changes. Moreover, it increases the competition for land that can be used for food production (Pasa et al., 2022; Shehab et al., 2023). To address the land footprint, **various strategies** can be employed to enhance production yields and reduce land requirements, including improved agricultural practices, double cropping, crop rotation, integrating crop farming with cattle farming and strict regulations regarding land use, as detailed by Liu et al. (2020) and UNCTAD (2016).

Adopting **improved agricultural practice** would for instance include the use of enhanced-efficiency fertilisers as it improves crop yields and reduces nitrogen losses (Liu et al., 2020). Another approach is **double cropping**, where two crops are grown sequentially on the same land within a single year, thereby improving soil health and reducing fertilizer needs (Borchers et al., 2014). Although currently underutilized, studies show that double cropping can significantly increase SAF production by optimizing land turnover times. By selecting appropriate crop pairs, the primary concerns associated with double cropping practices can be mitigated, such as soil erosion and nutrient depletion. Pairing certain crops together has the potential to enhance soil health. Typically, the most suitable crops for double cropping include legumes, oilseeds, and cereal crops. The crops that make the best double cropping pairs for maximum yield and emissions savings can assist policymakers in deciding how to apply economic subsidies (Demsky, 2023). Guarenghi et al.'s research showed that the production of corn and soybean in the same field is a feasible option (Guarenghi et al., 2022). **Crop rotation** is another strategy that involves alternating crops with different growing periods to minimise the land used. This method not only increases the yields of both crops compared to monocultures but also contributes to a more sustainable agricultural system (Behnke et al., 2018). Moreover, **integrating** crop production with **cattle farming** allows for the dual use of land. The integration makes it possible to increase sugarcane production without expanding land use. Above, byproducts of sugarcane can be used as cattle feed (Souza et al., 2019). Furthermore, **strict regulations** regarding land use for feedstock production can help mitigate iLUC risks. By ensuring that only previously non-productive or degraded lands are used for feedstock production, competition with land for food production is minimised (UCTDN, 2016; Guarenghi et al., 2022).

Additionally, the land footprint of **2-G energy crops** can be minimised on marginal lands with undesirable characteristics for agricultural cultivation (Pasa et al., 2022). An example that takes it one step further is the **CIFOR-ICRAF initiative,** which focuses on **restoring the land** while facilitating feedstock production. A key element of these projects is strategically selecting species that can restore ecosystems and produce seeds with high oil content simultaneously, such as the Pongamia tree. This model demonstrates a viable strategy for land restoration that can be adapted and implemented in various other regions, offering a sustainable solution to minimise land footprint and tackle both environmental and societal issues effectively (IAE Bioenergy, 2023)

To reduce the land footprint of the cultivating **3-G** and **4-G feedstocks**, **non-arable land** can be used that is otherwise unsuitable for traditional agriculture (Chisti Y., 2007). Moreover, **deserts** also are a great opportunity to cultivate microalgae. Deserts cover around one-fifth of the Earth's surface and emerge as one of the most under-utilized land areas. While they vary in characteristics, some may be potential sites for mass algae production (Rajvanshi and Sharma, 2012). Certain deserts, like the Antarctic and Arctic Deserts, are unsuitable due to extremely low temperatures and limited human habitability (Shokravi et al., 2022). Others, such as the Namib Desert and the Arabian Desert, face challenges like low temperatures, coastal fogs, and high dunes, making them unfavourable for microalgae cultivation in open ponds (Rajvanshi and Sharma, 2012). However, some deserts, like The Great Rann of Kutch in India, offer flat topography, proximity to the sea, and suitable conditions for microalgae cultivation, potentially meeting a significant portion of fuel production needs (Li et al., 2022). In Europe, the Tabernas Desert in Almeria, Spain, shows potential but is limited in size (Bosnajakovic and Sinaga, 2020; Li et al., 2022). Despite regional variations, exploring desert areas with flat topography, proximity to the sea, and moderate temperatures could provide promising locations for microalgae cultivation for biofuel production (Sharma et al., 2023).

In the Sahara Desert, the startup **Brilliant Planet** is pioneering large-scale cultivation of algae. After growing, the algae is harvested, dried, and stored just beneath the desert surface. This method is set to scale up significantly, with plans to construct a commercial plant that will capture 40 thousand tons of CO_2 annually (Brilliant Planet, n.d.). Even though this initiative does not use biomass, it shows that algae cultivation in deserts is feasible.

1.1.4.Water footprint

The **water footprint** emerges as the fifth critical factor for evaluating SAF feedstock production, emphasising the requirement of water resources. **1-G crops** and **2-G energy crops** typically require significant amounts of potable water for cultivation. This poses a sustainability challenge, particularly in water-scarce regions. While energy crops generally have lower water demands than conventional agricultural crops, they still contribute to substantial water use (Abdullah et al., 2019).

For **3-G and 4-G feedstocks**, which primarily include microalgae, the reliance on freshwater is also notable. However, cultivating these feedstocks presents an opportunity to utilise **alternative water sources**. Waste and seawater have been identified as viable alternatives, significantly reducing the strain on freshwater resources (Khan et al., 2022). This adaptation not only mitigates the environmental impact associated with water use but also expands the potential for cultivating these feedstocks in areas where freshwater is limited.

The earlier-mentioned start-up **Brilliant Planet**, located along Morocco’s coast, is a practical example of this practice. It uses a system that channels seawater to foster algae growth in the ponds (Brilliant Planet, n.d.).

1.1.5.Requirement for nutrients

Evaluating **nutrient requirements** is also important for feedstock cultivation, especially given the reliance on fertilisers and pesticides in **1-G crop production**, which poses significant environmental concerns (Abdullah et al., 2019). A first solution is to implement improved agricultural practices. For example, using **organic fertilizers** like animal manure can significantly decrease the energy inputs (University of Nebraska, n.d.). This practice not only enhances soil fertility but also reduces the dependency on chemical fertilisers. The second solution is **double cropping**, since this technique can minimise nutrient depletion and therefore reduces the necessity for fertilisers (Borchers et al., 2014). **Crop rotation** is a third effective strategy that optimises the use of resources such as fertilisers (de Souza et al., 2019).

For **3-G** and **4-G feedstocks,** the cultivation process heavily depends on specific nutrients and environmental conditions (Mata et al., 2010). The first solution is **wastewater**, especially from agricultural and food industries, which is rich in nutrients. Therefore, it can be useful for cultivating microalgae, providing a dual benefit of wastewater treatment and reduced costs (Wang et al., 2016; Castro et al., 2008). However, risks associated with the contamination from chemicals present in wastewater need careful management (Chew et al., 2018). Therefore, Mat Aron et al. advise that research should be directed towards cultivating microalgae within wastewater (2020).

The second alternative for cultivating microalgae is using **seawater**. This method can significantly reduce production costs and eliminate the need for additional nutrient expenses while enhancing lipid productivity (Park et al., 2018). Cultivating algae in the ocean is an interesting option as the waves naturally mix the algae, making it easier to grow. Additionally, nutrients are already present in the water, and much space is available in the ocean (Novoveska et al., 2016; Khan et al., 2022). As stated, **Brilliant Planet** is a practical example that uses seawater as source of nutrients (Brilliant planet, n.d.).

1.1.6. Environmental impact

Addressing the **environmental impact** is a pivotal sixth determinant in the assessment of feedstock viability for SAF.

The intensive production demands of **1-G feedstocks** can lead to GHG emissions, biodiversity loss, soil degradation, and overuse of natural resources, with additional concerns about pesticide and fertiliser use intensifying these impacts (Abdullah et al., 2019). The first solution is **double cropping** since for instance cultivating corn and soybean in the same field is beneficial to mitigate adverse environmental impacts. This co-cultivation method helps to reduce the ecological footprint of agricultural practices (Guarenghi et al., 2022). A second solution is the **integration** with **cattle farming**, since it has been shown with sugar cane that it effectively reduces overall climate impacts and minimises iLUC emissions. This integrated farming approach offers a sustainable pathway that enhances the environmental sustainability of SAF production (de Souza et al., 2019).

The **2-G waste feedstocks** offer a great opportunity to support a circular economy. Specifically, the management of the organic fraction of municipal solid waste (OFMSW) not only alleviates landfill issues but also prevents emissions of potent GHGs like methane and CO_2, thereby delivering substantial environmental benefits (Kowalski et al., 2022; Shebab et al., 2023).

The **3-G and 4-G feedstocks** offer considerable environmental opportunities since microalgae can effectively **capture atmospheric CO_2**. Over fifty percent of algae's biomass is carbon, which can be transformed into SAF. Notably, fourth-generation feedstocks exhibit enhanced traits such as improved light penetration and photosynthetic efficiency, offering even greater environmental benefits (Van Den Hende et al., 2011; Chisti Y., 2003). The earlier mentioned EU-funded initiative FuelGae aims to develop an innovative method for producing using various CO_2 emissions streams. Therefore, it focuses on two industrial sectors: biorefineries and energy-intensive industries. The pilot photobioreactor integrated into their infrastructure will employ selected microalgae strains (European Commission, 2023).

1.1.7. The conversion process

Solutions for this topic will be discussed in part E 1.3.

1.1.8. Financial

The **financial** aspect is another crucial determinant of the viability of SAF production. For **1-G feedstocks**, a study by Guarenghi et al. shows that **co-cultivating** corn and soybeans enhances land profitability and reduces production costs (Guarenghi et al., 2022). Additionally, integrating sugarcane production with cattle farming yields significant economic benefits, including improved return on investment and generating additional revenue through leasing and carbon credits. (de Souza et al., 2019).

Moreover, as discussed, **small agricultural producers** face significant barriers due to capacity limitations and the high costs associated with achieving sustainability certifications, often leading to unsustainable practices. Initiatives like the **RSB's smallholder project** help mitigate these certification costs, providing economic and environmental benefits to small farmers (UNCTAD, 2016). An illustration of a project to aid small-scale farmers is 'Project Solaris.' This project certified South African smallholders that produce Solaris seed tobacco intended for SAF. Through partnerships with SkyNRG, South African Airways (SAA), and Sunchem, the market opportunities have increased for local populations. Simultaneously a sustainable supply chain for SAF is established (ICAO, n.d.).

For **3-G and 4-G feedstocks,** the initial **setup costs** need reduction for viability (Leong et al., 2018). Slight adjustments in existing **refinery infrastructures** can facilitate the extraction and blending of SAF from algae, reducing the setup cost (Nair and Paulose, 2014). Moreover, **the high production costs** hinder widespread commercial adoption. However, microalgae contain multiple valuable nutrients, vitamins, and minerals, which means there is potential to **generate various outputs** from it (Hussain and Rittman, 2023). These compounds could address the cost barriers by using these byproducts to produce other high-value products (Ooms et al., 2016). For instance, microalgae create chemical terpenoids that can be used in the pharmaceutical sector (Zhou et al., 2022). Research by Nie et al. has developed methods to extract these compounds with high purity, improving the economic feasibility of microalgae as a feedstock (2021).

1.2. Upstream part of supply chain SAF

This section delves into strategic initiatives to improve the **upstream part** of the SAF supply chain, including feedstock viability, feedstocks logistics and pre-processing. These strategies are based on the 'SAF Grand Challenge Roadmap'. The overall goal is to lower the feedstock costs, boost the yield, improve sustainability, and create profitable opportunities for feedstock producers.

The first action point is to gain a better and deeper **understanding of the feedstock market**. This action point includes registering the feedstocks' availability in a **universally accessible database**. This would enable monitoring of the current feedstock supply, forecast, and alignment with the 2030 and 2050 targets. Identifying the trends and proportions of the feedstocks is essential for effective planning and achieving the targets. This includes considering the possible impact that climate change, such as changes in temperature, poses on the reliability and yield of various feedstocks used for SAF production.

Another objective should be a coordinated effort to enhance the **lipid feedstocks' 'Research, Design, Development, and Deployment (RDD&D)'**. Oil feedstock that contains lipids is expected to make up almost 90 % of the feedstocks by 2030. To boost the production of this feedstock, a **'multigenerational project plan'** should be developed. This plan involves understanding the potential for lipid aggregation through data collection and analysis of various lipid types and assessing characteristics, costs, volumes, and locations. In the short term, RDD&D aims to enhance cultivation practices and increase yield while reducing inputs and emissions. A critical long-term objective involves expanding the lipid resources, which includes exploring tree oils, algae, and lignocellulosic wastes as lipid resources. However, while working towards this objective, it is crucial to consider the potential adverse environmental impacts that may arise. Any possible consequences, such as deforestation and biodiversity loss, should be minimised.

However, for the mid-to-long-term success of SAF, the availability of useable and sustainable **feedstock resources** must be increased **beyond lipids**. This is crucial and requires R&D in technologies and strategies to enhance the production and collection of new biomass resources while reducing carbon intensity and overall costs (U.S. Department of Energy, 2021). This action point includes R&D efforts for new potential feedstocks emerging for SAF production, such as the non-biomass feedstocks PtL and StL (Fontaine et al., 2022).

The feedstock supply should also be improved by **enhancing the feedstock supply logistics** from collecting to prepossessing. The preparation processes should be localised near the biomass produced to achieve more efficiency and sustainability. Furthermore, R&D is required to improve or develop collection and harvesting systems. In the case of conventional biomass, where a supply system already exists and is well-established, incremental advancements are expected. The recent developments in artificial intelligence and sensors could speed up the pace of these improvements. However, sometimes disruptive technologies are needed to develop a new feedstock logistics system, such as direct air capture. Both types of improvement aim to create more diversified SAF resources at a better price and with greater carbon intensity.

Additionally, the **feedstock handling systems** must become more **reliable** and **efficient**. The bioenergy industry faces many challenges in handling and pre-processing feedstock operations, leading to operational difficulties and poor system performance. So, technologies and tactics must be created to boost SAF plant productivity and minimise downtime. This would decrease the perceived risk in feedstocks while increasing production. For instance, the variability in biomass materials needs to be better quantified, understood and managed from field to conversion. Subsequently, machines that tolerate the variability in feedstocks must be developed, while reliable and scalable preprocessing equipment and techniques need to be improved. To address these issues, R&D should compare equipment performance and cost trade-offs while developing modelling tools for a consistent feedstock handling performance. A multidisciplinary approach would improve feedstock handling and preprocessing operations so the bioenergy industry can operate continuously and profitably.

The last goal is to enhance the biomass and waste supply systems with **environmental, social** and **economic sustainability**. Extensive research is necessary to determine the effects of SAF resource production and collection on the environment, society, and economy. This understanding is essential for the success of existing and emerging supply chains, production systems, and SAF value propositions. The three aspects are interdependent; for example, profits drive the supply, compensating environmentally friendly feedstock producers leads to environmental benefits, and biomass production and waste collection impact communities and the environment. Subsequently, the R&D must be done at the systems level with NGOs and feedstock producers. This will provide valuable data that considers all three aspects to inform policy and facilitate a more equitable distribution of benefits and impacts of SAF (U.S. Department of Energy, 2022).

1.3. The conversion process

1.3.1. Conversion efficiency: advancing SAF production techniques

This section addresses specific problems in the SAF production conversion processes discussed in part B section 2.1. It is important to note that other potential solutions may exist that are not included in this text. The focus is on issues for which documented solutions are available.

Multiple actions can be taken to make the **thermochemical FT conversion** more effective, efficient and environmentally friendly. For instance, torrefaction and densification are feedstock preparation methods that can improve the quality and consistency of feedstock. Moreover, to enable large-scale operations, R&D is should focus on improving the design of the conversion process (Wang et Wu, 2023)

For the **oleochemical** conversion **HEFA-SPK**, more research is needed to address the low aromatics content. Solutions to address the feedstock supply challenges of microalgae for **HC-HEFA-SPK** were discussed in part D 1.1. For the **CHJ process**, integrating the CH process at **existing oil refineries** would create a more efficient production system, leading to competitive prices. However, technological integration challenges, such as the retrofitting of existing refinery setups to accommodate bio-feedstocks and ensuring the quality control of the blended products, require detailed engineering solutions and standardisation efforts (Eswaran et al., 2021).

Regarding the **biochemical** conversion, the **SIP-HFS process** could be simplified by using one fermentation tank for the fermentation (Usman et al., 2023). According to Usman et al., SIP-HFS is one of the most expensive pathways (2023). However, this cost is expected to decline as the supply chain expands. Currently, capital and operating expenditures comprise 75 % of the costs, but they are anticipated to decrease as the supply chain expands (Roland Berger, 2020). Despite these potential solutions, the SIP-HFS process, particularly in terms of required energy presents an ongoing challenge that necessitate additional research and development efforts (Usman et a., 2023). Solutions for the **ATJ-SPK** conversion high feedstock prices can be addressed with solutions of section 1.2; the other problems are not covered in this thesis.

The **co-processing conversion's** most significant opportunity is that there are more than 600 existing refineries. Moreover, the existing supply chain can be used, as the combined fuel is labelled CJF with renewable molecules. Nevertheless, production will be limited to the refineries capable of co-producing. Another benefit is the flexibility in feedstocks, as these refineries can switch between co-processing and pure crude oil to meet fluctuations in SAF demand (Air BP, 2022).

1.3.2. Blending limitations and innovations in SAF

To tackle the blending limitations, the first option is to adjust the **infrastructure** to enable pure SBC. Since the aircraft and infrastructure are incompatible with pure SBC, new aircraft could be engineered. The older aircraft would require adjustments to become compatible (Aerospace Technology Insitute, 2022). Secondly, fuel standard committees are exploring ways to enable 100 % SBC through **composition adjustments**. Several possible strategies exist to achieve this, such as blending two or more SBCs to create a fuel blend suitable for pure utilisation, adapting existing feedstocks and conversion processes to meet the required characteristics from one pathway, or developing new feedstocks and conversion processes. It is aimed to have approved pure SBC fuels available by 2030 (EASA, 2023).

The aviation industry is researching and testing flights to evaluate pure SBC's impact on emissions and aircraft performance. The preliminary findings are promising, and in 2021, a new United Airlines aircraft was fueled entirely by a mixture derived from cooking oil and other waste fats (EASA, 2023).

1.4. Cost dynamics and scalability of SAF

Determining the **total cost** of SAF production is **complex** and depends on various factors, including the type of conversion techniques, the feedstock used, and the production scale. This complexity can be addressed using **'Rules of Thumb'** developed by Washington State University and the University of Hasselt to estimate SAF costs and assess commercial feasibility (ICAO, n.d.).

When comparing SAF to CJF prices, the **MSP** of SAF remains **significantly higher** than that of CJF, even at its lowest. This presents a considerable challenge in making SAF competitive in the market. Some of the strategies discussed earlier for enhancing the feedstock viability, the upstream part of SAF, and advancement conversion technologies can reduce the gap between MSP and CJF. Moreover, governmental support can possibly further lower this gap, which will be discussed in section 3 of this part.

The potential for **scaling SAF production** varies among different feedstocks and conversion methods. Overall, ATJ has the possibility of achieving the highest SAF production per year, closely followed by HEFA. FT has a significantly lower production potential. The strategies discussed for enhancing the feedstock viability, upstream part of SAF, and advancement conversion technologies scale of SAF production apply likewise here. Moreover, increasing the blending limit, as discussed in section 1.3.2 of this part, is also possible.

1.5. Environmental challenges of SAF

Even though SAF is considered sustainable, through the analysis of Part B 3.2, some pathways showed environmental problems. Regarding the **LCE**, there are significantly different levels of CO_2 emissions across the lifecycle of the pathways. For instance, Ethanol in the ATJ conversion does not effectively reduce CO_2, having high LCEs that question its suitability for achieving net-zero targets. Additionally, the cost of **CO_2 abatement** varies greatly between different SAF production techniques and feedstocks. These costs are crucial to consider as they impact the overall environmental cost-effectiveness of SAF pathways. For example, the ATJ conversion with Isobutanol exhibits extremely high abatement costs, making it less environmentally economical compared to other options.

As discussed in **parts E 1.1 and E 1.2**, multiple strategies and solutions exist to optimize feedstock and conversion processes and reduce overall emissions in SAF production. Furthermore, part B 3.2 showed that the selected feedstock impacts the LCE. Choosing forest and agricultural residues for FT conversion results in an LCE that is one-fourth of the LCE with MSW.

The Global Bioenergy Partnership (GBEP) has crafted a series of **sustainability indicators** designed to evaluate and track the sustainability of biofuel practices. These indicators are intended to standardise sustainability assessments, especially for developing countries. They evaluate progress towards achieving a sustainable development trajectory as defined by individual nations. They encompass various aspects from environmental to social and economic sectors, aligning closely with the UN SDGs. To date, 14 countries, including Paraguay and Vietnam, have adopted the GBEP sustainability indicators (Iea Bionergy, 2023). These indicators can help to address the environmental impact of SAF feedstock production.

1.6. The SAF production market

Despite significant growth, **SAF production** still only represents a **small fraction** of total aviation fuel needs, projected at 0.53% of total fuel by 2024 (IATA, 2023).

A solution to increase the production market of SAF is by **fostering international trade** in SAF, (UNCTAD, 2016). **South Africa** exemplifies the potential of international trade in SAF markets, as it has been at the forefront of conducting feasibility studies for SAF. Therefore, it has a robust resource base and extensive experience with SAF production technologies, offering opportunities for export. More specifically, their feedstocks include oil seeds, molasses, industrial off-gases, and biomass from cleared invasive alien plants (IAP) and garden waste. These resources account for 50 to 66% of the nation's SAF production potential. The mandated removal of IAPs not only contributes to biomass potential but also aids in protecting biodiversity, reducing fire risks, securing water resources, enhancing land productivity, and maintaining ecosystem functions. However, it is important to notice that the success of the integration of SA in international trade relies on factors such as supportive policy frameworks. Despite financial constraints faced by many African airlines, the region benefits from the frequent activity of numerous international carriers and can thereby more integrate into the global market for SAF (Iae Bionergy, 2023)

The barriers for SAF suppliers, such as inconsistent policies with regional variability (Korkut et al., 2021), could be mitigated by effective and unified policies. International regulatory bodies can help with it. The limited **availability** of adequate **feedstocks** (Gegg et al., 2014)**,** can be mitigated by solutions discussed in 1.1 and 1.2 of this part. For instance, there is considerable potential for SAF production in non-OECD countries, where about two-thirds of the feedstock could come from non-food sources. This could enable the production of over 500 million tonnes of SAF annually (Iae bioenergy, 2023). Regarding the **infrastructure** challenges, airports can support the necessary infrastructure for SAF by assisting in the permitting process for environmental reviews of onsite fuel consortiums or fueling farms. Additionally, the Airports Council International (ACI) is currently developing guidelines to optimize SAF blending processes, which will further aid in addressing these challenges (Souza et al., 2015; RSB, 2023).

1.7. Summary strategies for uptake supply side

The supply of SAF can be categorised into the viability of SAF and the production of SAF by producers (Figure 19). Within each category, multiple opportunities exist to enable an uptake in sustainable production. It is important to note that both sides have overlapping challenges, moreover, improving the viability of SAF will lead to an increase in SAF production and vice versa.

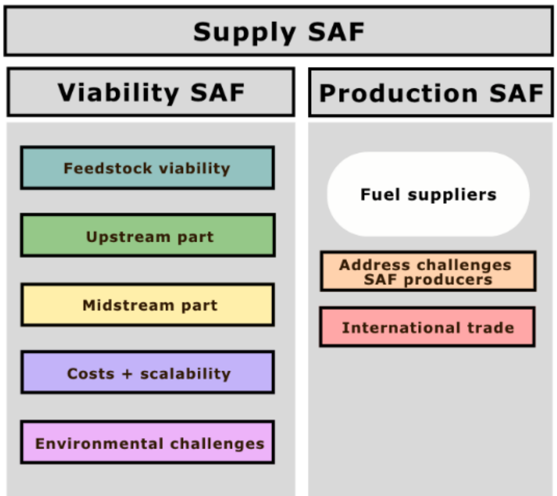


Figure 19: Opportunities for supply side SAF

1.7.1.SAF viability

To start, each **biomass generation** aligns with a more or less similar TRL and presents its unique advantages and challenges. Moving up the generations promises even greater sustainability, availability, reduced feedstock costs, and minimised competition. However, the higher-generation biomasses have less established supply systems and more complex collection and conversion processes, requiring varying technical efforts (Pasa et al., 2022). Figure 20 gives an overview of the opportunities to enhance the feedstock viability within each generation.

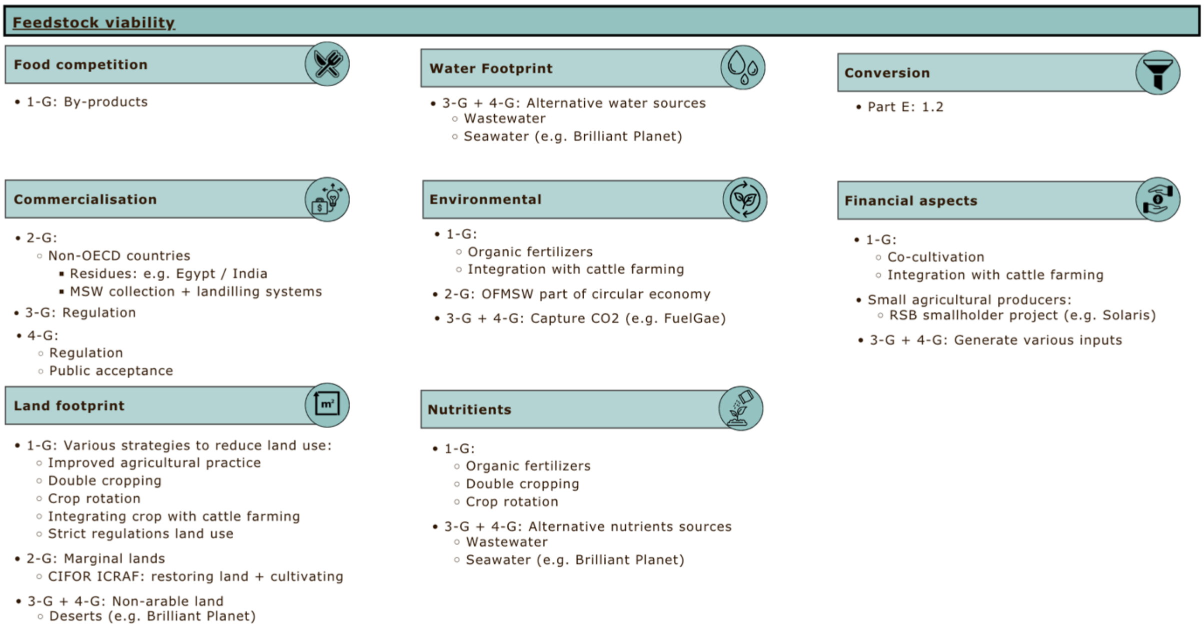


Figure 20: Opportunities to enhance feedstock viability

Above, the whole upstream part of the SAF supply chain can be significantly improved by adopting a **multifaceted plan** as shown in Figure 21. Succeeding in these points will increase feedstock production capacity, reduce costs, and improve sustainability.

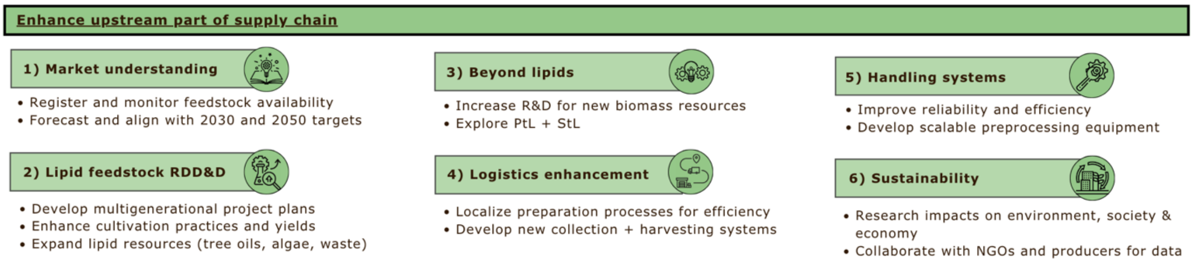


Figure 21: Strategies to enhance the upstream part of SAF supply chain

Enhancing the **midstream segment** of the SAF supply involves advancing the conversion processes to increase efficiency and output. It also encompasses developing technological methods for conversion, and exploring options that increase the % of pure SBC, as shown in figure 22.

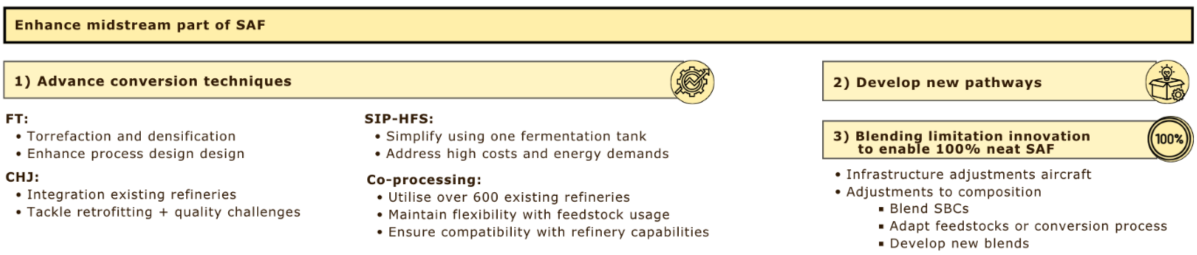


Figure 22: Strategies to enhance midstream part of SAF

Addressing **costs and scalability** of SAF production is crucial for its market expansion. Strategies include methods to determine costs and, from there on, focus on reducing the gap between MSP and CJF. Improving the scaling of operations should to benefit from economies of scale. These measures, shown in Figure 23, aim to improve the financial competitiveness of SAF.

Figure 23: Overview of opportunities regarding cost and scalability of SAF

To address **environmental challenges**, there should be focusing on minimising LCEs. Additionally, global sustainability standards such as the Global Bioenergy Partnership (GBP) are crucial to determine and minimise the environmental footprint. Abatement costs must be considered to assess the environmental cost-effectiveness of SAF production across various technologies and feedstocks. An overview is shown in Figure 24.

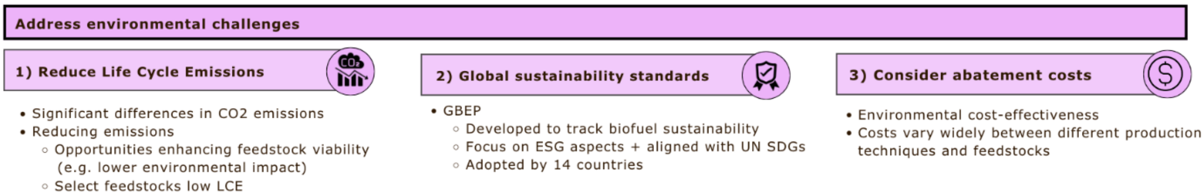


Figure 24: Overview of opportunities to address environmental challenges

1.7.2.Production of SAF

Figure 25 indicates the solutions to address the challenges faced by SAF producers, including policy inconsistency, infrastructure limitations, and feedstock availability.

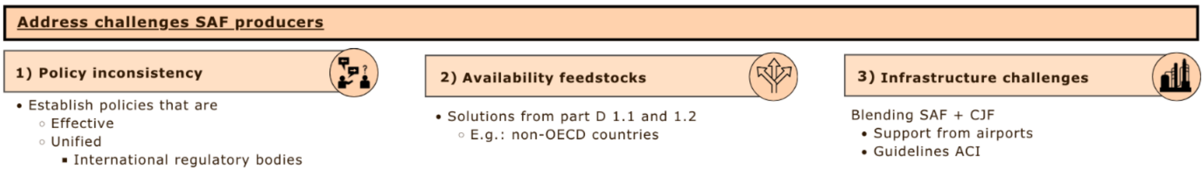


Figure 25: Overview solutions to address challenges SAF producers

Additionally, promoting **international trade** in SAF can potentially increase production and diversify sources (figure 26).

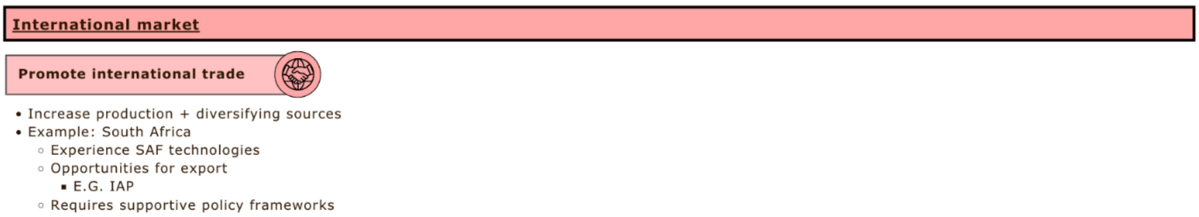


Figure 26: Opportunity to increase production market through international trade

2. The demand side

2.1. Individual demand

The challenges of the factors influencing a positive attitude towards SAF discussed in part B section 2.1 will be addressed again, and possible solutions will be analysed.

The first challenge regards an individual's recognition of **aviation's contribution to GHG emissions**. The EASA survey found that respondents were generally unaware of the CO2 impact of their air travel and expressed a desire to access environmental information about their flights (EASA, n.d.). Moreover, individuals have limited agency regarding their aviation emissions (Higham et al., 2019).

Research conducted by Baumeister and Onkila illustrates how **environmental labelling** initiatives can enhance passengers' awareness of aviation's environmental impact, thereby generating pressure for change (2017). The EASA has collaborated with various stakeholders to develop an ecological labelling scheme as part of the EU Sustainable and Smart Mobility Strategy. The aim is to inform passengers about the environmental impacts of different flight options. The labelling scheme is engineered to provide detailed emissions data to passengers during the flight booking process. This setup enables the comparison of flights based on their carbon footprint, factoring in enhancements from SAF usage and other technological advancements. By presenting this data transparently, the scheme educates passengers and drives broader sectoral changes through increased public demand for lower-emission flights. A survey by EASA showed that almost 75% indicated support for this label for flights. The system is currently undergoing testing with a few European airlines and global online travel platforms. As of 2025, EASA will start issuing environmental labels. Therefore, passengers will be able to see standardised information on the "carbon footprint" and "carbon efficiency" of flights in the EU, along with an explanation of the result (EASA, 2024).

A second challenge is the lack of **awareness** of **SAF utilisation** in aviation (Filimonau et al., 2018). Moreover, there is also **insufficient knowledge about SAF** among some consumers, including its environmental benefits and production processes (Xu et al., 2022; Filimonau and Högström, 2017). A solution to this would be to provide **additional information** to enhance the public's understanding. The key is to provide clear and accurate information about sustainable and eco-friendly practices. This involves communicating the benefits, helping people recognise the personal advantages of participating in sustainable behaviors, promoting a positive social norm that encourages green initiatives, and ensuring that individuals feel they have control over adopting sustainable practices. Moreover, possible concerns such as the 'food vs fuel' should also be addressed (Filimonau et al., 2018).

This can be facilitated through media, educational institutions, and partnerships with environmental organisations (Anderson et al., 2022; Yuriev et al., 2020). Kim et al. echo this recommendation, suggesting that enhanced public awareness of aviation biofuels and their advantages could fasten SAF adoption (Anderson et al., 2022). Nevertheless, it is important to note that, contrary to the assumption that increased knowledge fosters support, two studies focusing on biofuels generally found that heightened knowledge was associated with negative perceptions of biofuels. For instance, in research where participants were informed about the potential adverse effects, such as increased food prices and land use changes, they were less in favour of biofuels (Lanzini et al., 2016).

This strategy can also be used to further create a **positive social norm**, where those surrounding the individual also support SAF (Korba et al., 2023). As such, campaigns that involve influencers (e.g. Coldplay), environmental advocates (e.g. Greta Thunberg), and the aviation industry (e.g. commercial United Airlines x Sesame Street) can be implemented to promote SAF as a socially desirable choice. Encouraging high-profile endorsements and community-led initiatives can help shift social norms towards more sustainable aviation practices (Yuriev et al., 2020).

An example is the **collaboration of Neste with Coldplay**. The band is touring by teaming up with Neste as part of its commitment to reduce their direct GHG emissions by 0% compared to their previous tours. Chris Martin of Coldplay emphasised the necessity of sustainability, stating that 'SAF will play a major part in our efforts to minimise the tour's climate impact'. In addition to their proactive use of SAF, Coldplay promotes it on their social media platforms and official website. For all flights, the band ensures the use of SAF sourced exclusively from waste and residues like UCO, and e.g. explains it can reduce GHG emissions by up to 80% compared to traditional jet fuel (Neste, n.d.). This partnership serves as an inspiring model for sustainable touring practices globally.

A third challenge influencing the attitude is the relatively low trust in **policymakers**. This highlights the need to enhance trust in policymakers to foster support for SAF initiatives (Ahmad et al., 2019). Enhancing transparency and communications in implementing effective policies (section 3) can mitigate this challenge.

A fourth challenge is the **higher cost** of SAF compared to CJF (Ahmad and Xu, 2021). **Reframing** the optional surcharge for SAF as an investment in environmental benefits rather than a financial loss can positively influence passenger attitudes and behaviour (Gifford and Comeau, 2011).

The last challenge is the **attitude-behaviour conflict**, as many people experience feelings of dissonance regarding air travel (Schrems and Upham, 2020). Social marketers could use knowledge of this conflict to develop campaigns **highlighting** this **dissonance** to promote behaviour change (Korba et al., 2023).

Addressing these challenges and implementing targeted solutions can improve public perception and increase the adoption of SAF. Educating the public, addressing concerns transparently, and leveraging influential partnerships are key strategies that can drive the shift towards more sustainable aviation practices.

2.2. Economic players

2.2.1.Airlines

Concerning the price premium, airlines could choose to not only let it vary across let it vary across flight lengths, but also based on revenue share. (PWC, 2022). Lufthansa Group applies this system to determine the surcharge, and thus depending on booking class and aircraft type (Lufthansa, n.d.) Furthermore, airlines can adopt new loyalty programs that reward consumers for reducing their emissions, potentially through using SAF. Additionally, business-to-business collaborations can be set up between airlines and corporations that are committed to reducing their aviation emissions (Santos and Delina, 2021).

Additionally, the Environmental Labelling Scheme promotes a fair competition **framework** that **recognises sustainability efforts**. The aim is to bring transparency and, therefore, competitiveness to the market. EASA will look at actual historical data provided by airlines and project the carbon footprint per passenger and carbon efficiency for future flights to calculate the carbon footprint and carbon efficiency. Using real operational data guarantees greater accuracy and reliability for the calculation. Taking part in the Environmental Labelling Scheme will be voluntary for airlines. Airlines that choose to opt in will be required to submit flight data for all flights that fall under the scope of the initiative to EASA. They cannot choose to submit data only for certain routes. A further requirement for those who have opted in is that they need to display the result in their booking systems to ensure that this information reaches the passengers. EASA is launching an early adopters' plan for interested airlines to provide guidance and allow them to make an initial assessment (EASA, 2024; SAF investor, 2023)

2.2.2.Airports

The limited availability of SAF supply can be addressed with earlier solutions discussed in section 1 of this part. Besides, the **role of airports** in the implementation of SAF was not clear, so successful initiatives of airports supporting SAF integration can offer a model for other airports to replicate and adapt to their specific contexts. An 'example' for other airports could be **the Port of Seattle**, which has been a leader in SAF R&D since 2008 (Leavitt et al., 2018). Initially focusing on understanding the SAF landscape in collaboration with state agencies, they shifted to market development by building infrastructure for SAF and participating in cost-reduction programs. In 2017, the Port set a goal to fuel all flights at Sea-Tac with a 10% SAF blend by 2028 (WSU, 2020). Another example could be **Amsterdam Schiphol Airport**, which has collaborated with KLM's Corporate Biofuel Programme and invested in SkyNRG's SAF production facility to establish a large-scale SAF supply by 2025. Schiphol also implemented an airport-led incentive scheme supporting airlines with SAF cost premiums, benefiting 15 airlines. Additionally, Schiphol leads the EU-funded TULIPS project to accelerate sustainable aviation technologies and support passenger awareness programs (RSB, 2023).

2.2.3.Corporate aviation

To address the lack of awareness and education about the benefits of SAF on corporate level, the initiatives like the '**Travel Smart Campaign'** can offer a solution. This is international initiative is dedicated to help businesses lower their corporate travel emissions, e.g. through SAF. Moreover, it encourages companies and their employees to adopt a new culture of meaningful and efficient corporate travel (Transport & Environment, 2023).

2.3. Summary of strategies for uptake demand side

Figure 27 outlines the structure of demand for SAF, emphasizing various key players and strategies aimed at increasing its adoption. Airlines are depicted as the direct customers of SAF, primarily responsible for increasing its adoption due to their direct impact on fuel usage decisions. Airports play a significant role by supporting SAF, influencing airlines through infrastructure and policy adaptations that facilitate SAF uptake. The end-consumer focus is split between individual and corporate demand, highlighting different approaches to increasing SAF usage. For individuals, the strategy centers on fostering a positive attitude towards SAF. For corporations, the emphasis is on raising awareness about the benefits and applications of SAF, encouraging corporate responsibility towards more sustainable fuel options. Additionally, the category labelled 'other' encompasses non-commercial entities like private or military aviation sectors, which also contribute to the demand for SAF but are not the primary focus of this thesis.

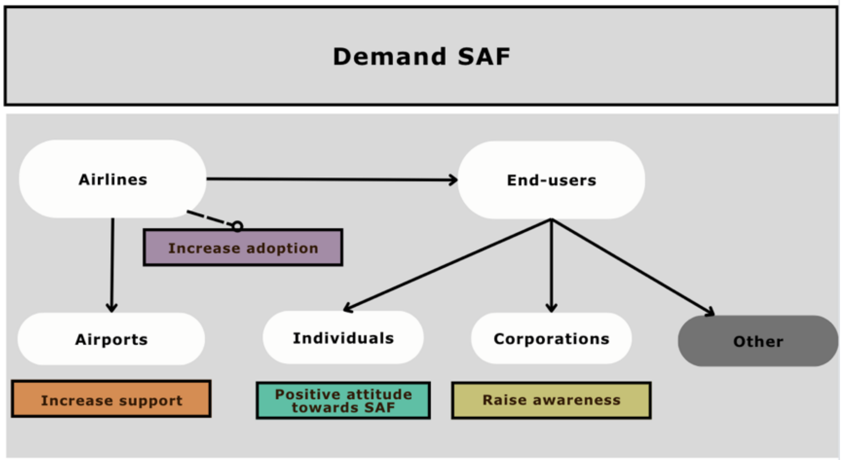


Figure 27: Overview demand SAF

Moreover, figure 28 outlines strategies to increase **positive attitudes** toward SAF among **individuals**, focusing on practical approaches across five key areas: awareness of GHG emissions from aviation, enhanced knowledge and use of SAF, promoting positive social norms, trust in policymakers, and cost perception of SAF.

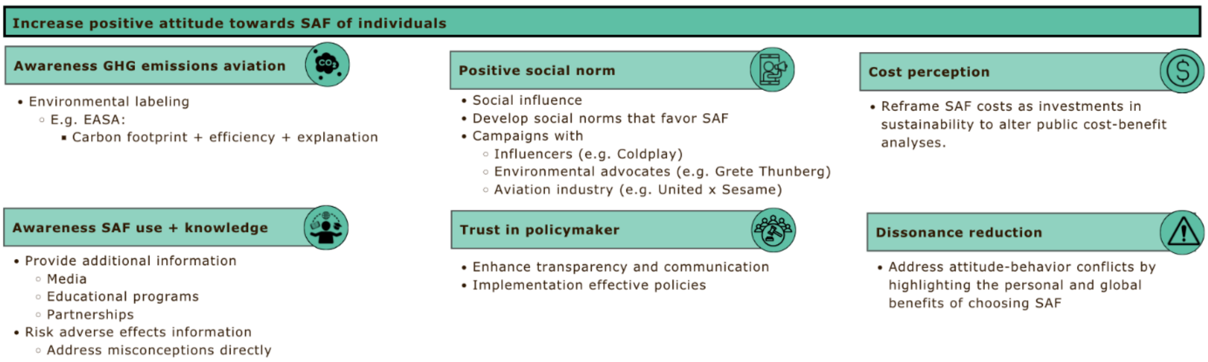


Figure 28: Overview of opportunities to increase individual adoption of SAF

Additionally, Figure 29 discusses strategies to increase the adoption of by **airlines, airports,** and **corporate aviation**. For airlines, the effect of the price premium must is important, covers variable pricing for SAF based on flight length and revenue sharing and creating competition of sustainability efforts. For airports, it highlights the role of example models like the Port of Seattle and Amsterdam Schiphol, which have invested in R&D and infrastructure to support SAF usage. Corporate aviation can be encouraged through awareness campaigns, exemplified by the "Travel Smart Campaign" to promote SAF and efficient travel.

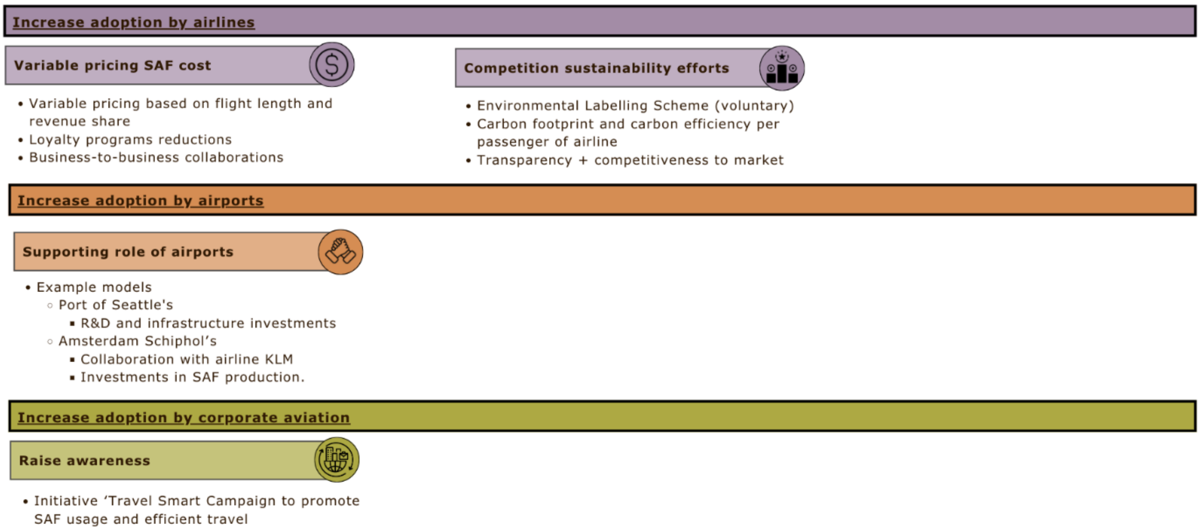


Figure 29: Overview of opportunities to increase adoption of SAF from economic players

3. The policy side

Policy mechanisms can stimulate SAF supply growth, create SAF demand and enable the SAF marketplace. Although SAFs have been technically validated, expanding their accessibility and achieving cost-efficient production continues to be a substantial hurdle. These challenges necessitate **policy interventions** to advance the production of SAF beyond its current limited scope (ICAO, 2023).

3.1. Requirements for effective SAF policies

An effective policy for SAF must navigate various complexities to further its development and adoption. Therefore, the CAEP FTG experts defined six core qualities that SAF policies should embody, as shown in figure 30 (ICAO, 2023).

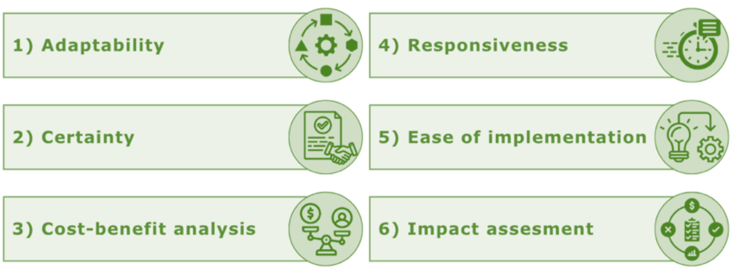


Figure 30: an overview of core qualities of effective SAF policies

Adaptability is essential to accommodate evolving technologies, circumstances, and priorities over time. It is also required to ensure supply chain policies integrate seamlessly into the market. This dynamic approach supports the continuous improvement and integration of new solutions in e.g. the upstream SAF supply chain, as discussed in part E 1.2.

Providing **certainty** about the policy's timeframe and legal stipulations is crucial for securing investor confidence and ensuring a stable investment environment. This certainty mitigates risks associated with policy fluctuations and is highlighted as a barrier for suppliers in part C 4.3.

Effective policies should align **financial costs** with environmental and societal **benefits**. Policies need justification, especially when they impact a high society, like food competition (referenced in part B 1.5). Contrarily, initiatives that provide significant societal benefits, such as the CIFOR-ICRAF initiative, warrant stronger financial backing. The cost-benefit analysis can be made by evaluating feedstock determinants (part B 1.5) and the environmental assessment of the pathways (part B 3.2).

Policies must be **responsive** to unforeseen external economic, environmental, or social events or changes. Establishing price limits can help stabilise responses to volatile market conditions, ensuring policies remain effective without unintended consequences.

The **ease of policy implementation** can impact its effectiveness. Simplifying the implementation and administration process, as well as clearly defining roles across different governance levels, can facilitate smoother policy application. This is particularly crucial for small agricultural developers who often struggle with certification and access to subsidies, as discussed in (part E 1.1.8).

The **impact** of the policies must also be **assessed**, which starts by explicitly defining targets for SAF deployment and GHG reduction. Strong regulatory frameworks ensure these goals are achieved, with proper monitoring and enforcement mechanisms in place (ICAO, 2023). Utilising sustainability indicators, as outlined in part E 1.4, provides a structured approach to assess the ongoing impact of these policies.

3.2. Four areas of focus in SAF policymaking

Creating an environment conducive to the scale-up of SAF requires a multifaceted policy approach that addresses investment, technological, economic, and legal aspects. According to the ICAO, four areas must be covered in SAF policymaking (Figure 31).

Figure 31: overview areas of focus SAF policymaking

Firstly, policies need to foster **investment** and **market stability**. This involves providing a predictable and stable regulatory environment that gives private-sector investors the confidence to commit capital. The policies should extend over a time frame that aligns with project development timelines, providing long-term predictability to investors and developers. It is also important that the policies allow the accumulation of benefits from multiple incentives.

Second, regarding **technological innovations** and performance incentives, policies must be neutral to foster a **diverse range** of production methods and supply chains. Such an approach encourages innovation and competition, driving the industry forward. In addition, to push the industry towards greener practices, incentives should be linked to performance by e.g. rewarding greater achievements in emissions reductions.

Thirdly, regarding **funding** and **economic integration**, it's essential to bridge the price gap that exists between renewable and fossil fuels. Compliance credit markets are instrumental in this respect, providing a mechanism for offsetting cost disparities. Additionally, non-dilutive financial instruments, such as grants and loans, are crucial for supporting pre-commercial entities that are at the forefront of SAF innovation.

Lastly, a **geopolitical legislative framework** must benefit SAF innovation across various regions. A policy with wide political support minimises the risk of sudden reversals, thereby creating a more secure landscape for long-term investments. It's important that policies can adapt to local conditions, while still being national in scope, to address the various opportunities and challenges across different areas (ICAO, 2023).

The combination of these policy elements should ensure a supportive ecosystem that can address the current barriers to SAF production and adoption.

3.3. Policies that enable the SAF market

This section will outline policy options for SAF, categorised in supply-side designs (section 3.3.1.), complementary policies (section 3.3.2.) and demand side measures (section 3.3.2.). It is important to note that the policies options might overlap with multiple categories.

3.3.1.Supply-side designs

3.3.1.1. Direct government provision

The first category focuses on **direct government funding**, which means the government directly provides R&D activities (R. Malina, 2022). This funding is crucial to nurturing early-stage SAF production innovations (ICAO, 2023).

An example is the U.S. Department of Energy (DOE), which **funds** R&D of SAF through the **Bioenergy Technologies Office** (BETO). These funds are directed towards projects aimed at improving feedstock logistics and developing new pathways. For instance, in 2023 BETO granted $2.18 million to three projects focused on minimising the scale-up risks associated with biorefineries. (U.S. Department of Energy, n.d.).

3.3.1.2. Thematic funding

Thematic funding involves the government setting **themes** for innovation and inviting eligible entities to propose projects that align with these themes. This type of funding is more **targeted** than horizontal subsidies and requires applicants to submit detailed proposals, which are then monitored through contractual agreements. Thematic funding allows for a focused approach, potentially leading to more impactful innovations within predefined areas of interest (Steinmueller, 2010).

An example of thematic funding is the European Union’s **Horizon 2020 research and innovation program**, which funded numerous projects to develop new technologies and processes for sustainable energy, including SAF. An example is BIO4A, initiated in June 2018, which aims to scale up industrial production and enhance the market for SAF derived from residual lipids. The funding for this project is almost 17 million euros (BIO4A, n.d.).

3.3.1.3. Signaling strategies

Signaling strategies involve government efforts to influence the expectations and behaviour of economic players regarding technology adoption and innovation. This can include promoting certain technologies or practices seen as beneficial but under-adopted. Large-scale education projects, demonstrations, contests, or signalling desirability are common forms of this strategy. These efforts aim to correct information asymmetries and motivate economic players to invest (Steinmueller, 2024).

The Civil Aviation Agency of North Macedonia organized an **educational project** in February 2024. The project involved a training session on SAF for national bodies, including ministers and industry stakeholders such as airports, airlines, and fuel suppliers. The training was based on the ECAC Guidance on SAF and aimed to explore opportunities and identify the next steps to advance the adoption of SAF in North Macedonia. A significant immediate follow-up action was the proposal to establish a national SAF working group to develop a comprehensive SAF national roadmap (ECAC-CEAC, n.d.).

The Department for Transport of the United Kingdom organised the **Green Fuels, Green Skies (GFGS) competition**. This competition offers £15 million in grant funding to support the early-stage development of SAF projects in 2021. It aimed to advance the UK SAF sector by focusing on, for example, the development and feasibility studies of 'First-Of-A-Kind' commercial SAF plants (GFGS, n.d.). This is also a financial measure.

The **EU's Renewable Energy Directive** (RED II) signals the desirability of SAF by setting ambitious targets for using renewable energy in transport, including aviation. RED II mandates that member states increase the share of renewable energy used in transport to at least 14% by 2030. This directive includes specific provisions to promote the adoption of SAF. The directive also establishes sustainability criteria, ensuring that SAF production is environmentally friendly and socially responsible. By providing a clear regulatory framework and long-term targets, RED II creates a favourable policy environment for SAF development, signalling to industry stakeholders that the EU prioritises sustainable aviation and is committed to supporting its growth. This regulatory support helps drive market confidence and investment in SAF production and infrastructure (EU Science, n.d.)

3.3.1.4. Financial measures

Financial measures aim to improve the financing environment for innovative activities, particularly in contexts with perceived underdevelopment in venture capital or conservative capital markets. These measures can involve, e.g., a tax credit, loan guarantees, capital grants, and feed-in tariffs. They are often justified by a perceived undervaluation of innovative activities by private finance and aim to stimulate investment in sectors (Steinmueller, 2010).

According to ICAO, expanding the **SAF supply infrastructure** requires financial measures due to higher financing costs and risk perceptions associated with SAF projects. Policies designed to reduce financial risk and tax burdens encourage private-sector capital investment in SAF. ICAO also highlights that **operational costs** and **risks** for SAF production are often higher than those for conventional fuel suppliers. Financial measures in this category help bridge the cost gap between SAF and fossil jet fuels, making SAF financially competitive and attractive to producers and consumers (ICAO, 2023).

In the **U.S., a tax credit** is applied uniformly to all producers of SAF who meet specified criteria of reducing GHG emissions compared to conventional petroleum-based jet fuel. A reduction of 50% in GHG emissions qualifies for a credit of $1.25 per gallon. Additionally, for each percentage point by which the reduction exceeds 50%, producers receive an extra $0.01 per gallon, up to a maximum of

$0.50 per gallon (Lane J., 2024; IATA, 2024). This tax credit stimulates investment in and production of SAF by providing a financial reward for environmental performance.

Loans are vital for financing SAF projects, but banks may hesitate if they perceive the repayment risk as too high. To mitigate this, public entities such as governments and multilateral development banks can assume part of the risk associated with these loans, known as **loan guarantees**. This reduces financial risk for banks, lowering the borrowing costs for projects (ICAO, 2023). For instance, the U.S.'s Clean Energy Financing Program provides financing for projects that reduce GHG emissions and air pollution. Under this program, World Energy LLC, a leading SAF producer, was invited to apply for a loan guarantee of approximately $2 billion. If awarded, this loan guarantee will fund the construction of World Energy's Houston renewable fuels facility, expected to produce over 250 million gallons of SAF annually (World Energy, n.d.). The loan guarantee not only supports the project's financial viability but also signals strong governmental backing for advancing the SAF industry.

The FAA's Fueling Aviation's Sustainable Transition (FAST) program provides **capital grants** up to $50 million to support SAF development, including production, transportation, blending, and storage. The projects must cut GHG emissions by over 50% and use biomass, waste streams, renewable energy, or gaseous carbon oxides. Eligible participants include state and local governments, air carriers, airport sponsors, higher education institutions, research institutions, SAF or low-emission aviation technology developers, and nonprofits (Alternative Fuels Data Center, n.d.).

Feed-in tariffs would ensure that SAF producers receive a guaranteed price for the fuel provided, however they are not yet implemented for SAF (ICAO, 2017).

3.3.2.Complementary designs

Complementary policy designs aim to strengthen the overall framework for effective integration and scalability of innovations (Steinmuller, 2010). For SAF, this includes **updating existing legislation** to include SAF as a qualified alternative fuel, thereby expanding its market presence beyond traditional road-transport fuels (ICAO, 2023).

Additionally, establishing clear and uniform standards for certifying the sustainability of SAF's feedstock and production processes ensures robust market acceptance and environmental integrity. Moreover, improving **methods** for calculating, crediting, and trading SAF's environmental attributes are important as well. This will underpin broad SAF market acceptance and ensure environmental integrity (ICAO, 2023). The environmental impact based on life cycle emissions and abatement cost, discussed in part 2: 3.2. can be useful in this validation and verification.

3.3.3.Demand side designs

To boost the uptake of SAF, several policy strategies emphasize the importance of fostering demand through mandates, incentives, and voluntary commitments. This is crucial because, as Steinmuller discusses, assumptions underpinning supply-side and complementary strategies typically expect a ready and willing market for innovations. Such assumptions usually hold when innovations either lower costs or enhance quality without raising prices. However, immediate market acceptance isn't always forthcoming when innovations alter the quality or introduce new products (2010). This underscores the vital role of demand-side policies in ensuring the successful adoption of innovations like SAF.

3.3.3.1. Adoption measures

Providing **subsidies to adopters** essentially lowers the cost of the adopted good and acts as signals that influence the expectations and understanding of potential adopters. If these signals positively impact adoption behaviours, the adoption rate could accelerate (Steinmueller, 2010). **Brussels Airport** provides a **subsidy** for **airlines using SAF** to offset the cost disparity with CFJ. The initiative is supported by government funding and aims to boost SAF adoption among all airlines operating from Brussels Airport. The incentive will cover 80% of the incremental cost of using blended SAF over CFJ, with a maximum of €1,000 per metric ton of SAF refueled. The total budget for 2024 is almost €2 million (EBAA, 2024; Brussels Airport, n.d.)

An adoption measure could involve **mandates** such as **renewable energy volume requirements,** which could progressively increase the volumes of SAF demand (ICAO, 2023). The European Commission has put forward a proposal for a SAF blending obligation at EU airports, starting with a 2% requirement in 2025. To meet the targets of this mandate, it is estimated that 2.3 million tonnes of SAF will be needed by 2030 (Easa, n.d.).

Another mandating approach involves **reductions in the carbon intensity** of the fuel supply, thus creating a market incentive for lower-carbon fuels like SAF (ICAO, 2023). An example of this is the **cap-and-trade system**, which sets a limit on the total GHG emissions allowed within a specific sector or across multiple sectors. This is done by issuing a finite number of emissions **allowances** that can be **traded** on the market. In the aviation sector, implementing a cap-and-trade system that includes specific allowances for aviation-related emissions could incentivise the use of SAF. Over time, the government can adjust the cap, leading to an increase in the price of these allowances, which would further encourage the use of SAF. Finding the right cap level can be difficult for the government because it must be severe enough to cause the desired level and pace of change while reducing overall economic costs (Kollmuss et al., 2008).

To tackle the issue of airlines and end-users in certain areas not having access to SAF, adoption policies should support the development and recognition of systems that manage environmental attribute ownership (ICAO, 2021). The **book-and-claim approach** has been introduced as a practical solution to overcome this hurdle. This approach involves tracking, documenting, and verifying the sustainability attributes of materials and products through a chain of custody. Unlike traditional models, book-and-claim decouples these attributes from the physical product, allowing them to be transferred separately through a dedicated registry. This innovative method supports a flexible chain of custody model that can adapt to the increasing global demand for SAF. One of the key advantages of the book-and-claim system is that it doesn't require a direct physical connection between the supply of SAF and its use. Customers purchasing SAF may not directly use the fuel for their flights or shipments, but their purchase still contributes to a demand that supports the global development of SAF supplies. As a result, these customers can claim the sustainability benefits associated with the fuel, such as reductions in greenhouse gas emissions, which count towards their voluntary environmental targets. Moreover, companies that rely heavily on business travel are increasingly engaging in book-and-claim agreements with airlines. These agreements allow corporations to support the SAF market, even when the fuel isn't physically available for their specific travel needs. The rise in such agreements across various industries is likely to facilitate broader adoption of SAF by generating positive demand signals, thus promoting its wider use and acceptance in the market (RSB, n.d.). Currently, numerous independent pilot programs are being implemented or are in the planning stages, including initiatives by e.g. the RSB. However, for these systems to truly be successful and earn the trust of both the airline industry and regulatory bodies, a uniform framework of principles is necessary. Moreover, a comprehensive and secure registry system is required to safeguards against double counting or claiming (ICAO, 2023).

The government should **demonstrate leadership** by **committing to using SAF** in government-operated aircraft or by contracting with commercial carriers to supply SAF for government travel (ICAO, 2023).

It is crucial to **support collaborative networks** and initiatives that involve SAF stakeholders. These consultation groups, as discussed in Part C section 5, are important in bringing together the various participants in the SAF supply chain. They directly coordinate efforts and can supply critical insights and feedback to policymakers. Prominent among these groups are discussed in the same section (ICAO, 2023).

Lastly, policies can focus on raising awareness and **educating** potential adopters about SAF benefits. These sensibilisation policies can result in earlier or more widespread adoption of new technologies (Steinmueller, 2010).

3.4. Summary taxonomy of the policy side

Figure 32 outlines various **supply-side policy designs** to support the adoption and production of SAF. It covers four main strategies: direct government funding, thematic funding, signaling strategies, and complementary policy designs. Direct government funding includes initiatives like the U.S. Department of Energy funding R&D for SAF through programs such as BETO. Thematic funding involves setting innovation themes by the government, such as the EU's Horizon 2020 program for scaling up SAF production. Signaling strategies highlight government efforts to promote SAF through education, demonstrations, and competitions, exemplified by various national and EU projects.

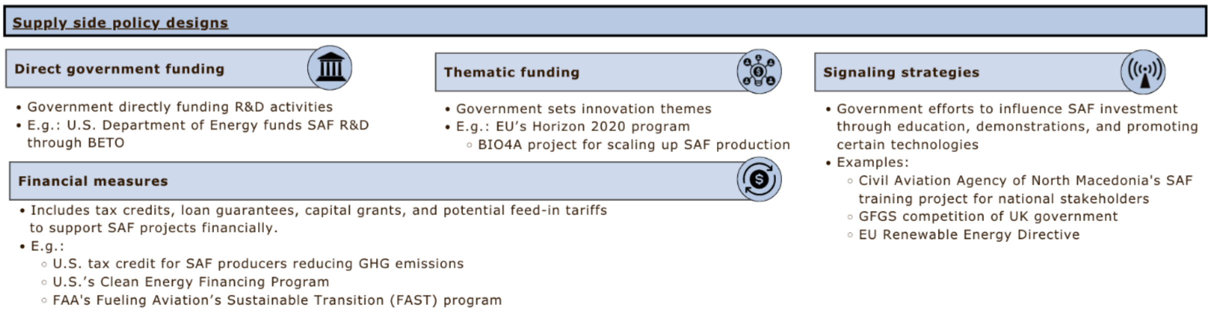


Figure 32: Overview supply side policies for SAF

Additionally, as shown in Figure 33, **complementary policy designs** could focus on updating existing legislation to recognise SAF as a qualified alternative fuel. Additionally, they could implement sustainability certification to establish clear standards for the sustainability of feedstocks and production processes. These efforts aim to enhance SAF's market presence and ensure its environmental attributes are credibly traded and accounted for.

Figure 33: Overview of complementary policy designs for SAF

Lastly, figure 34 discusses **demand-side policies** to boost the adoption of SAF. It highlights six key strategies: subsidies, mandates, demonstrating leadership, supporting collaborative networks, the book-and-claim approach, and education to raise awareness. Subsidies should be implemented to lower costs and encourage adoption. Mandates, like the EU's requirement for 2% SAF at airports by 2025, enforce adoption through legal requirements. Demonstrating leadership involves the use of SAF in government aircraft and travel contracts to set an example. Supporting collaborative networks facilitates coordination and feedback among stakeholders. The book-and-claim approach addresses logistical challenges by allowing the sustainability attributes of SAF to be traded separately from the fuel itself. Lastly, education initiatives aim to promote the benefits of SAF to potential adopters to increase uptake.

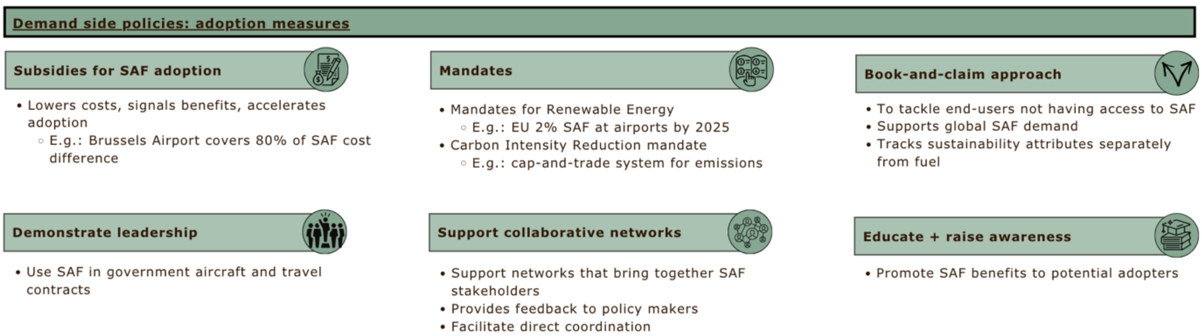


Figure 34: Overview of the demand side policies for SAF adoption

Part E: Conclusion

SAF is crucial for the aviation industry's transition towards climate neutrality. Despite their pivotal role, SAF is projected to constitute only 2% of total aviation fuels by 2025 (ICAO, n.d.). The shortfall in the widespread adoption of SAF underscores a critical need to identify and address challenges across SAF supply and demand.

The supply potential of SAF depends on its **viability**, which is currently constrained by several economic, social, and sustainable challenges. Key among these is the availability and sustainability of **feedstocks**, which strongly depends on their generation. For instance, issues such as competition with food resources, high land and water footprint, and environmental impacts of 1-G feedstocks limit their viability. Although more sustainable, 2-G, 3-G and 4-G feedstocks face hurdles in commercial scalability and require significant technological advancements to become viable options (Abdullah et al., 2019). Additionally, technological barriers to conversion, such as efficiency and blending limits, make large-scale production of SAF economically difficult (EASA, n.d.). Moreover, **SAF producers** have additional barriers due to regulatory inconsistencies, high initial investment costs, and a lack of robust supply chains (Ahmad and Xu, 2021). The **demand for SAF** is also challenged by several factors. These include the concerns of **airlines** regarding the price premium and the lack of clarity for **airports** regarding their role in SAF adoption (Dichter et al., 2020; RSB, 2023). When looking at the **end consumers**, including individuals and corporations, a common barrier is a lack of awareness of SAF and its benefits, as well as the higher cost compared to CJF (WEF, 2023; Ahmad et al., 2019)

Figure 35 summarises an integrated taxonomy to address the systemic issues impeding SAF deployment. This taxonomy identifies and organises various strategies into a framework and illustrates the interrelations and dependencies essential for enhancing SAF production and adoption.

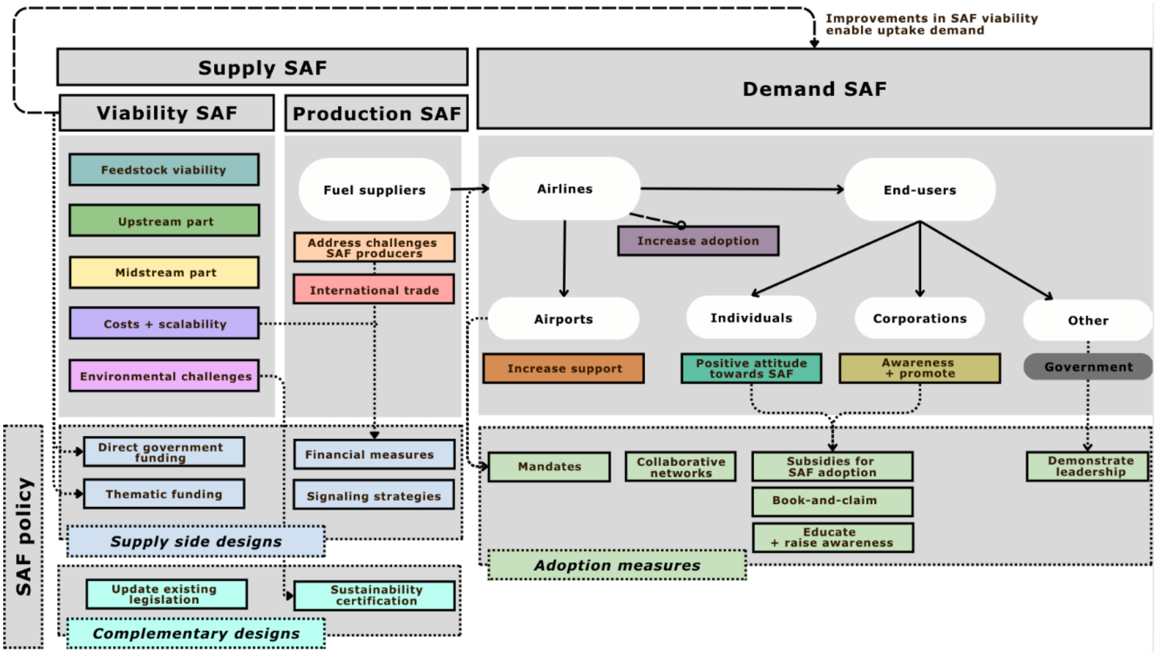


Figure 35: Integrated taxonomy for SAF production and adoption uptake

A pivotal goal of this thesis was to systematically explore and delineate strategies that enhance both the production and demand of SAF. These strategies, detailed in Figure 36, encompass a comprehensive array of initiatives for accelerating SAF adoption and propelling the aviation industry towards its sustainability objectives.

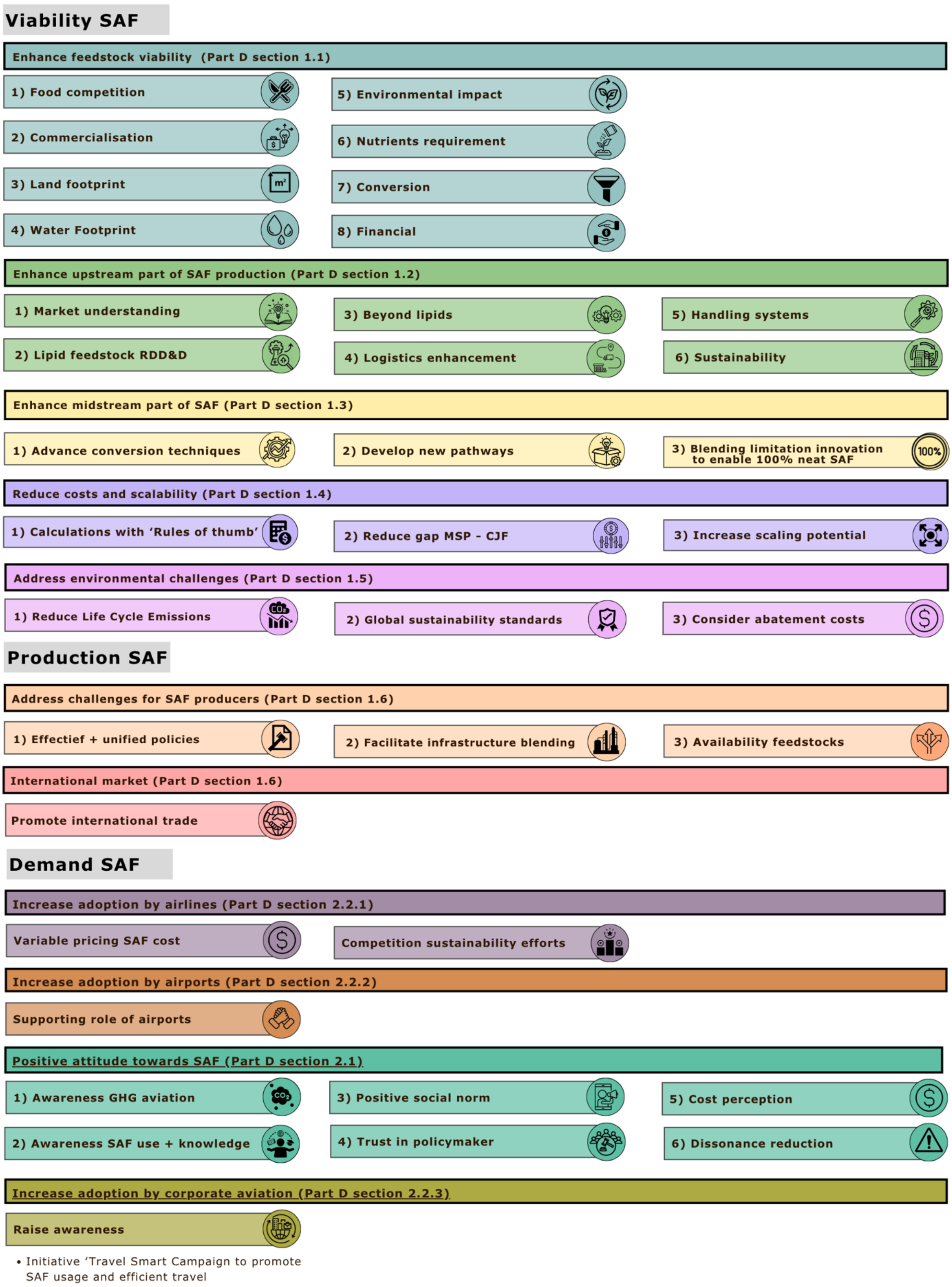


Figure 36: Initiatives to enable uptake of SAF viability, production and demand

The integrated taxonomy developed in this thesis addresses the central question of enhancing the production and demand of SAF. By categorising a wide range of strategies, from technological innovations to policy frameworks and market dynamics, it provides a clear and organised framework for understanding how various factors interact and influence SAF adoption. This taxonomy can serve as a tool for researchers, policymakers, and industry leaders to gain actionable insights of strategies for SAF uptake.

Despite the comprehensive scope of this analysis, the rapidly evolving nature of SAF technologies and the limited coverage of the extensive SAF field present **limitations** to this thesis. Moreover, the lack of unpublished industry data restricts deeper insights into commercial viability and scalability. Future research should address these gaps by continuously updating the taxonomy and expanding into unexplored areas, ensuring the relevance and applicability of the findings

In conclusion, this thesis established a structured approach to enhancing the production and adoption of SAF, setting a foundation for ongoing advancements in the field. By continuing to refine and expand the taxonomy based on emerging data and technologies, future research can significantly contribute to achieving the aviation industry's ambitious sustainability targets.

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