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Review

# Sustainable aviation fuel technologies, costs, emissions, policies, and markets: A critical review

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ABSTRACT

This critical review comprehensively assesses the current landscape of sustainable aviation fuel (SAF) technologies, their associated costs, emissions profiles, policy implications, and market dynamics. This review highlights several key findings regarding bio-jet fuels as a low-carbon emission alternative to traditional jet fuel. First, the hydroprocessed esters and fatty acids (HEFA) technology stands out, boasting the highest possible technology readiness level (TRL) and fuel readiness level (FRL) of 9, indicating its advanced stage of development and readiness for commercial deployment. Second, most bio-jet fuel production technologies entail costs averaging at least 120% higher than conventional fossil-based jet fuel while achieving emissions reductions of at least 27%. Despite these high costs, only 38% of existing policies provide monetary incentives to SAF producers, resulting in SAF production operating at only 3.5% of its total potential capacity. Consequently, the paper highlights open research questions at the intersection of SAF technology development, policy, and market.

## 1. Introduction

Motivated by the urgent need to reduce greenhouse gas (GHG) emissions, the International Air Transport Association (IATA), an international airline organization, has set a cap on net aviation $CO_2$ emissions from 2020 and a 50% reduction of $CO_2$ emissions by 2050 compared to 2005 levels (IATA, 2021). The most promising way to reduce GHG emissions in the aviation sector is to use alternative aviation fuels: bio-jet fuels, synthetic jet fuels, liquefied natural gas (LNG), liquefied hydrogen (LH2), electrofuels, and electricity (Atsonios et al., 2015; Dahal et al., 2021). Among these, bio-jet fuels appeal to aviation companies due to their economic competitiveness and drop-in compatibility with existing aircraft and fuel systems (Atsonios et al., 2015; Gutiérrez-Antonio et al., 2017; Santos et al., 2018). Bio-jet fuels reduce GHG emissions and meet stringent fuel property requirements, such as low sulfur content and high thermal stability (Wei et al., 2019).

Bio-jet fuels have gained considerable interest from the scientific community and have been highlighted in several recent review articles. Prior reviews focus on isolated dimensions of the complex bio-jet fuel landscape, ranging from production processes and techno-economic performance (Dahal et al., 2021; Gutiérrez-Antonio et al., 2017; Wei et al., 2019; Doliente et al., 2020; Emmanouilidou et al., 2023; Goh et al., 2022; Kargbo et al., 2021; Su-ungkavatin et al., 2023; Wang and Tao, 2016) to commercialization status and performance characteristics (Abrantes et al., 2021; Kandaramath Hari et al., 2015; Mawhood et al., 2016; Becken et al., 2023) and policies status (Larsson et al., 2019). Three recent reviews holistically evaluate the confluence of policies, markets, and technological innovations (Zhang et al., 2020; Shahriar and Khanal, 2022; Ng et al., 2021; Detsios et al., 2023). This article further examines the intricate interplay of policies, markets, and technological innovations. To the best of our knowledge, this critical review is the first to complete the following:

1) Extract techno-economic analysis (TEA) and life cycle analysis (LCA) data from over 50 sources.
2) Quantitatively assess the current and future market of sustainable aviation fuel (SAF).
3) Compare market reports (forecasts) and SAF policy adoption (data).
4) Identify critical research directions at the nexus of SAF technology, markets, and policy.

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**List of abbreviations**

| | |
|---|---|
| **APS** | Announced Pledges Scenario |
| **ASTM** | American Society for Testing and Materials |
| **ATJ** | Alcohol to Jet |
| **CCS** | Carbon Capture and Storage |
| **CHJ** | Catalytic Hydrothermolysis |
| **CORSIA** | Carbon Offsetting and Reduction Scheme for International Aviation |
| **DAC** | Direct Air Capture |
| **DSHC** | Direct Sugar to Hydrocarbons |
| **EIA** | Energy Information Administration |
| **ETS** | Emissions Trading System |
| **FOG** | Fats Oil and Grease |
| **FRL** | Fuel Readiness Level |
| **FT** | Fischer Tropsch |
| **GHG** | Greenhouse Gas |
| **HC-HEFA** | Hydrocarbon Hydroprocessed Esters and Fatty Acids |
| **HEFA** | Hydroprocessed Esters and Fatty Acids |
| **HFS** | Hydroprocessed Fermented Sugars |
| **IATA** | International Air Transport Association |
| **ICAO** | International Civil Aviation Organization |
| **IEA** | International Energy Agency |
| **ILUC** | Induced Land Use Change |
| **IRENA** | International Renewable Energy Agency |
| **LCA** | Life Cycle Analysis |
| **LCFS** | Low Carbon Fuel Standard |
| **LH2** | Liquified Hydrogen |
| **LNG** | Liquified Natural Gas |
| **LUC** | Land Use Change |
| **MJSP** | Minimum Jet Fuel Selling Price |
| **MSW** | Municipal Solid Waste |
| **NPV** | Net Present Value |
| **NZE** | Net Zero Emissions |
| **PtL** | Power to Liquid |
| **R&D** | Research and Development |
| **RFS** | Renewable Fuel Standards |
| **RIN** | Renewable Identification Number |
| **SAF** | Sustainable Aviation Fuel |
| **SIP** | Synthetic Iso-Paraffins |
| **SPK** | Synthetic Paraffin Kerosene |
| **SPK/A** | Synthetic Paraffin Kerosene with Aromatics |
| **STEPS** | Stated Policy Scenario |
| **TEA** | Techno-economic Analysis |
| **TRL** | Technology Readiness Level |
| **UN** | United Nations |
| **WEF** | World Economic Forum |
| **WEO** | World Energy Outlook |
| **$ $L^{-1}$** | U.S. Dollars per Liter |
| **$gCO_2eq\ MJ^{-1}$** | Grams of carbon dioxide equivalent per Megajoule of fuel |
| **$L\ year^{-1}$** | Liters per year |
| **$ $tonne^{-1}$** | US dollars per metric tonne |
| **$ $tonneCO_2^{-1}$** | US dollars per metric tonne of $CO_2$ |
| **£ $kg^{-1}$** | Euros per kilogram |

By synthesizing techno-economic, emissions, policy, and market dimensions, this review offers a comprehensive perspective on the opportunities and challenges ahead in realizing the full potential of bio-jet fuels amid the global imperative to combat climate change. The remainder of this article is organized as follows: Section 2 reviews the current technologies for producing SAF; Section 3 presents the current policy status for SAF; Section 4 presents the past, present, and future markets of SAF and discusses challenges for SAF implementation; and Section 5 summarizes the concluding remarks and open research directions.

## 2. SAF technologies

### 2.1. Methodology

Bio-jet fuel, also referred to as SAF, describes biomass and biomaterials derived synthesized paraffinic kerosene (SPK) that is blended into conventional petroleum-derived jet fuel (Jet A) (Doliente et al., 2020). This section thoroughly examines the seven American Society for Testing and Materials (ASTM)-certified SAF production technologies: Fischer-Tropsch (FT-SPK), Fischer-Tropsch synthetic kerosene with aromatics (FT-SPK/A), hydroprocessed esters and fatty acids (HEFA-SPK), synthetic iso-paraffins from fermented hydroprocessed sugar (HFS–SIP), alcohol-to-jet (ATJ-SPK), catalytic hydrothermolysis (CHJ-SPK), and hydrocarbon hydroprocessed esters and fatty acids (HC-HEFA-SPK) (Abrantes et al., 2021). Two additional ASTM-certified pathways for co-processing biomass feedstocks in petroleum refineries are discussed in Section 2.6.

This analysis offers a comprehensive understanding of the SAF production landscape, encompassing the technological aspects and the intricate interplay of economic and environmental considerations. The minimum jet fuel selling price (MJSP) and GHG emissions were used to quantify the status of each technology. The MJSP is calculated from a TEA and represents the selling price of SAF at the break-even net present value (NPV), meaning the selling price of SAF where the difference between the present value of cash inflows and cash outflows arising from the production and sale of SAF are equivalent (Li et al., 2018). The GHG emissions are calculated from an LCA of the SAF production process. A full LCA would include a "cradle-to-grave" approach by considering each step of the SAF life cycle: design/development of the product, raw material acquisition, manufacturing, distribution use/maintenance/reuse, and end-of-life activities (Jacquemin et al., 2012). The studies selected for our analysis include cradle-to-grave analyses and less inclusive LCA scopes. For example, Pipitone et al. (2023) used a "gate-to-gate" approach, considering only the manufacturing or process emissions. Section 2.4 discusses the impact of LCA scope inconsistencies across sources on a comparative analysis of SAF technologies.

The technology pathway review was conducted by searching the literature for recent peer-reviewed scientific papers from 2015 to 2023. The combination of the keywords "bio-jet fuel" and "sustainable aviation fuel" with "techno-economic," "life cycle analysis," and "emissions" yielded over 20,000 results in Google Scholar. The Google Scholar search listed results in order of relevance, and searches for each keyword combination were stopped on page 15 (a total of 150 results). Manual filtering was applied to select peer-reviewed articles that explicitly calculated the MJSP or GHG emissions and remove articles that studied non-ASTM-certified technologies (e.g., pyrolysis). After manual filtering, 73 pieces of literature met the above criteria. Table 1 categorizes the literature reviewed by economic analysis, life cycle analysis, economic and life cycle analysis, and technology reviews and specifies the technology pathway considered.

### 2.2. Technology descriptions

Seven ASTM-certified technologies for SAF production (Table 2) have been extensively reviewed in the literature (Table 1) and can be categorized into three feedstock types: bio-oils, biomass for sugar production, and lignocellulosic biomass. Fig. 1 illustrates the main process

**Table 1**
Categorized references for technology pathway review by literature topic (economic analysis, life cycle analysis, economic and life cycle analysis, and technology reviews) and technology pathway considered (FT-SPK, HEFA-SPK, ATJ-SPK, HFS–SIP, CHJ-SPK, and multiple technology comparison).

| Literature Topic | Technology | Reference | Scope |
|---|---|---|---|
| **Economic Analysis** | FT-SPK | Petersen et al. (2022) | This study simulated the production of SAF from invasive alien plants via the FT pathway. TEA was used to calculate the MJSP for high- and low-pressure FT, considering variable co-product recovery and SAF premium prices. |
| | | Wang et al. (2022) | This study compared the production of SAF from rice husk via pyrolysis and FT. Nominal MJSP, MJSP sensitivity, and fuel properties were reported for both processes. |
| | HEFA-SPK | Diniz et al. (2018) | This study performed a stochastic TEA to evaluate the probability of profitable production and sensitivity of SAF from camelina, carinata, and jatropha via the HEFA pathway. |
| | | Kumar et al. (2018) | This study simulated a biorefinery concept for producing SAF and bioethanol from lipid-producing sugarcane. TEA was used to calculate the MJSP and its sensitivity to process parameters. |
| | | Li et al. (2018) | This study simulated the commercial scale production of SAF and co-products from camelina oil in Canada via the HEFA pathway. TEA was used to calculate the MJSP and its sensitivity to process parameters. |
| | | Martinez-Hernandez et al. (2019) | This study simulated the production of SAF and biodiesel from vegetable oil via the HEFA pathway. TEA and Monte Carlo simulations were used to report robust estimations of MJSP. |
| | | Tao et al. (2017a) | This study investigated the geographic distribution, production levels, oil yield, prices, and chemical composition of 20 oil feedstocks. They selected camelina, pennycress, jatropha, castor bean, and yellow grease as feedstocks for SAF via the HEFA pathway for TEA. |
| | | Wang (2019) | This study reported the MJSP from TEA performed on 12 different feedstocks for SAF produced via the HEFA pathway in Taiwan. |
| | | Shila and Johnson (2021) | This study simulated the production of SAF from camelina via the HEFA pathway in the US. TEA was used to determine the MJSP and its sensitivity with and without onsite $H_2$ production. |
| | ATJ-SPK | Brandt et al. (2020) | This study simulated the production of SAF from forest residues via integrated ATJ biorefinery concepts. TEA was used to compare the MJSP for three co-product scenarios. |
| | | Romero-Izquierdo et al. (2021) | This study simulated an intensified ATJ process for SAF production from bioethanol. TEA was used to compare the intensified process to conventional ATJ. |
| | | (Seufitelli et al. (2022)) | This study investigated three different process scales for an integrated biorefinery concept producing SAF, xylitol, and formic acid from poplar. TEA was used to compare process economics and study their sensitivity. |
| | | Tao et al. (2017b) | This study compared detailed TEA results for SAF produced via the ATJ process from corn stover and grain. Sensitivity analysis was used to identify cost-reduction opportunities. |
| | | Yao et al. (2017) | This study performed a stochastic TEA to evaluate the probability of profitable production and compare MJSP for SAF produced from sugarcane, corn grain, and switchgrass via the ATJ pathway. |
| | CHJ-SPK | Eswaran et al. (2021) | This study reviewed the CHJ pathway and simulated the production of SAF from soybean oil, carinata oil, and yellow and brown grease. TEA was used to compare MJSP for each feedstock. |
| | | McGarvey and Tyner (2018) | This study performed a stochastic TEA to evaluate the probability of profitable production of SAF from brown grease, yellow grease, and carinata oil via the CHJ pathway. Different plant scenarios and SAF producer credits were considered. |
| | | Nguyen and Tyner (2022) | This study performed a stochastic TEA to evaluate the probability of profitable production of SAF from carinata oil via the CHJ pathway with and without government incentives. |
| | Multiple Technology Comparison | Atsonios et al. (2015) | This study compared the TEA results of SAF produced from wood chips via the FT and ATJ processes. |
| | | Bann et al. (2017) | This study used a stochastic TEA to evaluate six pathways for SAF production with consistent financial assumptions in the US with and without government incentives. |
| | | Brandt et al. (2022) | This study used TEA to study the impact of government incentives on SAF produced via HEFA, ATJ, and FT from varying biomass sources. |
| | | de Jong et al. (2015) | This study used harmonized TEA to compare the short-term economic feasibility of six conversion pathways for SAF production. |
| | | Diederichs et al. (2016) | This study used TEA to compare FT and ATJ pathways producing SAF from 1G and 2G lignocellulosic feedstocks. |
| | | Klein et al. (2018) | This study used TEA to compare sugarcane biorefineries integrated with HEFA, FT, and ATJ to produce SAF. |
| | | Michailos and Bridgwater (2019) | This study used TEA to compare HEFA, FT, and zeolite cracking pathways to upgrade bio-oils from forest residue to SAF. The MJSP was determined for each process, and Monte Carlo simulations were used to determine its sensitivity. |
| | | Petersen et al. (2021) | This study used TEA to compare biorefinery scenarios for producing SAF from bioethanol and bio-syncrude. |
| | | Tanzil et al. (2021a) | This study performed TEA to compare the MJSP of six SAF production pathways using standardized criteria. |
| **Life Cycle Analysis** | FT-SPK | Li et al. (2019) | This study performed a cradle-to-grave LCA on two FT process configurations that convert corn stalks to SAF. |
| | | Sun et al. (2021) | This study performed a cradle-to-grave LCA on SAF produced from corn stover via the FT pathway. |
| | HEFA-SPK | Castillo-Landero et al. (2023) | This study performed a gate-to-gate LCA on an intensified HEFA process producing SAF from palm oil. |
| | | Lokesh et al. (2015) | This study performed a cradle-to-grave LCA on SAF produced from camelina, microalgae, and jatropha via the HEFA pathway. |
| | | Mousavi-Avval and Shah (2021) | This study performed a well-to-gate LCA on SAF produced from pennycress via the HEFA pathway. |
| | | O'Connell et al. (2019) | This study performed a well-to-wheels LCA on SAF produced from rapeseed, sunflower seed, soybean, and palm oil. |

(continued on next page)

**Table 1** (*continued*)

| Literature Topic | Technology | Reference | Scope |
|---|---|---|---|
| | ATJ-SPK | Wang et al. (2023) | This study performed a well-to-wake LCA for five ATJ process configurations that convert corn, cassava, and corn cob to SAF. |
| | HFS–SIP | Budsberg et al. (2016) | This study performed a cradle-to-grave LCA on a novel HFS–SIP process that converts poplar biomass to SAF. |
| | Multiple Technology Comparison | Björnsson and Ericsson (2022) | This study performed a cradle-to-gate LCA on four SAF production processes from woody residues to assess the potential of reaching policy goals in Sweden. |
| | | ICAO (2019)) | This report contains default LCA values for CORSIA-eligible fuels, including cradle-to-grave emissions from multiple feedstocks for HEFA, FT, ATJ, and HFS–SIP pathways. |
| | | De Jong et al. (2017) | This study performed a well-to-wake LCA on FT, hydrothermal liquefaction, and ATJ SAF production technologies. |
| | | Han et al. (2017) | This study compared the well-to-wake LCA emissions of SAF produced via the ATJ and HFS–SIP pathways. |
| | | Prussi et al. (2021) | This study presents the LCA methodology for calculating the CORSIA core LCA values and induced land-use change values. |
| **Economic and Life Cycle Analysis** | FT-SPK | Michaga et al. (2022) | This study combined TEA and cradle-to-gate LCA to evaluate SAF production from forest residues, with and without carbon capture and storage. |
| | | Real Guimarães et al. (2023) | This study combined TEA and cradle-to-grave LCA to compare stand-alone and integrated SAF production from bagasse. |
| | HEFA-SPK | Alam et al. (2021) | This study combines TEA and cradle-to-gate LCA to evaluate SAF production from carinata in the US, considering scenarios with and without coproducts and RINs. |
| | | Barbera et al. (2020) | This study compared TEA and well-to-tank LCA results of SAF production from waste cooking oil via HEFA and a novel catalytic transfer hydrogenation process. |
| | | Liu et al. (2021) | This study used TEA and well-to-wake LCA to compare the MJSP and GHG emissions of SAF produced from jatropha and castor oilseeds in China. |
| | | Umenweke et al. (2023) | This study combined TEA and cradle-to-grave LCA to compare two configurations of the HEFA process to produce SAF from tall oil fatty acids. |
| | | Pipitone et al. (2023) | This study compared TEA and gate-to-gate LCA results for SAF produced from vegetable oils via the HEFA pathway using aqueous phase reforming for on-site hydrogen production. |
| | ATJ-SPK | Moretti et al. (2021) | This study used TEA and well-to-tank LCA to calculate the MJSP and GHG emissions of SAF produced from potato by-products via a novel ATJ process. |
| | | Park et al. (2022) | This study simulated SAF production from bioethanol with a data-driven reactor model. TEA and LCA were used to calculate the MJSP and cradle-to-grave $CO_2$ emissions. |
| | | Santos et al. (2018) | This study performed a TEA and LCA on an integrated sugarcane mill that produces SAF to calculate the MJSP and cradle-to-gate plus combustion GHG emissions. |
| | | Vela-García et al. (2020) | This study used TEA and gate-to-gate LCA to evaluate SAF produced via ATJ with a triisobutane alcohol intermediate. |
| | HFS–SIP | Michailos (2018) | This study used TEA and a cradle-to-grave LCA to calculate the MJSP and GHG emissions of SAF produced from bagasse. |
| | Multiple Technology Comparison | Bhatt et al. (2023) | This study combines TEA, cradle-to-grave LCA, policy, and logistics for three technologies to evaluate the deployment of SAF at Chicago's O'Hare International Airport. |
| | | Capaz et al. (2021) | This study used TEA and cradle-to-grave plus land-use change LCA emissions to calculate the cost of mitigating emissions for three SAF production technologies. |
| | | Julio et al. (2021) | This study compared the TEA and cradle-to-gate LCA results for producing SAF from palm oil via the HEFA and ATJ pathways. |
| | | Neuling and Kaltschmitt (2018) | This study used TEA and cradle-to-grave LCA to compare four SAF production technologies and feedstocks in Germany. |
| | | Tanzil et al. (2021b) | This study used TEA and cradle-to-grate LCA to compare five SAF production technologies integrated in a dry grind corn ethanol mill. |
| | | Tanzil et al. (2022) | This study used TEA and cradle-to-gate LCA to compare 20 integrated SAF-producing sugarcane mills with six different technologies. |
| | | Vela-García et al. (2021) | This study compared TEA results, gate-to-gate LCA emissions, and flight performance simulations for SAF produced from oleaginous crops via the HEFA and ATJ pathways. |
| **Technology Reviews** | Multiple Technology Comparison | Abrantes et al. (2021) | A review of SAF production technologies commercialization status and performance characteristics |
| | | Dahal et al. (2021) | A review of SAF production technologies and emerging propulsion systems |
| | | Doliente et al. (2020) | A review of supply chain components of SAF production technologies, including feedstock, production, storage, and transport |
| | | Emmanouilidou et al. (2023) | A review of SAF production technologies and economic performance from waste materials |
| | | Goh et al. (2022) | A review of catalysis advancements for SAF production technologies |
| | | Gutiérrez-Antonio et al. (2017) | A review of existing SAF production technologies and their economic performance to identify the most promising pathways for future implementation |
| | | Kandaramath Hari et al. (2015) | A review of SAF production technologies commercialization status and performance characteristics |
| | | Kargbo et al. (2021) | A review of SAF production technologies and economic performance |
| | | Mawhood et al. (2016) | A review of SAF production technologies' commercialization status in terms of FRL |
| | | Ng et al. (2021) | A holistic review of SAF technologies, markets, policies, and their uptake in the global aviation industry |
| | | Shahriar and Khanal (2022) | A holistic review of SAF technologies, markets, and policies worldwide |
| | | Su-ungkavatin et al. (2023) | A review comparing existing (bio-jet fuel) and emerging (electrofuels, hydrogen, etc) SAF production technologies |
| | | Wang and Tao (2016) | A review of SAF production technologies and their main challenges, including process design, costs, and emissions |
| | | Wei et al. (2019) | A review of seven SAF production technologies, including two non-certified technologies, and their economics, environmental impact, and development status |
| | | Zhang et al. (2020) | A holistic review of SAF technologies, markets, and policies |

**Table 2**
Feedstock, FRL, TRL, blend limit, and year of certification of seven ASTM-certified technologies. Adapted from (Dahal et al., 2021) and (Abrantes et al., 2021).

| Technology | Feedstock | FRL[b] | TRL[a] | Blend Limit | Year |
|---|---|---|---|---|---|
| Hydroprocessed Esters and Fatty Acids (HEFA-SPK) | Bio-oils | 9 | 9 | 50% | 2011 |
| Hydroprocessed Hydrocarbon Esters and Fatty Acids (HC-HEFA-SPK) | Bio-oils from Algae | 6 | – | 10% | 2020 |
| Catalytic Hydrothermolysis (CHJ-SPK) | Bio-oils | 6–7 | 4–6 | 50% | 2020 |
| Fischer Tropsch (FT-SPK) | Coal, Natural Gas, and Biomass | 6–7 | 6–8 | 50% | 2009 |
| Fischer Tropsch/Aromatics (FT-SPK/A) | Coal, Natural Gas, and Biomass | 6–7 | 6–8 | 50% | 2015 |
| Alcohol-to-Jet (ATJ-SPK) | Biomass | 7–8 | 6–8 | – | – |
| (Ethanol) | | | | 50% | 2018 |
| (Isobutanol) | | | | 30% | 2016 |
| Hydroprocessing of Fermented Sugars Synthesized Iso-paraffin (HFS–SIP) | Biomass for sugar production | 5–8 | 7–9 | 10% | 2014 |

[a] TRL are reported on a scale of 1–9, 1 representing "basic principles observed" (basic technology research) up to 9 representing "Full-scale plant audited" (fully commercialized).
[b] FRL ranges from 1 ″basic level" to 9 ″production capability level."

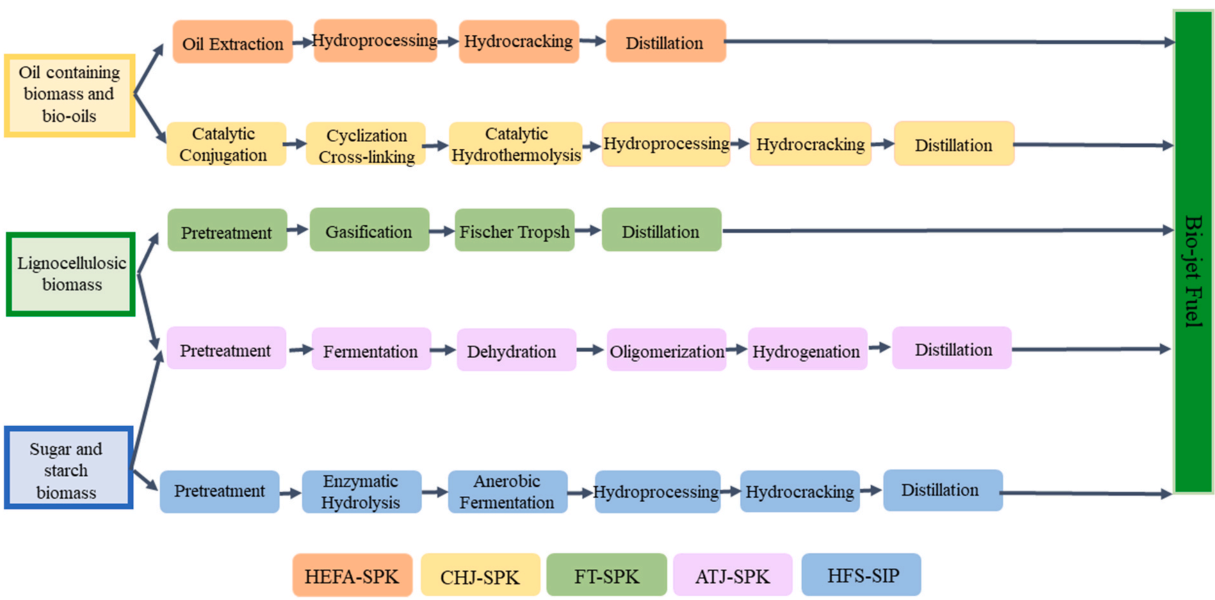


**Fig. 1.** Main process steps and feedstock categories for the pathways of five ASTM-certified technologies. Technology pathways are differentiated by color. HC-HEFA-SPK and FT-SPK/A are omitted as they have the same main process steps as HEFA and FT, respectively. Adapted from (Dahal et al., 2021) and (Goh et al., 2022).

steps for five ASTM-certified technologies from their feedstock group: FT, HEFA, CHJ, ATJ, and HFS–SIP. Table 2 lists the characteristics of seven ASTM-certified technologies, including feedstock type, technology readiness level (TRL), fuel readiness level (FRL), blend limit, and year of ASTM certification. Two additional ASTM-certified pathways for co-processing biomass feedstocks in petroleum refineries are discussed in Section 2.6. The TRL measures the progress of a technology toward commercialization. The FRL reflects the risk associated with the development of new fuels. The FRL classification is preferred over TRL in the aviation industry for communication of fuel technology maturity (Mawhood et al., 2016). The blend limit refers to the percent of SAF allowed to mix with conventional jet fuel.

HEFA is currently the only fully commercialized SAF technology, boasting a TRL and FRL of 9 (Dahal et al., 2021); however, with the urgent need for widespread global SAF capacity, developing and scaling additional technologies is imperative. Catalytic hydrothermolysis (CHJ), another oil-to-jet process, consumes less hydrogen than HEFA; however, the process has a lower TRL due to unfavorable operating conditions, i.e., temperatures from 450 °C to 475 °C and pressures of 210 bar (Wang and Tao, 2016; Eswaran et al., 2021). Fischer–Tropsch synthesis has been demonstrated commercially to produce syngas from coal and natural gas. Using biomass as a FT feedstock is more challenging due to its heterogeneous nature. Thus, biomass pretreatment is a critical and potentially costly step to achieve the desired properties of syngas (high carbon and hydrogen content and no impurities) (Goh et al., 2022; Hu et al., 2012). The ATJ process has strong potential for commercial development with bioethanol as a feedstock, given the current worldwide production, price, and market share advantages over other alcohols (Goh et al., 2022). However, with the widespread use of bioethanol in the petrochemical industry as a mandatory blended component of automobile fuel, the commercialization of ATJ may create competition between the air and ground transportation sectors regarding feedstock availability (Doliente et al., 2020). HFS–SIP, also called direct sugar to hydrocarbon (DSHC), converts biomass for sugar production to alkane-type fuels using anaerobic fermentation, bypassing the alcohol intermediate in ATJ (Wei et al., 2019). HFS–SIP is the only process resulting in a SIP fuel. HFS–SIP has a lower FRL (Santos et al., 2018; Wei et al., 2019; Doliente et al., 2020; Emmanouilidou et al., 2023), mainly due to the difference in fuel properties of SIP and Jet A, including a significant difference in fuel viscosity (Dahal et al., 2021).

### *2.3. Economic and environmental performance review*

SAF technologies' economic and environmental performance are arguably the most important metrics for commercialization. Fig. 2 displays the MJSP (a) and GHG emissions (b) reported in the literature for different feedstocks and technologies compared to the 2021 market price (0.5 $ $L^{-1}$ (IEA, 2021a)) and GHG emissions (89 $gCO_2$ $MJ^{-1}$ (Prussi

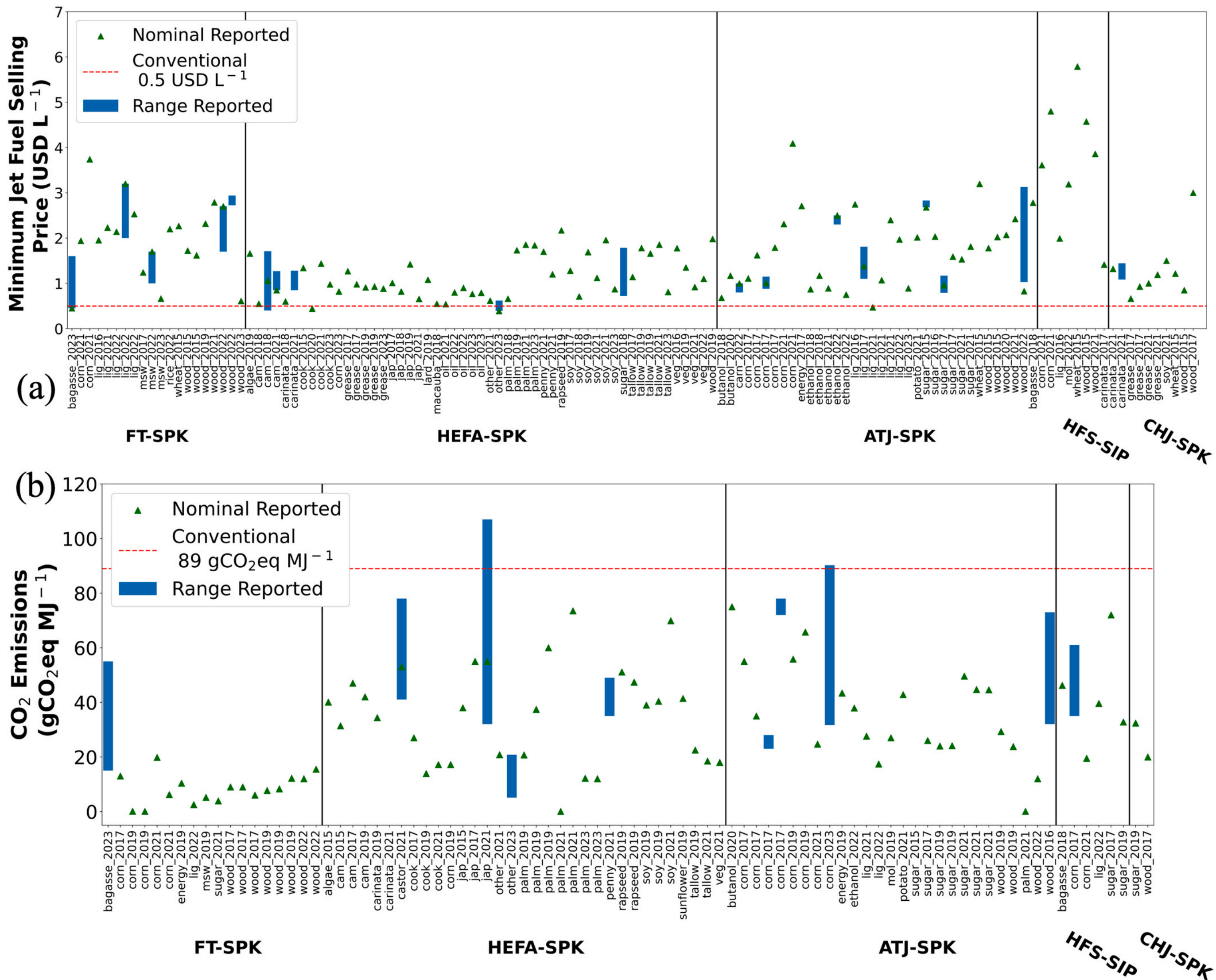


**Fig. 2.** Review of 58 papers MJSP (a) and $CO_2$ emissions (b) organized by technology, feedstock, and year of publication. Technologies are FT-SPK, HEFA-SPK, ATJ-SPK, HFS–SIP and ATJ-SPK. Feedstocks are corn, jap (jatropha fruit), lig (lignocellulose), MSW (municipal solid waste), rice, sugar (sugarcane), wheat, wood, algae, cam (camelina oil), carinata, castor, cook (used cooking oil), grease, lard, macauba, macaw, palm (palm oil), penny (pennycress), rapeseed, soy (soybean), sunflower, tallow, veg (vegetable oil), butanol, ethanol, energy (herbaceous energy crops), bagasse, mol (molasses), and other (tall oil fatty acids and Syncrude). Green triangles represent nominal points reported in the literature, and blue bars represent ranges reported in the literature. The red line represents the MJSP and $CO_2$ emissions of fossil-based jet fuel.

et al., 2021)) of conventional fossil-based jet fuel. Furthermore, we calculated each technology's average MJSP and GHG emissions across all sources and feedstocks (Table 3).

HEFA and CHJ stand out as economically attractive options with MJSP averages of 1.12 $ L$^{-1}$ and 1.30 $ L$^{-1}$, respectively (Table 3). HEFA excels due to the existing established biodiesel supply chain components, high yields from oil-based feedstocks, and a low number of process steps. CHJ similarly benefits from high-yielding oil-based feedstocks but needs more commercial-scale data (Eswaran et al., 2021). Two instances report SAF costs below fossil-based jet fuel (HEFA at 0.44 $ L$^{-1}$ from waste cooking oil (Barbera et al., 2020) and an intensified ATJ process at 0.47 $ L$^{-1}$ from lignocellulosic waste (Romero-Izquierdo et al., 2021)). HFS–SIP reports the highest MJSP of 5.79 $ L$^{-1}$ from a wheat straw feedstock (de Jong et al., 2015) and has the highest average MJSP among its reported data, 3.99 $ L$^{-1}$. Regarding GHG emissions, SAF generally emits less $CO_2$, except for one HEFA scenario (Liu et al., 2021). Table 3 indicates that, on average, FT reduces $CO_2$ emissions the most, while HEFA has the highest emissions among SAF pathways.

Our analysis indicates an unclear best technology across all metrics (TRL, FRL, MJSP, and GHG emissions). FT offers low $CO_2$ emissions, while HEFA excels in MJSP, FRL, and TRL. FT's average MJSP (2.08 $

**Table 3**
The average performance of each technology's MJSP and $CO_2$ emissions compared to conventional. Averages were calculated across nominal values (green triangles in Fig. 2). When a range was reported (blue bars in Fig. 2), the upper bound of the range was used for the calculation.

| Technology | MJSP Average ($ L$^{-1}$) | Percent Increase from Conventional | $CO_2$ Emissions Average (gCO2eq MJ$^{-1}$) | Percent Decrease from Conventional |
|---|---|---|---|---|
| FT-SPK | 2.08 | 320% | 7.84 | 92% |
| HEFA-SPK | 1.12 | 120% | 65.22 | 27% |
| ATJ-SPK | 1.69 | 240% | 38.67 | 57% |
| HFS–SIP | 3.99 | 700% | 42.02 | 53% |
| CHJ-SPK | 1.30 | 160% | 20.58 | 77% |

$L^{-1}$) is higher than HEFA's (1.12 \$ $L^{-1}$), but its average $CO_2$ emissions (7.84 gCO2eq $MJ^{-1}$) significantly outperform other pathways. Moreover, averages calculated in Table 3 are insufficient for directly comparing technologies due to varying analysis factors among sources, including feedstock variations, geographic variations, and different economic estimation parameters or LCA scopes across the studies. Among 58 quantitative analysis papers, 21 offer consistent technology comparisons (multiple technology comparisons in Table 1). For instance, Tanzil et al. (2021a) ranked HEFA as the most economical SAF pathway (0.88 \$ $L^{-1}$), credited to its high fuel yield. De Jong et al. (2017) found that FT significantly reduces emissions. Both studies affirm HEFA and FT as top-performing SAF pathways. However, the best choice hinges on specific criteria, including country/region, feedstock costs and availability, co-products, and land and water resources.

### 2.4. Comparative analysis

Next, we compare the trade-offs between MJSP and GHG emissions using results from 14 papers (from our initial 58 technology reports), which conducted TEA and LCA on the same process (Santos et al., 2018; Pipitone et al., 2023; Michaga et al., 2022; Real Guimarães et al., 2023; Alam et al., 2021; Liu et al., 2021; Umenweke et al., 2023; Moretti et al., 2021; Park et al., 2022; Vela-García et al., 2020; Michailos, 2018; Capaz et al., 2021; Tanzil et al., 2021b). Fig. 3 compares the MJSP values and GHG emissions for each study organized by technology. The arrows in Fig. 3 show the impact of a 100 \$ $tonneCO_2^{-1}$ carbon tax on the MSJP of SAF technologies. Most technologies with low $CO_2$ emissions (<40 $gCO_2$ $MJ^{-1}$) are minimally affected by this moderately high carbon tax. Furthermore, with the addition of a carbon tax, 9 SAF processes are cheaper than conventional fossil-based jet fuel (1.27 \$ $L^{-1}$). This highlights the impact carbon tax may have on the future of SAF.

For the FT technologies (blue), most studies report an MJSP of around 2.5 \$ $L^{-1}$ and $CO_2$ emissions below 25 $gCO_2$ $MJ^{-1}$. Two outliers stand out: Tanzil et al. (2021b) (6.2 $gCO_2$ $MJ^{-1}$, 3.74 \$ $L^{-1}$) and Real Guimarães et al. (2023) (16 $gCO_2$ $MJ^{-1}$, 0.45 \$ $L^{-1}$). Tanzil et al. (2021b) (6.2 $gCO_2$ $MJ^{-1}$, 3.74 \$ $L^{-1}$) produce SAF from corn stover in the US with a feedstock cost of 125 \$ $tonne^{-1}$. The corn stover is almost double the second highest feedstock cost among the FT studies (switchgrass 70 \$ $tonne^{-1}$ (Tanzil et al., 2022)). On the contrary, Real Guimarães et al. (2023) (16 $gCO_2$ $MJ^{-1}$, 0.45 \$ $L^{-1}$) produce SAF from

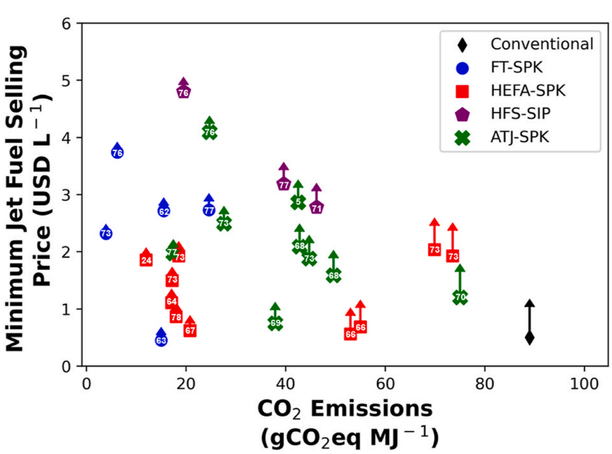


**Fig. 3.** Scatter plot contrasting MJSP and $CO_2$ emissions reported in the literature (Santos et al., 2018; Pipitone et al., 2023; Michaga et al., 2022; Real Guimarães et al., 2023; Alam et al., 2021; Liu et al., 2021; Umenweke et al., 2023; Moretti et al., 2021; Park et al., 2022; Vela-García et al., 2020; Michailos, 2018; Capaz et al., 2021; Tanzil et al., 2021b) for different SAF processes colored by technology. Arrows above each data point represent the total cost with a 100 \$ $tonneCO_2^{-1}$ carbon tax. The number inside each data point refers to the reference number that reported each data.

bagasse (a sugarcane mill by-product) in an integrated sugarcane mill in Brazil, resulting in a much lower MJSP. Ethanol is the main product of the integrated sugarcane mill concept, accounting for over 50% of the total mill revenue. Furthermore, they include a carbon credit of 10 \$ $tonneCO_2^{-1}$ for $CO_2$ avoided, further reducing the MJSP for SAF.

HFS–SIP studies (purple) consistently report higher MJSPs than the other SAF technologies (2.78 \$ $L^{-1}$ to 4.8 \$ $L^{-1}$). Like FT, feedstock cost plays a vital role in the MJSP of HFS–SIP. Michailos (2018) (46.2 $gCO_2$ $MJ^{-1}$, 2.78 \$ $L^{-1}$) studied HFS–SIP produced from bagasse. The cost of bagasse (44 \$ $tonne^{-1}$) is significantly lower than the remaining two HFS–SIP studies' feedstock costs (molasses 70 \$ $tonne^{-1}$ (Tanzil et al., 2022) and corn stover 125 \$ $tonne^{-1}$ (Tanzil et al., 2021b)), resulting in a lower MJSP. In contrast, Michailos (2018) (46.2 $gCO_2$ $MJ^{-1}$, 2.78 \$ $L^{-1}$) also report the highest $CO_2$ emissions of the HFS–SIP studies. The discrepancy in $CO_2$ emissions is attributed to different LCA scopes. Michailos (2018) (46.2 $gCO_2$ $MJ^{-1}$, 2.78 \$ $L^{-1}$) chose a cradle-to-grave LCA, including all $CO_2$ emissions from plant cultivation to SAF combustion. Tanzil et al. (2022) (39.6 $gCO_2$ $MJ^{-1}$, 3.19 \$ $L^{-1}$) and Tanzil et al. (2021b) (19.5 $gCO_2$ $MJ^{-1}$, 4.8 \$ $L^{-1}$) only consider a cradle-to-gate LCA, meaning emissions are only accounted for from plant cultivation to product production (no transportation emissions considered from SAF distribution or combustion).

ATJ technologies (green) report a wide range of MJSPs and $CO_2$ emissions. Reported MJSPs span from less than 1 \$ $L^{-1}$ to more than 4 \$ $L^{-1}$. Tanzil et al. (2021b) (24.7 $gCO_2$ $MJ^{-1}$, 4.09 \$ $L^{-1}$) report the highest MJSP from corn stover in the US costing 125 \$ $tonne^{-1}$ (the highest feedstock cost from the ATJ studies). On the contrary, Park et al. (2022) (37.9 $gCO_2$ $MJ^{-1}$, 0.75 \$ $L^{-1}$) report the lowest MJSP utilizing bioethanol produced from corn in the US as the feedstock. Starting with bioethanol (0.53 \$ $L^{-1}$) reduces biomass processing and supply chain costs. For $CO_2$ emissions, ATJ technologies span from less than 20 $gCO_2$ $MJ^{-1}$ to almost 80 $gCO_2$ $MJ^{-1}$. Tanzil et al. (2022) (17.5 $gCO_2$ $MJ^{-1}$, 1.97 \$ $L^{-1}$) and Tanzil et al. (2021b) (24.7 $gCO_2$ $MJ^{-1}$, 4.09 \$ $L^{-1}$) conducted a cradle-to-gate LCA (no SAF distribution or combustion emissions accounted for) and reported the lowest $CO_2$ emissions. The highest $CO_2$ emissions for ATJ are reported by Vela-García et al. (2020) (75 $gCO_2$ $MJ^{-1}$, 1.2 \$ $L^{-1}$). Vela-García et al. (2020) (75 $gCO_2$ $MJ^{-1}$, 1.2 \$ $L^{-1}$) used a gate-to-gate LCA scope, meaning only process emissions are accounted for, and there is no credit for emissions savings from the biomass feedstock.

Like FT, HFS–SIP, and ATJ, the MJSP and $CO_2$ emissions data reported for HEFA are heavily reliant on feedstock cost and LCA scope, respectively. HEFA technologies (red) reported similar MJSPs, ranging from less than 1 \$ $L^{-1}$ to 2 \$ $L^{-1}$, with variations attributed to feedstock choice. Liu et al. (2021) (53 $gCO_2$ $MJ^{-1}$, 0.56 \$ $L^{-1}$) report the lowest MJSP for SAF produced from castor oil in China. $CO_2$ emissions of HEFA technologies show much more variation, spanning from less than 20 $gCO_2$ $MJ^{-1}$ to almost 80 $gCO_2$ $MJ^{-1}$. In general Liu et al. (2021) (53 $gCO_2$ $MJ^{-1}$, 0.56 \$ $L^{-1}$ & 55 $gCO_2$ $MJ^{-1}$, 0.69 \$ $L^{-1}$) and Capaz et al. (2021) (73.5 $gCO_2$ $MJ^{-1}$, 1.93 \$ $L^{-1}$ & 69.9 $gCO_2$ $MJ^{-1}$, 2.03 \$ $L^{-1}$) report the highest emissions for HEFA produced from castor oilseed, jatropha oilseed, palm oil, and soybean oil, respectively. Liu et al. (2021) and Capaz et al. (2021) include land-use-change (LUC) from the feedstock in their LCA. These feedstocks (specifically palm oil) have high LUC, mainly due to the negative environmental impacts of deforestation for crop expansion (Zhao et al., 2021). Strangely, the lowest emissions reported for HEFA (Pipitone et al., 2023) (12 $gCO_2$ $MJ^{-1}$, 1.84 \$ $L^{-1}$) utilize a palm oil feedstock. However, Pipitone et al. (2023) consider a HEFA process utilizing on-site hydrogen produced by aqueous phase reforming, reducing the emissions by 54% compared to conventional fossil-based hydrogen utilization. Furthermore, for comparison, Pipitone et al. (2023) only perform a gate-to-gate LCA, meaning only process emissions are accounted for, and the environmental impact of the feedstock is not considered.

Feedstock is a significant component of SAF MJSP and GHG emissions. It is important to note that feedstock cost and availability vary from region to region. For example, the US and Brazil are the top two global ethanol producers from corn and sugarcane, respectively. Thus, for the ATJ pathway, Tanzil et al. (2021b) (24.7 $gCO_2$ $MJ^{-1}$, 4.09 \$ $L^{-1}$) and Park et al. (2022) (37.9 $gCO_2$ $MJ^{-1}$, 0.75 \$ $L^{-1}$) study SAF produced from corn stover (125 \$ $tonne^{-1}$) and corn ethanol (0.53 \$ $L^{-1}$) in the US. In contrast, Santos et al. (2018) (42.5 $gCO_2$ $MJ^{-1}$, 2.83 \$ $L^{-1}$) and Capaz et al. (2021) (44.7 $gCO_2$ $MJ^{-1}$, 1.9 \$ $L^{-1}$) studied SAF produced from sugarcane (22 \$ $tonne^{-1}$ and 18 \$ $tonne^{-1}$, respectively) in Brazil. SAF technology and feedstock selection should be tailored to the producer country/region.

### 2.5. Net-zero with SAF technologies

SAF mitigates GHG emissions but will not achieve net-zero emissions alone with the current 50% blending limit. SAF can be a transitory option to move from using fossil fuels to other net-zero energy alternatives such as green hydrogen, hybrid-electric, or electric aircraft (Dahal et al., 2021; Michaga et al., 2022). For example, the power-to-liquid (PtL) pathway offers a different approach, requiring clean electricity for water electrolysis to produce 'green' hydrogen and $CO_2$ to create e-kerosene in an FT process via methanation or methanol synthesis, effectively reversing the combustion process. Although the PtL process for e-fuels is still in development, the first industrial pilot plant opened in Germany in 2021, signifying progress in this domain (Becken et al., 2023). With the expected prevalence of net-zero and deep decarbonization technologies in the future (beyond 2050), SAF may be less competitive regarding environmental impacts. Fernanda Rojas-Michaga et al. (Michaga et al., 2022) investigated adding carbon capture and storage (CCS) to the FT process to produce SAF from forestry residues. The inclusion of the CCS in the FT biorefinery increased the MJSP from 3.03 £ $kg^{-1}$ to 3.27 £ $kg^{-1}$ and reduced the GHG emissions from 15.51 $gCO_2eq$ $MJ^{-1}$ to −121.83 $gCO_2eq$ $MJ^{-1}$ (Michaga et al., 2022). Bio-jet fuel fitted with CCS can serve as a $CO_2$ removal technology and should be a motivating research direction moving forward to ensure the long-term use of SAF. However, the limitations of natural sinks and CCS technologies present risks and challenges. The competition for land area between SAF production and nature-based removal, along with the competition with various carbon capture and storage methods, including e-kerosene, deserves more attention in aviation roadmaps. Acknowledging the implications of SAF usage for decarbonization and permanent carbon removal is vital in shaping the future of sustainable aviation fuels (Becken et al., 2023).

### 2.6. Co-processing biomass and fossil fuels can de-risk SAF technology development

Within the spectrum of technologies examined in this study, it is evident that, aside from HEFA, significant obstacles must be surmounted before attaining commercial profitability. Co-processing offers a pragmatic path forward, allowing companies to supplement a portion of conventional petroleum refinery feedstock with biomass that can undergo catalytic hydroprocessing or fluid catalytic cracking. This process allows biomass to be integrated with petroleum products within the conventional processing and blending framework. Biomass feedstocks suitable for co-processing encompass triglycerides containing plant oils, waste oils, or animal fats akin to HEFA feedstock.

The ASTM currently sanctions co-processing via fats, oils, and grease (FOG) for blending up to 5% by volume. Several organizations have started co-processing, with companies like Parkland (Vancouver, British Columbia) and Preem (Gothenburg, Sweden) leading the way. For instance, Preem, renowned for pioneering co-processing technologies, presently incorporates a biomass lipids ratio of up to 30% and boasts successful co-processing ventures with biomass ratios as high as 85% for green diesel production (Su et al., 2022). Liu & Yang (2023) show that coprocessing FOG can save up to ~8% in GHG emissions with a 5% by-volume blending limit. While co-processing may not rival standalone SAF technologies like FT or ATJ in terms of emissions reduction, it offers companies a financially prudent entry point into SAF technology development. Moreover, it serves as an effective hedge against the uncertainties surrounding future SAF demand and incentives.

Furthermore, the potential of repurposing traditional refineries to standalone SAF refineries presents a compelling avenue. Studies by Su et al. (2022) have drawn insightful comparisons between conventional petroleum refineries and standalone biorefineries, pinpointing critical changes required for this transition. These changes encompass refurbishing existing tanks to accommodate diverse feedstocks, establishing new pretreatment facilities, and enhancing existing wastewater treatment infrastructure for repurposing. Estimates suggest that repurposing efforts, e.g., the Eni biorefinery in Venice, Italy, can amount to 20%–25% of the costs of establishing a new greenfield facility. Additionally, modeling efforts, such as those conducted by Tanzil et al. (2021b), have explored integration scenarios that include the sharing of non-conversion infrastructures, the co-utilization of conversion and non-conversion infrastructures, and the repurposing of idle or shutdown petroleum refineries. These endeavors have yielded reductions in minimum fuel selling prices, greenhouse gas emissions, and overall process costs compared to greenfield approaches. With the global transition toward a sustainable future in full swing, repurposing holds promise in regions such as the US and Europe, where conventional refining infrastructure is already in place.

### 2.7. Will feedstock availability limit SAF adoption?

Generally, concerns about feedstock shortages for SAF production remain low. Numerous reports and scientific studies estimated biomass feedstock availability for SAF production using various methods, including spatial (Walter et al., 2021; Cervi et al., 2020; Leila et al., 2018; Carvalho et al., 2019) and general equilibrium models (Shahriar and Khanal, 2022; Ng et al., 2021; Capaz et al., 2021; Wolff and Riefer, 2020; Staples et al., 2018). These studies collectively suggest an ample biomass supply to meet the demand, even considering more sustainable biomass sources. Some authors advocate the use of advanced and waste feedstock options, including waste and residue lipids, oil trees on degraded lands, oil-cover crops, agricultural and forest residues, and municipal solid waste, which could potentially yield up to 490 million tons of SAF by 2030, surpassing the demand by a significant margin (Wolff and Riefer, 2020).

For instance, Staples et al. (2018) estimate substantial alternative jet fuel potential, projecting 225 million tons of SAF by 2050, based on an average of conservative scenarios proposed by various authors. HEFA is expected to remain the primary SAF production pathway until 2030. However, it is important to note that the HEFA process alone, heavily reliant on FOG feedstock, possibly leading to feedstock availability limitations in the next decade, falls short of delivering the required SAF volumes. Additionally, HEFA pathways are estimated to have the highest induced land use change (ILUC) emissions, mainly due to the direct or indirect linkages to the high deforestation and peat oxidation in Southeast Asia from palm expansion (Zhao et al., 2021). Furthermore, the HEFA process currently relies on hydrogen from fossil fuels for hydrotreatment, with only a small fraction coming from green hydrogen. In contrast, newer pathways like FT and ATJ allow for converting more diverse feedstocks into SAF. For instance, Aemetis has signed significant SAF agreements using orchard residues in California, and LanzaTech processes ethanol feedstock from steel mill waste gases in the UK to produce SAF (Becken et al., 2023).

## 3. Policy analysis

### 3.1. Methodology

For the policy analysis, a Google Scholar search was conducted using the keywords "sustainable aviation fuels" and "policies" covering 2017 to 2023. Twenty relevant articles were selected, including three distinct

**Table 4**
Policies to promote SAF classified by direct or indirect monetary incentives, instruments, and mechanisms.

| Direct Monetary-based | Instrument | Mechanism | Region | Policy Title | Status | Reference |
|---|---|---|---|---|---|---|
| No | Cap-and-trade targets | Carbon market regulation | Regional (European Union) | EU Emissions Trading System (EU ETS) | Adopted | ICAO (2023) |
| | | Carbon emission reduction targets for producers, fuel suppliers, or airlines | Canada (British Columbia) | Renewable & Low Carbon Fuel Requirements Regulation | Under development | ICAO (2023) |
| | | | Portugal | Portugal Carbon Emission Targets[a] | Under development | ICAO (2023) |
| | | | Spain | Spain Carbon Emission Targets[a] | Under development | ICAO (2023) |
| | | | Sweden | Sweden Carbon Emission Targets[a] | Under development | ICAO (2023) |
| | | | Australia | Managing the Carbon Footprint of Australian Aviation | Adopted | Commonwealth of Australia (2017) |
| | | | Canada | Clean Fuel Standard | Under development | ICAO (2023) |
| | | | Denmark | Denmark Fossil Fuel Targets[a] | Under development | ICAO (2023) |
| | | | ICAO (International) | CORSIA | Adopted | ICAO (2023) |
| | | | New Zealand | Sustainable Biofuels Mandate | Under development | (ICAO, 2023) |
| | | | United Kingdom | UK Carbon Emission Targets[a] | Under development | ICAO (2023) |
| | | Carbon emission reduction targets for producers and fuel suppliers and SAF blending targets | Germany | Germany Carbon Emission Targets[a] | Under development | ICAO (2023) |
| | | Carbon market regulation and carbon exchange market | China | China Civil Aviation Green Development Policy and Action | Adopted | State Council of People's Republic of China (2022) |
| | | Energy reduction goals | USA | Energy Independence and Security Act (EISA) | Adopted | Shahriar and Khanal (2022) |
| | Blending mandate | SAF blending targets | Brazil | Brazilian Carbon Emission Targets (under ProBioQAV program) [a] | Under development | ICAO (2023) |
| | | | Finland | Finland Carbon Emission Targets[a] | Under development | ICAO (2023) |
| | | | France | France Carbon Emission Targets[a] | Under development | ICAO (2023) |
| | | | India | India SAF blending target[a] | Under development | ICAO (2023) |
| | | | Indonesia | Indonesia Carbon Emission Targets[a] | Adopted | ICAO (2023) |
| | | | Japan | Japan Carbon Emission Targets[a] | Adopted | ICAO (2023) |
| | | | Norway | Norway Carbon Emission Targets[a] | Adopted | ICAO (2023) |
| | | | Regional (European Union) | ReFuelEU | Adopted | ICAO (2023) |
| | | Private financing or R&D projects and SAF blending targets | United Kingdom | Jet Zero Strategy | Adopted | ICAO (2023) |
| Yes | Capital subsidies | Capital subsidies | United States | Sustainable Aviation Tax Credit | Under development | ICAO (2023) |
| | | | United States | FAST-SAF and FAST-TECH Grant Programme | Adopted | ICAO (2023) |
| | Feedstock subsidies | Fiscal incentives | Brazil | National Biokerosene Programme | Adopted | ICAO (2023) |
| | | | Brazil | National Policy of Biofuels | Adopted | ICAO (2023) |

(*continued on next page*)

**Table 4** (*continued*)

| Direct Monetary-based | Instrument | Mechanism | Region | Policy Title | Status | Reference |
|---|---|---|---|---|---|---|
| | | | Netherlands | SAF roadmap | Under development | ICAO (2023) |
| | | | United Kingdom | Renewable Transport Fuel Obligation (RTFO) | Adopted | ICAO (2023) |
| | | | Panama | Ley N° 42 - Lineamientos para la política nacional sobre biocombustibles y energía eléctrica a partir de biomasa en el territorio nacional | Adopted | ICAO (2023) |
| | | | Paraguay | Zona Franca para la planta Omega Green | Adopted | Agencia de Información Paraguaya (2022) |
| | Output-based incentives | Benefit regarding the life cycle emission reductions compared to a petroleum fuel | USA (California) | Low Carbon Fuel Standard (LCFS) | Adopted | ICAO (2023) |
| | | Fiscal incentives proportional to the production volume | USA | Sustainable Skies Act | Under development | ICAO (2023) |
| | Price subsidies | Tax credit for used SAF | USA | Inflation Reduction Act (SAF blenders tax credit) | Adopted | ICAO (2023) |
| | | | USA (Illinois) | Invest in Illinois Act | Adopted | ICAO (2023) |
| | | | USA (Washington) | Washington SAF B&O Tax rate[a] | Adopted | ICAO (2023) |
| | | Carbon emission tax | Mexico | Impuesto al Carbon | Adopted | Reynoso and Montes (2016) |

[a] Unofficial policy title.

types of analysis: modeling and simulations (Ebrahimi et al., 2022; Jiang and Yang, 2021; Trinh et al., 2021; Rathore et al., 2020; Martinez-Valencia et al., 2021), stakeholder surveys (Ritchie et al., 2020; Ahmad and Xu, 2021; Yengin, 2021), and policy summaries and evaluations (Larsson et al., 2019; Shahriar and Khanal, 2022; Ng et al., 2021; Agencia de Información Paraguaya, 2022; Commonwealth of Australia, 2017; IEA, 2017; Reynoso and Montes, 2016; State Council of People's Republic of China, 2022; Nyström et al., 2019; ICAO, 2023; Wang et al., 2021; Gössling and Lyle, 2021).

The International Civil Aviation Organization's (ICAO) policy summary (ICAO, 2023) identified 30 global aviation policies. Three of these policies pertained to international or regional regulations, while the remaining policies were in development or adopted by 20 different countries. Subsequently, 17 countries with SAF facilities that were not listed in ICAO's policy summary were identified, based on the review by Nyström et al. (2019). A two-step approach was followed to assess policies for sustainable aviation fuels in these 17 countries: (i) a Google Scholar search, which yielded ten relevant results; however, none of them mentioned specific policies for sustainable aviation fuel, and (ii) an examination of government websites of each country. Searching government websites revealed seven additional policies in six countries: Australia, China, Mexico, Panama, Paraguay, and the United States (Agencia de Informacion Paraguaya, 2022; Commonwealth of Australia, 2017; Reynoso and Montes, 2016; State Council of People's Republic of China, 2022; ICAO, 2022).

Table 4 summarizes SAF policies, categorized as direct or indirect monetary incentives. Indirect monetary-based policies are further classified as cap-and-trade targets and blending mandates. The classification of direct monetary-based policies follows Wang et al.'s framework (Wang et al., 2021), which outlines four instruments: output-based incentives, feedstock subsidies, capital subsidies, and price subsidies. It is important to note that initiatives supporting SAF at non-governmental levels are essential but are not detailed in Table 4 (Shahriar and Khanal, 2022; Ng et al., 2021).

### 3.2. *Current policies to promote SAF*

Policy-focused papers are categorized into three groups: modeling SAF incentives, surveys of stakeholder perceptions, and SAF policy details. Modeling SAF incentives allows authors to compare aspects of SAF policies and their impact on SAF development (Ebrahimi et al., 2022; Jiang and Yang, 2021; Trinh et al., 2021; Rathore et al., 2020; Martinez-Valencia et al., 2021). Survey papers explore stakeholder attitudes and concerns about SAF policies (Ritchie et al., 2020; Ahmad and Xu, 2021; Yengin, 2021). The third group of papers reviews existing or proposed SAF policies, such as the European Union Emissions Trading System (EU ETS) and the ICAO's Carbon Offset and Reduction Scheme for International Aviation (CORSIA) (Larsson et al., 2019; Gössling and Lyle, 2021).

The ICAO has compiled a compendium of 30 distinct policies promoting SAF (ICAO, 2023). Furthermore, this review has identified an additional seven resolutions from countries including Australia, China, Mexico, Panama, Paraguay, and the United States (Shahriar and Khanal, 2022; Agencia de Información Paraguaya, 2022; Commonwealth of Australia, 2017; IEA, 2017; Reynoso and Montes, 2016; State Council of People's Republic of China, 2022), resulting in a global aggregate of approximately 37 policies devised to advance SAF adoption. Among these, 35 are regional or country-specific, with the remaining two operating internationally. Notably, 30 of these policies are in Europe and the Americas, as presented in Figs. 4 and 6.

Fig. 5 summarizes policies categorized by their mechanisms, encompassing output-based subsidies, feedstock subsidies, capital subsidies, and price subsidies. Output-based subsidies involve fiscal incentives based on the volume or type of fuels produced and sold, often rooted in market and regulatory motivations. An example of such a policy is California's Low Carbon Fuel Standard (LCFS), which

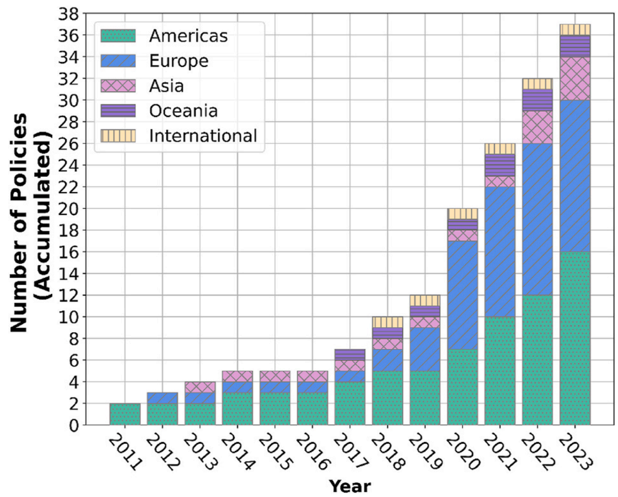


**Fig. 4.** Bar chart visualization of the accumulated number of SAF policies adopted or under development by year launch and continent. Adapted from (Agencia de Información Paraguaya, 2022; Commonwealth of Australia, 2017; IEA, 2017; State Council of People's Republic of China, 2022; ICAO, 2023):

distributes credits determined by the carbon intensity score of renewable jet fuels. Feedstock subsidies offer financial benefits to reduce operating costs for feedstock or support feedstock producers, exemplified by Brazil's National Biokerosene Program and South Africa's research and development (R&D), which foster research and biomass-based energy production. On the other hand, capital subsidies grant one-time monetary support for facility construction, as observed in the US Sustainable Aviation Tax Credit policy, aimed at reducing costs and accelerating domestic sustainable aviation fuel production.

Additionally, price subsidy policies, e.g., the Investment in Illinois Act, provide discounts on SAF prices. Currently, cap-and-trade policies and SAF blending mandates represent the most prevalent approaches, encompassing voluntary and market-based mechanisms, as exemplified by policies in Portugal, Norway, France, Denmark, and ICAO regulations. Gössling and Lyle (2021) mention "indirect" policy types, for example, additional taxes on flight tickets corresponding to carbon emissions; however, no such cases are reported in peer-reviewed literature. Voluntary initiatives like Qantas' Fly Carbon Neutral program allow customers to offset flight emissions through ticket purchases. Larsson et al. (2019) also mention tax on fossil jet fuel to decrease emissions and finance the public sector, as done in Japan and Norway.

### 3.3. Are existing policies sufficient?

Challenges emerge concerning existing SAF policies. The first pertains to policies offering monetary incentives for SAF, comprising only 38% of identified policies, which play a pivotal role in the economic viability of biofuels. This is crucial since technical SAF production pathways tend to be economically feasible only when subsidies are applied, as shown in Section 2. The International Energy Agency (IEA) estimates that commercial aviation biofuel costs, on average, exceed fossil-based jet fuel production costs by 155% (IEA, 2020). In contrast, our analysis indicates that depending on the technology (e.g., HEFA to HFS–SIP), SAF costs range from 120% to 700% higher than fossil-based jet fuels (see Table 3 and Fig. 2). Even when SAF is blended with fossil aviation fuel according to blending mandates in non-competitive settings, its costly production inflates flight ticket prices. Thus, these policies become essential in narrowing the price gap and facilitating commercial SAF adoption.

The second issue concerns the anticipated surge in SAF demand driven by carbon-target policies. Coupling this SAF demand surge with minimal monetary incentives, an imbalance between airlines that need

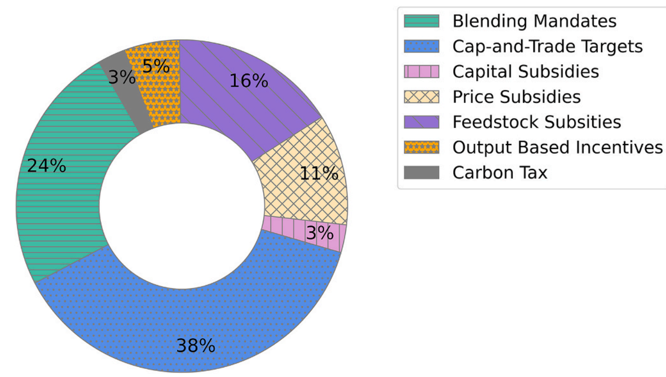


**Fig. 5.** Representation showing the percentage of SAF policies by mechanism. **Source**: (Agencia de Información Paraguaya, 2022; Commonwealth of Australia, 2017; IEA, 2017; State Council of People's Republic of China, 2022; ICAO, 2023).

to buy SAF and companies willing to invest in producing SAF is expected. Fig. 6 illustrates the geographical distribution of SAF incentive policies alongside the number of operational SAF production facilities. In this context, we exclude policies that do not go beyond the CORSIA scheme, even if voluntary. As elaborated in the next section, countries must significantly bolster their demand to reach untapped installed capacity to meet the $CO_2$ emission targets in the near term (present - 2030).

### 3.4. Interdependence of technology economics and policy

Fig. 6 reveals a strong correspondence between the existence of policies in a specific region and the location of planned and operational SAF facilities. As previously discussed, this relationship is primarily attributed to the inherently elevated costs associated with SAF production, rendering them economically unviable without accompanying financial incentives. While existing techno-economic analyses in the literature generally acknowledge the pivotal role of policies, quantitative assessments are relatively scarce. A few studies have quantitatively assessed the impact of monetary incentives as producer credits, such as renewable identification numbers (RINS) and LCFS (Nguyen and Tyner, 2022; Bann et al., 2017; Alam et al., 2021). Furthermore, other studies integrating TEA and policy design quantify minimum incentive values or structures to improve the probability of positive NPVs (Diniz et al., 2018; Ebrahimi et al., 2022). These instances exemplify the significance of policy influence on SAF technologies; however, integrating quantitative analyses to elucidate the nexus between economics, environmental impact, and policy remains an open research question.

## 4. Market analysis

### 4.1. Methodology

The market analysis covered the period from 2015 to 2023. A Google Scholar internet search resulted in 24 publications using the following keywords: "sustainable aviation fuels," "bio-jet fuel," "market," "future market," "demand," and "production." Eleven publications were included in the analysis. Six reports and seven peer-reviewed scientific papers were excluded due to the absence of quantitative information regarding SAF demand, supply, or capacity. Each publication was assigned a Source ID for reference in the visual analysis.

SAF market forecasts encompass key quantitative metrics, including capacity, demand, and production. The sources chosen for our analysis include the following: SkyNRG, IRENA, IEA Task-39, WEF, CIT Industriell Energi, and scientific studies by Bauen et al. (2020), Abrantes et al. (2021), and Fulton et al. (2015). These sources presented SAF capacity, production, and demand data with different timeframes and technology

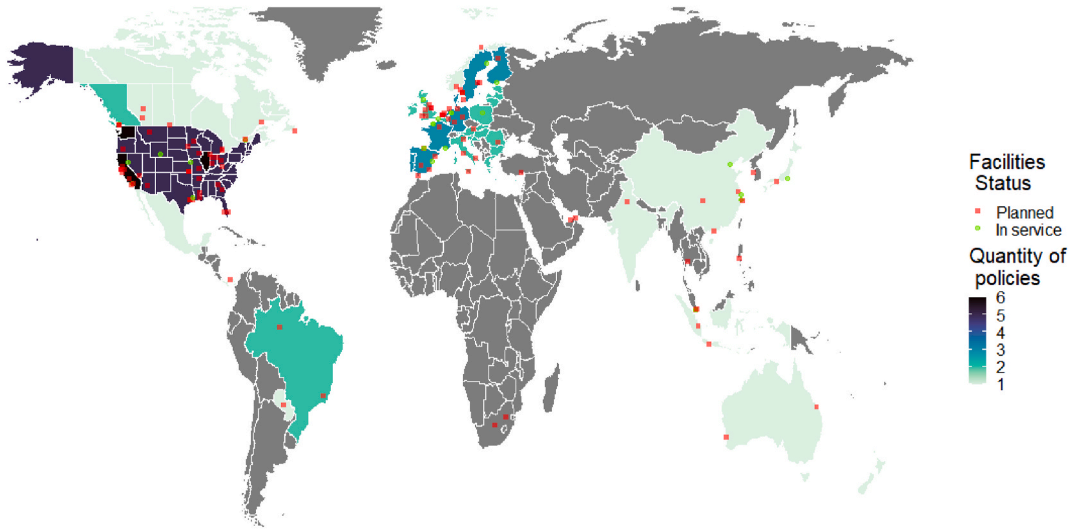


**Fig. 6.** Number of policies on SAF represented by color in each country. Canada and the U.S. are further divided by states. Countries in gray are those whose policies were not found. In Europe, countries that belong to the European Union have the blocks' policies counted. Planned SAF facilities (red squares) are expected to enter operation in the upcoming years, and facilities in service (green circles) are already operational. **Source** (Agencia de Información Paraguaya, 2022; Commonwealth of Australia, 2017; IEA, 2017; State Council of People's Republic of China, 2022; ICAO, 2023): Number of facilities is extracted from Nyström et al. (Nyström et al., 2019).

insights. Demand information was derived from IEA's World Energy Outlook (WEO) and Renewables Analysis (IEARen). Production data originated from IRENA's World Energy Transition Outlook and IEA's Task-39. Detailed descriptions of each information source are listed in Table 5. To ensure consistency in units, production, capacity, and demand data were converted using an energy density of 34.146 MJ $L^{-1}$ and a fuel density of 0.804 kg $L^{-1}$ (Kallio et al., 2014). For references reporting HEFA capacity, a factor of 0.5 (IEA, 2021b) was applied to represent the approximate jet fraction, as HEFA produces other liquid fuels like renewable diesel. These analyses underpin discussions and conclusions regarding future demand, idle capacity, and policy effectiveness.

### 4.2. Historical and imminent SAF capacity

Fig. 7 presents SAF capacity evolution from 2010 to 2027 based on eight references (Abrantes et al., 2021; Wolff and Riefer, 2020; Nyström et al., 2019; Bauen et al., 2020; Fulton et al., 2015; IEA, 2021b; SkyNRG. SAF Market Outlook, 2021; IRENA, 2017). Each bar is labeled above with its respective source and differentiated by color to represent

**Table 5**
Source of information for the market analysis, the variables they bring, their timeframe, technologies, and description.

| Source ID | Variable | Timeframe | Technologies | Description | Source |
|---|---|---|---|---|---|
| SkyNRG | Capacity | 2010–2027 | HEFA, Others | SkyNRG is a Dutch SAF company that publishes a SAF market outlook. Its latest edition, from 2021, provides quantitative information for capacity from 2010 to 2020 and forecasts based on industrial announcements to 2027. | SkyNRG. SAF Market Outlook (2021) |
| IRENA2017 | Capacity | 2016 | HEFA | In its technology brief in 2017, IRENA published a list of companies producing HEFA fuels, their location, and their capacity. | IRENA (2017) |
| WEF | Capacity | 2020–2025 | HEFA, ATJ, Others | Through their Clean Skies for Tomorrow initiative, the WEF published a report on the operational and planned capacity for different SAF technologies. | Wolff and Riefer, 2020 |
| IEARen | Demand | 2020, 2026 | Not specified | In this forecast for 2026, the IEA provides an analysis of biofuel demand, including aviation biofuels. The values in the report include the demand in 2020 and a projection for 2026. | IEA (2021a) |
| CIT | Capacity | 2018 | HEFA | CIT provides a status on the global level of the production of advanced biofuels, including existing and operational large-scale plants for hydrotreatment of fatty acid feedstocks up to the year of publication. | Nyström et al. (2019) |
| Task-39 | Capacity | 2020–2025 | HEFA, ATJ, Others | In 2021, the IEA Task-39 published a report on the progress in the commercialization of SAF, including an estimation of the SAF fraction of the total capacity of current and announced SAF facilities. | IEA (2021b) |
| WEO | Demand | 2030, 2050 | HEFA, Others | In the 2021 World Energy Outlook, IEA provides demand forecasts for conventional and advanced SAF for three scenarios: NZE: to achieve net zero $CO_2$ emissions by 2050; APS: assumes that all climate commitments made by governments around the world will be met in full and on time; and STEPS: what sector-specific measures governments have put in place, as well as specific policy initiatives that are under development. | IEA (2021c) |
| Bauen | Capacity | 2019 | HEFA, ATJ, Others | In this study, the authors provide different technologies' SAF potential production capacity as of June 2019. | Bauen et al. (2020) |
| IRENA | Production | 2021, 2030, 2050 | Not specified | In the World Energy Transitions Outlook 2022, IRENA provides a production forecast of SAF for the net-zero scenario. | IRENA (2022) |
| Task39Prod | Production | 2007–2018 | Not specified | In the same report on the progress in the commercialization of SAF, IEA task-39 provides information on the production of SAF from 2007 to 2018. | IEA (2021b) |
| Abrantes | Production | 2020–2030 | HEFA, ATJ, FT | This study estimates the production of SAF for each process. | Abrantes et al. (2021) |
| Fulton | Demand | 2010–2075 | Not specified | Estimates biofuel demand in aviation. | Fulton et al. (2015) |

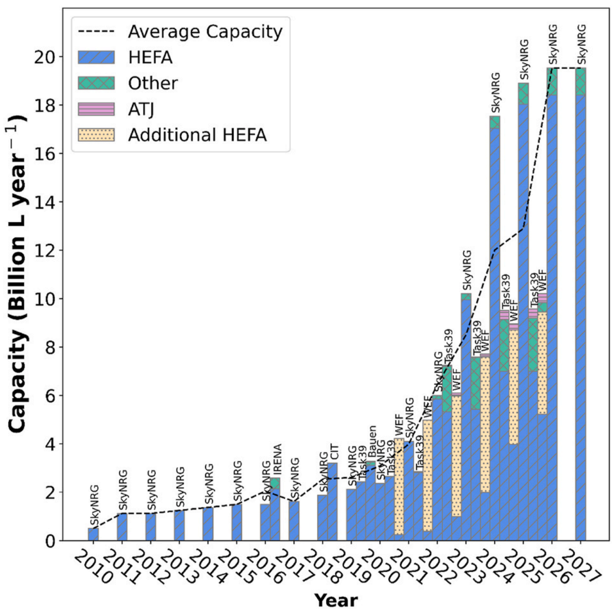


**Fig. 7.** SAF capacity by technology from 2010 to 2027 based on different information sources (bars) and their average (dashed line).
**Source:** (Abrantes et al., 2021; Wolff and Riefer, 2020; Nyström et al., 2019; Bauen et al., 2020; Fulton et al., 2015; IEA, 2021b; SkyNRG. SAF Market Outlook, 2021; IRENA, 2017)

various technologies. An average capacity line is included to aid in analysis.

Notably, capacity data varies significantly across references, particularly in forecasts of future installed capacity and the technical feasibility of SAF production. Data discrepancies up to 2020 are notably influenced by the prevalence of the HEFA process, as seen in sources like WEF, Task-39, and the SkyNRG database for 2020. In Fig. 7, WEF provides valuable insights into HEFA's actual utilization for SAF and its additional potential (additional HEFA, yellow bars) for SAF production, considering HEFA's technical limitations. Comparatively, SkyNRG and Task-39 data exceeds WEF's projections for future installed capacity. SkyNRG projections, influenced by industry announcements and modeling results, are less certain beyond 2023. Furthermore, SkyNRG, as a SAF company, differs from WEF and Task-39, with its predictions heavily reliant on as-yet-unadopted policies, such as the EU's envisioned SAF blending mandate of up to 63% in 2050 (SkyNRG. SAF Market Outlook, 2021).

From 2010 to 2027, SAF's average capacity is expected to increase 38-fold. The period up to 2021 has seen a considerable surge in installed capacity with technical potential for SAF production, marking a 700% increase. The most substantial annual increase occurred from 2010 to 2011, with a 125% capacity rise, aligning with the initiation of operational Neste HEFA plants in The Netherlands and Singapore, each boasting a 1.4 billion-liter per year capacity (including renewable diesel) (Nyström et al., 2019). Subsequently, a 62% increase was projected from 2021 to 2022, attributed to the expansion of Neste plants in Singapore and The Netherlands, with a capacity of 1.8 billion liters per year (IEA, 2021b). However, only the Singapore expansion was completed, with The Netherlands' share of expansion postponed to 2026 (Neste, 2023).

Regarding technology, HEFA is expected to maintain a significant role throughout the timeline, consistent with findings from techno-economic analyses. Bauen et al. (2020) reported 37 million liters per year of operational capacity and 129 million liters per year from alternative technologies (including gasification, pyrolysis, direct sugars to hydrocarbons, hydrothermal liquefaction, and power to liquids); other references only indicate the emergence of non-HEFA technologies, commencing in 2021 (IEA, 2021b) or 2022 (Wolff and Riefer, 2020; SkyNRG. SAF Market Outlook, 2021), particularly with the introduction of an ATJ facility in the United States (IEA, 2021b).

### 4.3. Future projections

Fig. 8 illustrates average capacity trends from 2010 to 2027 alongside current and projected SAF demand up to 2026 and 2075, depending on the information source. IRENA and IEA report demands under various scenarios. The Net Zero Emissions (NZE) scenario refers to the global energy sector achieving net zero $CO_2$ emissions by 2050. The Announced Pledges Scenario (APS) takes account of all the climate commitments made by governments around the world, including nationally determined contributions and long-term net-zero targets, and assumes that they will be met in full and on time. The Stated Policies Scenario (STEPS) provides a more conservative benchmark for the future, considering only existing policies and policies under development (IEA, 2021a). Complementary, Fulton et al. (2015) modeled the need for biofuels in aviation to reach the 2 °C increase scenario. For 2030 and 2050, the authors' projections fall on almost half of IEA forecasts. The authors, however, are the only source of information for 2075, showing a need for 368 billion liters per year of SAF to limit global warming to 2 °C.

Fig. 8 highlights that the historical (blue line) demand is an order of magnitude less than the historical installed capacity (black dashed line). This lag is primarily due to elevated consumer fuel prices and economically advantageous alternatives like renewable diesel. Consequently, implementing monetary incentives is imperative to harness existing capacity and stimulate SAF consumption.

Considering the existing capacities and policy landscape, the APS demand scenario (depicted by the red line in Fig. 8) emerges as the most probable outcome, forecasting an additional 91 million liters per year in technical installed capacity by 2030 compared to the projected 2027 capacity level. As previously discussed, prevailing monetary-based policies incentivize capacity expansion by offering credits to SAF producers. However, the current demand falls short by a factor of twenty. In practical terms, the absence of policies promoting SAF adoption poses a significant hurdle to achieving even the more modest 2030 emissions targets and sustainability objectives (Fulton et al., 2015).

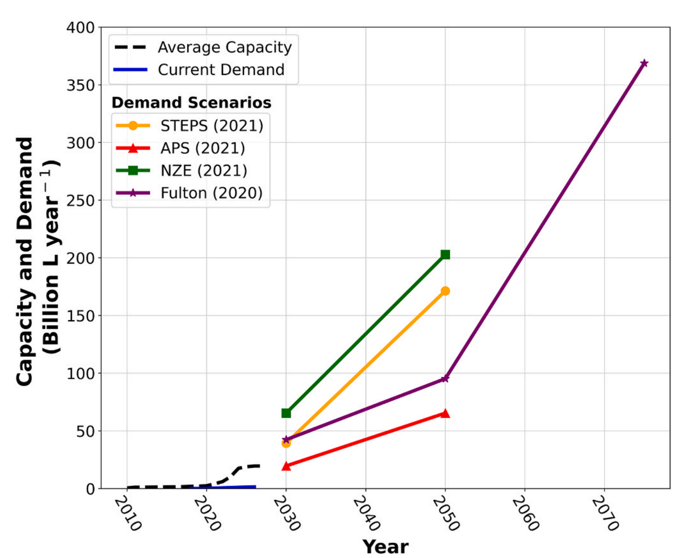


**Fig. 8.** Average capacity from 2010 to 2027 9 (black dashed line), demand from 2018 to 2026 (blue line) and demand in 2030 and 2050 (red, orange, purple, and green lines).
**Source:** (IEA, 2021a; Wolff and Riefer, 2020; Nyström et al., 2019; Bauen et al., 2020; Fulton et al., 2015; IEA, 2021b; SkyNRG. SAF Market Outlook, 2021; IRENA, 2017; IEA, 2021c)

Furthermore, the more aggressive STEPS (orange line) and NZE (green line) scenarios require a 101% (19,710 million liters) and 235% (45,868 million liters) increase in capacity, respectively, to guarantee meeting projected SAF demand in 2030. Similarly, for STEPS and NZE, current demand is behind by factors of 40 and 60, respectively. This indicates the gap between pledges (STEPS) and actual policies in place (APS) regarding climate actions based on the IEA WEO. Moreover, the NZE scenario would require considerable incentives to be achieved based on the current historical capacity trends.

### 4.4. Policy and market interactions

Fig. 9 depicts SAF production trends from 2007 to 2021 alongside yearly policy counts, both adopted and under development. Notably, SAF production (Fig. 9) lags significantly behind projected capacity (Fig. 7). For instance, in 2018, while the average capacity stood at 2.5 billion liters per year, actual production reached just 6.7 million liters, equivalent to 0.3% of the installed capacity. A notable surge in production occurred between 2018 and 2019 when Neste contributed approximately 125 million liters of SAF (IEA, 2021b). Remarkably, 2021 marked the highest SAF production at 3.5% of the installed technical capacity.

Fig. 9 also reveals a two to three-year lag between policy adoption and increased SAF production. Initial SAF policies were instituted between 2011 and 2013 in the US, Europe, and Asia. Europe integrated aviation emissions into the EU emissions trading system, requiring emissions tracking and reporting. Indonesia introduced a SAF mandate, specifying 2% bio jet fuel blending in 2016, with subsequent targets of 3% by 2020 and 5% by 2025. ICAO (ICAO, 2022) noted that the 2016 goal was not met due to national circumstances, but Indonesia's oil producer committed to commence production by late 2018. These policy actions corresponded with the first observed rise in SAF production in 2016, followed by a substantial increase in 2019.

Between 2020 and 2021, 14 policies were introduced, potentially leading to another significant capacity upturn (ICAO, 2023). However, this observation indicates correlation rather than causation. Research opportunities exist to explore causal inferences regarding policy impact on capacity and production, along with economy-wide modeling to ascertain subsidy levels.

In the short to medium term (present-2040), the economic viability of sustainable aviation fuels (SAFs) relies on financial incentives and government policies. Today, about 38% of existing policies are financially driven, while the remaining 62% set carbon emission limits, indirectly promoting carbon reduction. Indirect policies such as blending mandates and carbon tax play a significant role in driving SAF demand, but the lack of monetary incentives creates an imbalance in supply. In the medium term, these consumption-based incentives are expected to boost SAF demand significantly, potentially surpassing production capacity.

This demand gap underscores the urgent need for monetary incentives and policy frameworks to offset the high SAF production costs, encouraging utilization. SAFs currently have higher operating costs due to underdeveloped biomass supply chains. Feedstock subsidies, constituting 60% of existing monetary-based incentives, aim to address this issue. However, these subsidies are complex and do not always reduce biomass expenses. Additionally, because of the growing social and environmental concerns around "food vs. fuel," many feedstock subsidies focus on using advanced, non-food-based biomass, which traditionally has more complex pretreatment and technological challenges. The current policies are a step in the right direction, but there is still a significant gap in cost that is yet to be overcome. Thus, there is an opportunity to more closely couple techno-economic analysis of SAF processes and supply chains with economic modeling to understand the impacts of different incentive structures to guide policymakers.

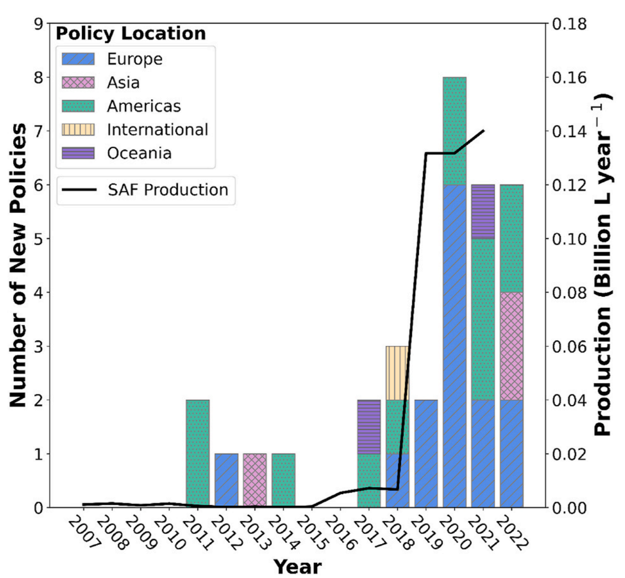


**Fig. 9.** Number of policies (bars, left axis) and SAF production from 2007 to 2022 (black line, right axis).
**Source:** (ICAO, 2023; IEA, 2021b; IRENA, 2022)

### 4.5. Emerging global supply chains

Furthermore, global supply chains are essential for SAF adoption. Transportation may become prohibitive if the SAF production facilities are far from the consumers (i.e., airports). For example, fossil refineries supply large jet fuel consumers through installed, cost- and carbon-efficient pipelines. The construction of such an infrastructure for SAF is not widely considered in current research or incentivized via policy. Global airlines will likely focus on using up to 50% SAF blends in regions/countries with desirable infrastructure. For example, Brazil was one of the first countries to use biomass fuels in the 1970s and is currently the second-largest producer of the world's bioethanol from the sugarcane industry (Li et al., 2022). We see an opportunity for Brazil to become an early global leader in SAF production from sugarcane and in the operation of aircraft fleets with high concentrations of blended SAF (Capaz et al., 2021; Cervi et al., 2020; Escalante et al., 2022). Similarly, based on policy concentration and SAF facilities in Fig. 6, we expect the US and Europe to be instrumental in the SAF transition. Global airlines can take lessons learned in Brazil, the US, and Europe and scale up globally to meet 2050 sustainability goals.

Beyond government and organizational policy implementation, in an increasingly environmentally conscious society, there are public relations (PR) incentives for airline companies to consume SAF. However, with the costs of SAF still above the cost of conventional fossil-based jet fuel, airline companies must be willing to pay a premium to reach company-wide PR goals. A premium price for SAF can be a monetary incentive for SAF producers, leading to more strategic development of SAF capacity globally. United, Cathay Pacific, Southwest Airlines, British Airways, Lufthansa, Qantas, and JetBlue have already established agreements with biofuel suppliers to start receiving some volume of SAF to blend with conventional fossil-based jet fuel (Ng et al., 2021).

## 5. Conclusions

This review evaluates SAF production's economic and environmental aspects, policies, and market landscapes. We highlight SAF's role in meeting sustainability goals and key adoption factors. Achieving 2050 GHG targets in aviation depends on addressing these challenges, leading to four identified research directions at the intersection of technology development, policy, and markets:

*How to reduce SAF costs and carbon footprint while expanding the market?* Our analysis shows SAF costs at least 120% higher than conventional jet fuel, yet it aligns with global climate objectives and facilitates a transition to renewable sources. SAF can leverage policies mandating greenhouse gas reductions, regional fuel chains, and aviation emissions commitments; however, challenges exist, including inadequate financial support, feedstock competition, land constraints, and costly scale-up. Developing realistic roadmaps for SAF technologies, addressing regional differences, and fostering collaboration among producers, airlines, and policymakers are crucial for meeting 2050 sustainability targets.

*What are the prospects for SAF beyond 2050?* Projected demands for 2050 sustainability goals could require significant renewable resources. Evaluating SAF alongside other aviation decarbonization options such as direct air capture (DAC), hydrogen fuel, and electrification is crucial. Long-term strategies like integrating carbon capture or transitioning to waste feedstocks may enhance SAF's longevity. Additionally, it is critical to understand the role of SAF beyond 2050 within a deeply decarbonized global economy.

*How to standardize guidelines for assessing SAF technologies*? Inconsistent TEA and LCA methodologies hinder direct comparisons and reliability. Urgent action is needed to establish consistent guidelines. CORSIA offers a starting point for internationally adopted GHG emission calculations. Furthermore, considering geographical factors and feedstock choices is essential for fair comparisons.

*How to integrate TEA and LCA with SAF policy?* Inadequate monetary incentives (only 38% of existing policies) hinder adoption despite government initiatives. Integrating TEA and LCA with SAF policy may aid in policy designs for attractive SAF investments, setting emissions thresholds for $CO_2$ penalization, and addressing long-term subsidy uncertainties.

### CRediT authorship contribution statement

**M.J. Watson:** Writing – original draft, Visualization, Methodology, Conceptualization. **P.G. Machado:** Writing – original draft, Visualization, Methodology, Conceptualization. **A.V. da Silva:** Writing – original draft, Visualization, Methodology, Conceptualization. **Y. Saltar:** Visualization. **C.O. Ribeiro:** Supervision. **C. Nascimento:** Supervision. **A.W. Dowling:** Writing – review & editing, Supervision.

### Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

### Data availability

Attached in the Supporting Information

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### Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2024.141472.

### References

Abrantes, I., Ferreira, A.F., Silva, A., Costa, M., 2021. Sustainable aviation fuels and imminent technologies - $CO_2$ emissions evolution towards 2050. J. Clean. Prod. 313.

Agencia de Información Paraguaya, 2022. Avanza el proyecto para instalar la planta de biocombustibles Omega Green en Paraguay [Internet]. https://www.ip.gov.py/ip/avanza-el-proyecto-para-instalar-la-planta-de-biocombustibles-omega-green-en-paraguay/.

Ahmad, S., Xu, B., 2021. A cognitive mapping approach to analyse stakeholders' perspectives on sustainable aviation fuels. Transport. Res. D Transp Environ. 100, 103076 https://doi.org/10.1016/j.trd.2021.103076.

Alam, A., Masum, M.F.H., Dwivedi, P., 2021. Break-even price and carbon emissions of carinata-based sustainable aviation fuel production in the Southeastern United States. GCB Bioenergy 13 (11), 1800–1813.

Atsonios, K., Kougioumtzis, M.A., Panopoulos, K.D., Kakaras, E., 2015. Alternative thermochemical routes for aviation biofuels via alcohols synthesis: process modeling, techno-economic assessment and comparison. Appl. Energy 138, 346–366.

Bann, S.J., Malina, R., Staples, M.D., Suresh, P., Pearlson, M., Tyner, W.E., et al., 2017. The costs of production of alternative jet fuel: a harmonized stochastic assessment. Bioresour. Technol. 227, 179–187.

Barbera, E., Naurzaliyev, R., Asiedu, A., Bertucco, A., Resurreccion, E.P., Kumar, S., 2020. Techno-economic analysis and life-cycle assessment of jet fuels production from waste cooking oil via in situ catalytic transfer hydrogenation. Renew. Energy 160, 428–449.

Bauen, A., Bitossi, N., German, L., Harris, A., Leow, K., 2020. Sustainable aviation fuels: status, challenges, and prospects of drop-in liquid fuels, hydrogen, and electrificationin aviation. Johnson Matthey Technology Review 64, 263–278. https://doi.org/10.1595/205651320X15816756012040.

Becken, S., Mackey, B., Lee, D.S., 2023. Implications of preferential access to land and clean energy for Sustainable Aviation Fuels. Sci. Total Environ. 886, 163883.

Bhatt, A.H., Zhang, Y., Milbrandt, A., Newes, E., Moriarty, K., Klein, B., et al., 2023. Evaluation of performance variables to accelerate the deployment of sustainable aviation fuels at a regional scale. Energy Convers. Manag. 275, 116441.

Björnsson, L., Ericsson, K., 2022. Emerging technologies for the production of biojet fuels from wood—can greenhouse gas emission reductions meet policy requirements? Biomass Convers. Biorefinery. https://doi.org/10.1007/s13399-022-02916-0.

Brandt, K.L., Wooley, R.J., Geleynse, S.C., Gao, J., Zhu, J., Cavalieri, R.P., et al., 2020. Impact of co-product selection on techno-economic analyses of alternative jet fuel produced with forest harvest residuals. Biofuels, Bioproducts and Biorefining 14 (4), 764–775.

Brandt, K.L., Martinez-Valencia, L., Wolcott, M.P., 2022. Cumulative impact of federal and state policy on minimum selling price of sustainable aviation fuel. Front. Energy Res. 10, 13.

Budsberg, E., Crawford, J.T., Morgan, H., Chin, W.S., Bura, R., Gustafson, R., 2016. Hydrocarbon bio-jet fuel from bioconversion of poplar biomass: life cycle assessment. Biotechnol. Biofuels 9, 1–13.

Capaz, R.S., Guida, E., Seabra, J.E.A., Osseweijer, P., Posada, J.A., 2021. Mitigating carbon emissions through sustainable aviation fuels: costs and potential. Biofuels, Bioproducts and Biorefining. 15 (2), 502–524.

Carvalho, F., da Silva, F.T.F., Szklo, A., Portugal-Pereira, J., 2019. Potential for biojet production from different biomass feedstocks and consolidated technological routes: a georeferencing and spatial analysis in Brazil. Biofuels, Bioproducts and Biorefining 13 (6), 1454–1475.

Castillo-Landero, A., Dominguillo-Ramírez, D., Aburto, J., Sadhukhan, J., Martinez-Hernandez, E., 2023. Improving the economic, environmental, and safety performance of bio-jet fuel production through process intensification and integration using a modularity approach. ACS Sustain. Chem. Eng. 11 (2), 660–669.

Cervi, W.R., Lamparelli, R.A.C., Seabra, J.E.A., Junginger, M., de Jong, S., van der Hilst, F., 2020. Spatial modeling of techno-economic potential of biojet fuel production in Brazil. GCB Bioenergy 12 (2), 136–157.

Commonwealth of Australia, 2017. Managing the carbon footprint of Australian aviationAustralia's Action Plan developed in response to the International Civil Aviation Organization (ICAO) 2010. www.infrastructure.gov.au. (Accessed 24 June 2022).

Dahal, K., Brynolf, S., Xisto, C., Hansson, J., Grahn, M., Grönstedt, T., et al., 2021. Techno-economic review of alternative fuels and propulsion systems for the aviation sector. Renew. Sustain. Energy Rev. 151, 111564.

de Jong, S., Hoefnagels, R., Faaij, A., Slade, R., Mawhood, R., Junginger, M., 2015. The feasibility of short-term production strategies for renewable jet fuels - a comprehensive techno-economic comparison. Biofuels, Bioproducts and Biorefining 9 (6), 778–800.

De Jong, S., Antonissen, K., Hoefnagels, R., Lonza, L., Wang, M., Faaij, A., et al., 2017. Life-cycle analysis of greenhouse gas emissions from renewable jet fuel production. Biotechnol. Biofuels 10, 1–18.

Detsios, N., Theodoraki, S., Maragoudaki, L., Atsonios, K., Grammelis, P., Orfanoudakis, N.G., 2023. Recent advances on alternative aviation fuels/pathways: a critical review. Energies 16 (4).

Diederichs, G.W., Ali Mandegari, M., Farzad, S., Görgens, J.F., 2016. Techno-economic comparison of biojet fuel production from lignocellulose, vegetable oil and sugar cane juice. Bioresour. Technol. 216, 331–339.

Diniz, A.P.M.M., Sargeant, R., Millar, G.J., 2018. Stochastic techno-economic analysis of the production of aviation biofuel from oilseeds. Biotechnol. Biofuels 11 (1), 161. https://doi.org/10.1186/s13068-018-1158-0.
Dodd, T., Yengin, D., 2021. Deadlock in sustainable aviation fuels: a multi-case analysis of agency. Transp Res D Transp Environ 94, 102799. https://doi.org/10.1016/j.trd.2021.102799.
Doliente, S.S., Narayan, A., Tapia, J.F.D., Samsatli, N.J., Zhao, Y., Samsatli, S., 2020. Bio-aviation fuel: a comprehensive review and analysis of the supply chain components. Front. Energy Res. 8, 110..
Ebrahimi, S., Haji Esmaeili, S.A., Sobhani, A., Szmerekovsky, J., 2022. Renewable jet fuel supply chain network design: application of direct monetary incentives. Appl. Energy 310, 118569.. https://doi.org/10.1016/j.apenergy.2022.118569.
Emmanouilidou, E., Mitkidou, S., Agapiou, A., Kokkinos, N.C., 2023. Solid waste biomass as a potential feedstock for producing sustainable aviation fuel: a systematic review. Renew. Energy 206, 897–907.
Escalante, E.S.R., Ramos, L.S., Rodriguez Coronado, C.J., de Carvalho Júnior, J.A., 2022. Evaluation of the potential feedstock for biojet fuel production: focus in the Brazilian context. Renew. Sustain. Energy Rev. 153, 111716. https://doi.org/10.1016/jrser.2021.111716.
Eswaran, S., Subramaniam, S., Geleynse, S., Brandt, K., Wolcott, M., Zhang, X., 2021. Techno-economic analysis of catalytic hydrothermolysis pathway for jet fuel production. Renew. Sustain. Energy Rev. 151, 111516.
Fulton, L.M., Lynd, L.R., Körner, A., Greene, N., Tonachel, L.R., 2015. The need for biofuels as part of a low carbon energy future. Biofuels, Bioproducts and Biorefining. 9 (5), 476–483.
Goh, B.H.H., Chong, C.T., Ong, H.C., Seljak, T., Katrašnik, T., Józsa, V., et al., 2022. Recent advancements in catalytic conversion pathways for synthetic jet fuel produced from bioresources. Energy Convers. Manag. 251, 114974..
Gössling, S., Lyle, C., 2021. Transition policies for climatically sustainable aviation. Transp Rev 41 (5), 643–658. https://doi.org/10.1080/01441647.2021.1938284.
Gutiérrez-Antonio, C., Gómez-Castro, F.I., de Lira-Flores, J.A., Hernández, S., 2017. A review on the production processes of renewable jet fuel. Renew. Sustain. Energy Rev. 79, 709–729. https://doi.org/10.1016/j.rser.2017.05.108.
Han, J., Tao, L., Wang, M., 2017. Well-to-wake analysis of ethanol-to-jet and sugar-to-jet pathways. Biotechnol. Biofuels 10, 21. https://doi.org/10.1186/s13068-017-0698-z.
Hu, J., Yu, F., Lu, Y., 2012. Application of fischer-tropsch synthesis in biomass to liquid conversion. Catalysts 2, 303–326. MDPI AG;.
IATA, 2021. Resolution on the Industry ' S Commitment to Reach Net Zero Carbon Emissions by 2050. Montreal. https://www.iata.org/contentassets/d13875e9ed784f75bac90f000760e998/iata-agm-resolution-on-net-zero-carbon-emissions.pdf (accessed 2022-06-14).
ICAO, 2019. CORSIA SUPPORTING DOCUMENT, CORSIA Eligible Fuels-Life Cycle Assessment Methodology. Tech. rep. ICAO, Montreal.
ICAO, 2022. ICAO Global Framework for Aviation Alternative Fuels. https://www.icao.int/environmental-protection/GFAAF/Pages/default.aspx (accessed 2022-06-14).
ICAO, 2023. Environmental Policies on Aviation Fuels. https://www.icao.int/environmental-protection/GFAAF/Pages/Policies.aspx (accessed 2022-06-14).
IEA, 2017. Biofuel Law 42 (Panama). https://www.iea.org/policies/6321-biofuels-law-ley-42-que-establece-lineamientos-para-la-politica-nacional-sobre-biocombustibles-y-energia-electrica-a-partir-de-biomasa-en-el-territorio-nacional (accessed 06-14-2022).
IEA, 2020. Tracking aviation.https://www.iea.org/reports/tracking-aviation-2020 (accessed 2022-06-14).
IEA, 2021a. Renewables 2021 - Analysis and Forecast to 2026. Paris. https://www.iea.org/reports/renewables-2021. (Accessed 14 June 2022).
IEA, 2021b. Progress in Commercialization of Biojet/Sustainable Aviation Fuels (SAF): Technologies , Potential and Challenges. Paris.
IEA, 2021c. World Energy Outlook 2021. Paris. www.iea.org/weo. (Accessed 14 June 2022).
IRENA, 2017. Biofuels for Aviation - Technology Brief. Abu Dhabi.
IRENA, 2022. World Energy Transitions Outlook. Abu Dhabi https://irena.org/publications/2021/March/World-Energy-Transitions-Outlook (accessed 2022-06-14).
Jacquemin, L., Pontalier, P.Y., Sablayrolles, C., 2012. Life cycle assessment (LCA) applied to the process industry: a review. Int. J. Life Cycle Assess. 17, 1028–1041.
Jiang, C., Yang, H., 2021. Carbon tax or sustainable aviation fuel quota. Energy Econ 103, 105570. https://doi.org/10.1016/j.eneco.2021.10557.
Julio, A.A.V., Batlle, E.A.O., Trindade, A.B., Nebra, S.A., Reyes, A.M.M., Palacio, J.C.E., 2021. Energy, exergy, exergoeconomic, and environmental assessment of different technologies in the production of bio-jet fuel by palm oil biorefineries. Energy Convers. Manag. 243, enconman.2021.114393 https://doi.org/10.1016/j.
Kallio, P., Pásztor, A., Akhtar, M.K., Jones, P.R., 2014. Renewable jet fuel. Curr. Opin. Biotechnol. 26, 50–55.
Kandaramath Hari, T., Yaakob, Z., Binitha, N.N., 2015. Aviation biofuel from renewable resources: routes, opportunities and challenges. Renew. Sustain. Energy Rev. 42, 1234–1244. Elsevier Ltd.
Kargbo, H., Harris, J.S., Phan, A.N., 2021. "Drop-in" fuel production from biomass: critical review on techno-economic feasibility and sustainability. Renew. Sustain. Energy Rev. 135. Elsevier Ltd.
Klein, B.C., Chagas, M.F., Junqueira, T.L., Rezende, M.C.A.F., Cardoso, T. de F., Cavalett, O., et al., 2018. Techno-economic and environmental assessment of renewable jet fuel production in integrated Brazilian sugarcane biorefineries. Appl. Energy 209, 290–305.
Kumar, D., Long, S.P., Singh, V., 2018. Biorefinery for combined production of jet fuel and ethanol from lipid-producing sugarcane: a techno-economic evaluation. GCB Bioenergy 10 (2), 92–107.
Larsson, J., Elofsson, A., Sterner, T., Åkerman, J., 2019. International and national climate policies for aviation: a review. Clim. Pol. 19 (6), 787–799. https://doi.org/10.1080/14693062.2018.1562871.
Leila, M., Whalen, J., Bergthorson, J., 2018. Strategic spatial and temporal design of renewable diesel and biojet fuel supply chains: case study of California, USA. Energy 156,. https://doi.org/10.1016/j.energy.2018.04.196, 181–95.
Li, X., Mupondwa, E., Tabil, L., 2018. Technoeconomic analysis of biojet fuel production from camelina at commercial scale: case of Canadian Prairies. Bioresour. Technol. 249, 196–205.
Li, M., Zhao, W., Xu, Y., Zhao, Y., Yang, K., Tao, W., et al., 2019. Comprehensive life cycle evaluation of jet fuel from biomass gasification and fischer-tropsch synthesis based on environmental and economic performances. Ind. Eng. Chem. Res. 58 (41), 19179–19188.
Li, L., Lin, J., Wu, N., Xie, S., Meng, C., Zheng, Y., et al., 2022. Review and outlook on the international renewable energy development. Energy and Built Environment 3, 139–157. KeAi Communications Co.
Liu, Z., Yang, X., 2023. The potential GHGs reduction of co-processing aviation biofuel in life cycle. Bioresour Bioprocess 10 (57).
Liu, H., Zhang, C., Tian, H., Li, L., Wang, X., Qiu, T., 2021. Environmental and techno-economic analyses of bio-jet fuel produced from jatropha and castor oilseeds in China. Int. J. Life Cycle Assess. 6, 1071–1084. https://doi.org/10.1007/s11367-, 021-01914-0.
Lokesh, K., Sethi, V., Nikolaidis, T., Goodger, E., Nalianda, D., 2015. Life cycle greenhouse gas analysis of biojet fuels with a technical investigation into their impact onjet engine performance. Biomass Bioenergy 77, 26–44.
Martinez-Hernandez, E., Ramírez-Verduzco, L.F., Amezcua-Allieri, M.A., Aburto, J., 2019. Process simulation and techno-economic analysis of bio-jet fuel and green diesel production — minimum selling prices. Chem. Eng. Res. Des. 146, 60–70. https://doi.org/10.1016/j.cherd.2019.03.042.
Martinez-Valencia, L., Garcia-Perez, M., Wolcott, M.P., 2021. Supply chain configuration of sustainable aviation fuel: review, challenges, and pathways for including environmental and social benefits. Renew. Sustain. Energy Rev. 152, 111680 https://doi.org/10.1016/j.rser.2021.111680.
Mawhood, R., Gazis, E., de Jong, S., Hoefnagels, R., Slade, R., 2016. Production pathways for renewable jet fuel: a review of commercialization status and future prospects. Biofuels, Bioproducts and Biorefining 10, 462–484. John Wiley and Sons Ltd.
McGarvey, E., Tyner, W.E., 2018. A stochastic techno-economic analysis of the catalytic hydrothermolysis aviation biofuel technology. Biofuels, Bioproducts and Biorefining 12 (3), 474–484.
Michaga, M.F.R., Michailos, S., Akram, M., Cardozo, E., Hughes, K.J., Ingham, D., et al., 2022. Bioenergy with carbon capture and storage (BECCS) potential in jet fuel production from forestry residues: a combined techno-economic and life cycle assessment approach. Energy Convers. Manag. 255, 115346.
Michailos, S., 2018. Process design, economic evaluation and life cycle assessment of jet fuel production from sugar cane residue. Environ. Prog. Sustain. Energy 37 (3), 1227–1235.
Michailos, S., Bridgwater, A., 2019. A comparative techno-economic assessment of three bio-oil upgrading routes for aviation biofuel production. Int. J. Energy Res. 43 (13), 7206–7228. https://doi.org/10.1002/er.4745.
Moretti, C., López-Contreras, A., de Vrije, T., Kraft, A., Junginger, M., Shen, L., 2021. From agricultural (by-)products to jet fuels: carbon footprint and economic performance. Sci. Total Environ. 775, 145848. https://doi.org/10.1016/j.scitotenv.2021.145848.
Mousavi-Avval, S.H., Shah, A., 2021. Life cycle energy and environmental impacts of hydroprocessed renewable jet fuel production from pennycress. Appl. Energy 297, 117098.
Neste, 2023. Neste - Production in Three Countries.https://www.neste.com/about-neste/who-we-are/production (accessed 2023-09-24).
Neuling, U., Kaltschmitt, M., 2018. Techno-economic and environmental analysis of aviation biofuels. Fuel Process. Technol. 171, 54–69.
Ng, K.S., Farooq, D., Yang, A., 2021. Global biorenewable development strategies for sustainable aviation fuel production. Renew. Sustain. Energy Rev. 150, 111502 https://doi.org/10.1016/j.rser.2021.111502.
Nguyen, N., Tyner, W.E., 2022. Assessment of the feasibility of the production of alternative jet fuel and diesel using catalytic hydrothermolysis technology: a stochastic techno-economic analysis. Biofuels, Bioproducts and Biorefining 16 (1), 91–104.
Nyström, I., Bokinge, P., Franck, P.Å., 2019. Production of Liquid Advanced Biofuels-Global Status. CIT Industriell Energi AB, Gothenburg, Sweden.
O'Connell, A., Kousoulidou, M., Lonza, L., Weindorf, W., 2019. Considerations on GHG emissions and energy balances of promising aviation biofuel pathways. Renew. Sustain. Energy Rev. 101, 504–515.
Park, H., Chae, H.J., Suh, Y.W., Chung, Y.M., Park, M.J., 2022. Techno-economic analysis and CO2 emissions of the bioethanol-to-jet fuel process. ACS Sustain. Chem. Eng. 10 (36), 12016–12022.
Petersen, A.M., Chireshe, F., Okoro, O., Gorgens, J., Van Dyk, J., 2021. Evaluating refinery configurations for deriving sustainable aviation fuel from ethanol or syncrude. Fuel Process. Technol. 219, 1–33.
Petersen, A.M., Chireshe, F., Gorgens, J.F., Van Dyk, J., 2022. Flowsheet analysis of gasification-synthesis-refining for sustainable aviation fuel production from invasive alien plants. Energy 245.
Pipitone, G., Zoppi, G., Pirone, R., Bensaid, S., 2023. Sustainable aviation fuel production using in-situ hydrogen supply via aqueous phase reforming: a techno-economic and life-cycle greenhouse gas emissions assessment. J. Clean. Prod. 418.

Prussi, M., Lee, U., Wang, M., Malina, R., Valin, H., Taheripour, F., et al., 2021. CORSIA: the first internationally adopted approach to calculate life-cycle GHG emissions for aviation fuels. Renew. Sustain. Energy Rev. 150, 111398.

Rathore, H., Nandi, S., Jakhar, S.K., 2020. The future of Indian aviation from the perspective of environment-centric regulations and policies. IIMB Management Review 32 (4), 434–447. https://doi.org/10.1016/j.iimb.2020.11.003.

Real Guimarães, H., Marcon Bressanin, J., Lopes Motta, I., Ferreira Chagas, M., Colling Klein, B., Bonomi, A., et al., 2023. Decentralization of sustainable aviation fuel production in Brazil through Biomass-to-Liquids routes: a techno-economic and environmental evaluation. Energy Convers. Manag. 276, 116547.

Reynoso, L.H., Montes, A.L., 2016. Impuestos ambientales al Carbono en México y su progresividad: una revisión analítica. Econ. Inf. 398 (2010), 23–39.

Ritchie, B.W., Sie, L., Gössling, S., Dwyer, L., 2020. Effects of climate change policies on aviation carbon offsetting: a three-year panel study. J. Sustain. Tourism 28 (2), 337–360. https://doi.org/10.1080/09669582.2019.1624762.

Romero-Izquierdo, A.G., Gómez-Castro, F.I., Gutiérrez-Antonio, C., Hernández, S., Errico, M., 2021. Intensification of the alcohol-to-jet process to produce renewable aviation fuel. Chemical Engineering and Processing - Process Intensification 160, 108270.

Santos, C.I., Silva, C.C., Mussatto, S.I., Osseweijer, P., van der Wielen, L.A.M., Posada, J. A., 2018. Integrated 1st and 2nd generation sugarcane bio-refinery for jet fuel production in Brazil: techno-economic and greenhouse gas emissions assessment. Renew. Energy 129, 733–747.

Seufitelli, G.V.S., El-Husseini, H., Pascoli, D.U., Bura, R., Gustafson, R., 2022. Techno-economic analysis of an integrated biorefinery to convert poplar into jet fuel, xylitol, and formic acid. Biotechnology for Biofuels and Bioproducts 15 (143).

Shahriar, M.F., Khanal, A., 2022. The current techno-economic, environmental, policy status and perspectives of sustainable aviation fuel (SAF). Fuel 325, 124905.. https://doi.org/10.1016/j.fuel.2022.124905.

Shila, J., Johnson, M.E., 2021. Techno-economic analysis of Camelina-derived hydroprocessed renewable jet fuel within the US context. Appl. Energy 287, 116525.

SkyNRG, 2021. SAF Market Outlook - Background Analysis. Amsterdam. https://skynrg.com/a-market-outlook-on-sustainable-aviation-fuel/ (accessed 2023-09-24).

Staples, M.D., Malina, R., Suresh, P., Hileman, J.I., Barrett, S.R.H., 2018. Aviation CO2 emissions reductions from the use of alternative jet fuels. Energy Pol. 114, 342–354.

State Council of People's Republic of China, 2022. China's Civil Aviation Sets Out Roadmap for Green Development. https://english.www.gov.cn/statecouncil/ministries/202201/29/content_WS61f4ecefc6d09c94e48a4879.html (accessed 2022-06-14).

Su, J., van Dyk, S., Saddler, J., 2022. Repurposing oil refineries to "stand-alone units" that refine lipids/oleochemicals to produce low-carbon intensive, drop-in biofuels. J. Clean. Prod. 376, 134335.

Su-ungkavatin, P., Tiruta-Barna, L., Hamelin, L., 2023. Biofuels, electrofuels, electric or hydrogen?: a review of current and emerging sustainable aviation systems. Prog. Energy Combust. Sci. 96. Elsevier Ltd.

Sun, H., Luo, Z., Li, S., Xue, S., Zhou, Q., Wei, T., et al., 2021. Comparative life cycle assessment (LCA) of biofuel production via corn stover: fermentation to ethanol, pyrolysis to bio-oil, and gasification to jet fuel. Biomass Convers Biorefin 13, 12809–12821.

Tanzil, A.H., Brandt, K., Wolcott, M., Zhang, X., Garcia-Perez, M., 2021a. Strategic assessment of sustainable aviation fuel production technologies: yield improvement and cost reduction opportunities. Biomass Bioenergy 145.

Tanzil, A.H., Zhang, X., Wolcott, M., Brandt, K., Stöckle, C., Murthy, G., et al., 2021b. Evaluation of dry corn ethanol bio-refinery concepts for the production of sustainable aviation fuel. Biomass Bioenergy 146.

Tanzil, A.H., Brandt, K., Zhang, X., Wolcott, M., Silva Lora, E.E., Stockle, C., et al., 2022. Evaluation of bio-refinery alternatives to produce sustainable aviation fuels in a sugarcane mill. Fuel 321.

Tao, L., Milbrandt, A., Zhang, Y., Wang, W.C., 2017a. Techno-economic and resource analysis of hydroprocessed renewable jet fuel. Biotechnol. Biofuels 10 (1).

Tao, L., Markham, J.N., Haq, Z., Biddy, M.J., 2017b. Techno-economic analysis for upgrading the biomass-derived ethanol-to-jet blendstocks. Green Chem. 19 (4), 1082–1101.

Trinh, J., Harahap, F., Fagerström, A., Hansson, J., 2021. What are the policy impacts on renewable jet fuel in Sweden? Energies 14. https://doi.org/10.3390/en14217194.

Umenweke, G.C., Pace, R.B., Santillan-Jimenez, E., Okolie, J.A., 2023. Techno-economic and life-cycle analyses of sustainable aviation fuel production via integrated catalytic deoxygenation and hydrothermal gasification. Chem. Eng. J. 452, 139215.

Vela-García, N., Bolonio, D., Mosquera, A.M., Ortega, M.F., García-Martínez, M.J., Canoira, L., 2020. Techno-economic and life cycle assessment of triisobutane production and its suitability as biojet fuel. Appl. Energy 268, 114897.

Vela-García, N., Bolonio, D., García-Martínez, M.J., Ortega, M.F., Almeida Streitwieser, D., Canoira, L., 2021. Biojet fuel production from oleaginous crop residues: thermoeconomic, life cycle and flight performance analysis. Energy Convers. Manag. 244, 114534.

Walter, A., Seabra, J., Rocha, J., Guarenghi, M., Vieira, N., Damame, D., et al., 2021. Spatially explicit assessment of the feasibility of sustainable aviation fuels production in Brazil: results of three case studies. Energies 14, 4972.

Wang, W.C., 2019. Techno-economic analysis for evaluating the potential feedstocks for producing hydro-processed renewable jet fuel in Taiwan. Energy 179, 771–783.

Wang, W.C., Tao, L., 2016. Bio-jet fuel conversion technologies. Renew. Sustain. Energy Rev. 53, 801–822. Elsevier Ltd.

Wang, Z.J., Staples, M.D., Tyner, W.E., Zhao, X., Malina, R., Olcay, H., et al., 2021. Quantitative policy analysis for sustainable aviation fuel production technologies. Front. Energy Res. 9, 1–10.

Wang, W.C., Liu, Y.C., Nugroho, R.A.A., 2022. Techno-economic analysis of renewable jet fuel production: the comparison between Fischer-Tropsch synthesis and pyrolysis. Energy 239, 121970.

Wang, X., Guo, L., Lv, J., Li, M., Huang, S., Wang, Y., et al., 2023. Process design, modeling and life cycle analysis of energy consumption and GHG emission for jet fuel production from bioethanol in China. J. Clean. Prod. 389.

Wei, H., Liu, W., Chen, X., Yang, Q., Li, J., Chen, H., 2019. Renewable bio-jet fuel production for aviation: a review. Fuel 254, 115599.

Wolff, C, Riefer, D, 2020. Clean Skies for Tomorrow: Sustainable Aviation Fuels as a Pathway to Net-Zero Aviation. World Economic Forum.

Yao, G., Staples, M.D., Malina, R., Tyner, W.E., 2017. Stochastic techno-economic analysis of alcohol-to-jet fuel production. Biotechnol. Biofuels 10 (18), 1–13.

Zhang, L., Butler, T.L., Yang, B., 2020. Recent trends, opportunities and challenges of sustainable aviation fuel. In: Green Energy to Sustainability. Wiley, pp. 85–110.

Zhao, X., Taheripour, F., Malina, R., Staples, M.D., Tyner, W.E., 2021. Estimating induced land use change emissions for sustainable aviation biofuel pathways. Sci. Total Environ. 779, 146238.