Economic analysis of selected SAF options

Task T3.1.1: Techno-economic data

WP3: Assessments for cost-effectiveness and sustainability

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EXECUTIVE SUMMARY

ICARUS – International cooperation for sustainable aviation biofuels - is a Horizon Europe project that aims at accelerating the scale-up of sustainable aviation biofuels production, in order to support the EU goals for climate mitigation in 2030 and 2050 and the ReFuelEU Aviation, enhance the potential to export European renewable fuel technologies into global developing markets, and improve sustainability of aviation fuels while reducing their cost worldwide.

The core activity of **ICARUS** is to address the whole value chains of three Sustainable Aviation Fuel (SAF) production routes by improving, with innovative solutions, critical and limiting technology steps, and by performing techno-economic, environmental, and social assessments for the complete value chains. Bringing together European expertise on the entire value chains for SAF production.

This Deliverable 3.2 on the economic analysis of selected SAF options focuses on the technical and economic assessment of the three ICARUS value chains, including the future production costs and market prices as well as the key factors influencing these costs. A literature review serves as the basis for the analysis of the value chains, while key performance indicators are used to reflect the status and effectiveness and to objectively assess the technical and economic performance. Drawing conclusions from the indicators analysed leads to a synthesis of information from multiple sources and examines how these costs will evolve as challenges in the value chains are overcome. In ICARUS this information is used to assess specific cases within the three value chains.

Contents

1 Introduction

With increasing environmental concerns, the production of Sustainable Aviation Fuels (SAFs) has grown significantly, with many countries now aiming to replace fossil-based aviation fuels with renewable alternatives. This trend, combined with increasing demand for air passenger transport and a growing number of aircraft orders, will require a rapid expansion of SAF production. However, this raises the question of the costs are associated with this growth.

SAFs provide an alternative to conventional jet fuel, offering the potential for significant reductions in aviation's carbon footprint and greater energy efficiency compared to traditional aviation fuel. However, at present, SAFs are minimum twice the price of conventional fuels. To meet growing demand, new feeedstocks and pathways will be necessary in the future. This deliverable focuses on the three value chain investigated in the ICARUS project, with a particular emphasis on technological improvements and economic constrains for these SAF production value chains:

1. “Biocrude oils to SAF” synthesis through Hydrothermal liquefaction (HTL)
2. “Isobutanol to SAF” via Alcohol-to-Jet production
3. “Syngas to SAF” via Fischer-Tropsch (FT) process

The focus will be on the advanced feedstock focussed in ICARUS including fats, waste oils, green and municipal waste, agricultural waste, and non-food crops and specified for every value chain.

This Deliverable concentrate on the specific aspects of techno-economic assessment, including the future costs that will be associated with these value chains and the main influencing factors that will determine these costs. Also addressing the question how these costs will develop once the remaining challenges of the value chains are solved.

It covers these topics and related aspects of techno-economic assessment and is divided into four chapters, starting with an introductory chapter that describes the selected indicators used for the assessment of the value chains. This is followed by three separate chapters explaining in detail the selected value chains.

2 Techno-economic key process indicators

The results of this deliverable are based on collected data from existing techno-economic assessments related to the specific SAF production chains aimed within the ICARUS project. The approach involves evaluating all aspects using Key Process Indicators (KPIs) that include both technical and economic factors. These KPIs are defined in terms of their relevance to the specific value chains under study. An overview of the KPIs is given in Table 3, with detailed descriptions in the following chapters. The collected scientific data will be analyzed and assessed with the aim of identifying possible techno-economic bottlenecks within the SAF value chains.

Table 3 Overview of the KPIs defined in the ICARUS project

Key process indicators	Abbr.	Description
Technology readiness level	TRL	A methodology for assessing the maturity of technologies
Fuel readiness level	FRL	A methodology for the evaluation of the development, certification and supply
Biomass-to-fuel efficiency	BtFE	Energy of the usable biomass that ends up in the energy content of the product
Specific production costs	SPC	Specific product production costs in relation to the energy yield
Capital expenditure	CAPEX	Costs on fixed assets
Operational expenditure	OPEX	All costs incurred in operating the commercial activities
Market price	MP	Reference price in relation to the fossil and bio-based alternatives

2.1 TRL and FRL

As a technology is developed, it passes through several phases of research, testing, demonstration and establishment on the market. The most widely used system to classify the respective development stage is the technology readiness level (TRL). The initially introduced approach by NASA was extended by e.g. the International Energy Agency and in the European Union as part of its Horizon program (European Union 2014; IEA 2020) and is divided into eleven stages: basic research (TRL 1 to 2), applied research (TRL 2 to 5), technical development (TRL 5 to 8), and market readiness (TRL 8 to 9), complemented by the market integration (TRL 10) and market stability (TRL 11). (IEA 2020)

Furthermore, the development process to introduce a fuel in the market, requires additional steps to those described by the TRL, such as fuel certification and testing to ensure it can be used in vehicles ("fit for purpose"). Herefor, the Fuel Readiness Level (FRL) introduced by the Commercial Aviation Alternative Fuels Initiative (CAAFI) can be used: The nine stages include the development cycles for fuel production (FRL 1-5), fuel certification (FRL 6 to 7), aircraft suitability and compatibility (FRL 4 to 7), and commercialization of the production technology (FRL 8 to 9). (CAAFI 2024)

Correlations and dependencies between the aforementioned readiness levels as well as the associated development stages and estimated time periods until market launch can be found in Figure 1.

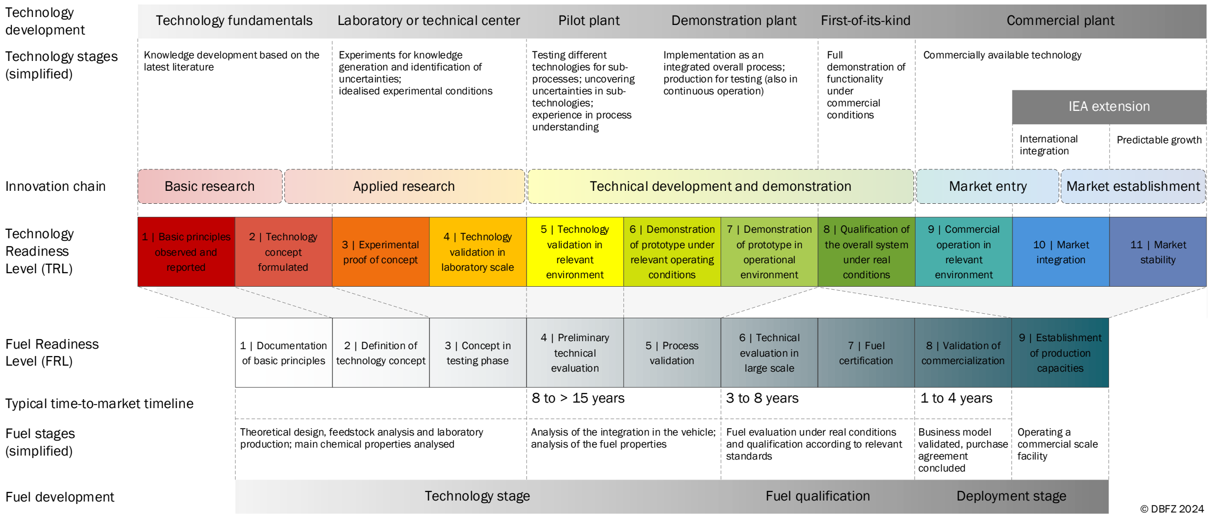

Figure 1 Overview of the Technology readiness level (TRL) und Fuel readiness level (FRL) (Hauschild et al. 2025)

2.2 BtFE

The selected value chains are multi-step and complex, and the biomass used as feedstock is highly variable with varying energy contents. In order to facilitate a more accurate comparison of these different biomass feedstock types and analyse the process chains in general, it is necessary to analyse the energetic biomass losses within the value chains. For this publication, a KPI is specifically formulated as the "biomass-to-fuel efficiency" and is calculated according to the following formula (with LHV, Lower Heating Value):

$$Biomass-to-Fuel-Efficiency = \frac{Fuel\ Output\ (energetic\ output\ (LHV), refers\ to\ all\ produced\ fuels)\ [GJ]}{Biomass\ Input\ (energetic\ biomass\ input\ (LHV), refers\ to\ the\ biomass\ used\ as\ feedstock)\ [GJ]}$$

This KPI can be used to indicate how much biomass passes through the value chains and what energy losses occur within the processes. It also can be used to analyse if other energy inputs (e.g. hydrogen, electricity) outweigh the energy input of biomass over the pathway.

2.3 CAPEX & OPEX

CAPEX (capital expenditure) refers to the costs associated with acquiring, installing, and commissioning assets or equipment that are required for a business or project. These costs are typically one-time expenses that are incurred at the beginning of a project and includes plant equipment, building, furniture and fixtures, and transportation equipment used directly in the production of the product SAF. Land, which is not depreciable, is often included. Characteristically it cannot be converted readily into cash. (AACE International 2018)

OPEX (operating expenditure) refers to the ongoing costs associated with operating and maintaining assets or equipment over the course of their useful life. These costs include expenses related to feedstock, labour (including salaries and benefits for employees), utilities (e.g. electricity, water, and hydrogen) and other operational activities. Additional to that it includes more plant relevant costs such as maintenance and repair costs for equipment and facilities as well as insurance, taxes, and licensing fees. (AACE International 2018)

2.4 SPC & MP

Specific production costs (SPC) refer to the total costs incurred in producing a single mass-based unit of a product or commodity, in this study to SAF. SPC includes all direct and indirect costs associated with production, such as feedstocks, labour, overhead, depreciation, and financing costs and can be directly calculated from CAPEX and OPEX. Scientific studies typically refer to SPC as the calculation and comparison with other studies is easier. Market price (MP), on the other hand, refers to the price at which a product or commodity is sold in a competitive market. MP is determined by supply and demand factors, as well as other market conditions such as competition, consumer preferences, and regulatory requirements and can be easily compared to products on the market. Nevertheless, the calculation with literature data is often not possible as market information are not available or comparable and in this study future SAF markets are assed that couldn't be available today.

3 Biocrude oils to SAF

The hydrothermal liquefaction (HTL) is a thermochemical process that transforms a wide range of dry and wet biomass feedstock into gas, liquid, and solid fractions in sub- or supercritical water, potentially with organic solvents and catalysts. The typical processing temperature ranges between 270 and 370 °C, while the pressure is maintained between 4 and 22 MPa. When the temperature and pressure approach the critical point (374 °C, 22 MPa), water's properties undergo significant changes. (Costa and Rodrigues 2024)

In ICARUS, the primary objective of HTL is to produce high-quality liquid biocrude oil as a substitute for SAF. The quality of biocrude oil is characterized by its higher heating values, viscosity, density, acidity, stability, molecular mass distribution, and chemical composition. However, HTL-derived biocrude oil faces limitations as a direct substitute for crude oil in liquid fuel production, being highly viscous, unstable, and containing a complex mixture of oxygenated compounds and organic acids that can cause corrosion in mechanical components. To address these issues, an upgrading step is required to produce a fossil cruder oil-like substance. Thermochemical treatments, including heat, pressure, hydrogen, and catalysts, modify the composition and properties of bio-oil. These processes, commonly used in crude oil refining, are gaining significant attention in both industry and academia for their potential in large-scale biofuel production. The most established method is catalytic Hydrodeoxygenation (HDO), which removes heteroatoms at high temperatures and pressures, offering a promising route for large-scale production of high-quality biofuels. (Costa and Rodrigues 2024)

3.1 Study approach

In this investigation about 37 scientific papers were selected and analysed, focusing primarily on algae and sewage sludge as feedstocks for HTL processes, as these feedstocks will be used in the following work package in the later project context of ICARUS for the project's own calculation. However, it is noteworthy that the feedstocks varied considerably between the different studies. The geographical distribution of the research papers was mainly from the US and Europe, and included special assumptions about these locations.

Table 4 Investigated scientific papers about the biocrude oils to SAF value chain, based on: (Aierzhati et al. 2021; Albrecht et al. 2016; Barlow et al. 2016; Bessette et al. 2018; Capaz 2021; Chen and Quinn 2021; Davis et al. 2014; Cheng and Luo 2022; Jong 2018; DeRose et al. 2019; Farooq et al. 2020; Funkenbusch et al. 2019; Gu et al. 2020; Haarlemmer et al. 2018; Hansen et al. 2019; Juneja and Murthy 2017; Li et al. 2021; Lippky 2017; Lozano et al. 2022; Magdeldin et al. 2017; Mahima et al. 2021; Nie and Bi 2018; Ou et al. 2022; Ou et al. 2015; Pedersen et al. 2018; Penke et al. 2022; Ranganathan and Savithri 2019; Jones et al. 2014; Snowden-Swan et al. 2016; Snowden-Swan et al. 2022; Snowden-Swan et al. 2017; Tzanetis et al. 2017; Wang et al. 2024; Watkins et al. 2024; Xin et al. 2018; Zhu et al. 2014; Zhu et al. 2019)

Specific feedstock	Number of results	Location	Number of results	Product	Number of results
Algae	19	US	18	Gasoline and diesel mix	12
Sewage sludge	9	unknown	16	Diesel substitute	11
Forestry residues	9	Europe	3	SAF	10
Straw	2	UK	3	Biocrude oil	5
Food waste	2	Brazil	2	Gasoline substitute	3
Manure	2	Canada	1	Upgraded biocrude	3
Miscanthus	1	Finland	1	Marine biofuel	2
Sugarcane residues	1	Netherlands	1		
Lignin	1	Sweden	1		

3.2 TRL & FRL

Currently, the commercialization of the entire biocrude oils to SAF production chain remains a challenge due to the complexity of the value chain. While some individual processes steps are already commercially available, such as the HTL process itself, achieving a fully functional SAF production chain requires further research, development, and collaboration between industry and academia. In addition to these challenges, the biomasses considered in ICARUS are not yet established in the entire value chain, and there is a lack of experience with algae biomass, which present additional difficulties due to its unique properties. Therefore, the current technology readiness level for the selected value chain with these biomasses is estimated to be between 4 and 5, indicating that further development and demonstration are needed before commercialization can be achieved.

The HTL process has been successfully implemented by BTG, achieving a TRL of 8 to 9. BTG has demonstrated its expertise in this field through the operation of three commercial-scale plants in Hengelo, the Netherlands, Lieska, Finland and Galve, Sweden (BTG Bioliquids 2025). In addition, a commercial HTL plant was recently announced by Arbios Biotech and Licella Pty Ltd. The plant will be located in Prince George, British Columbia, Canada, and is expected to operate at a demonstration to commercial scale (TRL 7-8). The Arbios Biotech plant will utilize Licella's proprietary Catalytic Hydrothermal Reactor) technology, which is designed to convert a wide range of feedstocks, including waste biomass, into bio-crude oil and other valuable byproducts. The Cat-HTR technology has been demonstrated at a pilot scale in Australia, achieving TRL 6, before being scaled up for commercial deployment in Canada. (Motola et al. 2024) Additionally, in Tofte, Norway a demonstration plant was built in 2019 by Silva Green Fuel utilizing the Steeper's Hydrofaction technology, which converts forest residues into a bio-crude oil at a rate of 4000 l/day achieving a TRL of 6/7. It is planned to bring the plant to a commercial scale by 2025. (Steeper Energy 2022)

The biocrude oils to SAF value chain discussed in ICARUS has not yet been certified by ASTM D7566. There are also no current certification processes underway for certification (ICAO 2025). In this respect, it is difficult to see a consortium or company that is willing and has the potential to certify this process within the ASTM standard within the next few years. However, for all certified processes, there are difficulties with the correct specification of feedstocks when dealing with the ASTM certification. This issue is particularly relevant for the relatively undefined and diverse bio-crude oil feedstocks and it could be very challenging in such a process to identify the specific feedstocks that could be certified. Currently, the ICARUS value chain could achieve, in directly relation to the TRL, a FLR 4 to 5. Achieving the next level, especial FLR 7 (Fuel certification) will definitively take a significant amount of time, probably at least ten years.

3.3 BtFE

Figure 2 shows the Biomass-to-Fuel-Efficiency of various feedstocks. The average efficiencies of the different feedstock categories are similar, ranging from 48 % to 55 %. Notably, lignocellulose has a comparatively lower efficiency of 33 %, which can be attributed to the lack of studies on this specific feedstock. The other feedstock pathways show a significant variety of efficiency ranging from 28 % to 77 %. This difference can be attributed to the heterogeneity of the feedstocks. In general, it should be noted that "reducing organics loss to the water phase attributes significantly to higher final product yields" (Zhu et al. 2014). Additionally, as noted by Gu et al. 2020, "the development of HTL reactors and new catalysts to improve bio-oil yield is of first priority".

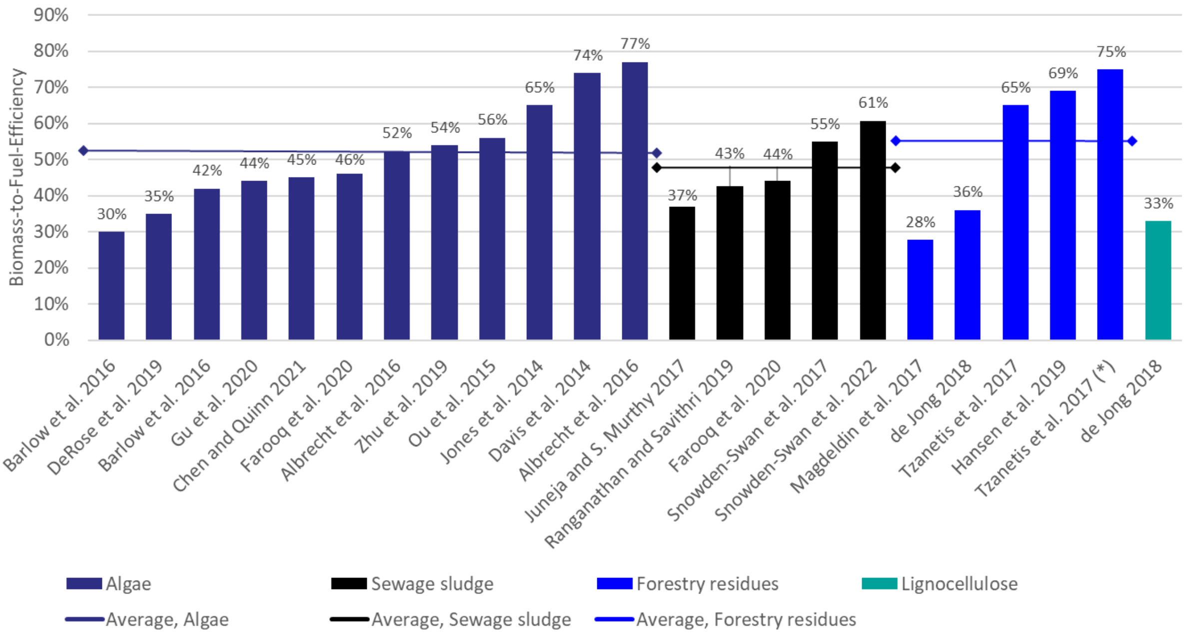

*Figure 2 Biomass-to-Fuel-Efficiency of biocrude-oil to SAF pathways using different (*SAF not final product within the study)*

With special focus on the for ICARUS selected feedstocks there has been carried out a more extensive review on algae and sewage sludge. For the algal feedstock an analysis has been conducted, investigating the dependency of the lipid content of algae with the Biomass-to-Fuel-Efficiency. Figure 3 below shows the results of the review which indicate that the lipid content has a positive influence on the efficiency.

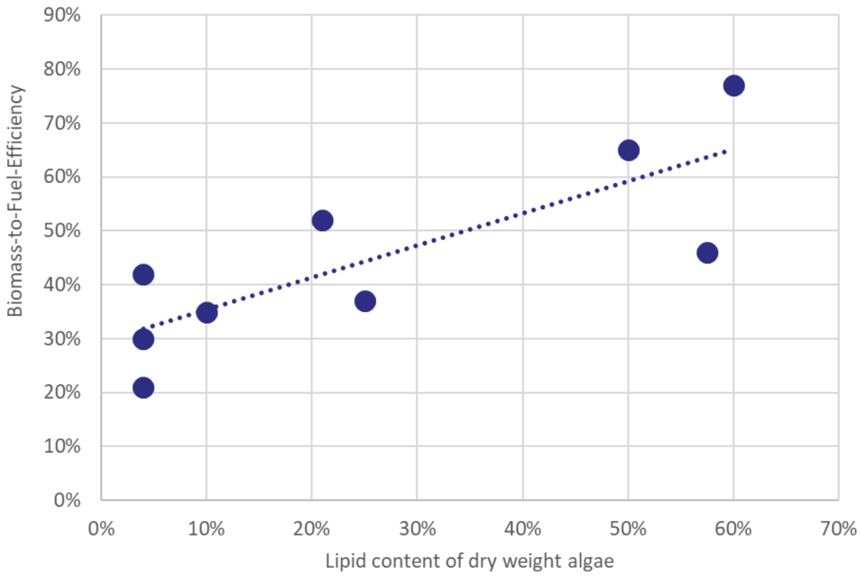

Figure 3 Biomass-to-Fuel-Efficiency of biocrude-oil to SAF pathways depending on the Lipid content of dry weight input-algae, based on (Farooq et al. 2020; Albrecht et al. 2016; Jones et al. 2014; Juneja and Murthy 2017; Barlow et al. 2016; DeRose et al. 2019)

Moreover, in the academic literature, this influence is investigated by different authors. Juneja and Murthy 2017 revealed that lipids can be converted to biocrude with up to 100 % efficiency and therefore are the major factors affecting the price of the fuel. Similarly, DeRose et al. 2019 points out the "increasing protein and lipid content boosts biocrude yields, therefore increases product sales and decreasing the MFSP. But increased protein content increases nitrogen in the fuel products. Nitrogen-rich fuels tend to be lower quality and would have to be used as a blend stock with lower nitrogen fuels." To increase the lipid productivity of algae it is an common approach as noted in Wang et al. 2024 to grow the algae partly in nutrient deficiencies, extreme stress, and environmental perturbations. However, these conditions bring barriers in the production yield. Consequently, "strains need to be better understood in terms of HTL processing, particularly for species screened and/or developed for high growth as opposed to lipid production. Detailed algal feed characterization is needed to assist in determination of the trade-offs (if any) between species, lipid content, ash characteristics and final product yield and quality" (Jones et al. 2014). Additionally, as suggested by Mahima et al. 2021 an acid pre-treatment through post-HTL wastewater improves the Higher Heating Value (HHV) and the lipid content of the algae biomass input due to the recovery of more nutrients.

Regarding sewage sludge it is described by Haarlemmer et al. 2018, that „high ash resources, low in organic material such as digested sewage sludge are less interesting. The oil yields are low and the biocrude is of low quality as it is very rich in inorganic material." Still it is possible to re-optimize the biocrude yields of high-ash sludges, for example by efficient dashing methods (Snowden-Swan et al. 2022).

3.4 Specific Production Costs & Market Price

The specific costs associated with the value chains utilizing residue and lignocellulosic feedstocks have been found to have a more defined price corridor, ranging from 12 to 55 EUR_{2024}/GJ, as can be seen in figure 4 and 5. The average prices of residue and lignocellulosic feedstocks are around 30 EUR_{2024}/GJ. Nevertheless, the sewage sludge feedstock value chains indicate the largest costs corridor, based on the findings from 12 individual studies. The uncertainty of costs from this feedstock can be attributed by the variety of parameters influencing the quality of the sewage sludge and the plant size investigated (Juneja and Murthy 2017). The quality of the sewage sludge depends, among others, on the moisture content and the composition of lipids, proteins, carbohydrates and ash in sludge (Li et al. 2021; Snowden-Swan et al. 2017). However, the most sensitive cost factors in this pathway are biocrude yield, feedstock costs, and HTL plant scale. Nevertheless, methodological factors such as the discount rate, the leverage rate and business risk factor vary within the scientific papers and may affect the costs as well. To decrease the costs of the process chain, it is feasible to recover a clean NH_3 coproduct from the aqueous phase (Snowden-Swan et al. 2022).

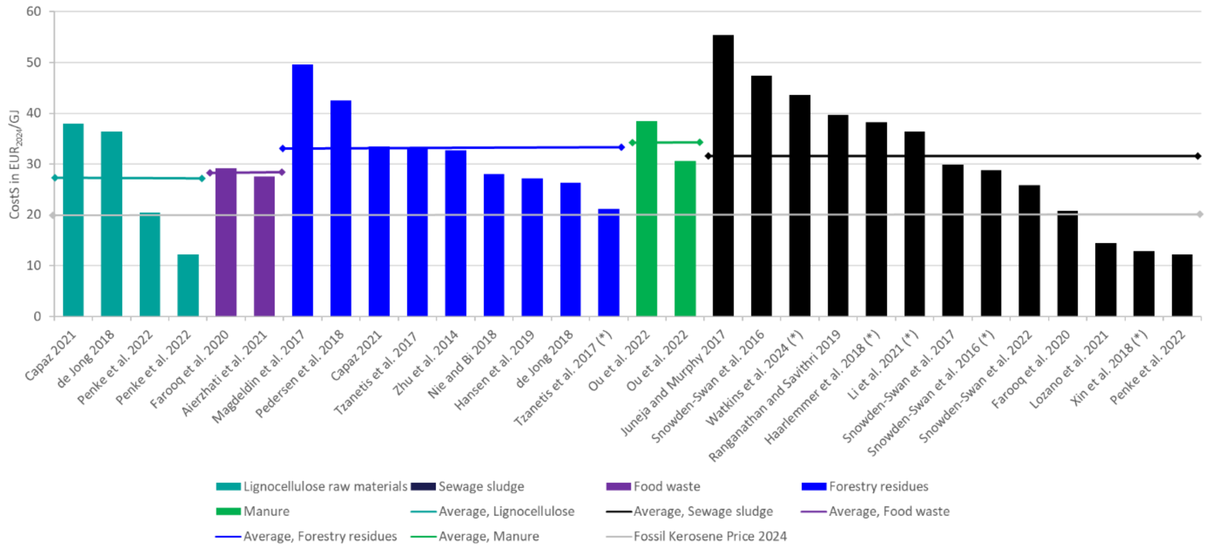

*Figure 4 Total costs of biocrude-oil to SAF pathways (*SAF not final product), categorized by different feedstocks, fossil price (EIA 2024)*

As shown in figure 5 the costs of biocrude oils to SAF from algal feedstock is with an average of approximately 100 EUR_{2024}/GJ three times higher compared to the costs of biocrude oils to SAF from other feedstocks. This is attributed to the high cost of producing algal carbon (Zhu et al. 2019). The academic papers used in the analysis employed a wide extend of algae prices for their results, ranging between 452 EUR_{2024}/t_{afdw}(ash free dry weight) (Jones et al. 2014; Chen and Quinn 2021) and 2.798 EUR_{2024}/t_{afdw} (Barlow et al. 2016). The assumptions of prices for algae change significantly due to various factors such as differences in potential algal production across chosen locations and distinctions between the production of algae, like heterotrophic and phototrophic growth methods (Albrecht et al. 2016; Lippky 2017). Additionally, the implementation of seasonality results in cost penalties incurred in off-peak seasons associated with under-utilization of equipment during off peak seasons (Davis et al. 2014).

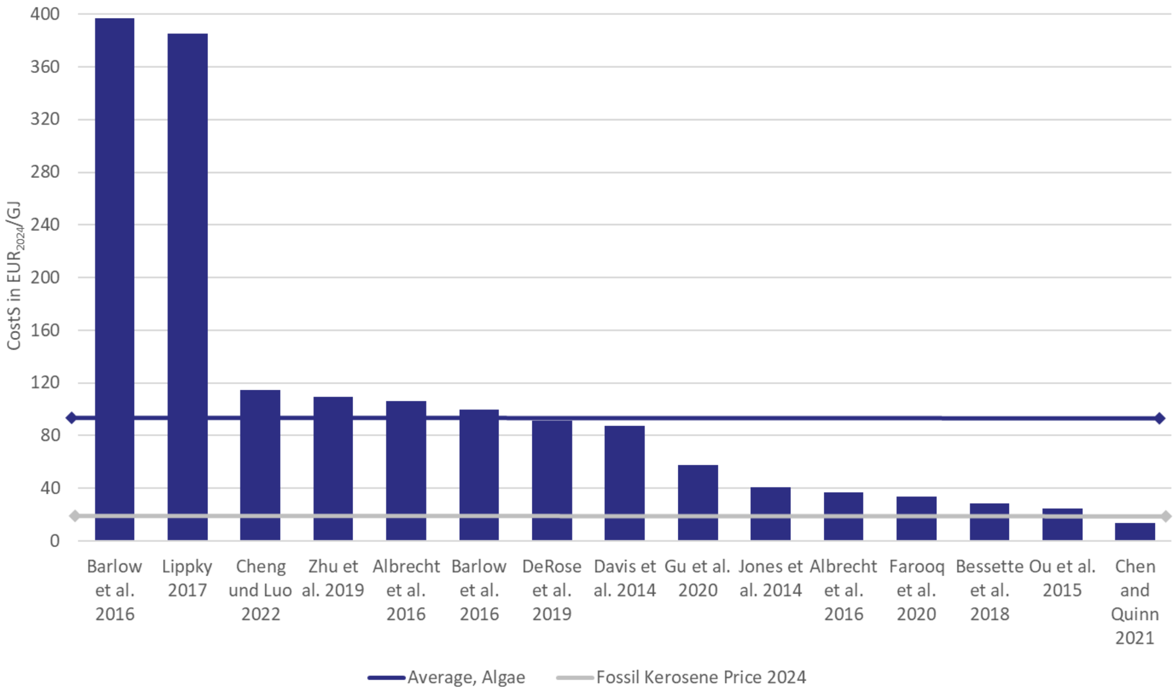

Figure 5 Total costs of biocrude-oil to SAF pathways using algae as feedstock, fossil price (EIA 2024)

The most sensible factors impacting the biocrude oil to SAF pathway from algae feedstock have been identified through a review of 13 individual studies. The three most critical factors include: (1) biocrude yield, mentioned in 8 studies; (2) feedstock costs, highlighted in 4 studies; and (3) the scale of HTL plants, written in 3 studies. To improve the biocrude yield, it is recommended to "consider converting aqueous carbon to higher value products, such as additional fuel and/or chemicals. Large scale continuous testing by using HTL aqueous phase for algae cultivation needs to be developed" (Zhu et al. 2019).

Comparing the specific production prices with current market prices of SAF, it is noticeable that current SAF prices (69.6 EUR_{2024}/GJ) are significantly higher than the predicted costs in the academic papers. The notable difference can be attributed to the prediction of economy of scales lowering the predicted prices. However, for the estimate for future market prices of renewable kerosene by the EASA (44.5 EUR_{2024}/GJ) a closer alignment can be observed with the price averages of biocrude oils to SAF pathways from residues and lignocellulosic biomass input (26.8 to 35 EUR_{2024}/GJ) (EASA 2024).

3.5 CAPEX & OPEX

One of the main challenges associated with biomass conversion technologies is the relatively high OPEX compared to fossil-based alternatives, this also meets the results concerning the biocrude oils to SAF value chains. This is due in part to the need for specialized equipment and processes to handle biomass feedstocks, which often have lower energy densities and higher moisture contents. Another challenge associated with biomass conversion technologies is the relatively high CAPEX required to build and operate a commercial-scale facility. The high CAPEX, reaching up to 35 EUR_{2024}/GJ, is due to the need for specialized equipment and processes, as well as the costs associated with sourcing and transporting biomass feedstocks to the conversion facility. In Table the average distribution of the costs for the different feedstocks is presented, while these values are relatively comparable over all materials.

Table 5 Average values of CAPEX and OPEX of the considered scenarios in the studies

Feedstock	OPEX	CAPEX
Algae	75%	24%
Lignocellulose	64%	35%
Residues	65%	35%

Figure 6 shows a comparison of the process costs for SAF using various feedstocks, including algae. It is evident that the process costs associated with algae as a biomass are significantly higher than other feedstocks. This difference can be attributed primarily to the high production costs of algae. Although a CAPEX per ton product for algae-based SAF is comparable to those of other feedstocks, the OPEX associated with algae cultivation and harvesting are significantly higher, due to low biomass yields of most algal strains, the high energy inputs required for cultivation and harvesting, as well as the need for specialized equipment and processes to handle algae.

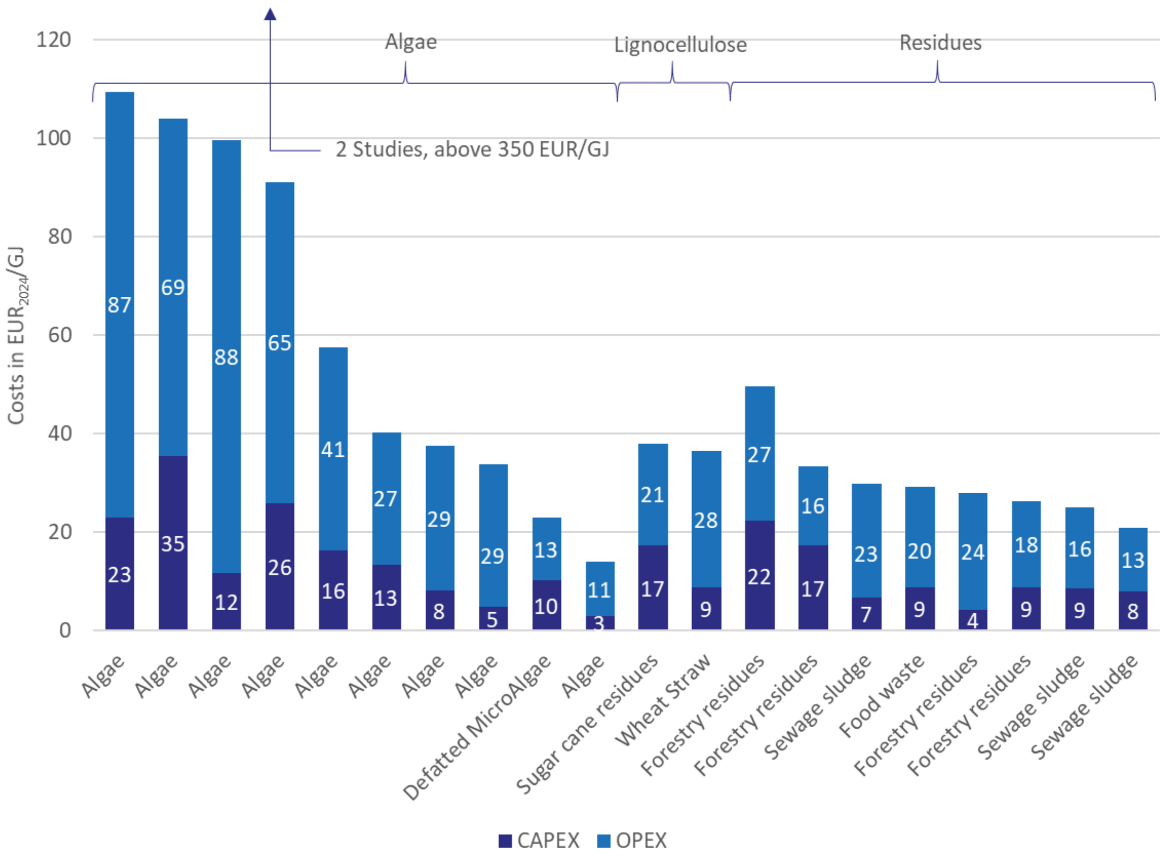

Figure 6 CAPEX and OPEX of biocrude-oils to SAF, based on (Albrecht et al. 2016; Barlow et al. 2016; Capaz 2021; Chen and Quinn 2021; Jong 2018; Farooq et al. 2020; Gu et al. 2020; Jones et al. 2014; Lippky 2017; Magdeldin et al. 2017; Nie and Bi 2018; Ou et al. 2015; Snowden-Swan et al. 2017; Snowden-Swan et al. 2022; Zhu et al. 2019)

Figure 7 compares the costs explicit excluding the costs of algae cultivation. This allows for a more direct comparison of the conversion process-related costs. Interestingly, the CAPEX for these processes are quite similar, when considering biomass-to-fuel efficiency, it becomes clear that only value chains with very low efficiencies have higher costs associated with them. Overall, while there are variations in cost structures across bio-jet fuel production processes, the elimination of algae cultivation costs allows for a more straightforward comparison of these costs, revealing that conversion process-related costs are comparable across most technologies.

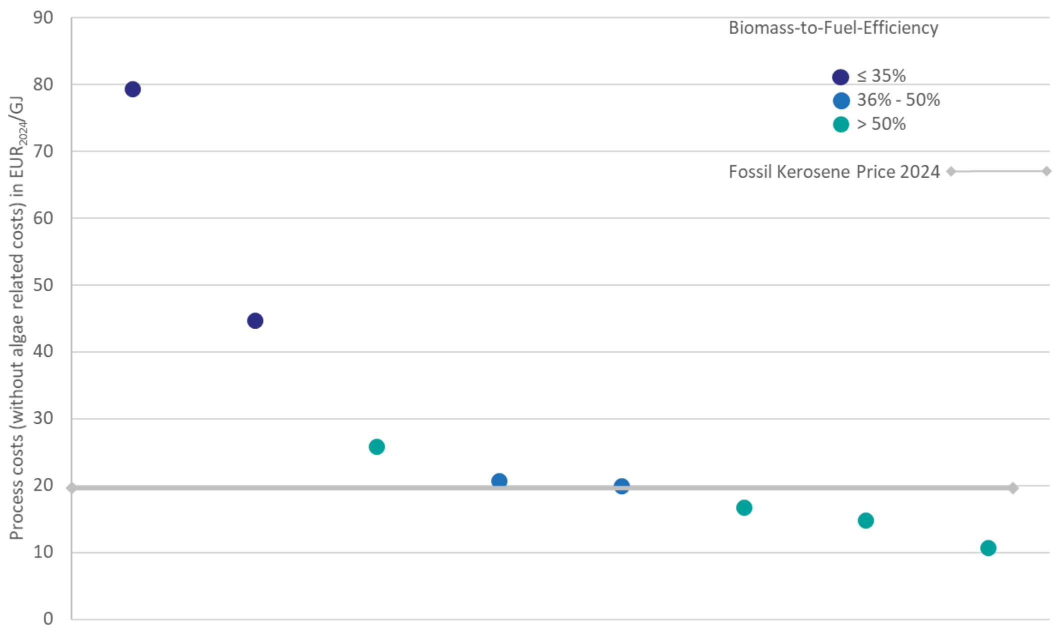

Figure 7 Process costs of biocrude-oil to SAF pathways from algae feedstock categorized by the Biomass-to-Fuel-Efficiency, based on (Barlow et al. 2016; Davis et al. 2014; Pedersen et al. 2018; Zhu et al. 2019; Gu et al. 2020; Jones et al. 2014; DeRose et al. 2019; EIA 2024)

3.6 Challenges to be addressed in ICARUS

Several challenges must be addressed to advance this technology to commercial-scale deployment. One of the key challenges in the HTL conversion process is the need to improve yield and quality of biocrude oil. According to Penke et al. 2022, advancing technologies already tested on a pilot scale, such as aqueous phase treatment, can help to improve yield, see also chapter 3.3. Aqueous phase treatment can increase the yield of valuable components in the biocrude oil, making the process more efficient and cost-effective. Another challenge in the HTL conversion process is integrating high-value co-product extraction processes and co-conversion with other feedstocks. By optimizing the size and location of HTL plants using spatially explicit data, capital costs can be decreased Lozano et al. 2022. Chen and Quinn 2021 recommend more research on the integration of these pathways to bring algal fuels closer to economic parity with current biodiesel markets. In addition to technological advances, non-technological measures may be necessary to achieve economic competitiveness for the SAFs (Tzanetis et al. 2017). Watkins et al. 2024 suggests that incorporating additional feedstocks through co-feeding is essential for creating an economically feasible input process. The potential of mixed feed processing, such as combining different algal species or mixing algae with lignocellulosic biomass, should be explored to overcome algal productivity seasonal variations and enhance the economic viability of the process, as suggested Jones et al. 2014.

While there are several challenges in the production of biocrude oil from HTL conversion, advances in technology, integration with co-product extraction processes, and optimization of plant size and location can help to bring this technology closer to commercial-scale deployment.

3.7 Summary

In this chapter on biocrude oils to SAF value chains, the focus is primarily on algae and sewage sludge as feedstocks. The current TRL and FRL for these value chains with the ICARUS dedicated biomasses are estimated to be between 4 and 5, indicating that further development and demonstration is required before commercialization can be achieved. The mean of the Biomass-to-Fuel-Efficiency ranges from 48 % to 55 %. Outliers exists in all feedstock groups and can be attributed to the heterogeneity of feedstocks, unique process designs and diverse system integration. Production costs associated with pathways utilizing residue and lignocellulosic feedstocks have been found to have a more defined price corridor within the studies, ranging from 12 to 55 EUR_{2024}/GJ. The most sensitive cost factors in this value chain are biocrude yield, feedstock costs, and HTL plant scale and especial for algae. The main challenge for the value chain is the relatively high OPEX compared to fossil-based alternatives. Specific CAPEX per product for algae-based bio-jet fuel is comparable to those of other feedstocks as the OPEX associated with algae cultivation and harvesting are significantly higher. Challenges in the production of biocrude oil from HTL conversion include advances in technology, integration with co-product extraction processes, and optimization of plant size and location. The results highlight the need for further research and development to overcome these challenges, optimize process parameters, and reduce operating costs.

4 Isobutanol to SAF

The in ICARUS investigated isobutanol to SAF value chain based on lignocellulosic feedstocks. These materials could be used as a feedstock for isobutanol production, but limitations include its complex nature and the release of inhibitory compounds during processing. No naturally occurring organism produces industrially relevant levels of isobutanol, but modification of natural producers has led to engineering higher production rates. After isobutanol fermentation, separation of alcohol products from fermentation broth involves distillation, with decanters and stripping columns required to obtain pure alcohol streams. SAF production from isobutanol involves afterwards the catalytic steps of dehydration into olefin, the oligomerization into SAF range olefins followed by the hydrogenation and finally the fractionation of the synthetic paraffin products. Oligomerization traditionally produces a variety of liquid fuels including gasoline, diesel and SAF range hydrocarbons. The resulting mixture of synthetic paraffins in the kerosene range is fractioned off to produce jet, while remaining cuts could be used for naphtha or diesel equivalent products. (Viar et al. 2024)

The production of isobutanol from lignocellulosic materials has been described rarely in the scientific literature to date. Therefore, this study also included ethanol value chains for these feedstocks. By also considering ethanol value chains and studies focused on SAF, the study aimed to gain a comprehensive understanding of the potential for producing alcohol-based fuels from these materials.

4.1 Study approach

In total, 14 scientific papers are included in this study to evaluate the value chain. Isobutanol is mainly described in the literature as being produced from grain as can be seen in table 6. Ethanol value chains considered in this study concentrated on relevant lignocellulosic material, mainly straw, but also residues. Studies were considered in this research that include SAF as a product, along with a few studies focusing on other products in range.

Table 6 Investigated scientific papers concerning the isobutanol to SAF value chain and 2G-ethanol to SAF (Brandt et al. 2020; Cervi et al. 2021; Geleynse et al. 2018; Klein et al. 2018; Neuling and Kaltschmitt 2018; Olson et al. 2023; Tao et al. 2017; Vela-García et al. 2020; Viswanathan et al. 2021; Wang et al. 2021; Yao et al. 2017; Zhao et al. 2021; Bullerdiek et al. 2019; Capaz 2021)

Value chain	Specific material	Number of results	Location	Number of results	Product	Number of results
Isobuthanol to SAF	Grain	5	Brazil	1	SAF	7
	Alcohol	2	Germany	3	Triisobutane	1
	Sugarcane Residues	1	US	1		
			Spain	1		
			Unknown	1		
Ethanol to SAF	Straw	6	Brazil	5	SAF	11
	Industrial Hemp	2	US	2	Biodiesel	1
	Forestry Residues	2	Unknown	8	Ethanol	1
	Sugarcane Residues	1				
	Switch Grass	1				
	Eucalyptus	1				

4.2 TRL & FRL

For the evaluation of the TRL the production capacities of the isobutanol to SAF value chains have to be evaluated. Gevo, Inc. processes corn into isobutanol at their facility in Luverne, Minnesota, USA. In demonstration scale, Gevo produces ATJ-SPK in Silsbee, USA. There is a plan to start operation of a commercial plant in Lake Preston, South Dakota, USA for 2026. The processes for the production of isobuthanol to SAF are on the path to commercialization, with a TRL between 6 and 8 (Hauschild et al. 2025). In regards to the production of SAF via the described value chain, it can be categorized accordingly. However, the preparation of isobutanol from the lignocellulosic material considered in this study is significantly different. There is no industry producing isobutanol from lignocellulosic sugar yet. Possible limitations include the complexity of lignocellulose materials, the release of inhibitory compounds during pre-treatment and the hydrolysis of the lignocellulosic material. NovelYeast has developed an isobutanol strain that can produce isobutanol from C5 and C6 sugar from lignocellulose biomass. This paved a way for the realization of the 2G isobutanol production (Viar et al. 2024). It will need additional efforts for commercialization of this value chain. Current experiments are at lab scale, and therefore, the classification of the examined value chain is estimated to be at a technology readiness level of 2 – 3.

The Alcohol to Jet Synthetic Paraffinic Kerosene (ATJ-SPK) value chain has been included in Annex A5 of ASTM D7566 since 2016 (ASTM D7566-21), which permits the individual use of ethanol, isobutanol, and isobutene. The alcohols can be derived from any source. Therefore, the formal process for this value chain has already been established, and if the produced SAF is available, it could already be used in commercial scale, which corresponds to an FRL of 7. However, the technical evaluation of the process with lignocellulosic material is not as advanced as it should be for an FRL of 7 as described above, so the current FRL could be only 2 – 3.

4.3 BtFE

The defined Biomass-to-Fuel-Efficiency for the SAF value chains via isobutanol and ethanol could be found in Figure 8. It is immediately apparent that the feedstock dependency of this efficiency is evident. The lignocellulosic value chains have significantly lower efficiency, which can be attributed to the clearly lower sugar content. However, there appear to be no differences between isobutanol and ethanol value chains in terms of efficiency, which could be expected due to the similarity of the processes in both value chains. The efficiencies for residues are quite good for the feedstocks. In this project, which includes the lignocellulosic value chains with the least favorable efficiencies (18 – 30 %).

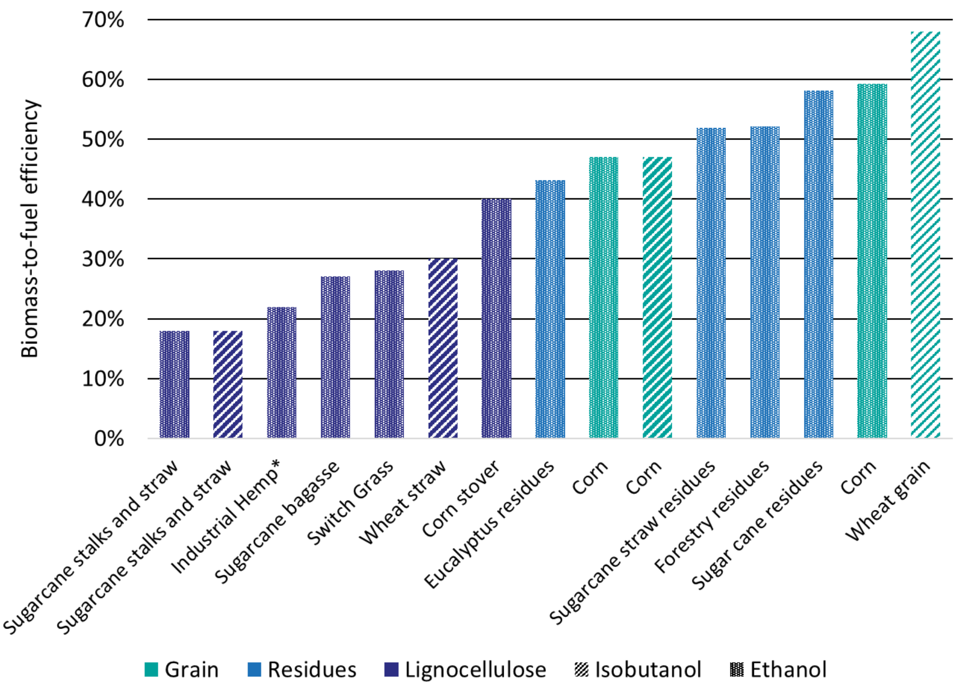

*Figure 8 Biomass-to-Fuel-Efficiency of isobutanol to SAF and Ethanol to SAF value chains (*SAF not final product), based on (Klein et al. 2018; Wang et al. 2021; Yao et al. 2017; Neuling and Kaltschmitt 2018; Tao et al. 2017; Cervi et al. 2021; Bullerdiek et al. 2019; Capaz 2021)*

In addition to efficiency, other technology parameters are relevant, especially when comparing the ethanol and isobutanol value chains, as shown in the table 7, it has a higher mass yield, fuel production rate but no influence on the jet proportion, which also explains the comparative efficiency.

Table 7 Technical properties for the simulation of ethanol and isobutanol to jet value chain (Geleynse et al. 2018)

Property	Ethanol-to-jet	Isobutanol-to-jet
Overall mass yield	0.6	0.75
Fuel production rate [kt yr^{-1}]	39.15	49.25
Oligomerization recycle ratio	1.27	0.02
Product distribution (gasoline/jet/diesel) [%]	10/70/20	30/70/0

4.4 Specific Production Costs & Market Price

The specific production cost of isobutanol to SAF in figure 9 from different materials are comparable (21 – 37 EUR_{2024}/GJ), possibly linked to the limited information based mainly on the a few sources (only one company (Gevo)) and feedstocks (grain). No statements could be made regarding feedstock dependencies due to the limited sources, while the renewable kerosene production costs appear to be competitive with fossil-based kerosene, more research and data are needed to fully understand the cost implications of different feedstocks and processes.

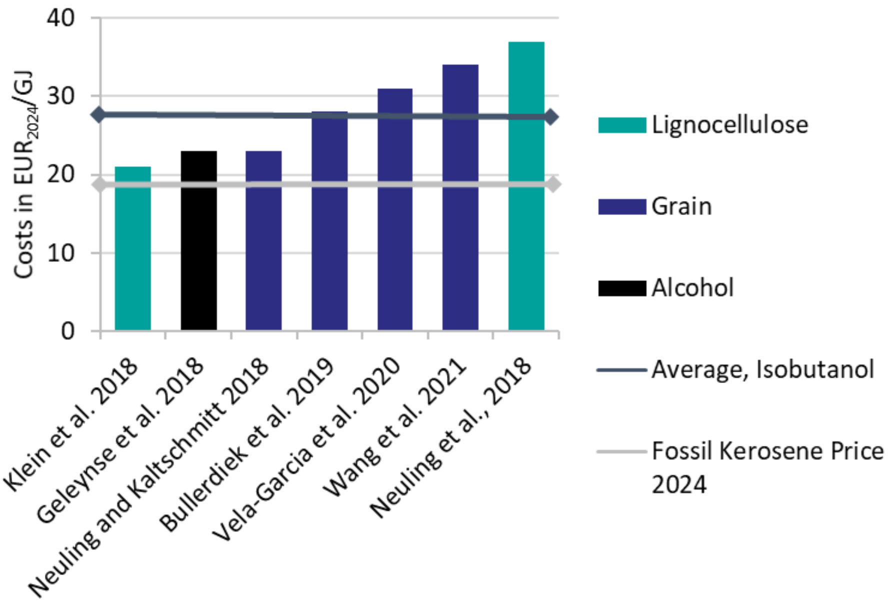

Figure 9 Specific production costs of isobutanol to SAF value chains, with fossil price (EIA 2024)

To cover the spectrum of feedstocks examined in this project, several ethanol value chains were included in figure 10, alongside the isobutanol value chain, found with significantly higher costs than their isobutanol counterparts, with the primary driver of these cost differences being the feedstocks used. Despite the overall trend of higher costs for ethanol-based SAF, there is still a considerable range in costs across the different value chains but compared to fossil-based kerosene, the costs for ethanol-based SAF were approximately double. These findings suggest that while isobutanol based SAF from low cost grain may have an economically good potential as an alternative fuel source, on the other hand, the higher feedstock cost of lignocellulosic biomass handling and usage remains a significant barrier to widespread adoption.

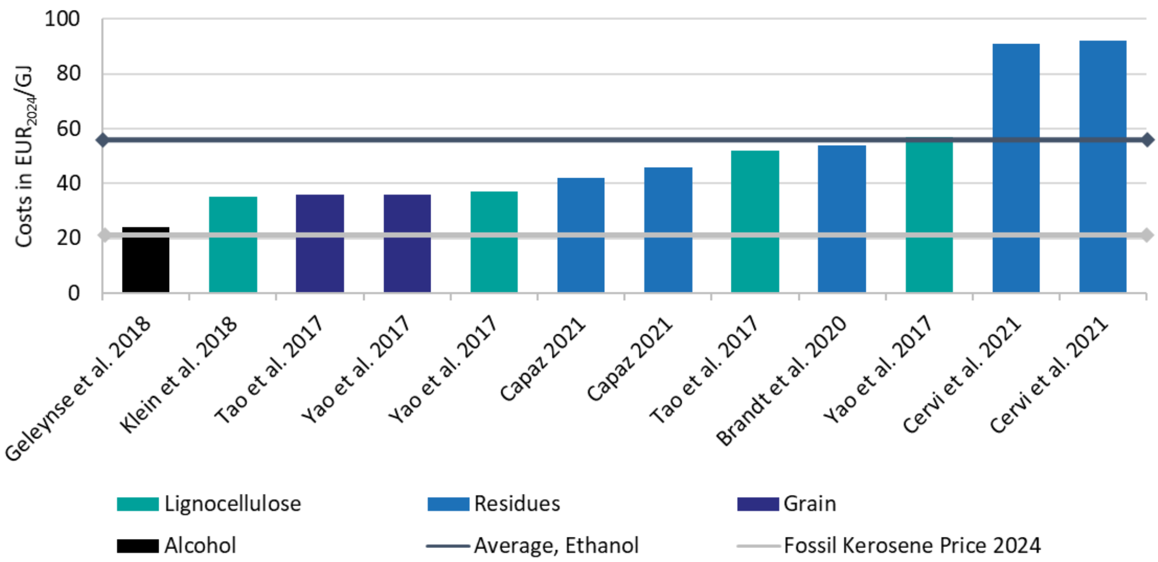

Figure 10 Specific production costs of ethanol to SAF value chains, with fossil price (EIA 2024)

Current market prices for renewable kerosene are well above the fossil prices (2 to 10 times) and there is no clear timeline for when a commercial market will emerge (EASA 2024). However, it is expected that future market prices will fall within the range of costs currently estimated for various production value chains. The International Civil Aviation Organization has provided a reliable estimate for future market prices of renewable kerosene. Specifically, isobutanol-based kerosene is projected to market prices between 47 and 60 EUR_{2024}/GJ, this could be to the average of the studies in figure 9 with 38 EUR_{2024}/GJ (cost are lower than prices). However, significant cost reductions due to economies of scale are not predicted by ICAO (41 – 53 EUR_{2024}/GJ for the n^{th} plant), which is also in line with the results above. (ICAO 2024)

4.5 CAPEX & OPEX

To gain a deeper understanding of the cost structure for isobutanol to SAF production, a breakdown of CAPEX and OPEX was conducted in figure 11. This analysis revealed that the OPEX accounted for 68% of total costs, indicating a high proportion of operational expenses associated with producing renewable kerosene. The CAPEX, on the other hand, varied across different production value chains, with some being relatively low in cost. In particular, isobutanol-based value chains had lower CAPEX per ton this could be associated with higher specific feedstock costs. Another explanation could be the lesser afford for the dehydration plant section within the value chain, Geleynse et al. 2018 calculated with half of the investment cost for isobutanol value chain mainly based on the reduction in this part of the value chain.

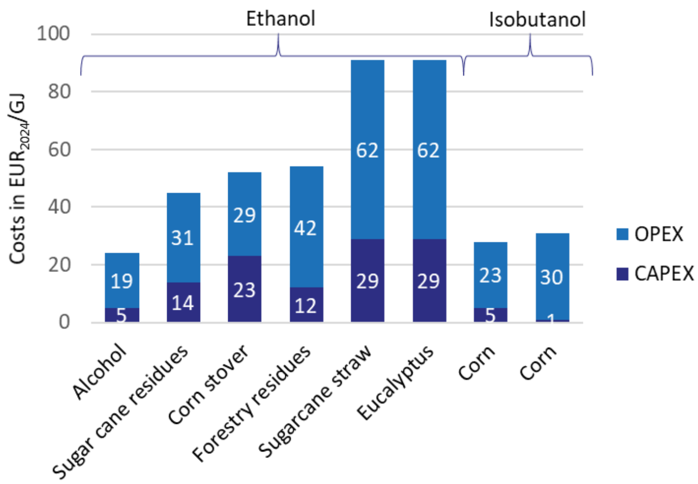

Figure 11 CAPEX and OPEX and specific production costs of isobutanol and ethanol to jet value chain, (Brandt et al. 2020; Capaz 2021; Cervi et al. 2021; Geleynse et al. 2018; Tao et al. 2017)

The cost of feedstocks in figure 12 varies significantly across different renewable kerosene production value chains. While some feedstocks, such as waste residues, offer low costs, other options, including lignocellulosic materials, are not significantly cheaper than grain-based value chains. In particular, the possible hope of low feedstock costs for lignocellulosic feedstocks hasn't been sustained in this analysis. This suggests that there are limited cost advantages to using these types of feedstocks compared to corn and grain.

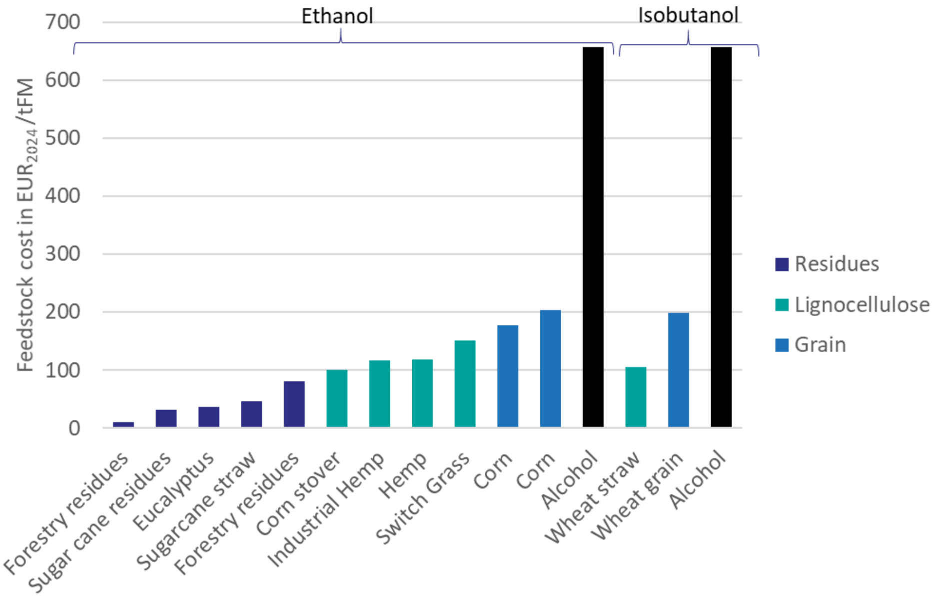

Figure 12 Feedstock costs sorted by feedstock categories, (Brandt et al. 2020; Capaz 2021; Cervi et al. 2021; Geleynse et al. 2018; Neuling and Kaltschmitt 2018; Tao et al. 2017; Viswanathan et al. 2021; Wang et al. 2021; Yao et al. 2017)

4.6 Challenges to further address in the ICARUS project

The studies reviewed identify various challenges related to the technology and cost, for example the "significant uncertainty [that] exists around the technology performance" (Wang et al. 2021). Five studies mentioned that „the ethanol-to-fuel (or feedstock-to-ethanol) conversion has the highest impact" on the costs (Yao et al. 2017). A more general weakness is the "poor energy efficiency due to high losses during the overall conversion process induced by the manifold of chemical conversion reactions each characterized by obligatory losses" (Neuling and Kaltschmitt 2018), this has been shown with the Biomass-to-Fuel-Efficiency in chapter 4.3. Feedstock costs are also relevant, as five studies state that "feedstock costs show [...] [the] greatest sensitivity" (Geleynse et al. 2018). An actual focus in the research is the constrain of high cost of enzymes needed to break down lignocellulosic material, which can account for 20-25% of the total expenses in ethanol production. In order to address this issue, NovelYeast, as part of the ICARUS project, aims to enhance the cellulase secretion capacity in the 2G-isobutanol strain they have developed. While it may not be possible to completely eliminate the need for commercial enzymes, this development should significantly decrease their usage, making the commercial production of 2G-isobutanol viable (Viar et al. 2024).

4.7 Summary

The literature review of the isobutanol to SAF production and, by comparison, focusing on lignocellulosic feedstocks, the ethanol to SAF production shows a consistent picture. There is no literature on producing isobutanol directly from lignocellulosic materials as the value chain has not realized in laboratory scale and therefor isn't discussed in the literature yet. So, ethanol-based value chains with lignocellulosic feedstocks are also considered to better understand the potential for alcohol-based fuels from these materials. The cost structure of producing isobutanol-based renewable kerosene, with OPEX accounting for 68% of total costs. CAPEX varies based on production value chains, and isobutanol-based value chains have lower CAPEX due to the smaller dehydration plant section. Feedstock costs differ significantly between production value chains, with some feedstocks, like waste residues, being cheaper and others, such as lignocellulosic materials, not offering significant cost advantages over grain-based materials. The ICARUS project aims to develop an own cost calculation of the value chain to improve understanding of the feasibility of large-scale isobutanol production from lignocellulosic material, which has been not be described in the scientific literature yet.

5 Syngas to SAF

The Fischer-Tropsch (FT) synthesis combined with the gasification technology qualifies for the production of jet fuel by directly converting biomass (municipal solid waste (MSW), forest and agricultural residues) into synthesis gas (mainly a mixture of H_2 and CO) through gasification. Gasification operates at high temperature (900 °C and above) and pressure using gasifying agent such as oxygen, steam, air or CO_2. Likewise, the high oxygen content in feedstock leads to a low H_2/CO ratio (0.8 to 1.1), which necessitates adjustment to 2:1 prior to being fed to the FT-reactor. This tuning can also be achieved through the water-gas shift reaction. The obtained syngas is processed into long chain hydrocarbons using catalytic FT-reactor. The derived hydrocarbons are then hydrotreated and refined into SAF. SAF production can be enhanced by integration of processes such as alkylation, hydrocracking and others to the FT-process segment.

5.1 Study approach

Similarly, the aforementioned KPIs and economic parameters are also utilised to methodically evaluate the syngas to SAF production. The research papers encompassed in this study are classified based on feedstock types, geographical focus and product output as shown in table 8. Furthermore, the authors of the research papers have studied different feedstock combinations or varied feedstock variations within the assessed cases, thereby tailoring them to the developed scenarios under purview. This has ensured a comprehensive evaluation by considering multiple feedstock selections to determine feasibility within the defined parameters. Moreover, the approach accepted to identify KPIs and economic parameters involved choosing both the base and optimal cases across multiple scenarios in a single paper, thus defining the scope of the study. In the absence of multiple process scenarios, the studied cases were primarily utilised. All cases were chosen in case the authors neither specified the base condition and nor concluded about the optimum scenario. The feedstock costs are mentioned in the Annex table 11 concise outline of the processing steps of biomass is mentioned in the Annex table 12.

Table 8 Investigated scientific papers concerning the syngas to SAF value chain (Ahire et al. 2024; Albrecht et al. 2017; Cervi et al. 2021; Diederichs et al. 2016; Habermeyer et al. 2024; IRENA 2014; Jong et al. 2015; Kargbo et al. 2022; Klein et al. 2018; López et al. 2024; Michailos and Bridgwater 2019; Michailos et al. 2017; Oliveira et al. 2023; Real Guimarães et al. 2023; Santiago et al. 2024; Dyk 2024; Wang et al. 2022; Wang et al. 2021; Rogachuk and Okolie 2024)

Specific material	Number of results	Location	Number of results	Product	Number of results
Wheat Straw	1	EU	3	Jet fuel	13
Forest residues	5	USA	5	FT kerosene	2
Woody biomass/Wood residues	3	Brazil	5		
Sugarcane, LCM (baggage/straw)	5	Taiwan	1		
Eucalyptus, LCM, Harvest residues	2	Unknown	1		
MSW	1				
Rice husk	1				
Agro-residual waste	1				

5.2 TRL & FRL

It is evident that the gasification of biomass or wastes coupled with FT-synthesis is a viable route for producing second generation biofuels and has demonstrated notable strides in both TRL and FRL. Gasification process involves conversion of biomass or waste into syngas, followed by FT-synthesis to produce quality liquid hydrocarbons suitable for aviation. IEA Bioenergy – Task 33 reported that the TRL of this pathway varies between 6 and 8 depending on the operational scale and progress of specific projects. For instance, Waste2Value in Austria has reached TRL 6-7, showcasing prototype under operational conditions, while the

BioTfueL situated in France operates at TRL between 7 and 8, demonstrating full functionality of technology under relevant conditions. These developments indicate that the technology is progressing from pilot scale towards full scale commercialisation, having met stringent aviation standards and certification. (IEA Bioenergy 2024)

On the other hand, FRL plays a decisive role in advancing sustainable fuel solutions within the aviation sector through regulatory frameworks as developed by the Commercial Aviation Alternative Fuels Initiative (CAAFI 2025). This fuel qualification process by CAAFI incorporates rigorous testing and assessment to confirm the SAF complies with the technical and regulatory rules for use in aviation. IEA Bioenergy – Task 39 further support this fuel evaluation, highlighting that FT kerosene received approval for use in jet engines in 2015 under ASTM D7566 Annexure 4 approved SAF (blending percentage - up to 50%) (Dyk 2024). This certification is a clear milestone for widespread adoption in the aviation sector. Fulcrum Bioenergy based in Nevada is at full scale production stage with a processing capacity of 41.3 million litre per year. Several projects (Velocys Bayou Fuel facility in Mississippi, USA Bioenergy from Texas and others) based on FT kerosene are planned globally.

5.3 BtFE

The Biomass-to-Fuel-Efficiency was calculated as the ratio of fuel output to the biomass input only (both in GJ unit). This efficiency for syngas to SAF is dependent on the feedstock characteristics, process design and system integration factors such as recycling of off gases, carbon capture and others (Habermeyer et al. 2024). The higher the conversion to liquid fuel, better is the efficiency. Ail and Dasappa revealed that for Biomass-to-liquid process that include exported electricity, the BtFE can be expected in the range of 35 to 40%. Overall, the BtFE can be augmented to 50–55% by developing better-yielding catalysts and designing effectual FT reactors with good heat transfer rates, together with developments in technologies for oxygen generation, purification of syngas and CO_2 separation, as desirable in the gasification. The BtFE under the purview of this study is as under figure 13 with the biomass and product output in kg/s (Refer Annex table 13). The extremely high and low values are attributed to the input parameters chosen by the author for the selected process and are specific to the biomass input and fuel output used for calculating the parameter. The product output in the electrolysis assisted process was 198.8 MW_{LHV} from the input biomass of 200 MW_{LHV} as reported by Dietrich et al., thereby increasing efficiency.

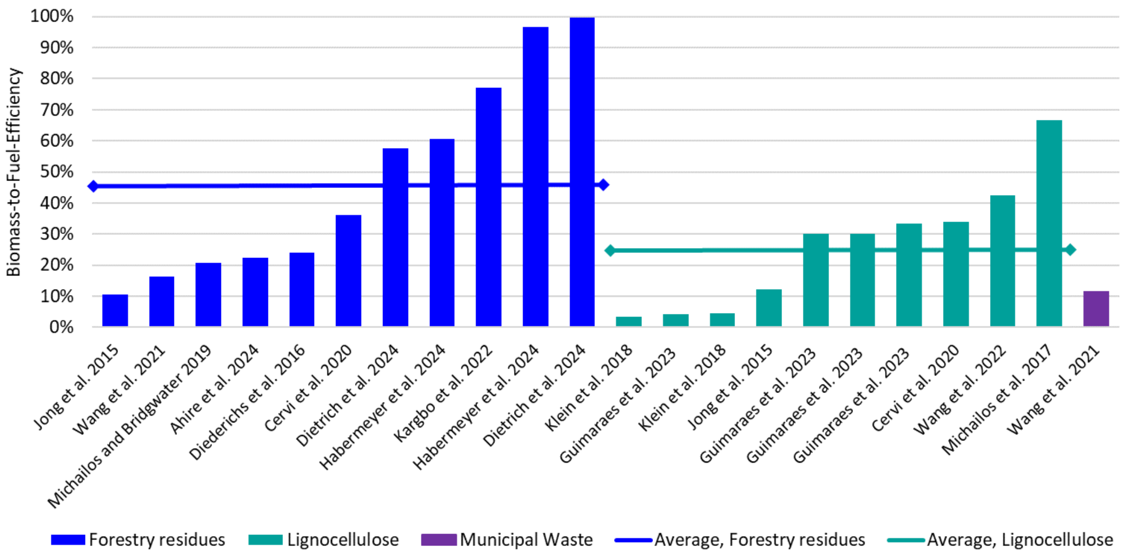

Figure 13 Biomass-to-Fuel-Efficiency of different selected syngas to SAF value chains

5.4 Specific Production Costs & Market Price

The range of MP ($/L) of n^{th} plant is expected to fall in the range between 0.9 and 2 for varied biomass. The impact of established and well-defined SAF supporting policies could enable MP in close parity with conventional kerosene (ICAO 2024). The MP and the production cost of fuels for different selected syngas to SAF value chain are as shown in figure 14 and figure 15.

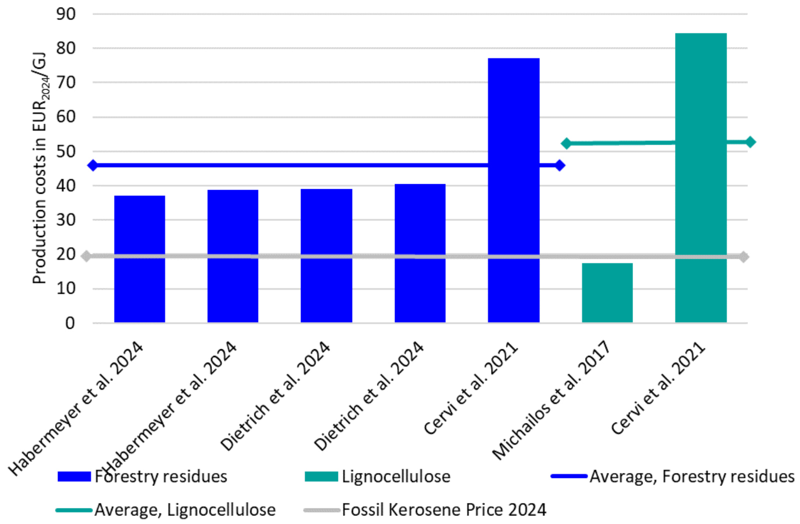

Figure 14 Production costs of fuel for different selected syngas to SAF value chains, with fossil price (EIA 2024)

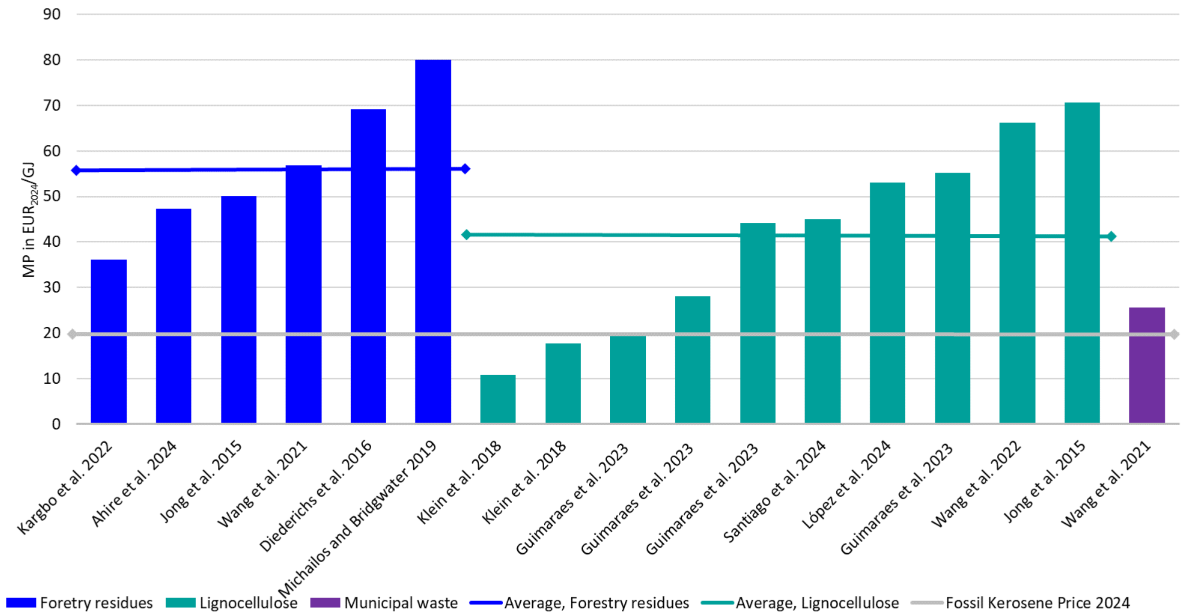

Figure 15 MP of fuel for different selected syngas to SAF value chains, with fossil price (EIA 2024)

The cost pertaining to biomass purchase including transportation, catalysts and CAPEX are major contributors to MP and specific production cost as shown in table 9. The annual cost of biorefinery and electrical power are other significant parameters (López et al. 2024).

The cost of biomass supply affecting production cost is influenced by three aspects: supply-side changing aspects (availability and associated costs), demand-side stimuli (competing prices for food, energy consumption, and land distribution for food, feed, and energy crops), and policy-driven reasons (tax protocols and blending directives). Collection and transportation cost of biomass residues are adjusted according to local factors (IRENA 2014). Any saving in the feedstock cost will affect the overall price of SAF.

Table 9 Major impact factors on the MP/Production cost

Research Paper [Author, Year]	MP/Production cost
(Ahire et al. 2024)	Biomass
(Cervi et al. 2021)	CAPEX>O&M>Biomass
(Jong et al. 2015)	Biomass->CAPEX>Other OPEX
(Real Guimarães et al. 2023)	Biomass purchase>Capital>Other cost
(Habermeyer et al. 2024)	Electrical power>Indirect OPEX>Biomass (Favorable case) Biomass>Indirect OPEX (Base case)
(López et al. 2024)	Biorefinery annual cost>Transportation cost of feedstock
(Diederichs et al. 2016)	Biomass>Catalyst

5.5 CAPEX & OPEX

The major impact factors inducing CAPEX in the syngas to SAF processes are the fuel synthesis unit and the gasification island (GI). These sections form the central contributors to the complete investment required. Nonetheless, the addition of a feedstock preparation and reception unit along with reforming section, further intensifies the capital costs associated with the process. The gasification island encompasses the gasifier and the syngas cleaning unit for removing tar and other contaminants in syngas, both essential for converting feed into clean synthesis gas. And, the fuel synthesis segment includes the FT-unit and the subsequent refinement processes obligatory to produce high-quality jet fuel. All these elements play a role in defining the total capital expenses, with their complexity and scale significantly impacting the overall cost structure and investment decision (Dyk 2024).

For the operational expenses of the process, the key cost drivers are biomass-related costs and utility requirements. The cost associated with obtaining, transporting, and preparing biomass feedstock for the process indicates a significant portion of the total operational expenditure. Utility costs, such as energy and water consumption, also contribute considerably to the overall expenses. The choice of gasifying agent also influences operational costs. For instance, the use of oxygen as the gasifying agent increases costs because of the added energy and infrastructure vital for oxygen production and handling. Electricity costs become the overriding factor influencing operational expenses in an electrolysis-assisted process because it requires electricity to produce hydrogen, which is used in the downstream processes. Another notable contributor to operational costs is the use of catalysts. Catalysts, essential for the FT-synthesis and other reactions, add to OPEX because of their fixed lifespans and the necessity for periodic replacement in case of special catalysts. Indirect maintenance costs likewise add to OPEX depending on the used resources. Both the CAPEX and OPEX for different selected syngas to SAF processes can be referred to figure 16.

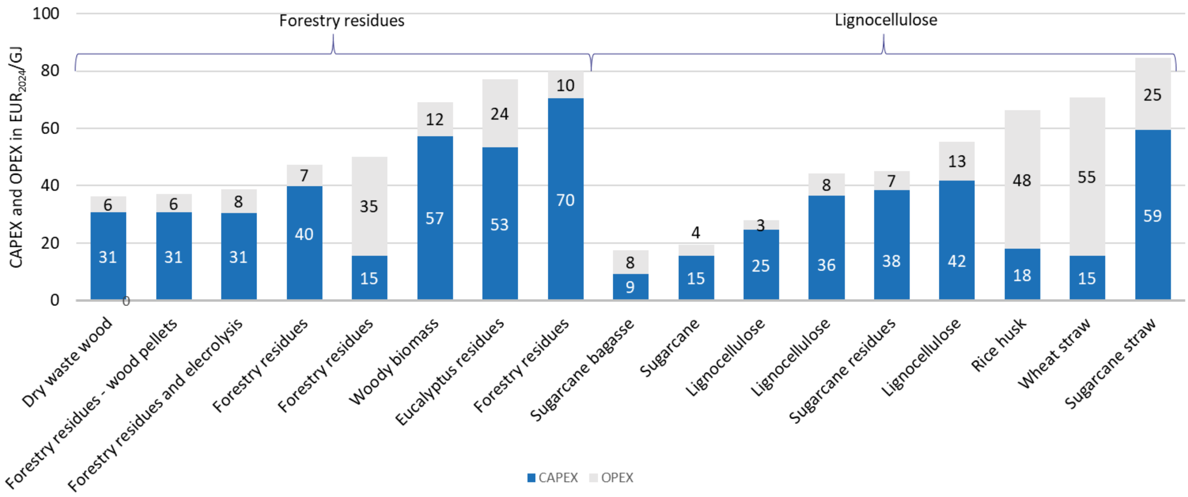

Figure 16 CAPEX and OPEX for different selected syngas to SAF value chains (Ahire et al. 2024; Cervi et al. 2021; Diederichs et al. 2016; Habermeyer et al. 2024; Jong et al. 2015; Kargbo et al. 2022; Michailos et al. 2017; Real Guimarães et al. 2023; Santiago et al. 2024; Wang et al. 2022)

The electrolysis is an energy intensive process that needs electrical power to produce hydrogen for use in the production of SAF, thus affecting the production cost or the market price of SAF. Depending on the energy mix and the geographical location, the cost of renewable electricity can vary. Furthermore, the gasification and FT-synthesis incur significant capital cost varying based on the selected processing routes for syngas production and subsequent fuel synthesis and technology scale. High CPAEX must be carefully considered for large scale applications (Dyk 2024).

Overall, the aforesaid factors (refer table 10) collectively shape the capital and operational cost structure of the syngas-to-SAF process, with variations depending on the application of specific technologies and configurations.

Table 10 Key factors influencing the CAPEX and OPEX

Research Paper	CAPEX	OPEX
(Ahire et al. 2024)	Gasification island (GI)>FT synthesis and hydro processing	Facility>Biomass>Utility
(Real Guimarães et al. 2023)	GI>Utilities>1 G mill>Fuel synthesis	Biomass>FT inputs>Maintenance cost
(Habermeyer et al. 2024)	GI (Base case)	Biomass>Indirect OPEX
(Habermeyer et al. 2024)	AEL>GI (Favorable case)	Electrical power>Indirect OPEX>Biomass
(Diederichs et al. 2016)	GI>FT synthesis>Autothermal reformer	--
(Michailos and Bridgwater 2019)	GI>Feedstock reception and pretreatment>FT synthesis	Biomass>Maintenance>Oxygen and catalyst
(Kargbo et al. 2022)	FT synthesis and hydro processing>Gasification island	Biomass
(Santiago et al. 2024)	GI>1G mill->FT synthesis and hydro processing	
(Wang et al. 2022)	FT synthesis and hydro processing>Gasification island	Biomass>catalyst>utility

5.6 Challenges to further address in the ICARUS project

As highlighted by Ahire et al. 2024, the sustainability of syngas to SAF of forest residues can be achieved by realising economic feasibility while abating environmental impacts. Future actionable insights for stakeholders include optimising the feedstock supply chain by reducing transportation costs, improving yield of feedstock, and enhancing carbon conversion efficiency. Recognising high-value usage for by-products, alongside policy development and social evaluations, is crucial for maintaining economic capability. Conducting regional and country-specific case studies enriched with forest residue resources will be requisite for the successful integration of this process into the aviation sector. Similarly, López et al. 2024 emphasised the need to address various logistical challenges for agro-industrial wastes including regional level transport cost with taxes, transportation vehicles for feedstock, feedstock segregation based on moisture content, fuels, distances from the processing unit (in case of biorefinery concept) and emissions. The authors also underscored the importance of volume constraints during project scalability without impacting the final fuel price for the end users by introducing government supported favourable taxes and incentives, although syngas to SAF showed promising outcomes in the study setting. Habermeyer et al. 2024 stated that long delivery contracts at constant price with suppliers are essential and sourcing feedstock from nearby locations to the SAF refinery provide added advantage for influencing the feedstock cost. On the other hand, Wang et al. 2021 identified that a single incentive policy initiative has less impact on the NPV and MP unless a combination of policies, tailored to the local availability and type of feedstock is implemented. Cervi et al. 2021 equally highlight the need for further research on policy incentives, decreasing residue supply costs, and integrating biorefineries to produce competitive SAF in Brazil. Given the country's vast size and inadequate fuel distribution infrastructure, optimisation of plant locations and capacities is essential. Besides above, Dyk 2024 reported that gasification technology uses varied biomass feedstocks, such as MSW, forest residues, and agricultural residues, to produce syngas. However, challenges are encountered in the feedstock supply chain, including low energy density of forest residues limiting scalability of refinery and logistical concerns (collecting and transporting) concerning cost of transportation. Forest residues are economical over short distance due to high presence of water and oxygen. Also, the seasonal availability (harvesting, collecting), high ash content, and low density of agricultural residues pose significant supply chain hurdles along with low yields.

Dyk 2024 pointed out that the early-stage research and development of catalysts have shown promising results and are capable of improving the jet fuel fraction beyond 40%, avoiding the Anderson-Schulz-Flory (ASF) statistical model. However, challenges continue in gaining approval under ASTM D7566 Annexure-1. Catalyst with higher selectivity to kerosene is still under development stage. Dyk 2024 stated that even though the FT-process is fully commercialised, the upstream processing stages that are currently under development have yet to reach commercialisation.

Local availability of renewable biomass (agricultural and forest residues) should be evaluated to avoid competition with other sectors. According to Dyk 2024, SAF production will necessitate access to cheap and abundant supply of feedstock. The adequacy and reasonable pricing of renewable electricity for the Power-and-Biomass-to-Liquid process (PBtL) process incorporating syngas to SAF route must be considered as suggested by Albrecht et al. 2017. Furthermore, Habermeyer et al. 2024 pointed out the underlying challenge of securing green and affordable electricity in the PBtL, a requirement that is not yet met by several European countries. Biomass, electricity and electrolysers contribute maximum to the capital and operating expenses. Challenges pertaining these local conditions may influence the optimal process design and the choice of using electrolytic hydrogen in this process. The main goals remain lowering the cost of renewable electricity and electrolysers. The development of optimum syngas to SAF concepts exploiting lignocellulosic biomass and integrated with sugar mills in Brazil relies on optimizing plant locations, which, in turn, depends on feedstock availability and conversion technology (Klein et al., 2018).

Incentives based policies are vital for achieving renewable energy with reduced emission for standalone syngas to SAF plant (unless integrated to ethanol distilleries in Brazil) to contribute to the net zero emission target by 2050. The standalone system faces lower economic return and high carbon price incentives to compete with fossil fuel price. Challenges prevails also for decentralized systems. In addition, densification of lignocellulosic biomass resources increases both feedstock costs and emission, as reported in the study by Real Guimarães et al. 2023.

The feedstock cost also provides a significant challenge to reach profitability for the two-stage syngas to SAF process (for waste wood) when using capacities below 1000 t/d. Additional optimization of the TSG process economics is critical as mentioned by Kargbo et al. 2022. The cost of the GI and FT-synthesis units remains an important challenge. Further process optimization is critical for the purification and conditioning of syngas, as well as for the FT- process (Oliveira et al. 2023).

Overall, the evaluation of regional context of feedstock supply, the impact of policy intrusions, the development of catalysts and the optimisation of downstream process conditions are still the key challenges in order to precisely assess the economic viability of syngas to SAF process. Challenges continue concerning the feedstock cost, the availability of renewable electricity and the expenses associated with the GI and FT units.

5.7 Summary

Gasification of biomass and waste integrated with FT-synthesis has shown noteworthy progress, with few operational and various planned projects globally. The certification and scalability of FT kerosene, supported by frameworks TRL and FRL, describes its potential as a decarbonizing solution for the aviation sector. BtFE specifically influenced by the characteristics of biomass, process configuration and the system design. The price of SAF is majorly influenced by the cost of biomass and its transportation, CAPEX and catalyst, while the integrated biorefineries incur high annual costs. Furthermore, biomass related cost and utility are the primary determinants of OPEX, and the application of renewable electricity can further increase OPEX in case of Power-and-Biomass-to-Liquid process. Notably, the CAPEX is determined by GI and fuel synthesis unit, both of which play a crucial role in the economic feasibility of the selected process.

Challenges associated with the syngas to SAF process principally revolve around the accessibility of affordable renewable electricity, which is critical for the Power-and-Biomass-to-Liquid process. Obtaining a consistent and cost-effective supply of feedstock also poses a substantial complication, mainly in regions where competition with other sectors or logistical constraints can increase costs. Likewise, optimising plant locations and logistics based on local conditions is important to ensure economic feasibility, as well as addressing the challenges by offering different form of incentives-based initiatives to counterbalance high operational costs, reducing feedstock expenses, and promoting emissions reductions with improved unit operations. Advancements in catalysts that do not follow the Anderson-Schulz-Flory statistical model have shown prospects, but requires approval from ASTM. The upstream processes prior to the FT-section are still in the process of transitioning to commercialisation. The expenditures linked to the gasification and FT-units continue to offer a significant challenge. Enhancing process condition is crucial, predominantly in the purification and conditioning of syngas, as well as in optimising the FT-process.

Publication bibliography

AACE International (2018): Cost Engineering Terminology. International Recommended Practice No. 10S-90.

Ahire, J. P.; Bergman, R.; Runge, T.; Mousavi-Avval, S. H.; Bhattacharyya, D.; Brown, T.; Wang, J. (2024): Techno-economic and environmental impacts assessments of sustainable aviation fuel production from forest residues. In *Sustainable Energy Fuels* 8 (19), pp. 4602–4616. DOI: 10.1039/d4se00749b.

Aierzhati, Aersi; Watson, Jamison; Si, Buchun; Stablein, Michael; Wang, Tengfei; Zhang, Yuanhui (2021): Development of a mobile, pilot scale hydrothermal liquefaction reactor: Food waste conversion product analysis and techno-economic assessment. In *Energy Conversion and Management: X* 10, p. 100076. DOI: 10.1016/j.ecmx.2021.100076.

Ail, Snehesh Shivananda; Dasappa, S. (2016): Biomass to liquid transportation fuel via Fischer Tropsch synthesis – Technology review and current scenario. In *Renewable and Sustainable Energy Reviews* 58, pp. 267–286. DOI: 10.1016/j.rser.2015.12.143.

Albrecht, Friedemann G.; König, Daniel H.; Baucks, Nadine; Dietrich, Ralph-Uwe (2017): A standardized methodology for the techno-economic evaluation of alternative fuels – A case study. In *Fuel* 194, pp. 511–526. DOI: 10.1016/j.fuel.2016.12.003.

Albrecht, Karl O.; Zhu, Yunhua; Schmidt, Andrew J.; Billing, Justin M.; Hart, Todd R.; Jones, Susanne B. et al. (2016): Impact of heterotrophically stressed algae for biofuel production via hydrothermal liquefaction and catalytic hydrotreating in continuous-flow reactors. In *Algal Research* 14, pp. 17–27. DOI: 10.1016/j.algal.2015.12.008.

Barlow, Jay; Sims, Ronald C.; Quinn, Jason C. (2016): Techno-economic and life-cycle assessment of an attached growth algal biorefinery. In *Bioresource technology* 220, pp. 360–368. DOI: 10.1016/j.biortech.2016.08.091.

Bessette, Andrew P.; Teymouri, Ali; Martin, Mason J.; Stuart, Ben J.; Resurreccion, Eleazer P.; Kumar, Sandeep (2018): Life Cycle Impacts and Techno-economic Implications of Flash Hydrolysis in Algae Processing. In *ACS Sustainable Chem. Eng.* 6 (3), pp. 3580–3588. DOI: 10.1021/acssuschemeng.7b03912.

Brandt, Kristin L.; Wooley, Robert J.; Geleynse, Scott C.; Gao, Johnway; Zhu, Junyong; Cavalieri, Ralph P.; Wolcott, Michael P. (2020): Impact of co-product selection on techno-economic analyses of alternative jet fuel produced with forest harvest residuals. In *Biofuels Bioprod Bioref* 14 (4), pp. 764–775. DOI: 10.1002/bbb.2111.

BTG Bioliquids (2025): Plants - BTG Bioliquids. Available online at https://www.btg-bioliquids.com/plants/, checked on 2/14/2025.

Bullerdiek, Niels; Buse, Joachim; Dögnitz, Niels; Feige, Andreas; Halling, Ann-Marlen; Hauschild, Stephanie et al. (2019): Einsatz von Multiblend-JET-A-1 in der Praxis. Zusammenfassung der Ergebnisse aus dem Modellvorhaben der Mobilitäts- und Kraftstoffstrategie. DBFZ. Leipzig.

CAAFI (2024): Fuel Readiness Level. Available online at https://caafi.com/tools/Fuel_Readiness_Level.html, updated on 10/25/2024, checked on 2/13/2025.

CAAFI (2025): Fuel Qualifications. Edited by Commercial Aviation Alternative Fuels Initiative. Available online at https://www.caafi.org/fuel-qualifications, updated on 1/29/2025, checked on 1/29/2025.

Capaz, Silva R. (2021): Alternative aviation fuels in Brazil. Delft University of Technology.

Cervi, Walter Rossi; Lamparelli, Rubens Augusto Camargo; Gallo, Bruna Cristina; Oliveira Bordonal, Ricardo de; Seabra, Joaquim Eugênio Abel; Junginger, Martin; van der Hilst, Floor (2021): Mapping the environmental and techno-economic potential of biojet fuel production from biomass residues in Brazil. In *Biofuels Bioprod Bioref* 15 (1), pp. 282–304. DOI: 10.1002/bbb.2161.

Chen, Peter H.; Quinn, Jason C. (2021): Microalgae to biofuels through hydrothermal liquefaction: Open-source techno-economic analysis and life cycle assessment. In *Applied Energy* 289, p. 116613. DOI: 10.1016/j.apenergy.2021.116613.

Cheng, Fangwei; Luo, Hongxi (2022): Evaluating the minimum fuel selling price of algae-derived biofuel from hydrothermal liquefaction. In *Bioresource Technology Reports* 17, p. 100901. DOI: 10.1016/j.biteb.2021.100901.

Costa, Paula; Rodrigues, Alda J. (2024): Overview of the VC Biocrude oils to SAF.

Davis, Ryan E.; Fishman, Daniel B.; Frank, Edward D.; Johnson, Michael C.; Jones, Susanne B.; Kinchin, Christopher M. et al. (2014): Integrated evaluation of cost, emissions, and resource potential for algal biofuels at the national scale. In *Environmental science & technology* 48 (10), pp. 6035–6042. DOI: 10.1021/es4055719.

DeRose, Katherine; DeMill, Chad; Davis, Ryan W.; Quinn, Jason C. (2019): Integrated techno economic and life cycle assessment of the conversion of high productivity, low lipid algae to renewable fuels. In *Algal Research* 38, p. 101412. DOI: 10.1016/j.algal.2019.101412.

Diederichs, Gabriel Wilhelm; Ali Mandegari, Mohsen; Farzad, Somayeh; Görgens, Johann F. (2016): Techno-economic comparison of biojet fuel production from lignocellulose, vegetable oil and sugar cane juice. In *Bioresource technology* 216, pp. 331–339. DOI: 10.1016/j.biortech.2016.05.090.

Dietrich, R.-U.; Adelung, S.; Habermeyer, F.; Maier, S.; Philippi, P.; Raab, M.; Weyand, J. (2024): Technical, economic and ecological assessment of European sustainable aviation fuels (SAF) production. In *CEAS Aeronaut J* 15 (2), pp. 161–174. DOI: 10.1007/s13272-024-00714-0.

Dyk, Susan van (2024): IEA-Bioenergy-Task-39-SAF-report. Available online at https://www.ieabioenergy.com/wp-content/uploads/2024/06/IEA-Bioenergy-Task-39-SAF-report.pdf, checked on 1/29/2025.

EASA (2024): State of the EU SAF market in 2023. Fuel reference prices, SAF capacity assessments. Available online at https://www.easa.europa.eu/en/document-library/general-publications/state-eu-saf-market-2023, checked on 2/12/2025.

EIA (2024): U.S. Gulf Coast Kerosene-Type Jet Fuel Spot Price FOB (Dollars per Gallon). Edited by U. S. Energy Information Administration. Available online at https://www.eia.gov/dnav/pet/hist/LeafHandler.ashx?n=PET&s=EER_EPJK_PF4_RGC_DPG&f=A, updated on 1/16/2025, checked on 1/16/2025.

European Union (2014): HORIZON 2020 – WORK PROGRAMME 2014-2015. Technology readiness levels (TRL). Available online at https://ec.europa.eu/research/participants/data/ref/h2020/wp/2014_2015/annexes/h2020-wp1415-annex-g-trl_en.pdf, checked on 2/13/2025.

Farooq, Danial; Thompson, Ian; Ng, Kok Siew (2020): Exploring the feasibility of producing sustainable aviation fuel in the UK using hydrothermal liquefaction technology: A comprehensive techno-economic and environmental assessment. In *Cleaner Engineering and Technology* 1, p. 100010. DOI: 10.1016/j.clet.2020.100010.

Funkenbusch, LiLu T.; Mullins, Michael E.; Vamling, Lennart; Belkhieri, Tallal; Srettiwat, Nattapol; Winjobi, Olumide et al. (2019): Technoeconomic assessment of hydrothermal liquefaction oil from lignin with catalytic upgrading for renewable fuel and chemical production. In *WIREs Energy & Environment* 8 (1), Article e319. DOI: 10.1002/wene.319.

Geleynse, Scott; Brandt, Kristin; Garcia-Perez, Manuel; Wolcott, Michael; Zhang, Xiao (2018): The Alcohol-to-Jet Conversion Pathway for Drop-In Biofuels: Techno-Economic Evaluation. In *ChemSusChem* 11 (21), pp. 3728–3741. DOI: 10.1002/cssc.201801690.

Gu, Xiangyu; Yu, Liang; Pang, Na; Martinez-Fernandez, Jose Salomon; Fu, Xiao; Chen, Shulin (2020): Comparative techno-economic analysis of algal biofuel production via hydrothermal liquefaction: One stage versus two stages. In *Applied Energy* 259, p. 114115. DOI: 10.1016/j.apenergy.2019.114115.

Haarlemmer, Geert; Briand, Morgane; Roubaud, Anne; Roussely, Julien; Déniel, Maxime (2018): ECONOMIC EVALUATION OF A HYDROTHERMAL LIQUEFACTION PROCESS. In *Detritus* In Press (1), p. 1. DOI: 10.31025/2611-4135/2018.13695.

Habermeyer, Felix; Weyand, Julia; Maier, Simon; Kurkela, Esa; Dietrich, Ralph-Uwe (2024): Power Biomass to Liquid — an option for Europe's sustainable and independent aviation fuel production. In *Biomass Conv. Bioref.* 14 (14), pp. 16199–16217. DOI: 10.1007/s13399-022-03671-y.

Hansen, Nick H.; Pedersen, Thomas H.; Rosendahl, Lasse A. (2019): Techno-economic analysis of a novel hydrothermal liquefaction implementation with electrofuels for high carbon efficiency. In *Biofuels Bioprod Bioref* 13 (3), pp. 660–672. DOI: 10.1002/bbb.1977.

Hauschild, Stephanie; Costa de Paiva, Gabriel; Tuschewitzki, Wolfram; Prieß, Tobias; Mendler, Felix; Neuling, Ulf et al. (2025): Produktionstechnologien zur Bereitstellung von erneuerbaren Kraftstoffen. Leipzig (Monitoringbericht erneuerbare Energien im Verkehr).

ICAO (2024): Guidance on policy measures for SAF development and deployment. Edited by ICAO Committee on aviation enviromental protection. Available online at https://www.icao.int/environmental-protection/Documents/SAF/Guidance%20on%20SAF%20policies%20-%20Version%203.pdf, checked on 1/16/2025.

ICAO (2025): Conversion processes. Edited by ICAO Committee on aviation enviromental protection. Available online at https://www.icao.int/environmental-protection/GFAAF/Pages/conversion-processes.aspx, updated on 2/12/2025, checked on 2/12/2025.

IEA (2020): ETP Clean Energy Technology Guide. Available online at https://www.iea.org/data-and-statistics/data-tools/etp-clean-energy-technology-guide, updated on 2/13/2025, checked on 2/13/2025.

IEA Bioenergy (2024): Biomass and Waste Gasification for the Production of Fuels – Task 33. Available online at https://task33.ieabioenergy.com/fuels-from-biomass-and-waste-gasification/, updated on 11/13/2024, checked on 11/13/2024.

IRENA (2014): Global Bioenergy Supply and Demand Projections: A working paper for REmap 2030. Available online at https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2014/IRENA_REmap_2030_Biomass_paper_2014.pdf, checked on 1/29/2025.

Jones, S.; Zhu, Y.; Anderson, D.; Hallen, R. (2014): Process Design and Economics for the Conversion of Algal Biomass to Hydrocarbons: Whole Algae Hydrothermal Liquefaction and Upgrading. Edited by U.S. Department of Energy Bioenergy Technologies Office. Available online at https://www.pnnl.gov/main/publications/external/technical_reports/PNNL-23227.pdf, checked on 1/15/2025.

Jong, Sierk de (2018): Green Horizons. On the production costs, climate impact and future supply of renewable jet fuels. Edited by Copernicus Institute of Sustainable Development, Utrecht University. Available online at https://dspace.library.uu.nl/handle/1874/364514, checked on 1/29/2025.

Jong, Sierk de; Hoefnagels, Ric; Faaij, André; Slade, Raphael; Mawhood, Rebecca; Junginger, Martin (2015): The feasibility of short-term production strategies for renewable jet fuels – a comprehensive techno-economic comparison. In *Biofuels Bioprod Bioref* 9 (6), pp. 778–800. DOI: 10.1002/bbb.1613.

Juneja, Ankita; Murthy, Ganti S. (2017): Evaluating the potential of renewable diesel production from algae cultured on wastewater: techno-economic analysis and life cycle assessment. In *AIMS Energy* 5 (2), pp. 239–257. DOI: 10.3934/energy.2017.2.239.

Kargbo, Hannah O.; Ng, Kok Siew; Phan, Anh N. (2022): Evaluation of the economic feasibility of a two-stage gasification system for hydrogen, liquid fuels and energy production from residues. In *Energy Conversion and Management* 253, p. 115126. DOI: 10.1016/j.enconman.2021.115126.

Klein, Bruno Colling; Chagas, Mateus Ferreira; Junqueira, Tassia Lopes; Rezende, Mylene Cristina Alves Ferreira; Cardoso, Terezinha de Fátima; Cavalett, Otavio; Bonomi, Antonio (2018): Techno-economic and environmental assessment of renewable jet fuel production in integrated Brazilian sugarcane biorefineries. In *Applied Energy* 209, pp. 290–305. DOI: 10.1016/j.apenergy.2017.10.079.

Li, Shuyun; Jiang, Yuan; Snowden-Swan, Lesley J.; Askander, Jalal A.; Schmidt, Andrew J.; Billing, Justin M. (2021): Techno-economic uncertainty analysis of wet waste-to-biocrude via hydrothermal liquefaction. In *Applied Energy* 283, p. 116340. DOI: 10.1016/j.apenergy.2020.116340.

Lippky, Gesa Ulrike Dorit (2017): Evaluation von Herstellprozessen alternativer Kraftstoffe durch mikrobielle Photosynthese. Eine techno-ökonomische Betrachtung. Edited by Fakultät für Biologie der Universität Bielefeld. Available online at https://pub.uni-bielefeld.de/download/2917375/2917811/Dissertation_GesaLippky.pdf, checked on 1/29/2025.

López, Mauricio; Leon, Sergio; Rocha, Sergio; Saenz, Johan; Rincon, Santiago; Silva, Vladimir et al. (2024): Analysis of the Potential for Sustainable Aviation Fuel (SAF) Production from Colombian Agro-Industrial Residues. In *Chemical Engineering Transactions* 109, pp. 31–36. DOI: 10.3303/CET24109006.

Lozano, E. M.; Løkke, S.; Rosendahl, L. A.; Pedersen, T. H. (2022): Production of marine biofuels from hydrothermal liquefaction of sewage sludge. Preliminary techno-economic analysis and life-cycle GHG emissions assessment of Dutch case study. In *Energy Conversion and Management: X* 14, p. 100178. DOI: 10.1016/j.ecmx.2022.100178.

Magdeldin, Mohamed; Kohl, Thomas; Järvinen, Mika (2017): Techno-economic assessment of the by-products contribution from non-catalytic hydrothermal liquefaction of lignocellulose residues. In *Energy* 137, pp. 679–695. DOI: 10.1016/j.energy.2017.06.166.

Mahima, Jain; Sundaresh, Ramesh Kumar; Gopinath, Kannappan Panchamoorthy; Rajan, Panneer Selvam Sundar; Arun, Jayaseelan; Kim, Sang-Hyoun; Pugazhendhi, Arivalagan (2021): Effect of algae (Scenedesmus obliquus) biomass pre-treatment on bio-oil production in hydrothermal liquefaction (HTL): Biochar and aqueous phase utilization studies. In *The Science of the total environment* 778, p. 146262. DOI: 10.1016/j.scitotenv.2021.146262.

Michailos, Stavros; Bridgwater, Anthony (2019): A comparative techno-economic assessment of three bio-oil upgrading routes for aviation biofuel production. In *Int J Energy Res*. DOI: 10.1002/er.4745.

Michailos, Stavros; Parker, David; Webb, Colin (2017): A techno-economic comparison of Fischer–Tropsch and fast pyrolysis as ways of utilizing sugar cane bagasse in transportation fuels production. In *Chemical Engineering Research and Design* 118, pp. 206–214. DOI: 10.1016/j.cherd.2017.01.001.

Motola, V.; Scarlat, N.; Buffi, M.; Hurtig, O.; Rejtharova, J.; Georgakaki, A. et al. (2024): Clean Energy Technology Observatory, Advanced biofuels in the European Union – Status report on technology development, trends, value chains & markets – 2024: Publications Office of the European Union.

Neuling, Ulf; Kaltschmitt, Martin (2018): Techno-economic and environmental analysis of aviation biofuels. In *Fuel Processing Technology* 171, pp. 54–69. DOI: 10.1016/j.fuproc.2017.09.022.

Nie, Yuhao; Bi, Xiaotao T. (2018): Techno-economic assessment of transportation biofuels from hydrothermal liquefaction of forest residues in British Columbia. In *Energy* 153, pp. 464–475. DOI: 10.1016/j.energy.2018.04.057.

Oliveira, Diego C. de; Lora, Electo E.S.; Venturini, Osvaldo J.; Maya, Diego M.Y.; Garcia-Pérez, Manuel (2023): Gas cleaning systems for integrating biomass gasification with Fischer-Tropsch synthesis - A review of impurity removal processes and their sequences. In *Renewable and Sustainable Energy Reviews* 172, p. 113047. DOI: 10.1016/j.rser.2022.113047.

Olson, André L.; Tunér, Martin; Verhelst, Sebastian (2023): A Review of Isobutanol as a Fuel for Internal Combustion Engines. In *Energies* 16 (22), p. 7470. DOI: 10.3390/en16227470.

Ou, Longwen; Li, Shuyun; Tao, Ling; Phillips, Steven; Hawkins, Troy; Singh, Avantika et al. (2022): Techno-economic Analysis and Life-Cycle Analysis of Renewable Diesel Fuels Produced with Waste Feedstocks. In *ACS Sustainable Chem. Eng.* 10 (1), pp. 382–393. DOI: 10.1021/acssuschemeng.1c06561.

Ou, Longwen; Thilakaratne, Rajeeva; Brown, Robert C.; Wright, Mark M. (2015): Techno-economic analysis of transportation fuels from defatted microalgae via hydrothermal liquefaction and hydroprocessing. In *Biomass and Bioenergy* 72, pp. 45–54. DOI: 10.1016/j.biombioe.2014.11.018.

Pedersen, Thomas Helmer; Hansen, Nick Høy; Pérez, Oscar Miralles; Cabezas, Daniel Esteban Villamar; Rosendahl, Lasse A. (2018): Renewable hydrocarbon fuels from hydrothermal liquefaction: A techno-economic analysis. In *Biofuels Bioprod Bioref* 12 (2), pp. 213–223. DOI: 10.1002/bbb.1831.

Penke, C.; Özal, G.; Bellot, F.; Moser, L.; Batteiger, V. (2022): Performance evaluation of jet fuel production by hydrothermal liquefaction in Europe. In *IOP Conf. Ser.: Mater. Sci. Eng.* 1226 (1), p. 12058. DOI: 10.1088/1757-899X/1226/1/012058.

Ranganathan, Panneerselvam; Savithri, Sivaraman (2019): Techno-economic analysis of microalgae-based liquid fuels production from wastewater via hydrothermal liquefaction and hydroprocessing. In *Bioresource technology* 284, pp. 256–265. DOI: 10.1016/j.biortech.2019.03.087.

Real Guimarães, Henrique; Marcon Bressanin, Jéssica; Lopes Motta, Ingrid; Ferreira Chagas, Mateus; Colling Klein, Bruno; Bonomi, Antonio et al. (2023): Decentralization of sustainable aviation fuel production in Brazil through Biomass-to-Liquids routes: A techno-economic and environmental evaluation. In *Energy Conversion and Management* 276, p. 116547. DOI: 10.1016/j.enconman.2022.116547.

Rogachuk, Brooke E.; Okolie, Jude A. (2024): Comparative assessment of pyrolysis and Gasification-Fischer Tropsch for sustainable aviation fuel production from waste tires. In *Energy Conversion and Management* 302, p. 118110. DOI: 10.1016/j.enconman.2024.118110.

Santiago, York Castillo; Guimaraes, Henrique R.; Chagas, Mateus F.; Bressanin, Jessica M.; Simoes, Diogo A.; Bonomi, Antonio (2024): Production of Sustainable Aviation Fuel in Brazil Integrating Biochemical and Thermochemical Routes. Techno-economic and Environmental Assessment Considering Alcohol to Jet and Fischer-tropsch Strategies. In *Chemical Engineering Transactions* 109, pp. 73–78. DOI: 10.3303/CET24109013.

Snowden-Swan, Lesley; Li, Shuyun; Jiang, Yuan; Thorson, Michael; Schmidt, Andrew; Seiple, Timothy et al. (2022): Wet Waste Hydrothermal Liquefaction and Biocrude Upgrading to Hydrocarbon Fuels: 2021 State of Technology.

Snowden-Swan, Lesley J.; Zhu, Yunhua; Jones, Susanne B.; Schmidt, Andrew J. (2016): Hydrothermal Liquefaction and Upgrading of Municipal Wastewater Treatment Plant Sludge: A Preliminary Techno-Economic Analysis. September 2016. Edited by U.S. Department of Energy. Available online at https://www.pnnl.gov/main/publications/external/technical_reports/PNNL-25464Rev1.pdf, checked on 1/29/2025.

Snowden-Swan et al. (2017): Conceptual Biorefinery Design and Research Targeted for 2022: Hydrothermal Liquefaction Processing of Wet Waste to Fuels. December 2017. Edited by U.S. Department of Energy. Available online at https://www.pnnl.gov/main/publications/external/technical_reports/PNNL-27186.pdf, checked on 1/29/2025.

ASTM D7566-21, 8/2/2022: Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons.

Steeper Energy (2022): Hydrofaction. Advanced Biofuels Technology Rapidly Approaching Commercial Acceptance. Available online at https://steeperenergy.com/wp-content/uploads/2022/06/Steeper-Energy-Overview-Q2-2022.pdf, checked on 3/12/2025.

Tao, Ling; Markham, Jennifer N.; Haq, Zia; Biddy, Mary J. (2017): Techno-economic analysis for upgrading the biomass-derived ethanol-to-jet blendstocks. In *Green Chem.* 19 (4), pp. 1082–1101. DOI: 10.1039/C6GC02800D.

Tzanetis, Konstantinos F.; Posada, John A.; Ramirez, Andrea (2017): Analysis of biomass hydrothermal liquefaction and biocrude-oil upgrading for renewable jet fuel production: The impact of reaction conditions on production costs and GHG emissions performance. In *Renewable Energy* 113, pp. 1388–1398. DOI: 10.1016/j.renene.2017.06.104.

Vela-García, Nicolas; Bolonio, David; Mosquera, Ana María; Ortega, Marcelo F.; García-Martínez, María-Jesús; Canoira, Laureano (2020): Techno-economic and life cycle assessment of triisobutane production and its suitability as biojet fuel. In *Applied Energy* 268, p. 114897. DOI: 10.1016/j.apenergy.2020.114897.

Viar, Nerea; Múgica, Claudia; Aguerrezabal, Iker; Demeke, Mekonnen; Thevelein, Johan (2024): Overview of the value chain Isobutanol to SAF. Task 1.3: Isobutanol to SAF value chains – WP1: Framework conditions for SAF development in Europe and MICs. Available online at https://www.icarus-biojet.eu/project-outputs/public-deliverables/ICARUSD13.pdf, checked on 1/16/2025.

Viswanathan, Mothi Bharath; Cheng, Ming-Hsun; Clemente, Tom Elmo; Dweikat, Ismail; Singh, Vijay (2021): Economic perspective of ethanol and biodiesel coproduction from industrial hemp. In *Journal of Cleaner Production* 299, p. 126875. DOI: 10.1016/j.jclepro.2021.126875.

Wang, Min; Ye, Xiaoxue; Bi, Hongwen; Shen, Zhongbao (2024): Microalgae biofuels: illuminating the path to a sustainable future amidst challenges and opportunities. In *Biotechnol Biofuels* 17 (1), p. 10. DOI: 10.1186/s13068-024-02461-0.

Wang, Wei-Cheng; Liu, Yu-Cheng; Nugroho, Rusdan Aditya Aji (2022): Techno-economic analysis of renewable jet fuel production: The comparison between Fischer-Tropsch synthesis and pyrolysis. In *Energy* 239, p. 121970. DOI: 10.1016/j.energy.2021.121970.

Wang, Z. Juju; Staples, Mark D.; Tyner, Wallace E.; Zhao, Xin; Malina, Robert; Olcay, Hakan et al. (2021): Quantitative Policy Analysis for Sustainable Aviation Fuel Production Technologies. In *Front. Energy Res.* 9, Article 751722. DOI: 10.3389/fenrg.2021.751722.

Watkins, Jacob; Zhu, Yunhua; Valdez, Peter; Lords, Clayton; Zeller, Ashton; Bohutskyi, Pavlo; Sims, Ronald C. (2024): Techno-economic analysis of bioplastic and biofuel production from a high-ash microalgae biofilm cultivated in effluent from a municipal anaerobic digester. In *Algal Research* 84, p. 103774. DOI: 10.1016/j.algal.2024.103774.

Xin, Chunhua; Addy, Min M.; Zhao, Jinyu; Cheng, Yanling; Ma, Yiwei; Liu, Shiyu et al. (2018): Waste-to-biofuel integrated system and its comprehensive techno-economic assessment in wastewater treatment plants. In *Bioresource technology* 250, pp. 523–531. DOI: 10.1016/j.biortech.2017.11.040.

Yao, Guolin; Staples, Mark D.; Malina, Robert; Tyner, Wallace E. (2017): Stochastic techno-economic analysis of alcohol-to-jet fuel production. In *Biotechnology for biofuels* 10, p. 18. DOI: 10.1186/s13068-017-0702-7.

Zhao, Jikai; Lee, Juhee; Weiss, Thomas; Wang, Donghai (2021): Technoeconomic Analysis of Multiple-Stream Ethanol and Lignin Production from Lignocellulosic Biomass: Insights into the Chemical Selection and Process Integration. In *ACS Sustainable Chem. Eng.* 9 (40), pp. 13640–13652. DOI: 10.1021/acssuschemeng.1c05169.

Zhu, Yunhua; Biddy, Mary J.; Jones, Susanne B.; Elliott, Douglas C.; Schmidt, Andrew J. (2014): Techno-economic analysis of liquid fuel production from woody biomass via hydrothermal liquefaction (HTL) and upgrading. In *Applied Energy* 129, pp. 384–394. DOI: 10.1016/j.apenergy.2014.03.053.

Zhu, Yunhua; Jones, Susanne B.; Schmidt, Andrew J.; Albrecht, Karl O.; Edmundson, Scott J.; Anderson, Daniel B. (2019): Techno-economic analysis of alternative aqueous phase treatment methods for microalgae hydrothermal liquefaction and biocrude upgrading system. In *Algal Research* 39, p. 101467. DOI: 10.1016/j.algal.2019.101467.

6 Annex

Table 11 BtFE and total costs of biocrude-oil to SAF pathways

Source	Specific feedstock	BtFE	CAPEX EUR2024/GJ	OPEX EUR2024/GJ	Costs EUR2024/GJ
(Lippky 2017)	Pondalgae	NA	87	298	385
(Barlow et al. 2016)	Algae	21%	95	779	874
(Barlow et al. 2016)	Algae	30%	62	335	397
(Zhu et al. 2019)	Algae	54%	23	87	110
(Albrecht et al. 2016)	Algae	52%	35	71	106
(Barlow et al. 2016)	Algae	42%	12	88	100
(DeRose et al. 2019)	Algae	35%	25	63	88
(Davis et al. 2014)	Algae	74%			88
(Gu et al. 2020)	Chlorella sorokinian	44%	16	41	58
(Jones et al. 2014)	Algae	65%	14	27	41
(Albrecht et al. 2016)	Algae	77%	8	29	37
(Farooq et al. 2020)	Algae	46%	5	29	34
(Bessette et al. 2018)	Algae	NA			29
(Ou et al. 2015)	Defatted MicroAlgae	56%	11	13	24
(Chen and Quinn 2021)	Algae	45%	2	11	14
(Funkenbusch et al. 2019)	Lignin	NA			14
(Capaz 2021)	Sugar cane residues	50%	17	21	38
(Penke et al. 2022)	Miscanthus	NA			20
(Penke et al. 2022)	Cereal Straw	NA			12
(Jong 2018)	Wheat Straw	33%	9	28	36
(Jong 2018)	Forestry residues	36%	9	18	26
(Pedersen et al. 2018)	Timber residue + Glycerol	NA			43
(Tzanetis et al. 2017)	Residual wood	65%			33
(Tzanetis et al. 2017)	Residual wood	75%			21
(Juneja and Murthy 2017)	Wastewater Algae	37%			55
(Magdeldin et al. 2017)	Forestry residues	28%	22	27	50
(Snowden-Swan et al. 2016)	Sewage sludge	NA			47
(Ranganathan and Savithri 2019)	Wasterwater Algae	43%			40
(Ou et al. 2022)	Swine manure	NA			39
(Haarlemmer et al. 2018)	Sewage sludge	NA			38
(Li et al. 2021)	Wastewater Algae	60%			31
(Capaz 2021)	Forestry residues	50%	17	16	33
(Zhu et al. 2014)	Forestry residues	NA			33

(Ou et al. 2022)	Swine manure	NA			31
(Snowden-Swan et al. 2017)	Sewage sludge	55%	7	23	30
(Farooq et al. 2020)	Food waste	40%	9	20	29
(Snowden-Swan et al. 2016)	Sewage sludge	NA			29
(Nie and Bi 2018)	Forestry residues	NA	4	24	28
(Aierzhati et al. 2021)	Food waste	NA			28
(Hansen et al. 2019)	Forestry residues	69%			27
(Snowden-Swan et al. 2022)	Sewage sludge	61%	9	16	26
(Farooq et al. 2020)	Sewage sludge	44%	8	13	21
(Lozano et al. 2022)	Sewage sludge	NA			14
(Xin et al. 2018)	Sewage sludge	NA			13
(Penke et al. 2022)	Sewage sludge	NA			12
(Watkins et al. 2024)	Microalgea	NA			44
(Cheng and Luo 2022)	Algae	NA			115

Table 12 BtFE and total costs of isobutanol and ethanol to SAF pathways

Source	Intermediate Product	Specific feedstock	BtFE	CAPEX EUR_{2024}/GJ	OPEX EUR_{2024}/GJ	Costs EUR_{2024}/GJ
(Klein et al. 2018)	Isobutanol	Sugarcane stalks and straw	18%			21
(Klein et al. 2018)	1G2G Ethanol	Sugarcane stalks and straw	18%			35
(Wang et al. 2021)	Ethanol	Industrial Hemp	22%	4	97	101
(Vela-García et al. 2020)	Isobutanol	Cornstover		1	30	31
(Wang et al. 2021)	Isobutanol	Corn				34
(Geleynse et al. 2018)	Ethanol	Alcohol	27%	5	19	24
(Yao et al. 2017)	Ethanol	Sugarcane bagasse	27%			37
(Geleynse et al. 2018)	Isobutanol	Alcohol	28%	3	20	23
(Yao et al. 2017)	2G ethanol	Switch Grass	28%			57
(Neuling and Kaltschmitt 2018)	Isobutanol	Wheat straw	30%			37
(Brandt et al. 2020)	2G ethanol	Forestry residues		12	42	54
(Viswanathan et al. 2021)	Ethanol	Industrial Hemp				63
(Tao et al. 2017)	Ethanol	Corn stover	40%	23	29	52
(Cervi et al. 2021)	2G ethanol	Eucalyptus	43%	30	62	92
(Yao et al. 2017)	Ethanol	Corn Grain	47%			36
(Bullerdiek et al. 2019)	Isobutanol	Corn	47%	5	23	28
(Cervi et al. 2021)	2G ethanol	Sugarcane straw	52%	29	62	91
(Capaz 2021)	2G ethanol	Forestry residues	52%	15	27	42
(Capaz 2021)	2G ethanol	Sugar cane residues	58%	14	32	46
(Tao et al. 2017)	Ethanol	Corn	59%	13	23	36

(Neuling and Kaltschmitt 2018)	Isobutanol	Wheat grain	68%	23

Table 13 Feedstock cost of syngas to SAF value chains

Source	Specific feedstock	Location	Base Year	Original Price of Feedstock /t	Price of Feedstock (EUR/t) – Base Year
(Ahire et al. 2024)	Forest Residue	US centric	2022	40.00 $	37.98
(Cervi et al. 2021)	Sugarcane straw (SCS)	Brazil	2015	25.00 $	22.53
(Cervi et al. 2021)	Eucalyptus harvest residue (EHR)	Brazil	2015	66.00 $	59.48
(Jong et al. 2015)	Forest residues	EU	2013	95.00 €	95.00
(Jong et al. 2015)	Wheat straw	EU	2013	190.00 €	190.00
(Dietrich et al. 2024)	Forest residues	EU	2019	42.23 €	42.23
(Real Guimarães et al. 2023)	Sugarcane	Brazil	2019	22.05 $	19.69
(Real Guimarães et al. 2023)	Sugarcane straw	Brazil	2019	27.70 $	24.74
(Habermeyer et al. 2024)	Forestry residues - wood pellets	EU	2020	42.23 €	42.23
(Habermeyer et al. 2024)	Agricultural residue - sunflower husk (AR)	EU	2020	40.01€	40.01
(Klein et al. 2018)	Sugarcane stalks	Brazil	2015	16.49 $	14.86
(Klein et al. 2018)	Sugarcane straw	Brazil	2015	17.74 $	15.98
(Klein et al. 2018)	Eucalyptus	Brazil	2015	95.28 $	85.87
(López et al. 2024)	Agro industrial waste	Brazil	2019	NA	NA
(Diederichs et al. 2016)	Woody biomass	US centric	2014	95.60 $	71.95
(Michailos and Bridgwater 2019)	Forest residues	US centric	2017	90.00 $	79.67
(Michailos and Bridgwater 2019)	Sugarcane baggage	NA	2014	10.00 £	12.41
(Kargbo et al. 2022)	Dry waste wood	US centric	2020	50.00 $	43.77
(Santiago et al. 2024)	Lignocellulosic sugarcane residues	Brazil	2019	12.00 $	10.72
(Wang et al. 2022)	Rice husk	Taiwan	2017	0.19 $	0.168
(Wang et al. 2021)	Forest residues	US centric	2011	95.54 $	68.69
(Wang et al. 2021)	MSW	US centric	2011	0 $	0

Table 14 Description of biomass processing for syngas to SAF value chains

Sources	Major process units	Product
(Ahire et al. 2024)	Pretreatment->GU->SCU->WGS->FT-> Fuel Synthesis Unit->Product	SAF, green diesel, green propane, off gas, electricity
(Cervi et al. 2021)	Favorable case: ASU>Pretreatment->GU->TR->SCU->Steam reforming->FT-> Fuel Synthesis Unit->Product, waste water treatment +utilities, steam+power plant, hydrogen recovery plant	BJF, electricity, naphtha
(Jong et al. 2015)	ASU>Pretreatment->GU->TR->SCU->Steam reforming->FT-> Fuel Synthesis Unit->Product, waste water treatment +utilities, steam+power plant, hydrogen recovery plant	Jet fuel, green diesel, naphtha
(Dietrich et al. 2024)	Base case: Electrolyser inactive Pretreatment->GU->SCU->FT-> Fuel Synthesis Unit->Product	FT kerosene, off gas
(Dietrich et al. 2024)	Favorable case: Electrolyser active Pretreatment->GU->SCU->FT-> Fuel Synthesis Unit->Product	FT kerosene, off gas
(Real Guimarães et al. 2023)	Favorable case: 1G mill->GU->SCU->FT->Fuel Synthesis Unit->Product	SAF, Ethanol
(Habermeyer et al. 2024)	Base case: ASU-GU->SCU->FT->Fuel Synthesis Unit->Product	FT kerosene, off gas, steam (high)
(Habermeyer et al. 2024)	Electrolyser-GU->SCU->FT->Fuel Synthesis Unit->Product	FT kerosene, off gas, steam (high, medium)
(Klein et al. 2018)	GU-> TR->SCU-> FT-> Fuel Synthesis Unit->PSA->Product, waste water treatment +utilities, steam+power plant, hydrogen recovery plant using PSA	RJF, green naphtha, electricity, green diesel
(López et al. 2024)	NA	FT kerosene
(Diederichs et al. 2016)	ASU->GU->SCU->ATR->FT-> Fuel Synthesis Unit->Product, waste water treatment +utilities, steam+power plant, hydrogen recovery plant	jet fuel, naphtha, off gas
(Michailos and Bridgwater 2019)	Pretreatment->GU->WGS->SCU->FT-> PSA->Fuel Synthesis Unit->Product, CHP unit	jet fuel, diesel, kerosene
(Michailos and Bridgwater 2019)	Pretreatment->GU->Catalytic tar reformer>SCU->FT->Fuel Synthesis Unit->Product, CHP unit	FT kerosene
(Kargbo et al. 2022)	pyrolysis unit->GU->SCU->FT Fuel Synthesis Unit->Product	Liquid fuel
(Santiago et al. 2024)	1G mill->GU->SCU->FT->Fuel Synthesis Unit->Product	SAF, electricity, green gasoline, green diesel
(Wang et al. 2022)	Pretreatment->GU->SCU->FT-> Fuel Synthesis Unit->Product	RJF, naphtha, propane, off gas
(Wang et al. 2021)	NA	FT kerosene

GU: Gasification Unit

WGS: Water Gas Shift

FT: Fischer Tropsch

SCU: Syngas Cleaning Unit

ASU: Air Separation Unit

TR: Tar Reformer

1G- First Generation

ATR: Autothermal Reformer

Table 15 Biomass input and product output of the selected syngas to SAF value chains

Source	Scenario	Biomass input (kg/s)	Product output (kg/s)
(Ahire et al. 2024)		6.95	0.31
(Cervi et al. 2021)	SCS	21.04	3.18
(Cervi et al. 2021)	HER	21.04	3.18
(Jong et al. 2015)	FR	23.14	0.98
(Jong et al. 2015)	WS	25.20	1.01
(Dietrich et al. 2024)	EA	10.28	4.53
(Dietrich et al. 2024)	BA	10.28	2.62
(Real Guimarães et al. 2023)	LCM+Sugarcane - Scenario 1	168.35	3.03
(Real Guimarães et al. 2023)	(LCM - Scenario 2	21.74	3.03
(Real Guimarães et al. 2023)	Bio-oil - Standalone - Scenario 3	24.55	3.03
(Real Guimarães et al. 2023)	Bio-oil -Integrated- Scenario 4	24.55	3.03
(Habermeyer et al. 2024)	PBtL	6.27	1.10
(Habermeyer et al. 2024)	BtL	6.27	0.69
(Klein et al. 2018)	Sugarcane stalks/straw	146.63	1.14
(Klein et al. 2018)	Eucalyptus +SS	167.33	2.77
(López et al. 2024)		3846.53	186.74
(Diederichs et al. 2016)		21.71	2.21
(Michailos and Bridgwater 2019)		27.78	2.41
(Michailos et al. 2017)		27.78	2.53
(Kargbo et al. 2022)		194.44	56.63
(Santiago et al. 2024)		21.74	3.11
(Wang et al. 2022)		6.95	1.00
(Wang et al. 2021)	FR	14.55	0.81
(Wang et al. 2021)	MSW	7.23	0.37