



INTERNATIONAL COOPERATION FOR
SUSTAINABLE AVIATION BIOFUELS

D4.1 Best practices and concepts on upscaling of SAF

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List of acronyms

Acronym	Meaning
AI	Artificial intelligence
ASTM	ASTM International fuel certification standard
ATJ	Alcohol-to-Jet
BTL	Biomass-to-Liquid
CAPEX	Capital expenditure
CC(U)S	Carbon capture, utilization and storage
EC	European Commission
EU	European Union
EUBCE	European Biomass Conference and Exhibition
e-BTL	Electro-based biomass-to-liquid
e-SAF	Synthetic aviation fuel / electro-SAF
EPC	Engineering, procurement and construction
ETO	Ethanol-to-Olefins
ETS	Emissions Trading System
FCC	Fluid catalytic cracking
FID	Final investment decision
FOAK	First-of-a-kind
FPIC	Free, Prior and Informed Consent
FT	Fischer-Tropsch
FTS	Fischer-Tropsch synthesis
GHG	Greenhouse gas
HDO	Hydrodeoxygenation
HDN	Hydrodenitrogenation
HEFA	Hydroprocessed esters and fatty acids

HTL	Hydrothermal liquefaction
IEA	International Energy Agency
IRA	Inflation Reduction Act
LCA	Life cycle assessment
LCoP	Levelized cost of production
LPG	Liquefied petroleum gas
LTFT	Low-temperature Fischer-Tropsch
MSW	Municipal solid waste
MSP	Minimum selling price
NZIA	Net-Zero Industry Act
OPEX	Operational expenditure
PCB	Polychlorinated biphenyl
PFAS	Per- and polyfluoroalkyl substances
PtL	Power-to-Liquid
R&D	Research and development
R&I	Research and innovation
RED	Renewable Energy Directive
RSB	Roundtable on Sustainable Biomaterials
SAF	Sustainable aviation fuel
SCWG	Supercritical water gasification
STIP	Sustainable Transport Investment Plan
TNO	Netherlands Organisation for Applied Scientific Research
TCP	Technology Collaboration Programme
TRL	Technology readiness level
VFAs	Volatile fatty acids
WGS	Water-gas shift
WP	Work Package

Executive summary

This deliverable was developed to identify best practices and forward-looking concepts that can accelerate the scale-up of sustainable aviation fuels (SAF) in Europe and beyond. The work combines evidence generated through literature reviews, techno-economic, environmental and social sustainability assessments developed in other work packages in the ICARUS project, sixteen in-depth stakeholder interviews, three international co-creation webinars, and a large multi-stakeholder workshop organized during the 34th European Biomass Conference & Exhibition (EUBCE 2026). Together, these activities provide a comprehensive understanding of the opportunities, limitations, and future development needs of the three selected SAF value chains of ICARUS: biocrude oils to SAF, syngas to SAF, and alcohols to SAF. While the assessments provided quantitative and analytical insights, the extensive stakeholder engagement activities helped validate findings, identify practical deployment challenges, and capture lessons learned from industrial experience. Despite differences in geographical context, organizational background, and technological focus, a remarkable degree of convergence emerged across all stakeholder engagement activities. While each value chain presents its own technological characteristics and development needs, common themes appeared throughout the interviews, webinars, workshop discussions, as well as supporting assessments.

The **biocrude oils to SAF pathway** occupies a distinct position within the SAF landscape because it expands the renewable feedstock base beyond conventional lignocellulosic biomass and enables the utilization of wet biomass, sewage sludge, digestates, wastewater-derived biomass, and other difficult-to-manage waste streams. Across the analyses and stakeholder discussions, feedstock flexibility consistently emerged as one of the strongest advantages of the pathway. In addition to fuel production, the route offers opportunities for waste management, nutrient recovery, wastewater treatment, carbon capture, and integration within broader circular economy concepts.

The assessments performed within ICARUS highlight the favourable carbon conversion efficiency of HTL and its ability to process feedstocks that are unsuitable for many alternative technologies. At the same time, both the assessments and stakeholder discussions converge on several important limitations. Continuous operation remains insufficiently demonstrated, contaminants in feedstocks and biocrudes create significant upgrading challenges, and corrosion, fouling, solids handling, and the need for the management of large amounts of process water continue to impede commercial deployment. The lack of ASTM certification was also identified as a major obstacle to market entry. While economic and environmental assessments confirm the potential benefits of the pathway, they also emphasize the importance of feedstock quality, upgrading requirements, and external energy and hydrogen demand in determining overall sustainability and cost performance.

Several innovation priorities emerged throughout the work. These include aqueous phase valorisation, recovery of nutrients and chemicals, salt separation technologies, improved phase separation, more robust catalyst systems, integration with green hydrogen, and approaches for improving biocrude quality prior to upgrading. Emphasis was placed on process stability and the need to achieve a consistent production of biocrude with predictable quality over long operating periods.

Among the three pathways investigated, the **syngas to SAF** route emerged as the most widely recognized candidate for large-scale SAF production in Europe and many other regions. This conclusion is supported by the literature review, the interviews, webinars, and workshop discussions.

Several factors contribute to this favourable position. The pathway can utilize large volumes of agricultural residues, forestry residues, municipal solid waste, and other eligible feedstocks, thereby overcoming many of the feedstock limitations associated with lipid-based SAF production (HEFA) being, currently, the only commercial route. The technology also benefits from the maturity of Fischer-Tropsch synthesis, ASTM certification, product flexibility, and strong greenhouse gas reduction potential. The environmental analyses further suggest that gasification to FT frequently achieves some of the lowest greenhouse gas emissions (GHG) among the pathways assessed, especially when residue-based feedstocks are utilized.

Despite the advantages, significant barriers remain. Across all stages of the value chain, high capital expenditure was identified as the dominant challenge. Feedstock logistics, gas cleaning requirements, catalyst sensitivity to contaminants, and the absence of fully integrated commercial biomass-to-SAF facilities were also highlighted. In addition, stakeholders stressed that many historical gasification projects failed not because of shortcomings in Fischer-Tropsch synthesis itself, but because of challenges associated with scaling, feedstock supply, gas cleaning, system integration, and financing. The importance of aligning plant scale with realistic biomass availability emerged as a lesson learned.

Future development priorities are therefore focused not only on technology performance but equally on reducing costs and deployment risks. Improved gasification of challenging feedstocks, enhanced syngas cleaning technologies, more robust and selective catalysts, better integration with renewable hydrogen, increased carbon utilization, and broader industrial integration concepts such as e-BTL systems were identified as innovation needs. In parallel, stable financing mechanisms and support for demonstration and first-of-a-kind (FOAK) facilities were viewed as essential to unlock commercial deployment. The findings suggest that gasification to FT is likely to become one of the most important SAF pathways beyond 2030, especially after feedstock constraints begin to limit further growth in HEFA production.

The alcohol to jet pathway presents a more complex picture than the other two value chains. The pathway benefits from several important strengths. Existing experience from ethanol production, established logistics and supply chains, ASTM certification, feedstock flexibility, and opportunities for process integration all support future scale-up. The analyses and stakeholder inputs also highlighted the attractive fuel properties of alcohol-derived intermediates, particularly isobutanol, which offers advantages in downstream conversion efficiency and fuel quality. Furthermore, integrated biorefinery concepts create opportunities to generate multiple products and improve overall process economics.

Nevertheless, almost all assessments and stakeholder activities returned to the same fundamental constraint: the availability of sustainable and eligible alcohol intermediates, particularly when considering the EU. While ethanol production from sugar and starch containing crops is globally mature, advanced lignocellulosic alcohol production remains limited. In Europe, the current regulatory framework restricts the use of first-generation feedstocks, reducing the availability of suitable alcohol streams. In the specific case of isobutanol, the findings indicate that although the molecule itself is highly attractive, commercial production of lignocellulosic isobutanol has not yet been demonstrated at economically viable scale and requires substantial research and innovation to advance the technology.

Economic considerations dominate the identified barriers. High feedstock costs, enzyme costs and investment risks were identified as major challenges. Technical constraints remain as well, including limitations in fermentation performance, microbial productivity, inhibitor tolerance, product toxicity, recovery systems, and process integration. While many of these issues are expected to improve through continued innovation, they currently contribute to significant uncertainty regarding future competitiveness.

Future progress will depend on advances in biotechnology and process integration. The identified priorities include improved microorganisms through advanced genetic engineering, membrane-based product recovery systems, lower-cost enzymes, integrated biorefineries, enhanced catalyst systems, and improved utilization of all biomass fractions. The findings suggest that alcohol to jet pathways will likely play an important role in the global SAF landscape, particularly in regions with abundant sugar- and starch-based resources. However, under current European feedstock eligibility rules, their contribution is expected to remain more limited than that of the leading thermochemical pathways.

Across all assessments, interviews, webinars, and workshop discussions, a remarkably consistent picture emerged regarding the **conditions required for successful SAF upscaling**.

First, the **dominant barriers are no longer primarily scientific or technological**. While technical improvements remain necessary, economics were identified as the principal constraint across all pathways. High capital expenditure, uncertain returns on investment, insufficient financing

mechanisms, and weak project bankability were consistently viewed as the most important obstacles to deployment.

Second, **policy was recognized both as the main driver and one of the main sources of uncertainty.** ReFuelEU Aviation was considered essential for creating demand and providing long-term market direction. However, stakeholders emphasized that demand-side mandates alone are insufficient to unlock local or European production, resulting in dependence on imports. Additional measures supporting production, financing, demonstration plants, and commercialization are needed to accelerate deployment. RED III's restrictive feedstock eligibility criteria significantly constrain feedstock availability, making the scale-up of SAF production in Europe more challenging.

Third, closely linked to the policy discussion above, **feedstock supply emerged as a universal challenge.** Regardless of technology pathway, participants consistently stressed the importance of feedstock flexibility, supply chain development, diversification of biomass resources, improved logistics, and competition with other sectors for limited biomass resources. Feedstock availability was identified as one of the key factors determining the eventual success of any SAF value chain.

Fourth, the **transition from demonstration to commercialization** remains the most critical development bottleneck. Throughout all interactive activities, participants emphasized the need for additional demonstration projects, support for FOAK facilities, improved learning from previous failures, and financing mechanisms capable of bridging the so-called "valley of death" between technology validation and commercial deployment.

Fifth, **sustainability certification and traceability systems were recognized as increasingly important** for future SAF markets. While certification is necessary to ensure environmental integrity and public trust, participants also highlighted the need for greater flexibility, harmonization, simplification, and innovation in certification approaches to avoid unnecessarily limiting deployment.

Finally, all findings point toward the same overall conclusion: **future SAF demand cannot be met by any single technology, feedstock, or region.** Large-scale aviation decarbonization will require a diversified portfolio of sustainable pathways operating in parallel. Success will depend on combining different feedstocks, conversion technologies, business models, policy instruments, and financing mechanisms while maintaining continued investment in research, innovation, and collaboration across the entire SAF value chain.

1 Introduction

In October 2023, the ReFuelEU Aviation Regulation was adopted with the aim to boost both the demand for and supply of sustainable aviation fuels (SAF), thereby reducing the carbon footprint of the aviation sector and ensuring a level playing field for sustainable air transport across the EU. This new EU legislation was designed to provide greater regulatory certainty to aircraft operators and fuel suppliers, while paving the way for the large-scale deployment of SAF.

ReFuelEU sets very ambitious yet progressive targets for SAF uptake, beginning with a 2% blend by 2025, increasing to 6% by 2030, and ultimately reaching 70% by 2050. Acknowledging that the current supply of SAF is practically negligible and mainly based on HEFA-SPK, meeting these targets and others worldwide will require a rapid and substantial scale-up of production and supply within a relatively short timeframe.

Within this context, the ICARUS project has identified three promising value chains for SAF production: 1) hydrothermal liquefaction-derive biocrude (HTL) to SAF, 2) isobutanol from lignocellulosic biomass to SAF and, 3) synthetic Fischer-Tropsch (FT) from biomass gasification to SAF, and it has identified critical technology steps that at present hinder the wider deployment of these three pathways.

This report, with a stepwise approach, is part of the work carried out in ICARUS Work Package 4 (WP4), which aims to develop best practices and forward-looking concepts to accelerate the global scale-up of these three value chains. These best practices build on results and insights generated within the project- particularly from WP1 and WP3, which focus on a literature review and cost-effectiveness and sustainability assessments, respectively, as well as on external expertise from leading European and international industrial stakeholders and research and innovation (R&I) experts. These external perspectives have been gathered through in-depth interviews, co-creation webinars and a co-creation workshop, covering all three value chains, and have been systematically organized into three key categories: drivers, barriers, and innovations.

2 Feedstocks

The literature review conducted in WP1 has been focused on four main types of feedstocks, i.e., 1) non-food oilseed crops, 2) lignocellulosic energy crops, 3) agricultural and forestry residues and waste streams, and 4) aquatic biomass. For each of these four categories, emerging feedstocks with large innovation potential for SAF production through the three selected value chains have been identified, as shown in Table 2.1.

The specific feedstocks addressed in the project are highlighted in turquoise. In cases where such feedstocks were used for experimental activities in the project are also highlighted in the same colour. These feedstocks form the basis for the development of the best practices and concepts.

Table 2.1 Potential feedstocks for SAF production and their relevance for the three value chains addressed within ICARUS.

Type of feedstock	Specific feedstock	Value chain relevance
Lignocellulosic energy crops	Biomass sorghum, sunn hemp, switchgrass, miscanthus, reed canary grass, giant reed)	Biocrude oils to SAF, isobutanol to SAF, syngas to SAF,
Agricultural/forestry residues and waste streams	Agricultural residues: Straw (not exploited for animal feed), pruning Residues from forestry industry	Biocrude oil to SAF, isobutanol to SAF, syngas to SAF Biocrude oil to SAF, isobutanol to SAF, syngas to SAF
Aquatic biomass	Microalgae Aquaculture residues	Biocrude oils to SAF Biocrude oils to SAF

2.1 Drivers

Four main drivers have been identified regarding feedstocks for SAF production. The first three drivers have a non-technological nature whereas the fourth one is technological. The first driver is the **expansion of the renewable feedstock pool by considering waste and residue materials**. These types of feedstocks will be crucial to enlarging feedstock availability and ensuring sufficient SAF production to meet the targets set in ReFuelEU. The second driver is the **diversification of crops** for SAF production such as cover crops (camelina, carinata), intercrops, etc., not competing directly with food/feed to enlarge the Renewable Energy Directive (RED) III Annex IX part A feedstock availability which is a type of feedstock that will be eligible for SAF production. This second driver is linked to the third one dealing with having a **sustainable feedstock pool**. Just recently, the European Commission amended the RED by adding intermediate crops in Annex IX Part A to be used for SAF production purposes¹. However, this addition is rather constrained, specifying multiple criteria for crops eligibility, and has generated doubt and discussions among experts, questioning the sustainability of this type of feedstock. The fourth and final driver is related to intercropping systems, where two or more crops are grown in the same land and simultaneously. The **short harvesting window associated with seasonal availability** enables this kind of innovative feedstock production system.

2.2 Barriers/Constraints

There are multiple significant barriers associated with feedstocks for SAF production. With regards to non-technological barriers, the use of **biomass residues** implies either **high-cost logistics**, mainly related to collection and transportation, or **low-quality** (low energy content) feedstock. Another important barrier is the long distances between feedstock production sites and conversion plants, resulting often in high transportation costs. Two additional barriers result in insufficient feedstock availability, thus challenging the upscaling of SAF. On the one hand, the current **limited feedstock mobilisation** and, on the other hand, the **competition for the same feedstock with other sectors** of the bioeconomy. Other non-technological barriers identified are **farmers' concern of adopting innovative feedstock** production systems like intercropping, and the demanding requirements for **high levels of farm organisation and new skills**.

As for technological barriers, they are mainly related to feedstock logistics. The first barrier is the **large variety of harvesting/collection equipment** needed due to the large diversity of types of crops and crop residues with low density to be considered. The second constrain is related to multi-cropping systems and refers to the stringent demand for diversified agri-equipment in such systems.

2.3 Innovations

The main innovation regarding feedstocks for SAF production is the development of **innovative cropping systems** which aim to support the supply of appropriate feedstocks through the integrated production of food, feed, and other biobased products sustainably. In this respect it is worth mentioning the **multicropping system concept** for both **sequential cropping** where two crops are cultivated in the same land in a temporal sequence and **intercropping systems** where two or more crops are cultivated in the same land simultaneously – for instance through alternating rows of various crops, strip cropping or relay cropping. Intercropping is a great system to i) increase diversity in the system and ii) reduce nitrogen fertilization (use of a legume that fixes de nitrogen). However, because these intercropping systems consider annual crops and there are not enough energy crops to just do rotation based on that, these systems need integration on a food/feed rotation.

The **most promising multicropping systems** are based on sorghum, a non-food crop growing well in warm climates and having the highest yielding potential, even in cold climates (C4 plant). So, the most promising mixtures will include **sorghum and other warm season crops**, particularly legumes that help

¹ <https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32024L1405>

reduce nitrogen such as **sun hemp**. Despite the multiple advantages attributed to these innovative multicropping systems, their sustainability will largely depend on the land used for growing the crops and the growing yields (the lower the yields, the higher the carbon intensity). It is worth noting that approximately 60% of the whole value chain emissions for SAF production through multicropping come from the biomass production systems. So, it is essential to conduct life-cycle analysis of the production of any crop mixture to ensure sustainability. Also, it should be mentioned that the use of crop mixtures will be challenging for the syngas to SAF value chain when SAF is produced via gasification because these crop grasses have a high ash content² which can create technical problems during down-stream conversion.

Innovations are also developed on **intermediate** oilseed **crops** like **camelina** which are cultivated during the winter season, once the food or feed crops have been harvested. These oilseed crops fit within the rotation of crops and do not have land use change issues associated. Their extracted oils are easily transported and oilseed crops can be rotated with energy crops like sorghum.

An illustrative summary of the drivers, barriers and innovations attributed to feedstocks for SAF production is available in Figure 2.1.

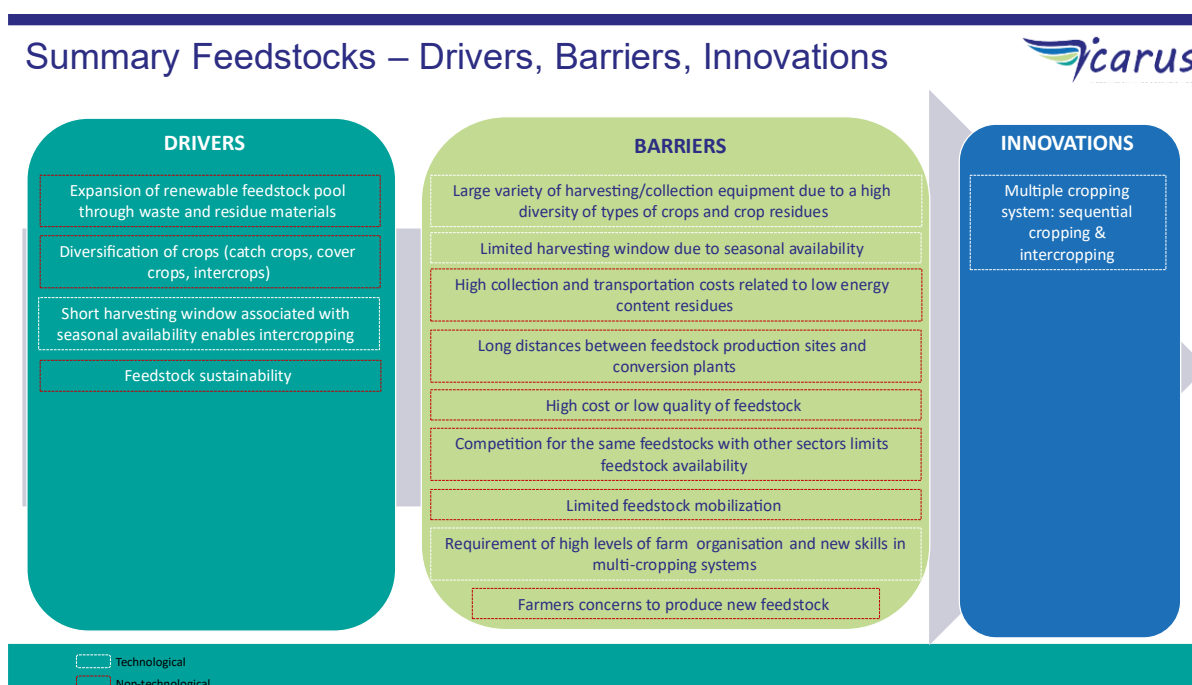


Figure 2.1. Illustrative summary of drivers, barriers and innovations related to feedstock for SAF production

3 Biocrude oils to SAF

In the ICARUS project, the biocrude oils to SAF value chain focuses on the production and upgrading of biocrude from hydrothermal liquefaction to SAF, with special emphasis on the reduction of nitrogen content in the biocrude. Although a broad selection of feedstock is suitable for HTL, in ICARUS the experimental work is based on *Spirulina sp.*, a high-protein microalgae with high nitrogen content. This species has been selected as a model feedstock because of its consistent properties, high nitrogen content as well as availability. However, spirulina is costly and typically used for food purposes. Therefore, when targeting SAF, other microalgae species are considered such as oil-producing

² Christou, Myrsini; Zafiris, Christos; Gavril, Loukas; Papamichail, Ioanna; Zegada-Lizarazu, Walter; Ferro, Elena; Gírio, Francisco, Moura, Patrícia, Eusebio, Ana; Duarte, Luis; Costa, Paula. Overview of biogenic feedstocks. March 2025.

microalgae species grown in wastewater. The availability of such feedstock for research purposes is currently scarce, and their properties are strongly dependent on the production site.

In this report, the drivers, barriers and innovations associated with the biocrude oil to SAF value chain are identified considering not only microalgae as feedstock in ICARUS but also other relevant feedstock sources.

3.1 Drivers

A key driver when using the hydrothermal liquefaction technology (HTL) to produce SAF is **feedstock flexibility**. HTL is suitable for any kind of high-water content biomass and especially appealing for the conversion of **low-cost biomass** such as residues and waste streams (e.g. sewage sludge). Additionally, HTL can be applied to convert aqueous biomass (microalgae) growing in wastewaters³. These systems have two benefits. On the one hand, the wastewaters where aqueous biomass grow become clean and, on the other hand, algae capture CO₂, contributing to climate neutrality and even carbon negativity. Another driver when converting high-water content biomass is the **no need for drying** prior to HTL.

It is also worth noting the **mid-to-high carbon conversions** obtained when HTL is applied and the **high-quality biocrude** produced compared to pyrolysis bio-oil. The possibility to **co-process** the biocrude oil in traditional refineries is also of critical importance. Such co-processing presents several benefits, primarily allowing the reuse of existing refinery and downstream infrastructure and thereby significantly reducing implementation time frames and capital expenditures (CAPEX). Additionally, it enhances cost-effectiveness by producing synthetic, chemically equivalent drop-in products, including high-value products, with a smaller environmental footprint.

An illustrative summary of the drivers presented for the biocrude oils to SAF value chain is depicted in Figure 3.1.

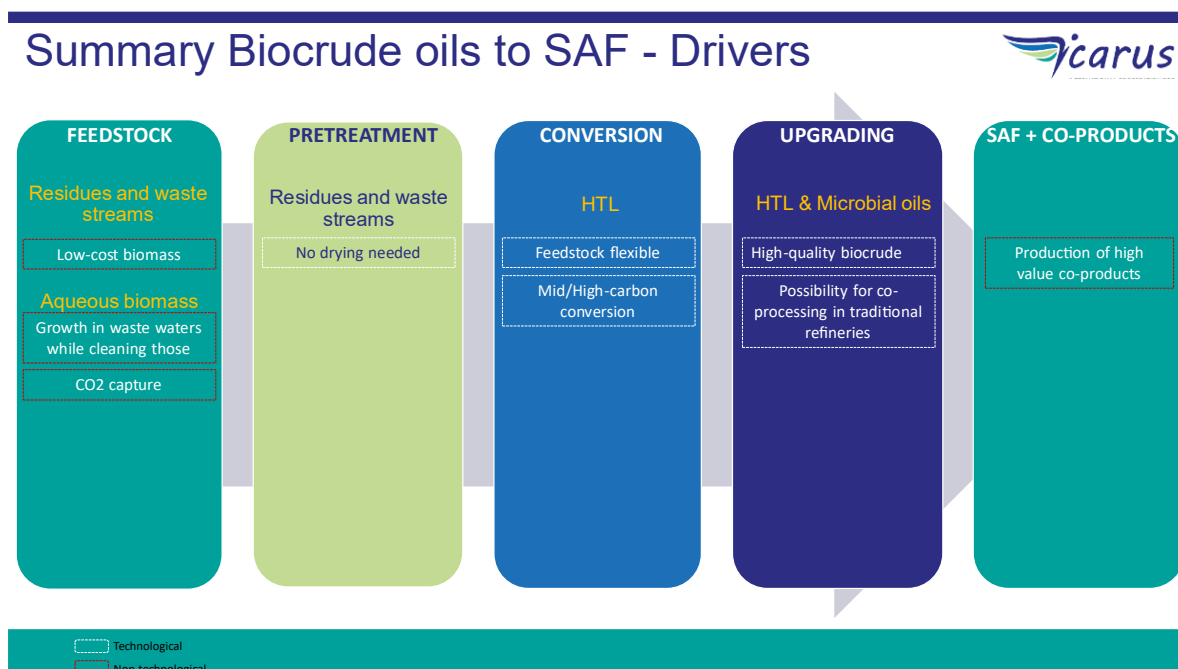


Figure 3.1. Illustrative summary of drivers across the *Biocrude oils to SAF* value chain

³ <https://www.sciencedirect.com/science/article/pii/S2666498422000618>

3.2 Barriers/Constraints

The use of low-cost biomass implies **low-quality feedstocks** which typically present challenging properties for the conversion process in terms of heating value, ash content, contaminants such as nitrogen or sulphur, etc.

With regards to the conversion process there are three main constraints. The first one is the difficulty to **separate the aqueous phase from the oil phase** in the conversion of certain feedstocks (such as microalgae), leading often to low biocrude oil yields. The second important barrier when conducting HTL is to be able to **operate in continuous mode**, particularly in terms of multiphase flow, corrosion, fouling, erosion, pumpability and heat exchange. The process must deal with complex mass flows with unknown properties at times. The third essential barrier is the low TRL (~ 6) - only a **few demonstration facilities** are being installed across the globe.

As for the upgrading step, four critical barriers have been identified. First, the **biocrude oil** generated through HTL requires filtering to **remove particulates/solids** and **deep upgrading** to remove nitrogen, oxygen and sulphur and hence improve its quality and stability to be suitable for SAF production. The **simultaneous removal** of some of these compounds, in particular nitrogen and oxygen, in one single step makes the upgrading process even more challenging. Further, the presence of impurities in biocrude oil in downstream processing can lead to **corrosion** phenomena in mechanical components, complicating the operational process significantly. The commonly used technique for biocrude oil upgrading is **catalytic hydrodeoxygenation (HDO)**. However, this process consumes **large amounts of hydrogen** and suffers from **short catalyst lifetime** due to the impurities mentioned above.

An additional barrier inherent to the biocrude oils to SAF value chain based on HTL is the fact that the SAF produced has **not been ASTM-certified yet**.

A summary of all the barriers described above is shown in Figure 3.2.

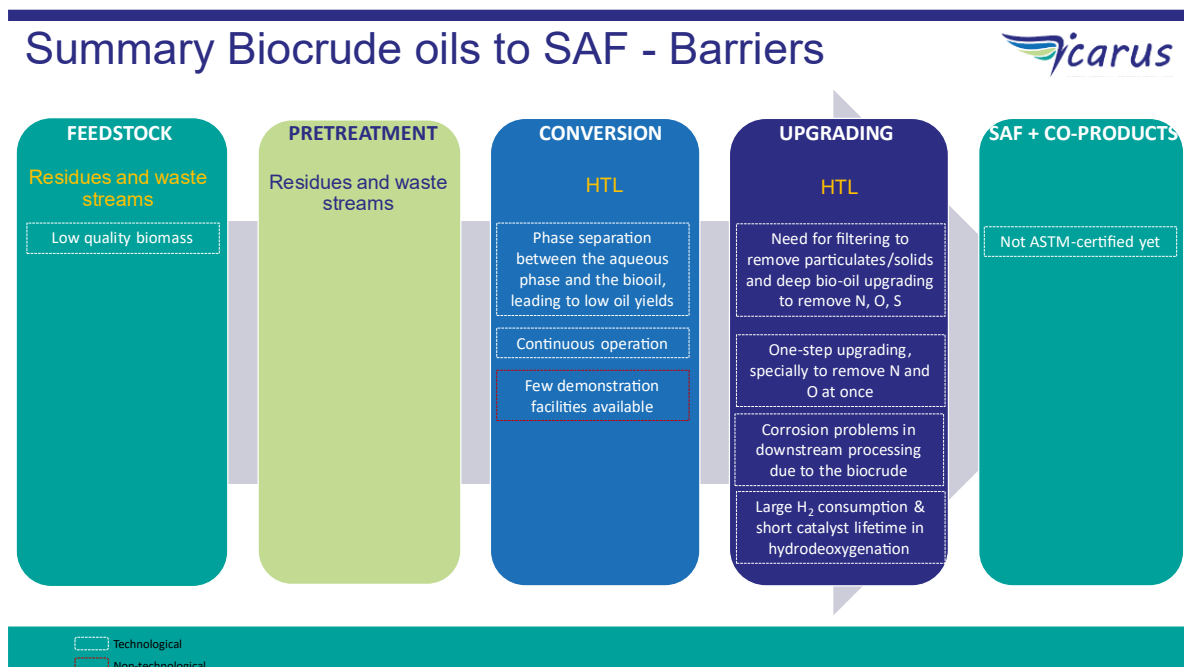


Figure 3.2. Illustrative summary of barriers across the *Biocrude oils to SAF* value chain

3.3 Innovations

Multiple innovations across the entire value chain and TRL framework are being investigated to overcome the barriers that hinder the scale up of SAF production through the biocrude oil to SAF pathway. In terms of pretreatment, the research community is putting significant efforts on **salt separation technologies** prior to i) prevent corrosion to the HTL reactor and associated equipment, ii) improve the quality of the biocrude produced and iii) enhance the overall process efficiency. Salt separation is particularly important when processing low-quality or aqueous biomass with considerable amounts of inorganics and salts.

With regards to the HTL step as such, it is worth highlighting the ongoing innovations on **aqueous phase valorisation**. The aqueous phase is a by-product that limits the economics and technical scalability of the HTL process. However, it is rich in organic carbon and nutrients such as potassium, nitrogen, etc. which can be recycled, leading to an enhanced energy return and economic viability of the HTL process.

The innovations related to the upgrading phase focus essentially on **catalyst development**. On the one hand there is the need to develop catalysts for the **simultaneous removal of oxygen and nitrogen** present in the biocrude oil and, on the other hand the **robustness of the catalysts** used for upgrading requires further improvement to expand the lifetime of such catalysts.

Figure 3.3 compiles all these innovations.

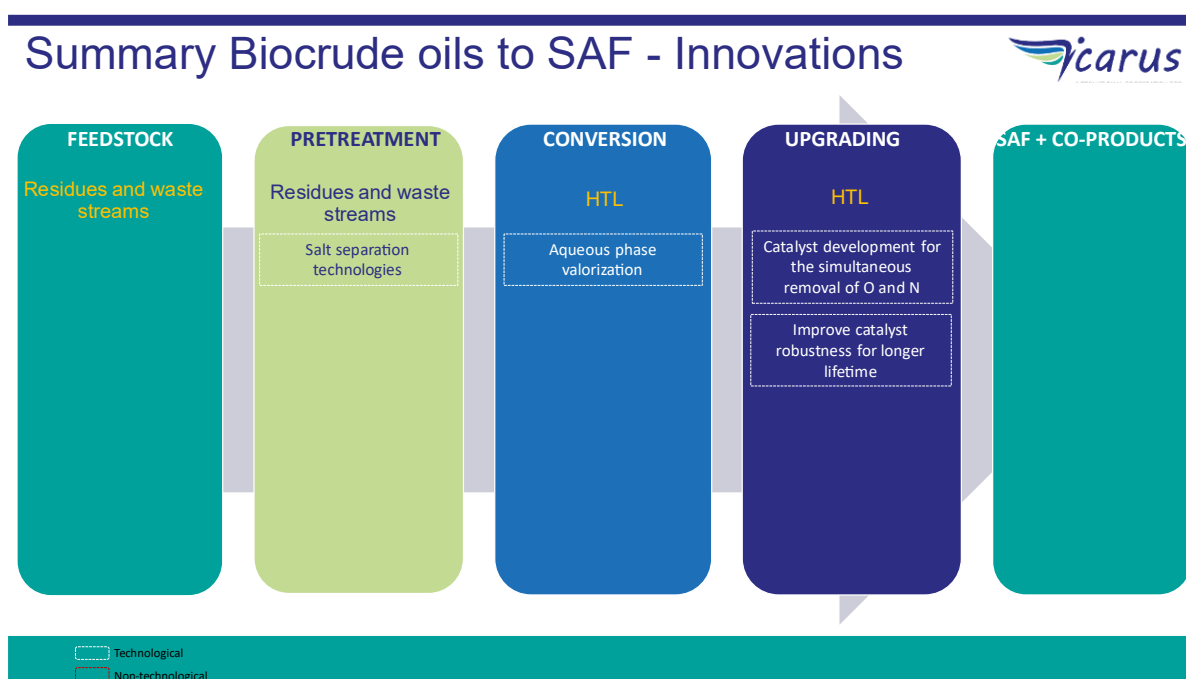


Figure 3.3. Illustrative summary of innovations across the *Biocrude oils to SAF* value chain

4 Isobutanol to SAF

The production of SAF through alcohol-to-jet technologies consists of two main steps, i.e., first, generating alcohol from biomass through hydrolysis and fermentation; and second, converting the resulting alcohol into SAF. While ICARUS primarily focuses on the production of isobutanol from advanced feedstocks (i.e., lignocellulosic biomass) and its subsequent conversion to SAF, the drivers, barriers, and innovations discussed in this document are applicable to the broader value chain. Where relevant, they also encompass considerations related to the ethanol-to-SAF pathway.

4.1 Drivers

The main driver of the isobutanol to SAF technological pathway is the overlap of the ethanol and isobutanol route, which means the learnings from the more developed ethanol route can be utilized. This pathway can also process **low-cost biomass**, improving the overall economy of the SAF production process. Compared to sugar and starch containing biomass types, lignocellulosic biomass is much more abundant. Concerning the steps where sugars from lignocellulosic biomass are produced, drivers deal with **pretreatment minimization** to reduce inhibitors production, enzyme concentration and hence the overall cost of this step. With regards to **isobutanol production through fermentation**, one key driver is the suitability of *Saccharomyces cerevisiae* (Brewer's yeast) for isobutanol production. *S. cerevisiae* is the most utilized yeast for alcohol production with a natural metabolic route to isobutanol and a well-known genome after decades of genetic engineering. It is **robust and has relatively high tolerance** towards the alcohols produced. Another key driver is the **commercial availability of in-situ ethanol removal** through membrane pervaporation that can be retrofitted to continuous isobutanol removal, a crucial element to minimize the product toxicity towards the yeast.

Moving forward to the **conversion of alcohol to SAF**, the most significant drivers are i) the use of **low temperatures**, resulting in **energy savings** and **improved catalyst performance**, both in terms of stability and activity towards SAF production. When comparing the two alcohols for which the ATJ route is certified (i.e., ethanol and isobutanol), the main driver for using ethanol is that it is commercially available. However, when using isobutanol, the dehydration step in the conversion to SAF is less energy intensive and therefore more affordable.

Finally, with regards to the **end-products**, two drivers are identified. The first one is the **production of higher-value products** (lignin- and microcellulose-based), contributing to an improved economy of the value chain. The second driver is that the alcohol to jet synthetic paraffinic kerosene, including isobutanol is **ASTM-certified** up to 50% maximum blend ratio.

An illustrative summary outlining the drivers described above is available in the figure below (Figure 4.1).

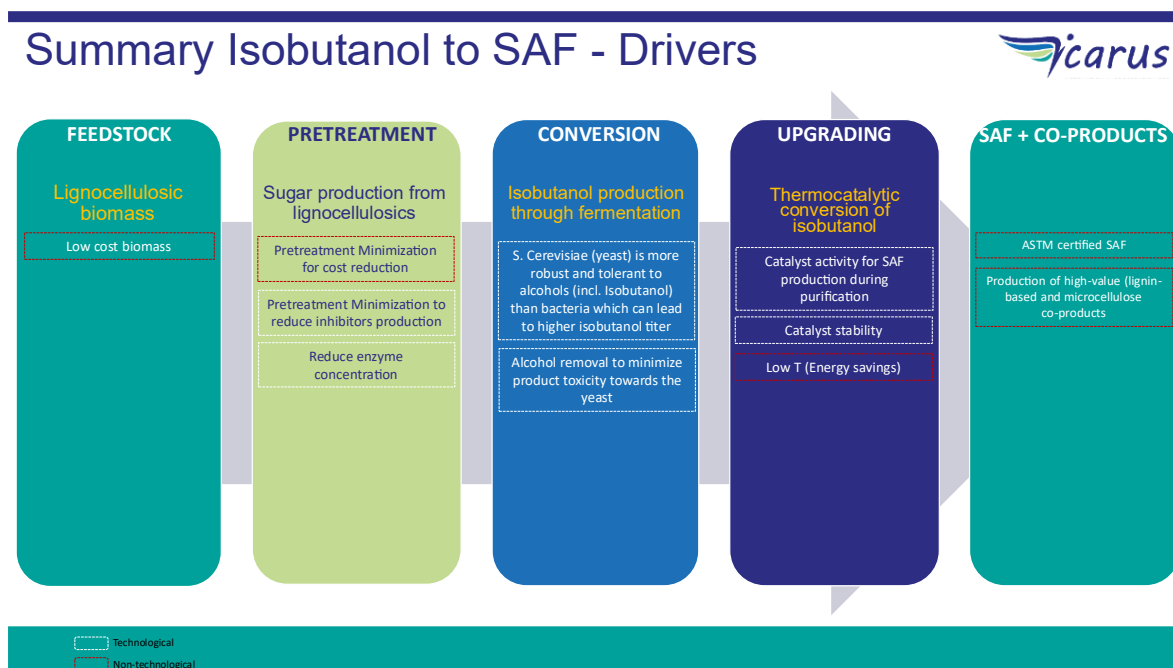


Figure 4.1. Illustrative summary of drivers across the *Isobutanol to SAF* value chain

4.2 Barriers/Constraints

The identified barriers characterizing the isobutanol to SAF value chain are numerous and diverse. Starting with the **production of sugars from lignocellulosic biomass**, there are three distinct barriers. Firstly, the lignocellulosic biomass cannot be directly digested by enzymes, therefore **pretreatment** is needed. The applied pretreatment is often complex and depending on feedstock. Secondly, this pretreatment step generates a wide range of **by-products** that can **inhibit** enzymes and microorganisms. These inhibitory compounds limit productivity and increase separation costs. Lastly, the hydrolysis of lignocellulosic biomass requires **expensive enzyme cocktails** which can jeopardize the economic viability of the value chain.

The number of barriers is even larger when producing **isobutanol through fermentation of sugars**. Due to the **metabolic limitations of microbial hosts** for isobutanol production, the **productivity is low** and, to increase it, engineering of microorganisms is paramount. Firstly, when using *S. cerevisiae*, ethanol is a major fermentation product, competing for the sugar substrate. Secondly, the isobutanol metabolic pathway is naturally partitioned, leading to lower conversion efficiency due to the transfer required within the cell. For increased efficiency, part of the metabolism must be repositioned and the entire pathway collocated through genetic engineering. In addition, when utilizing sugars originating from lignocellulosic biomass, genetic engineering to utilize xylose (C5 sugars) is required.

Further, productivity is also lowered by the fact that the fermenting microorganisms (even though *S. cerevisiae* has comparably better tolerance) are **highly intolerant to the produced isobutanol**, which requires continuous removal of the isobutanol during fermentation.

Finally, it is important to note that the **scalability of the fermentation process** for isobutanol production has been reported to be remarkably challenging, as microbial behaviour can vary significantly across different production scales. This leads to lower isobutanol yields and the need for a separation process for isobutanol and ethanol, increasing the cost of the downstream processing.

With regards to **thermocatalytic conversion of isobutanol to SAF**, the main constraint is the need for **multiple stages and purification steps** due to the low selectivity of the process towards SAF (production of side products apart from SAF). All these steps result in undesired high energy consumption and costs. In the specific case of one-pot synthesis, it is also worth noting the **deactivation effect of water** released when dehydration of the alcohol occurs **on the catalyst**.

Figure 4.2 outlines all these barriers.

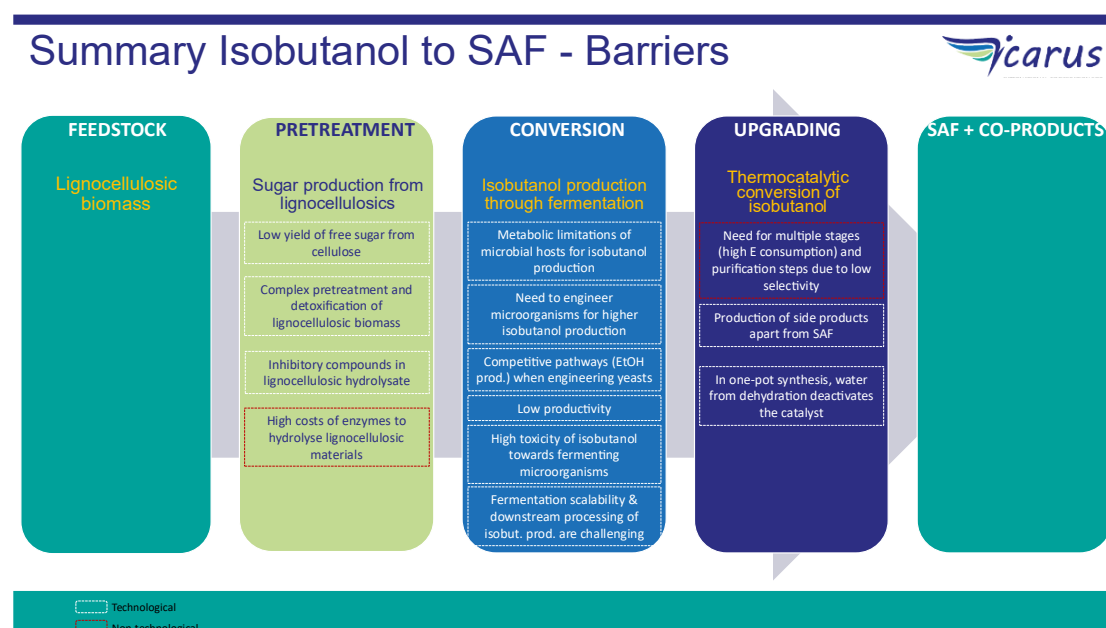


Figure 4.2. Illustrative summary of barriers across the *Isobutanol to SAF* value chain

4.3 Innovations

Aligned with the previous chapter 4.2, the innovation bulk regarding the isobutanol to SAF value chain is focused on the fermentation process for isobutanol production and on the conversion of the alcohol to SAF to provide solutions to the existing barriers.

Most of the innovations target microorganism development through genetic engineering. First, the isobutanol yield must be increased as microorganisms only produce isobutanol in trace amounts naturally. Compared to yeast, researchers could achieve higher isobutanol yields in bacteria, but yeast is more robust and tolerant towards the alcohol produced. Therefore, effort is concentrated on further **increase the isobutanol yield** produced by yeast. As mentioned previously, the two primary focuses in engineering the *S. cerevisiae* are: i) the co-location of the entire isobutanol pathway, and 2) improving the glucose tolerance when the ethanol-producing route is damaged. For the latter, one alternative is to keep the ethanol route intact and co-produce ethanol and isobutanol, as the combined route currently produces more isobutanol. However, this approach requires a separation step and consumes more sugar. Another interesting approach is to develop **cell-free systems utilizing purified enzymes**. Although the results are promising with high isobutanol yields, the cost of the system is high.

For lignocellulosic biomass utilization, current innovations target the development of strains efficiently **converting C5 sugars** (xylose) present in lignocellulosic feedstocks for isobutanol production. In addition, there is some innovative work on the **engineering of cellulolytic enzymes** secreted in the isobutanol-producing yeast with the purpose of limiting the use of expensive commercial enzymes.

In addition, significant research efforts are dedicated to **in-situ removal of isobutanol** and on **genetic modifications to increase the tolerance** of product toxicity as described earlier in the document.

As for the **thermocatalytic conversion of isobutanol to SAF**, innovations are present in various phases. For the **dehydration** of the alcohol, novelties focus on the development of **structured catalysts** leading to high stability and high conversion rates. For the **oligomerization** step, innovations include the development of a catalyst for higher SAF selectivity at lower temperatures. Other important innovation is the integration of all necessary steps for SAF from isobutanol (dehydration, oligomerization, hydrogenation and fractionation) into a single stage, i.e., **one-pot synthesis**, and the development of **catalysts compatible across all four steps**.

A summary of the key innovations in the isobutanol to SAF value chain is illustrated in Figure 4.3.

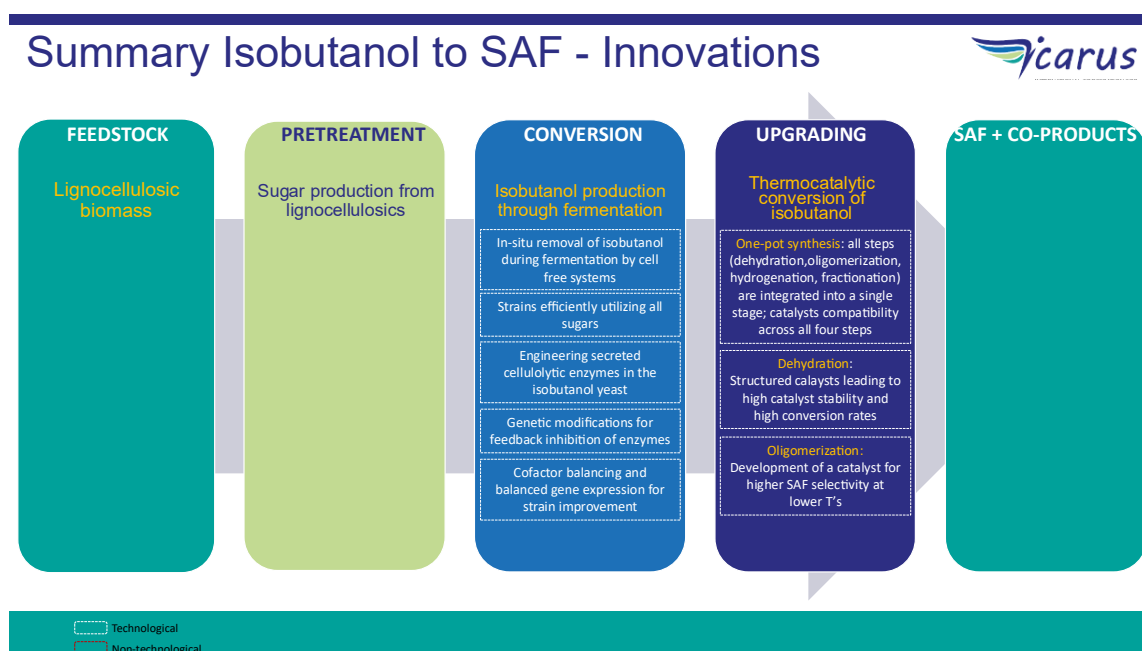


Figure 4.3. Illustrative summary of innovations across the *Isobutanol to SAF* value chain

5 Syngas to SAF

The syngas to SAF value chain assessed in ICARUS focuses on the Fischer-Tropsch synthesis (FTS), with the aim to demonstrate a pathway where syngas is directly converted to liquids, decreasing capital costs and hence improving the economic viability of the overall value chain. The syngas considered originates from the gasification of biomass and subsequent gas upgrading.

5.1 Drivers

The cost of biomass is one of the main barriers to wider biofuels/SAF deployment. Alike the two previous value chains selected in ICARUS, the syngas to SAF pathway enables processing **low-cost feedstocks**, impacting positively to the overall economy of the value chain.

The entire syngas to SAF route is commercially available, although with different (fossil) feedstock. With regards to biomass processing in the technological steps prior to FTS, i.e., **drying, gasification and gas upgrading**, the main driver is that although commercial operation has not been achieved, all these technologies are **demonstrated** in relevant environments.

With reference to **FTS and FT hydrocracking** (FT waxes upgrading), the technologies are well known and **commercially successful**. Besides, in **low temperature Fischer-Tropsch** (LTFT), the use of **Cobalt-catalysts** leading to **high lifetime, stability and high conversions**, is also a valuable driver.

In terms of final products, the drivers are i) **SAF** produced through this value chain is **ASTM-certified** and ii) the resultant **co-products** can be **co-processed** in existing refineries providing flexibility to the system.

Finally, it is worth noting that, among the three value chains evaluated in this project, publicly available data compiled for our internal LCA assessments generally suggest that biomass gasification followed by Fischer-Tropsch (FT) synthesis is often the conversion pathway associated with the lowest GHG emissions⁴.

A recap of all these drivers is available in Figure 5.1.

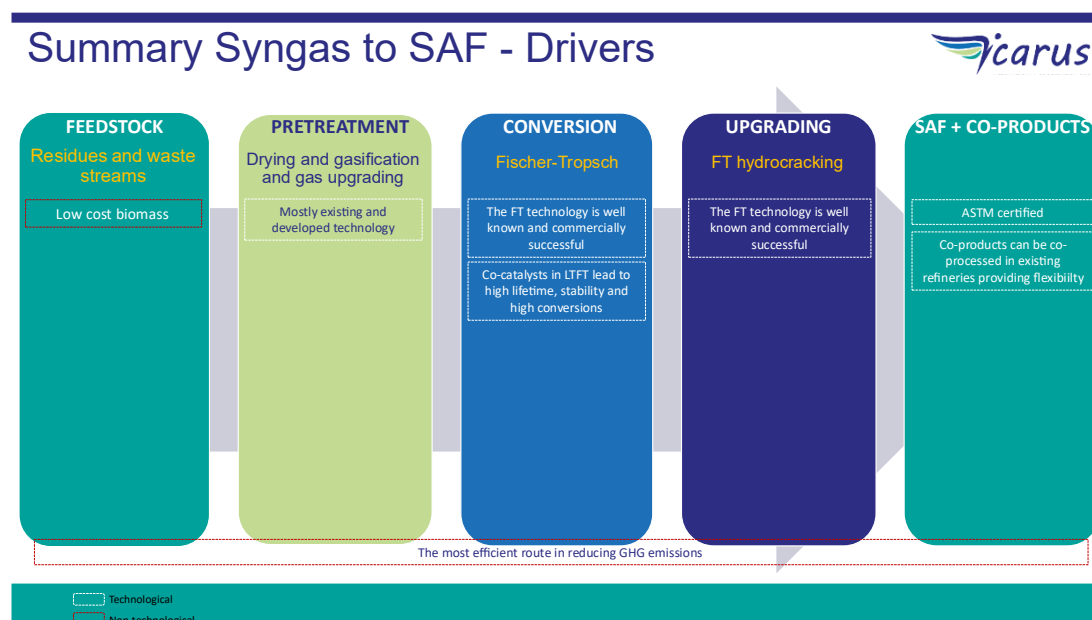


Figure 5.1. Illustrative summary of drivers across the *Syngas to SAF* value chain

⁴ [D.B. Watanabe, Marcos; P. Ballal, Vedant; Cherubini, Francesco. LCA and SDG analysis of SAFs: Screening of sustainability indicators. March 2025](#)

5.2 Barriers/Constraints

The large **variation** in the **chemical composition of the feedstock**, typically in low-cost/low-quality biomass, complicates the drying, gasification and gas upgrading steps, becoming a clear challenge for the overall value chain.

In the **FTS** conversion step, one critical barrier is the **sensitivity to impurities**, requiring a high level of syngas purification. This additional purification process results in higher costs and therefore, effective removal of these impurities is essential. A second major challenge in FTS is the **low selectivity to SAF**, resulting in low SAF yields.

With relation to the **hydrocracking** of FT waxes a key challenge is the remarkable amounts of **pressurized hydrogen** required. Producing, recovering and purchasing hydrogen impacts significantly refinery operating costs. A second important barrier associated with both steps, FTS and hydrocracking of the generated waxes, is the **low overall SAF yields** achieved.

Across the entire **value chain**, a crucial barrier to be overcome is the **high CAPEX**, making the commercial viability of this SAF production route challenging.

A visual overview of these obstacles is shown in Figure 5.2.

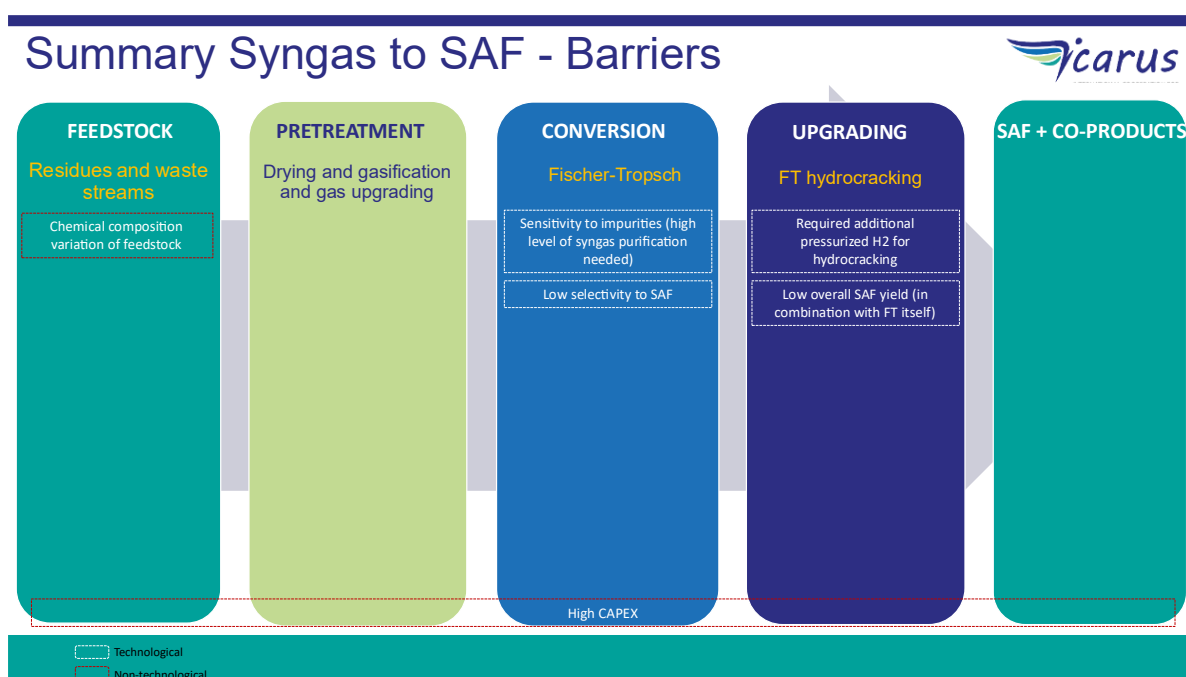


Figure 5.2. Illustrative summary of barriers across the *Syngas to SAF* value chain

5.3 Innovations

The innovations in the syngas to SAF value chain are primarily focused on both the FTS and the FT hydrocracking steps. With regards to FTS, one promising innovation is the development of a novel direct syngas to SAF process where **FTS** and **hydrocracking** are **integrated** in one **single step**. In this case there is no need for downstream wax hydrocracking. For this purpose, significant research efforts are put on the development of **bifunctional catalysts** where FT catalysts are embedded in zeolite catalysts.

Another route that has gained attention in the recent years to produce SAF from syngas is the **direct syngas to olefins** pathway. This process can either use FTS catalysts or alternative non-FTS catalysts, and it consists of two stages. Firstly, the syngas is converted to light olefins and thereafter these olefins

are oligomerized and hydrogenized. The main innovation when considering this alternative pathway is the development of catalysts for (mixtures of) olefines to SAF.

All these innovations are outlined in Figure 5.3.

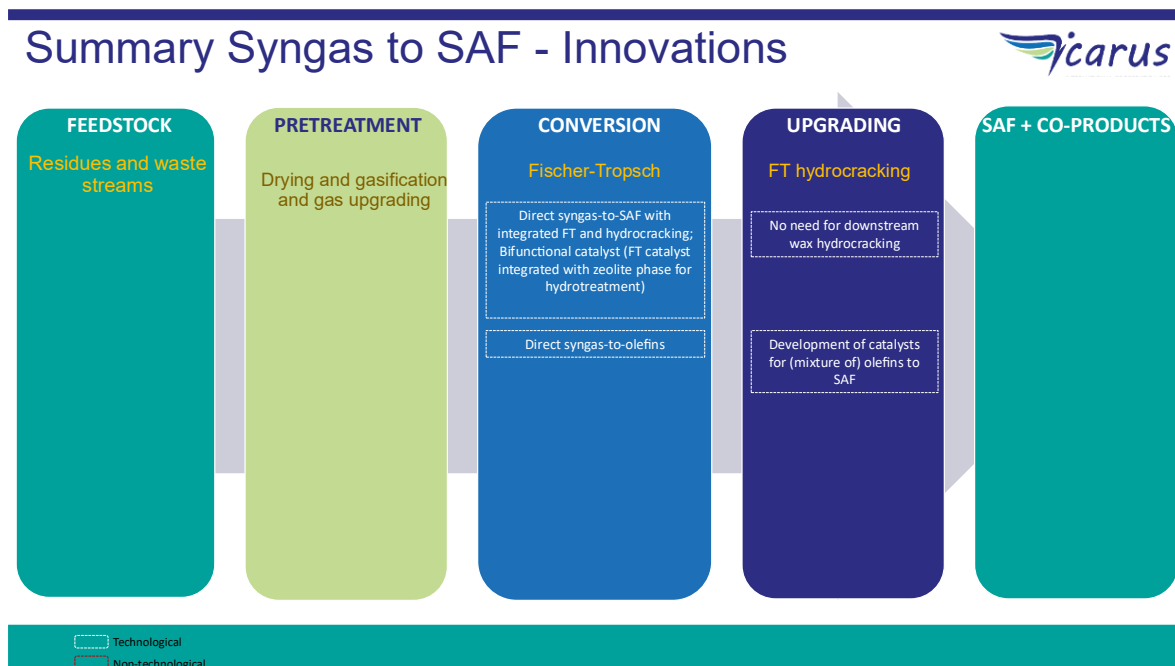


Figure 5.3. Illustrative summary of innovations across the *Syngas to SAF* value chain

6 Key messages from cost-effectiveness and sustainability project assessments

6.1 Techno-economic assessment

The techno-economic landscape of SAF production varies substantially across the three value chains, each presenting distinct opportunities and challenges. An extensive assessment of techno-economic data for these three pathways was recently reported by Dögnitz et al⁵ within the ICARUS project. This chapter will summarize the main findings of the deliverable.

For the biocrude oils to SAF route, HTL stands out for its ability to process mixed, low-cost feedstocks – such as residues and sewage sludge – which supports year-round operation and enhances overall system resilience. In addition, HTL enables the production of valuable co-products and allows relatively straightforward optimization of reactor scale and co-product extraction, both of which can help reduce operational expenses. Despite these advantages, the biomass conversion is constrained by low product yields when low-quality feedstocks are used. These feedstocks typically exhibit wide variations in moisture content and biochemical composition, and seasonal fluctuations can disrupt supply consistency, making co-feeding strategies necessary to maintain stable production. Although high-yield feedstocks such as algae can improve performance, they entail very high operating costs, particularly due to cultivation and harvesting.

⁵ Dögnitz, Niels; Müller, Max John; Gogoi Saikia, Madhumita. Economic analysis of selected SAF options, March 2025

In alcohol-based pathways, economic performance is largely determined by the variability in feedstock costs. Waste residues generally provide the cheapest option, while lignocellulosic materials tend to fall within a similar cost range as grain-based feedstocks, offering some flexibility in supply choices. A significant contributor to overall production costs is the use of enzymes, which can account for up to 25% of total alcohol (typically ethanol) production expenses. This reliance on costly enzymes underscores the need for continued technological innovation to reduce costs and improve process efficiency. In addition to feedstock and enzyme costs, alcohol to SAF pathways face substantial uncertainty regarding technological performance and cost projections. These uncertainties hinder investor confidence. Market ambiguity reinforces the perception of financial risk and slows investment in commercial-scale deployment. Operational expenditures further affect viability, especially in isobutanol-to-jet routes, where OPEX represents approximately 68% of total production costs. Such a high operational cost share highlights the importance of improving process efficiencies, optimizing energy use, and reducing reliance on costly intermediates. Together, these improvements have strong potential to significantly enhance the overall economic performance and competitiveness of alcohol-based SAF pathways.

Syngas to SAF pathways show promising future cost trajectories, with projections for nth-of-a-kind plants indicating production costs between 0.9 and 2 units, depending on the biomass source used. Their economic performance can be further enhanced through the valorisation of co-products such as naphtha, which provides an additional revenue stream, and through ongoing advancements in catalyst technology aimed at improving selectivity toward SAF-range products. Nonetheless, these catalysts remain expensive and are still in the early stages of development, presenting a notable constraint on near-term commercial deployment. Another important factor influencing the techno-economics of this pathway is the integration of renewable electricity. While incorporating renewable power can significantly reduce greenhouse gas emissions and improve the sustainability profile of the process, it also leads to increased operational expenses, creating a trade-off between environmental performance and economic competitiveness. Beyond energy inputs, feedstock logistics pose further challenges. Similar to the previous two pathways, low energy-density residues can substantially increase transportation costs, and regional differences in biomass availability – together with policy-driven variations in feedstock markets – have a major impact on overall feedstock pricing. Given these dynamics, improving both feedstock yield and carbon conversion efficiency is critical for enhancing the overall cost-effectiveness of syngas to SAF route. Advancements in these areas would not only reduce resource requirements but also mitigate some of the logistical and economic constraints currently limiting scalability.

6.2 Environmental assessment

Environmental impacts also differ across pathways. Within the ICARUS framework, an extensive assessment of LCA data for these three value chains was recently reported by Watanabe et al⁴. This chapter will present their key findings.

In HTL systems, GHG emissions are strongly affected by external energy inputs, especially the type of fuel to heat the plant and the source of hydrogen used in biocrude upgrading. Green hydrogen from renewable electricity offers considerably lower impacts than grey hydrogen derived from methane steam reforming. Thanks to high biomass-to-fuel conversion efficiencies, HTL exhibits strong potential for large-scale climate mitigation.

Alcohol to SAF pathways can likewise achieve lower (> 70%) GHG intensities than fossil kerosene, particularly when using second-generation feedstocks. Nonetheless, the hydrolysis and fermentation steps in producing 2G alcohols are environmentally intensive due to chemical inputs, which can be mitigated through better integration of upstream material used in the pretreatment and hydrolysis phases with energy supply chains low in carbon such as renewable electricity.

For syngas based SAF, FT conversion can potentially deliver the lowest GHG intensities as compared to the other two ICARUS routes and typically requires less external energy for the biofuel plant operation.

However, using feedstocks with substantial non-biogenic content, such as municipal solid waste, may lead to emissions similar to fossil jet fuel, although this is less common in literature. When agricultural and forestry residues are used instead, GHG reductions can exceed 85% relative to fossil alternatives.

Across all pathways, reductions in climate impacts may lead to trade-offs such as increased eutrophication or acidification, particularly when crop cultivation and fertilizers are involved. Using residues instead of dedicated crops helps minimize these trade-offs.

6.3 Social assessment

Social sustainability is an essential dimension of SAF deployment. Within the ICARUS project, a social assessment of selected SAF options was conducted and recently reported by Dimou, et al.⁶ and a short summary is presented here.

The transition must not only focus on environmental performance but also address social justice, particularly in regions of the Global South where feedstock cultivation and biomass harvesting occur. Without strong safeguards, SAF production risks intensifying community displacement, gender inequalities, and exploitative labour practices. It may also perpetuate colonial patterns of resource extraction by shifting environmental and social burdens onto marginalized populations. To avoid these outcomes, future SAF strategies should diversify feedstocks to reduce land-use conflicts, invest in advanced technologies that lower costs and minimize resource pressures, and ensure participatory governance that includes affected communities. Social safeguards must include protection of land tenure through Free, Prior, and Informed Consent (FPIC), promotion of gender-equitable labour standards, and fair distribution of revenues within feedstock-producing regions. In short, the future of aviation must aim not only for lower emissions but also for more equitable and socially responsible fuel value chains.

7 Policy and market

Beyond the technological and non-technological aspects attributed to each of the three value chains, the work on best practices and concepts has also looked into policy and market features with a clear impact on the upscaling of SAF.

7.1 Drivers

There are multiple **policy-oriented drivers** supporting the market deployment of SAF. One of the most recent ones is the establishment of the **ReFuelEU** legislation⁷, one of the key components of the EU's Fit for 55 package. ReFuelEU sets very ambitious targets for SAF (and e-SAF) uptake compared with the current market availability of SAF and the relatively short timeline to meet the targets. With this new obligation, fuel suppliers are mandated to blend increasing shares of SAF at EU airports, starting with 2% share in 2025 and up to 70% in 2050. A second and essential policy driver to enhance the deployment of SAF is the **harmonization of standards to calculate carbon emissions reduction and sustainability**^{8,9}. Without that, the comparison of emissions reductions and sustainability across value chains is practically impossible. **Regulations and support schemes for investment security**⁸ are also crucial drivers for SAF deployment. SAF production facilities are highly costly and investment in such

⁶ Dimou, Georgia; Pachakis, Ioannis; Karytsas, Spyridon; Ampatzis, Lida; Christou, Myrsini. Social assessment of selected SAF options. March 2025

⁷ https://transport.ec.europa.eu/transport-modes/air/environment/refueeu-aviation_en

⁸ <https://www.strategyand.pwc.com/de/en/industries/aerospace-defense/sustainable-aviation-fuel/strategyand-sustainable-aviation-fuel.pdf>

⁹ <https://publications.tno.nl/publication/34635015/Mfn271/TNO-2019-R11486.pdf>

infrastructure requires therefore stable and reliable policies supporting that. Finally, the deployment of SAF will also be enhanced if a **robust traceability framework**^{10,11} is in place so that SAF sustainability can be documented and verified.

Regarding **market, SAF offtake agreements**^{12,13} between SAF producers and airlines are key enablers to boost the deployment of SAF. Such agreements are long term and outline the conditions for future delivery of SAF, aiming to provide certainty of supply and demand and hence mitigate the risk of investment in new technologies and infrastructure. Also, in terms of market, it is essential to have in place policy incentives promoting **investment in demonstration facilities and pilot plant** development projects which have a critical role in bridging the development of new technologies with the creation of a first commercial market¹⁴. At the moment, investment in this kind of facilities for SAF production is quite limited¹⁵, hindering scalability of SAF. Lastly, mention must be made on the existence of **global book and claim systems**^{16,17} for SAF. These systems are meant to offer a solution to the logistical challenges of introducing SAF to the market. This model enables airlines (or their customers) to purchase SAF (or SAF emissions reductions) without the need for a direct connection with a SAF supply site. In this way, although the airline/customer is not technically flying on SAF, the purchase of SAF reduces their CO₂ emissions, which is then claimed in the system and promotes the global deployment of SAF.

Besides policy- and market-oriented policies there are other types of **societal drivers** such as increased **public awareness** for and **trust** in SAF. Airports have been proactive players in raising awareness among passengers to incentivise the use of SAF. To a large extent, air travellers, either do not know what SAF are or are not convinced SAF is a good solution to decarbonise the aviation sector¹⁸. In this respect, educational campaigns to revert this situation is vital. To these societal drivers it is imperative to add **investment in research and development** on SAF to enhance cost-efficiency and sustainability. Investment emerging technologies that lead to higher SAF yields while decreasing costs and decreasing carbon intensity is vital to boost scale-up over the coming decades.

7.2 Barriers/Constraints

The number of policy and market related barriers limiting SAF production and deployment is still significant.

With regards to biomass sources, there is a **lack of policy to support the development of energy crops and biomass logistics** in the EU. In the US and India, for instance, dedicated policies for this are in place. There is also a **lack of instruments to increase biomass availability and support farmers and foresters**. Solutions to these challenges are imperative considering the ambitious targets set in ReFuelEU, expected to increase very rapidly over time when considering the current market availability of SAF. Not only meeting the targets set in ReFuelEU is challenging but also the high complexity of **feedstock eligibility** for SAF production under this legislation¹⁹, with a need to **regularly assess the**

¹⁰https://www.iscc-system.org/wp-content/uploads/2024/09/Flying-on-Certified-SAF-Challenges-and-Developments-from-the-Global-Airlines-Perspectives_12092024_ISCCSAFTC.pdf

¹¹https://www.iata.org/contentassets/0bf212bfc0548f2b6ad4c1e229f7e94/guidance-document-on-saf-sustainability-certification-v0.41_rm-indepth.pdf

¹²<https://www.weforum.org/stories/2023/06/title-7-watchouts-when-undertaking-your-first-saf-offtake/>

¹³<https://www.iata.org/en/iata-repository/publications/economic-reports/sustainable-aviation-fuel-offtake-commitments-rise-in-q3/>

¹⁴<https://www.sciencedirect.com/science/article/abs/pii/S0048733316300798>

¹⁵<https://www.icao.int/environmental-protection/Documents/SAF/Guidance%20on%20SAF%20policies%20-%20Version%203.pdf>

¹⁶https://www3.weforum.org/docs/WEF_Scaling_Sustainable_Aviation_Fuel_Supply_2024.pdf

¹⁷<https://rsb.org/wp-content/uploads/2021/11/21-11-08-Book-Claim-FAQ-.pdf>

¹⁸<https://www.iata.org/en/iata-repository/publications/economic-reports/air-travelers-views-on-saf-highlight-a-range-of-issues/>

¹⁹https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=OJ:L_202302405

compliance (notably in terms of **sustainability**) of feedstock in Part A of Annex IX under the Renewable Energy Directive (RED)²⁰. It is also notable to add that with ReFuelEU, aiming to create a level playing field across the EU, Member States are **not allowed** to implement **national mandates** surpassing the ReFuelEU targets²¹. This is for instance the case in The Netherlands where a 14% blending mandate by 2030 (more ambitious than the 6% set by ReFuelEU). Instead, member states must find alternative ways to incentivize fuel suppliers to blend more SAF and stimulate the voluntary uptake of SAF.

Furthermore, Europe **lacks** policy supporting **European SAF production**. Although the European Commission is convinced that ReFuelEU mandates will also incentivise production, there are concerns that after 2030 the supply of SAF to achieve the ReFuelEU ramp up will not be sufficient unless production is supported with dedicated policies. Nonetheless, it is worth noting that from 2027 onwards, the European Commission will revise the scope of the regulation every four years, encompassing an evaluation of potential support mechanisms for the production and uptake of SAF²².

Finally, regarding policy-driven barriers, it is worth mentioning the **lack of financing instruments** to support the jump from **demonstration into commercialization**, as underlined in The Draghi report on the future of EU competitiveness²³. In November 2025 the European Commission launched the Sustainable Transport Investment Plan (STIP)²⁴ to accelerate renewable and low-carbon fuel production for the aviation and maritime sector. STIP is an umbrella for existing financing instruments, such as InvestEU, the Innovation Fund, Horizon Europe, the European Hydrogen Bank as well as through the e-SAF Early Movers Coalition pilot project.

Although the European Commission is continuously trying to improve the issues with the late phase financing, the instruments have not yet succeeded in unlocking substantial renewable fuel production. A similar conclusion emerged from an assessment on financing instruments based on presentations, discussions and analysis of a detailed questionnaire conducted by multiple stakeholders during the “Sustainable Aviation Fuels - Time for take-off” conference²⁵ organised by CRES in Athens on 7-8 November 2024. Overall, there is belief that the EU SAF ecosystem has not reached sufficient maturity yet. Therefore, additional measures are needed especially in financing innovative technologies. Overall, it was agreed that there is urgent need for more effective and dedicated financial support for First-of-a-Kind plants (FOAK) and CAPEX support, as well as additional support measures such as loan guarantees. More targeted financial support for projects with TRL 7-9 is necessary to facilitate demonstration and technology commercialisation. This will help stakeholders move beyond the valley of death. This challenge in combination with inconsistent and restrictive regulations results in many European companies seeking for financing to scale up and commercialize their businesses abroad like the US where financing conditions are more favourable, as those through the Inflation Reduction Act (IRA)²⁶.

Concerning **market**, there are three outstanding constraints to upscale SAF production. Firstly, the **high cost of SAF** which can be between two to seven times more expensive than the Jet A-1 price²⁷. This has a great impact on airlines, considering that jet fuel represents ~20-30% of the overall costs for an

²⁰ https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=OJ:L_202401405

²¹ <https://skynrg.com/refueeu-how-it-will-shape-the-saf-market/>

²² <https://www.easa.europa.eu/en/domains/environment/eaer/sustainable-aviation-fuels/saf-policy-actions#refueeu-aviation>

²³ https://commission.europa.eu/document/download/97e481fd-2dc3-412d-be4c-f152a8232961_en?filename=The%20future%20of%20European%20competitiveness%20-%20A%20competitiveness%20strategy%20for%20Europe.pdf

²⁴ https://transport.ec.europa.eu/news-events/news/commission-unveils-sustainable-transport-investment-plan-strategic-approach-boost-renewable-and-low-2025-11-05_en

²⁵ <http://www.cres.gr/cres/saf/>

²⁶ <https://www.energy.gov/edf/inflation-reduction-act-2022>

²⁷ Webinar entitled *The Price of Sustainability: Exploring the Economics of Sustainable Aviation Fuel*. Organised by Johnson Matthey. September 2024.

airline. Secondly, the **enormous demand competition for biomass and biofuels** with other transport sectors such as maritime and road transports. And thirdly, the **lack of investors** in SAF production due to **lack of assurance of a return**⁸ which in turn leads to lack of technological deployment and lack of SAF supply.

Additional barriers beyond policy and market include the **lack of public awareness** and **acceptance** on **SAF** in society.

Figure 7.1 presents an illustrative summary of policy and market related drivers, barriers and innovations.

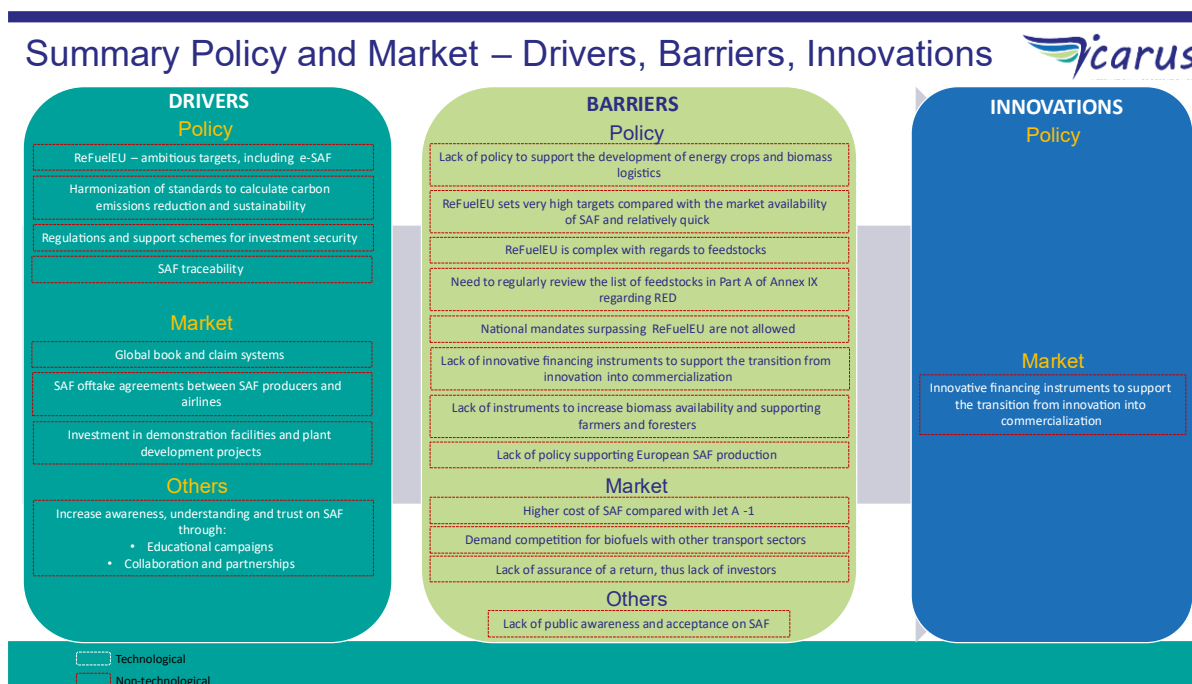


Figure 7.1. Illustrative summary of drivers, barriers and innovations related to policy and market for up-scaling of SAF

8 Insights from extensive interviews with key stakeholders

This chapter summarizes the learnings and personal insights provided during the interviews carried out between November 2024 and February 2025 to 16 experts in the field of sustainable aviation biofuels. The interviewees represent companies that are active in the oil and gas sector, chemicals, startups and consultants. Approximately 80% of the participants were based in the European Union, while the remaining 20% represented Mission Innovation countries.

8.1 Feedstocks

When asking for the most promising feedstocks for SAF production in **Europe**, most of the stakeholders ranked **agricultural/forestry (lignocellulosic) residues** and **waste streams** (sewage sludge, industrial wastes, municipal solid waste (MSW)) as key resources. The **agricultural and forestry** residues are suitable for the **isobutanol to SAF and syngas to SAF** value chains. Agricultural residues are notably dominant in Eastern Europe whereas residual wood is mainly available in Northern Europe and partly in the Southwestern part of France and Northern Spain.

With regards to **waste streams**, **syngas to SAF** is the preferred technology pathway if the waste streams are dry enough while **biocrude oils to SAF** through hydrothermal liquefaction (HTL) is the route to choose when converting wet streams. A few other interviewees also acknowledged the potential of **lignocellulosic energy crops** (and mixtures of them) such as sorghum and sunn hemp. These feedstocks are particularly appropriate for the **isobutanol to SAF** pathway, due to their high ash content, expected to give the least disturbance in this value chain. The syngas to SAF value chain would face difficulties due to the relatively high ash content in the grasses, causing problems during the gasification step. In summary, we could say that most of the interviewees basically recognized the relevance of **Annex IX Part A feedstocks** listed in **RED III** for aviation purposes.

The potential of the remaining two feedstock categories added in Table 2.1, i.e., **non-food oil seed crops** such as camelina and **aquatic biomass**, particularly algal oil (microalgae), were also mentioned, however, to a much lesser extent. Non-food oil seed crops could be especially relevant to cultivate in Southern Europe where traditional lands no longer suitable for traditional agricultural purposes due to the impacts of climate change on land erosion, lack of irrigation, etc.

Although most of the stakeholders indicated the need for low grade biomass for SAF production in Europe, **mixtures of different feedstock qualities** were also indicated as necessary to test how much low-grade biomass can be added into the standard-quality feedstock so that the mixture is converted with the minimum technical issues possible. Additionally, the principle of **feedstock flexibility** was underlined as crucial to control the cost of biomass - avoiding single source suppliers (monopoly) - and hence purchase low-priced feedstock.

As for the **Mission Innovation Countries** considered within ICARUS, i.e., **USA, Brazil, India, Canada**, multiple interviewees pointed out the utilization of **first-generation feedstock** like corn in the USA, Brazil and India to initially boost SAF production while advancing the maturity of technological pathways to produce SAF from second-generation biomass feedstocks. Both in Brazil and in India **agricultural residues** (e.g. sugar cane bagasse in Brazil) are utilized in combination with first-generation ethanol production and they have already been successfully tested at demo scale for cellulosic ethanol production.

8.2 Biocrude oils to SAF

Most of the takeaways from the interviews addressing the biocrude oil to SAF value chain reinforced the key messages collected from literature. Nonetheless, the interviews provided additional intelligence.

In terms of **drivers**, one of the interviewees underlined the importance of **expanding the feedstock pool** for SAF production with the **digestate (biosolids) from sewage sludge**, i.e., the last product of the wastewater treatment process. Such digestate is constantly generated in remarkable amounts and can thus contribute to **feedstock security**. Although in a few European countries it is still allowed to apply such digestate to the field as fertilizer, this is no longer the case in many other countries in Europe like in Germany. As for landfilling, it is the least-used method as it has been prohibited in most EU countries in compliance with the EU Landfill Directive 99/31/EC²⁸. In the countries where these practices are forbidden it is thus crucial to look for alternative solutions to manage this problematic waste and the conversion of it through HTL is promising. Besides, digestate from sewage sludge is generated regularly and in significant amounts.

With regards to **barriers**, the main points identified through literature were complemented with several additional takeaways. Firstly, the difficulties of operating under **supercritical conditions in HTL**, making very challenging the process of bringing the **feedstock up to high pressures and in the reactor**, particularly when the feedstocks contain solids. Secondly, the **large amounts of energy** needed to operate in such severe conditions. Thirdly, the presence of **contaminants**, not only in the biocrude

²⁸ <https://www.sciencedirect.com/science/article/pii/S0956053X21005857>

(already mentioned in the illustrative summary from literature) but also in the initial **wastes** and **residues**, making the HTL conversion more problematic. Finally, it is worth noting that, to make a commercial plant successful, the by-products (aqueous phase and char) – generated in significant quantities – need to be either valorised or minimized, depending on the market conditions.

Despite this bottleneck limiting the economy and technical scalability of the HTL process, it also holds promise as an untapped source of nutrients, energy and chemical blocks. Both the research community and industry see in the byproduct **valorisation** a great **innovation potential** and stress the need for further research and innovation on this matter. Also, with regards to innovation, the interviews indicated the potential of **coupling HTL with green hydrogen from renewable electricity**. In this case, green hydrogen from electrolysis can on the one hand be used to upgrade the biocrude oil while on the other hand, carbon dioxide streams from the HTL process can react with additional green hydrogen from electrolysis to produce additional fuel/chemical blocks such as methanol.

8.3 Isobutanol to SAF

In general terms, the outcome of the interviews undoubtedly spotted a lack of interest and poor engagement towards the isobutanol to SAF pathway, despite acknowledging two key **drivers** that make this value chain interesting. On the one hand, isobutanol is a **branched C4-molecule**, without the need to add aromatics when aiming for SAF. From a chemical point of view, thus, it is a better molecule than ethanol, which is so far, the most used alcohol for SAF production. On the other hand, the production of **SAF from isobutanol is more affordable** than from ethanol, once the alcohol is available (ethanol to SAF is a complex process with three steps with high CAPEX).

These drivers seem to be counterbalanced by multiple **barriers** that might explain why the isobutanol to SAF value chain has not been successfully upscaled yet. The main challenges are of an economic nature and are particularly linked to the **isobutanol production step** where the **cost of the enzyme cocktails** in industrial processes is still very high and remain commercially expensive, as also underlined in the summary of the main takeaways from the literature review conducted in the project. As of today, **no one has successfully proven to economically produce cellulosic isobutanol from fermentation of sugars**. Due to the lack of supply of eligible (cellulosic) isobutanol in Europe, this value chain appears hardly relevant for the EU.

While production of SAF from cellulosic isobutanol suffers from major bottlenecks and requires significant improvements for its commercialization, primarily in terms of cost reduction, it also opens the door for breakthrough **innovations**, particularly with respect to the development of i) **yeast strains that produce isobutanol instead of ethanol** and, ii) **innovative membranes for in-situ isobutanol recovery** from the fermentation broth. These innovation potentials are well aligned with the findings of the literature study. Finally, it must be noted that contradictory opinions apply for the **isobutanol to SAF** value chain. Whereas some believe the demand for commercial isobutanol is currently non-existent and the focus should be on ethanol, some others believe that the demand will be huge in the future.

8.3.1 Ethanol to SAF

Considering the limited interest in the isobutanol to SAF value chain, we opened the door for insights into the ethanol to SAF route, which is at a more advanced TRL level. In terms of **barriers**, the key message was that, despite its higher TRL, this technological pathway has not been widely proven for the conversion of lignocellulosic biomass. Only two companies, one in Brazil – Raizen – and another in India – Praj – seem to succeed. However, both companies are at early stages of the demonstration phase and only time will show whether they can persist. With regards to **innovation potentials**, the following points were raised. Firstly, **alternatives to high purity intermediates** like ethylene to decrease OPEX. Secondly, more work is needed on the **fixed bed catalyst technology** and the development of highly selective **catalysts in the oligomerization** step to maximize SAF production and minimize costs. Furthermore, innovation potentials were also identified on **integration** aspects,

including green hydrogen production, to minimize carbon intensity as well as on **process integration/intensification** and multistep reaction approaches.

8.4 Syngas to SAF

The syngas to SAF value chain through gasification was largely identified as the **most promising route for SAF production in Europe**, given the **abundance of eligible feedstock** in the continent (agricultural and forestry residues as well as waste streams) and the **product flexibility** it offers. From syngas one can produce, for instance, biomethane, expected to increase its demand tremendously in line with the recent EU policy development widely supporting production and uptake of this energy carrier.

Although some of the interviewees have the opinion that the only **showstopper** to scale up SAF production through this value chain is the **large investment costs**, making investors hesitant to invest in this technology, several technological constraints were also recognized as crucial. With regards to the gasification step, **bed agglomeration, fouling, clogging** and **char formation** can still be problematic, especially when converting biomass and waste with high ash content. When municipal solid waste (MSW) is considered, extensive **corrosion due to nitric acid formation** has shown to be an issue at first-of-a-kind plants that still needs to be solved. Many of the interviewees, however, think that the main technological barriers lie in the syngas cleaning and purification steps after gasification where the aim is the **produce highly pure syngas** for SAF applications in an economical and environmentally responsible manner – particularly when utilizing sewage sludge as feedstock. A few respondents also highlighted the lack of proven technology for biomass gasification to high-quality syngas as a key element hindering investments in this technology. Finally, further **improvements in terms of selectivity and cost reduction** were also mentioned.

Concerning **innovations**, several inputs were gathered. Firstly, innovations are still needed regarding feedstock preparation in the sense of finding the **optimal format** in which **biomass is introduced in the gasifier**. Secondly, innovations are foreseen in the **gasification of very dirty residues** such as municipal solid waste. The question here is to balance how dirty a given feedstock can be while still making the gasification process work. The last innovation potential was in terms of **reduction of catalyst consumption**.

8.5 Across value chains

Numerous broader observations encompassing the three value chains were also collected. It was underlined that those **technologies well-positioned** in the **economic merit order** will succeed in the SAF aviation market. Although for many, SAF upscaling is pulled by policy and market rather than by technology potentials, **remaining technological challenges** impede **technology diversification** – having direct impact on feedstock supply -, resulting in monopolies and a less competitive market. Therefore, it is imperative to find solutions to these challenges. Other relevant barriers identified included the **excessively rapid pace** at which the **scaling up of SAF production plants** has often occurred, in some cases skipping piloting and/or demonstration steps. Further, it was noted that in many other regions around the globe security of supply, even if fossil fuel based, is prioritized over green energy solutions. In this regions, SAF upscaling can also become a significant challenge.

Some messages were also conveyed regarding **innovation potentials**. Concretely, three recommendations were provided. First, the need to keep on innovating to **reduce the cost of SAF**, either by reducing CAPEX of existing designs or by improving OPEX by better integrating processes, by developing new types of catalysis, by upgrading equipment, etc. Furthermore, additional efforts are required to ensure feedstock flexibility to keep the biomass cost as controlled as possible. Lastly, more research is necessary on modularization for small scale solutions which will also contribute to cost reduction.

8.6 Policy and market

The considerable number of messages collected on policy and market indicates how crucial these aspects are when discussing the upscaling of SAF production. Nearly all shared perspectives referred to either drivers or barriers, alike the gatherings from literature.

Starting with **policy drivers**, the most persistent message was the imperative of establishing **long-term stability for investors'** confidence to invest in SAF. There was great consensus on the fact that **ReFuelEU** creates a **solid framework** and provides **clear guidance** to develop a (policy-driven) SAF market in Europe while allowing for gradual increases of SAF blends that aims to avoid massive shock to the airline industry in the short term and gives time to technological advancements and solutions. Several interviewees also underlined the crucial role of **national governments in supporting both the uptake and production of SAF** and referred to the UK government as best practice²⁹. Another main takeaway with regards to policy was the urgency to establish and consolidate **incentive schemes to de-risk SAF production** along the whole value chains, starting already at lab scale and all the way to commercialization. The **tax credits** introduced in the US by the **Inflation Reduction Act** a couple of years ago with the purpose to incentivize SAF production and use were also identified as best practice, having contributed to catapult the biofuels industry in the country. However, this policy framework is, since Trump came back to the White House, uncertain. Although the Trump's administration has targeted several Biden-era climate actions since the very beginning of Trump's second mandate, many anticipate that a significant portion of the IRA will persist, as it provides subsidies for technologies being implemented in areas of interest to the Trump administration³⁰. Lastly, the **pivotal role research and innovation** play to strengthen European competitiveness was emphasized and with that, the need to reinforce policy supporting these features, despite the already existence of suitable funding instruments such as Innovation Fund for the deployment of innovative net-zero and low-carbon technologies like SAF.

With respect to **market**, numerous **drivers** were compiled, starting with a reassuring message to technology providers and investors stating that the **SAF market is rapidly expanding**, created by regulatory mandates, voluntary uptakes and technology advancements, and in the long run it will be **large** and become a good business case. Further on SAF investments, it was strongly suggested to engage **feedstock suppliers** to be **investors** in SAF production in collaboration with other key partners such as technology providers. Additionally, the great importance of establishing **long-term offtake agreements**. The **commercialization of green byproducts** from SAF production pathways is also key to be successful. A third factor supporting the upscaling of SAF is the **production and use of waste-based fuels** which promotes waste valorisation and a circular economy while reducing costs and enhancing public acceptance. Beyond the European landscape, the enormous potential for **SAF production in Africa** was also mentioned. Africa is gaining much attention given its great climate conditions for renewable energy production, abundant lignocellulosic biomass (sugarcane) and low labour costs.

Moving forward to **barriers** for upscaling of SAF, the list is even longer. With regards to **policy**, even though ReFuelEU was recognized as a driver, it was also pointed out as a constraint due to multiple reasons. Some responders raised concerns about **ReFuelEU** being too ideologically pure with respect to **feedstock eligibility** as compared, for instance, to the US where carbon intensity is the main factor in policy making. Additionally, there were critical voices about the list of eligible feedstocks in Annex IX of the renewable energy directive which is frequently changing. This leads to uncertainty and instability. As for the volume mandates, there was complete unanimity that, until 2030, the targets are achievable and even considered by someone as too conservative if upscaling of SAF production is to be boosted as it needs to meet the 2050 target. The great **challenge** will appear **beyond 2030** when the shares of SAF blends cannot longer be complied only with HEFA, Europe's most abundant SAF, and

²⁹ <https://www.gov.uk/government/calls-for-evidence/saf-mandate-saf-supply-and-industry-certainty-in-an-evolving-market/saf-mandate-saf-supply-and-industry-certainty-in-an-evolving-market>

³⁰ <https://time.com/7262600/how-trump-is-trying-to-undo-the-inflation-reduction-act/>

other eligible feedstocks are in direct competition with either other sectors such as the chemical or construction industry or with other parts of the world. If the **targets** beyond 2030 were found to be overly ambitious and the European Commission decided to **relax** them, the green premium would be significantly larger and become a showstopper for all SAF demo projects. As the price gap will always be too large due to high CAPEX and OPEX (particularly with regards to feedstock) associated to SAF production, it needs to be heavily regulated. An additional factor that could put policy stability at risk is the current political trends, not just in Europe but also worldwide, with an increase of populism shifting towards hard-right forces denying climate change and the need for green/sustainable solutions. The voice of the European Commission differs on this point. As stated in the regulation, the European Commission shall evaluate every fourth year, starting by January 2027, whether there is the need to revise the scope of ReFuelEU³¹. With such eventual revisions, the European Commission want to open the door for reality checks and opportunities to improve, rather than create uncertainty. A final reflection regarding ReFuelEU was the fact that it can result in **sharp rises in flight fares**. This could then end up with political pressures, creating uncertainty and financial risks, making investors reluctant/hesitant to invest in SAF production.

Additional takeaways from the interviews such as **lack of legislation to increase/mobilize feedstock availability** and **lack of incentives to support European SAF production** are fully aligned with the findings from the literature study. These two aspects are essential to establish long-term SAF offtake agreements. With regards to **governmental support** to aid companies to de-risk, (subsidies, bank guarantees, etc.) identified earlier as a key driver for SAF upscaling – especially for first-of-a-kind (FOAK) projects, the responders consider that the current level of support is totally insufficient. In some countries, even, there is a **lack of governmental strategy and prioritization** on biofuels/SAF.

The **market-oriented bottlenecks** brought up by the interviewees are somewhat complementary to those identified from publicly available information. Most of the messages related to the **lack of investment** and **financing in SAF production technologies beyond HEFA**, with recurring annual postponements of investments, and the **limited engagement** of key players such as **oil majors/oil refineries** in this field. It is well known that such stakeholders are currently investing a lot in HEFA, however, some believe it is rather opportunistic in the sense that it makes full sense for them because the adjustments needed to convert oil refineries into HEFA-based biorefineries is minor compared to the significant changes required if any of the three technological pathways selected within ICARUS was considered. At this stage, it is unclear if oil majors' engagement will persist beyond HEFA. Other key players with limited commitment so far are **banks** and **fuels suppliers** and both should be more involved if SAF upscaling is to succeed. A couple of other barriers spotted during the interviews were on the one hand the **competition for biomass to produce other products** with higher added value such as biochemicals and biomaterials and, on the other hand, the fact that **decarbonization of other transport sectors** will remain **cheaper** than decarbonization of the aviation sector.

8.7 Future production and upscaling of SAF in Europe and beyond

Extending beyond the knowledge acquired regarding technology, policy, and market dynamics, we also gained insights in what the interviewees think about the future production and upscaling of SAF, both in Europe and in other parts of the world.

8.7.1 SAF production in Europe

There was wide consensus that European SAF production will take off, primarily due to the ReFuelEU regulation. The current engagement of fuel suppliers was also mentioned as positive, however the question is whether their engagement will be limited to HEFA also in the future. Domestic production is vital for job creation, energy security/autonomy and European competitiveness. According to a

³¹ Regulation (EU) 2023/2405 of the European Parliament and of the Council of 18 October 2023 on ensuring a level playing field for sustainable air transport (ReFuelEU Aviation)

recent study³² by the European Commission, the projected production capacities for advanced biofuels in Europe by 2050 are so significant that, in some scenarios, Europe could meet the ReFuelEU targets without imports.

In the **short term - up to 2030** - all interviewees agreed that **HEFA** will be the primary route for SAF production. It is worth remembering that Europe is currently world leader in HEFA commercial facilities with multiple stakeholders involved in this business such as ENI, Neste, Total, St-1, etc. In the longer term, beyond 2030, Europe will need to complement the HEFA volumes with lignocellulosic SAF. Most of the respondents believe that **thermochemical technological pathways** will dominate the European landscape. Among thermochemical routes, the **gasification to syngas to-SAF** value chain was recognized as the most promising one, with potential production in numerous countries/regions such as the Nordic countries, Eastern Europe, Southwest of France and Northern Spain. One of the key drivers to prioritize this pathway is the fact that suitable and eligible feedstock is available in large quantities. Furthermore, the gasification step provides product flexibility which builds a solid base for SAF upscaling. Besides syngas, one can also produce biomethane, the demand of which has dramatically increased since the REPowerEU communication and other European policy flagships such as Net-Zero Industry Act - NZIA³³ and it is expected to continue doing so.

With regards to **alcohol to jet**, nearly all interviewees think this pathway is less suitable for European conditions as cellulosic alcohol is not available in the continent and the recent industrial activities which focused on this route have failed. This is for instance the case for Clariant, in Romania, which has recently shut down its sunliquid® bioethanol production³⁴ and decreased related activities of the business line Biofuels & Derivatives in Germany due to economic losses making the business unsustainable. With this recent European failure in biofuels production from cellulosic alcohols there is little hope that Europe can succeed in the future. It is also worth noting that cellulosic ethanol, the alcohol that currently attracts most interest among stakeholders, is also relevant for a market - the road transport - that is rapidly being electrified. Therefore, it is less attractive to establish a new cellulosic ethanol facility. In consequence, it seems like if the alcohol to jet pathway is to succeed in Europe, second generation alcohols complying with ReFuelEU will need to be imported from countries like Brazil, India, etc., where such alcohols are expected to be produced in significant quantities.

8.7.2 SAF production outside Europe

Beyond Europe, the **technological choice** will be based on **feedstock availability** and will vary across different regions. **Biocrude oils to SAF via HTL** will be particularly relevant in **highly populated areas/cities** such as the North American cities New York and New Jersey, with large amounts of waste residues. On the other hand, **alcohol to jet** and **syngas to SAF via gasification** will be dominant in **agricultural-rich** and **forestry-rich** regions, with the US, Brazil, India and some Australian regions being big players globally. It was also noted that the technologies accumulating the highest number of carbon credits - meaning those with lower carbon intensity - are expected to emerge as the frontrunners in the competition.

8.8 Key insights and future recommendations

Upon concluding the interviews, the respondents were invited to share key insights and future recommendations for the SAF community, drawing from their own experiences. The gathered insights

³² [European Commission: BEST, BTG, Directorate-General for Research and Innovation, E3Modelling, Exergia, POLITO, Wageningen University & Research, Georgiadou, M., Goumas, T., Chiaramonti, D., Development of outlook for the necessary means to build industrial capacity for drop-in advanced biofuels – Final report, Georgiadou, M.\(editor\), Goumas, T.\(editor\) and Chiaramonti, D.\(editor\), Publications Office of the European Union, 2024.](#)

³³ https://single-market-economy.ec.europa.eu/industry/sustainability/net-zero-industry-act_en

³⁴ <https://www.clariant.com/en/Corporate/News/2023/12/Clariant-shuts-its-sunliquid-bioethanol-plant-in-Romania>

conveyed key messages across three primary areas, namely **industrial opportunities**, **collaboration** and **policy & market**.

With regards to seizing **industrial opportunities**, it is crucial that **European industries maintain** their **competitiveness** and avoid disadvantages in global markets. In this respect, the European Commission has recently (January 2025) presented The Competitiveness Compass³⁵, a strategic roadmap to boost Europe's economic growth and competitiveness. An additional insight regarding industrial achievements was the importance of becoming a **first mover in technology development**. Furthermore, several interviewees underlined the value of **thoroughly demonstrating new technologies** to minimize failures and hence ensure their viability. If industrial failures occur, understanding of the causes is vital to further enhance strategic advancements, paving the way for successful implementation and sustained industrial growth.

Concerning **collaboration**, several messages appointed towards the need to **enhance and reinforce existing partnerships** to secure the entire value chain. This requires forming **strong teams** that bring together experts from both the **scientific community and businesses**. Strengthened collaboration between **regulators and traditional oil and gas companies** was also highlighted as a key driver to invest in SAF production, providing that return of investment is assured. Additionally, **technology providers** should **enhance coordination**, jointly work on solutions, and openly share information – to the greatest extent possible - to foster innovation and efficiency.

Most of the future recommendations addressed **policy & market** aspects and a first message was that **airlines should be encouraged**—through regulations—to **adopt SAF despite current cost disadvantages**. However, multiple interviewees stressed that in the absence of a coordinated support strategy and the establishment of **stable and long-term offtake agreements** and **regulation**, crucial to ensure the bankability of SAF projects. Another recommendation to policy makers is that they must strike a **balance** between **regulation and flexibility**, allowing temporary measures like book and claim to facilitate market entry. **Large energy providers**, such as ExxonMobil and Shell, should take on a **greater role**, leveraging their financial capacity and risk tolerance to drive technological advancements. Additionally, experiences from successful demonstration projects in the past, including Güssing, GobiGas, BioTfuel, and Chemrec, indicate that these technologies should receive continued support to transition into commercial viability and facilitate their entry into the market.

9 Outcomes from the co-creation webinar series

This chapter complements the intelligence gathered from the initial literature review (WP1) and the 16 in-depth interviews with key stakeholders and R&I experts by incorporating additional insights from a co-creation webinar series. This series consisted of three events, each dedicated to one of the technological pathways explored within ICARUS.

The co-creation process generated valuable outputs through:

- Expert presentations: Each webinar featured three carefully selected external experts, who provided targeted insights.
- Participant contributions: attendees shared individual inputs via the Teams Whiteboard digital tool.

Beyond the invited speakers, each webinar brought together a diverse group of experts and stakeholders, including:

- Technology and value chain specialists from industry and academia

³⁵ https://commission.europa.eu/document/download/10017eb1-4722-4333-add2-e0ed18105a34_en?filename=Communication_1.pdf

- Members of EU sister projects such as BioTheRos and SUSTEPS
- The 16 interviewees
- ICARUS Advisory Board members
- End-user representatives
- EU policymakers
- Relevant IEA communities, including Task 33 (Gasification), Task 34 (Liquefaction), Task 39 (Transport Biofuels), and TCP Advanced Motor Fuels

To ensure focused and productive discussions, the webinars were organized as closed, *by-invitation-only* events. This format enabled deeper technical engagement and facilitated an efficient co-creation process.

Each webinar followed a structured format comprising three main segments:

1. **Brief introduction of ICARUS and presentation of key project findings** (~ 30 min), highlighting drivers, barriers, innovation potentials, and lessons learned within the investigated value chain. These findings were based on the competence internally generated within the project and the additional analysis of the 16 dedicated interviews. This segment was used to set the scene.
2. **Targeted expert inputs** (~ 30 min), offering specialized perspectives aligned with the webinars' thematic focus. For that, three renowned experts were asked to share a brief insight into the value chain from their point of view. To ensure coherence and alignment with the webinar's objectives, individual pre-meetings were held with each expert to discuss their contributions and streamline content across them.
3. **Interactive co-creation discussions** (~ 60 min), where participants, with the guidance of a moderator, exchanged insights and experiences on drivers, barriers and innovation potentials, contributing to the development of best practices and scalable concepts for Sustainable Aviation Fuel (SAF). Additionally, once all inputs were provided, attendees were also encouraged to indicate which ones they considered most and least relevant.

9.1 Co-creation webinar on biocrude oils to SAF

9.1.1 Insights from the external presentations

In the first co-creation webinar with focus on biocrude oils to SAF (held on 3rd June, 14-16 CEST, with 36 participants), the following three selected speakers, representing both the research community and industry, shared their insights into drivers, barriers and innovation potentials of the value chain:

- *Patrick Biller, Associate Professor, Aarhus University, Denmark*
- *Valentin Batteiger, Coordinator Future Aviation Fuels, Bauhaus Luftfahrt, Germany*
- *Umesh Pandey, Process Engineer, Silva Green Fuel, Norway*

Starting with **DRIVERS**, a handful of key factors were identified. The first drivers mentioned referred to **feedstock** and particularly to the potential of **using residues and wastes** such as manure, wastewater sludge, food waste and digestate from anaerobic digestion to provide significant volumes of biocrude. With the use of such feedstock, regions with high population density can become key hotspots due to the abundant availability of sewage sludge and municipal solid waste (MSW). Rural areas can also play a significant role, particularly in the context of agricultural residues. These feedstocks share common characteristics: they are widely available (although highly variable), contain high levels of water and inorganic materials, and are rich in phosphorus (P) and nitrogen (N), which make these feedstocks unsuitable for many other technologies. The **efficiency** of the hydrothermal liquefaction process was also underlined as a significant driver. HTL technology exhibits relatively **high carbon and thermal conversion efficiencies**. Approximately 60% of the carbon content is successfully converted into fuel. Additionally, the heat transfer occurs between liquid phases which allows to design highly **efficient** heat exchangers for **heat recovery**. A key advantage of the process is its

relatively low energy demand, which is largely due to the unnecessary feedstock drying step and the utilization of water in its liquid phase.

A third driver brought up by the selected speakers was related to **economies of scale**. For the production and distribution of SAF via hydrothermal liquefaction, a **hub-and-spoke distribution model** can be a **key enabler of economies of scale**. With such model, the spoke-plants, located near the biomass sites, will locally produce HTL-based biocrude. The biocrude, which is a concentrated energy product, will then be transported to a larger, centralized facility, i.e., the hub-plant, where the oil will be upgraded to SAF. In this way, the high penalty to transport wet feedstock, typically used in HTL, will be minimized, while the upgrading can benefit from increased economics of scale.

When moving on to **BARRIERS**, a comprehensive list of key factors was presented as well. Regarding **feedstock**, important challenges are 1) the cost aspect of **transporting wet biomass** feedstocks, where dewatering may minimize the costs this barrier represents and 2) **feedstock properties**, especially challenging ones, influencing the HTL product quality and process performance. The HTL biocrude **resembles**, to some extent, **the characteristics of the feedstock used**, which can result in poor biocrude qualities with increased upgrading needs when certain feedstock is used. HTL-based SAF produced from sewage sludge, for instance, exhibits some properties very similar to conventional jet fuel. However, its high residual nitrogen content poses significant challenges. Additionally, HTL biocrudes derived from residues often contain micropollutants and heavy metals, which may even limit their suitability for upgrading to fuel.

A second main constraint hindering the scalability and commercialization of the HTL process is **process water management**. The HTL process generates **large volumes** of process water, approximately 7 cubic meters per cubic meter of biocrude produced, with a **highly complex composition**. The process water generated has high chemical oxygen demand (COD), and high levels of aromatics, nitrogen, and other compounds. **Water recycling** within the HTL process can limit the amount of process water generated but is only feasible for dry feedstocks like straw and wood, and thus not feasible when applying the HTL technology on highly wet feedstock such as sludges. Another significant issue related to processing water is the **presence of recalcitrant or inhibitory compounds**, posing challenges for biological wastewater treatment.

Operational challenges attributed to **erosion**, **fouling** and **corrosion** remain major barriers in HTL implementation. The HTL feedstock is prepared as slurry of particulate matter and water, which causes erosion and wear on piping and reactor components. In addition, char and coke formation - both inherent to the HTL process - pose further constraints. Coke deposits on reactor surfaces, valves and piping, leading to fouling, operational disturbances and even reactor blockages. Additionally, the presence of solids in biocrude requires a separation process. **Corrosion**, caused by certain compounds in the feedstock and aggravated by corrosive species such as oxygen, chlorides, alkalis, and carbon dioxide, is another critical issue, resulting in system degradation, including leaks, ruptures, and reduced durability of the equipment.

Lastly, the external speakers pinpointed the fact that HTL-produced SAF is **not ASTM-certified** yet as another major barrier to market entry. Meeting jet fuel specifications requires multi-step pretreatment, conditioning, and upgrading processes. Different HTL biocrudes often need tailored upgrading approaches, and nitrogen and contaminants removal—especially from feedstocks like sewage sludge with up to 30%wt nitrogen—requires harsh processing conditions.

The three invited speakers were also asked to provide their views on **INNOVATION OPPORTUNITIES**. Multiple innovations were identified across the value chain, starting with opportunities for process **water valorisation**. Anaerobic treatment has shown potential; however, the COD load is mentioned as a burden. A promising alternative is non-catalytic wet oxidation which has been explored by Aarhus University during the past years. This is an exothermic process that besides providing heat to HTL, allows recovery of valuable compounds such as ammonia, volatile fatty acids (VFAs) and CO₂. Advancements in all these areas could be key enablers to unlock the full potential of HTL technology. A second major innovation opportunity is carbon capture, utilization and storage (CC(U)S) as CO₂ can

be nearly fully recovered (>90%), allowing e-fuels production when combined with hydrogen and carbon-negative biofuels production when sequestered. **Phase separation** remains a key challenge and therefore several innovations are needed in this field. A reliable, efficient, economic and sustainable system for biocrude recovery needs to be established and inspiration can be drawn from oil sands and other dirty petroleum products. Further research and innovation are also needed on biocrude **upgrading** such as catalyst development (beyond standard petroleum refining catalysts) for SAF production. More research is also needed on biocrude issues such as N-containing aromatics, metal content and boiling point distribution with regards to jet cut. The need to better understand the performance of reactors such as slurry hydrotreaters and fluid catalytic cracking (FCC) when different HTL biocrudes are considered was also pinpointed as relevant. A last innovation potential mentioned regarding upgrading was related to general improvements in the oil quality by identifying the optimal process window that minimizes fouling. Other innovation opportunities lay around **HTL-reactor design**. As an example, the Danish company Circlia Nordic has co-developed, together with Aarhus University, an integrated system where wet oxidation is combined with HTL, significantly improving the energy efficiency and introducing new solutions for heat and pressure exchange as well as solid separation. Another best-practice came from the Norwegian company Silva Green Fuel which observed significant improvements when utilizing **corrosion-resistant alloys** that improved the durability of the reactor material. It is essential to keep on conducting comprehensive testing of alternative construction materials in high-temperature and high-pressure environments, along with the redesign of critical heat exchanger components using cost-effective, corrosion-resistant materials. As for solids formation and fouling, hindering continuous operation, reactors need to be re-designed to allow for **continuous solid removal**. Additionally, optimized operational parameters and flow characteristics in feed heaters and reactors can help mitigate fouling, improving the overall process stability and efficiency.

After sharing their insights on drivers, barriers and innovation potentials, the speakers were challenged to reflect over how they see the role of the HTL-based biocrude for **FUTURE SAF PRODUCTION**. Their main take away is that the potential to play an important role is there, however, it is uncertain to which extent it will do so. They pointed out that marine fuel is the largest fuel fraction from wood liquefaction and only a limited portion (less than 10%) of the upgraded oil becomes SAF after current upgrading methods. If the share of SAF is to become larger, additional upgrading or other chemical modifications as well as further research and innovation will be required.

9.1.2 Additional gains from the co-creation exercise

The co-creation process led to fruitful and interactive discussions moderated by Judit Sandquist, research scientist at SINTEF.

Figure 9.1 illustrates the **DRIVERS** compiled during the co-creation session. Participant contributions from the process are displayed in lowercase letters. The key findings from the project until that point in time were also added as a reference with text in capital letters.

The drivers identified revolved around three main categories and related to those provided by the external speakers, i.e., 1) feedstock, 2) product/market and 3) economies of scale.

With regards to **feedstock**, the co-creation session highlighted the benefits of **converting wastes and residues**, with large potential and management problems in the EU, as well as plastic management opportunities. HTL has the potential to serve as a **waste management solution** for feedstocks such as straw, manure, and maize stover, and has emerged as an attractive option for treating various waste streams, including sewage sludge. In the specific case of manure, continuous conversion via HTL can eliminate greenhouse gas emissions associated with mandatory manure storage whereas in the case of sewage sludge, where contaminants such as drugs or PCB/PFAS are of concern, these can be destructed under HTL. Additionally, wastewater can be cleaned with algae that is later processed via HTL and adds the benefit of capturing CO₂ from the air during its growth. Finally, co-processing solid

and liquid feedstocks (e.g., solid agricultural waste combined with sludge) can help optimize the feed intake for the process.

Regarding **markets and products**, the collected drivers provided additional insights and also introduced new or previously overlooked perspectives. The potential of HTL to produce marine fuels, which require a less demanding upgrading process compared to SAF, was identified as a key driver for accelerating the early scale-up of this technology. Furthermore, several inputs reflected the advantage of HTL - and its variants like HTL-Wet Oxidation of HTL-Hydrothermal Gasification – of enabling **nutrient recovery** (primarily phosphorous (P) and nitrogen (N)) and fertilizer production. **Phosphorus (P)** on the one hand, has limited global reserves, its recovery and recycling are increasingly strategic and essential, and in fact, policymakers are already addressing this issue. In Germany, for instance, operators of sewage treatment plants will be mandated to recover and recycle P from sewage sludge from 2029 at the latest ³⁶. On the other hand, excess phosphorus sprayed on already saturated fields results in environmental damage, therefore the spreading of manure is limited in many countries in Europe. Recovery of the phosphorus from waste feedstocks and its reuse in phosphorus as a separated fertilizer in lean areas is therefore imperative. In addition to P, HTL processes also allow for the **recovery of nitrogen (N)**, primarily as ammonia recovered from the aqueous phase. The recovery can be potentially maximized when applying wet oxidation or hydrothermal gasification.

Concerning **economies of scale**, the inputs emphasized the opportunity of **integrating decentralized and centralized** fuel production concepts, aligning with the hub-and-spoke model. The advantage of transporting high-quality biocrude from HTL facilities located in small, decentralized sites, to larger, centralized upgrading plants were highlighted. This approach supports efficient logistics and SAF scalability. In addition, HTL compared to, for example, anaerobic digestion, requires less space, making it easier to integrate into smaller communities. Its smaller footprint contributes to a better economy of operation.

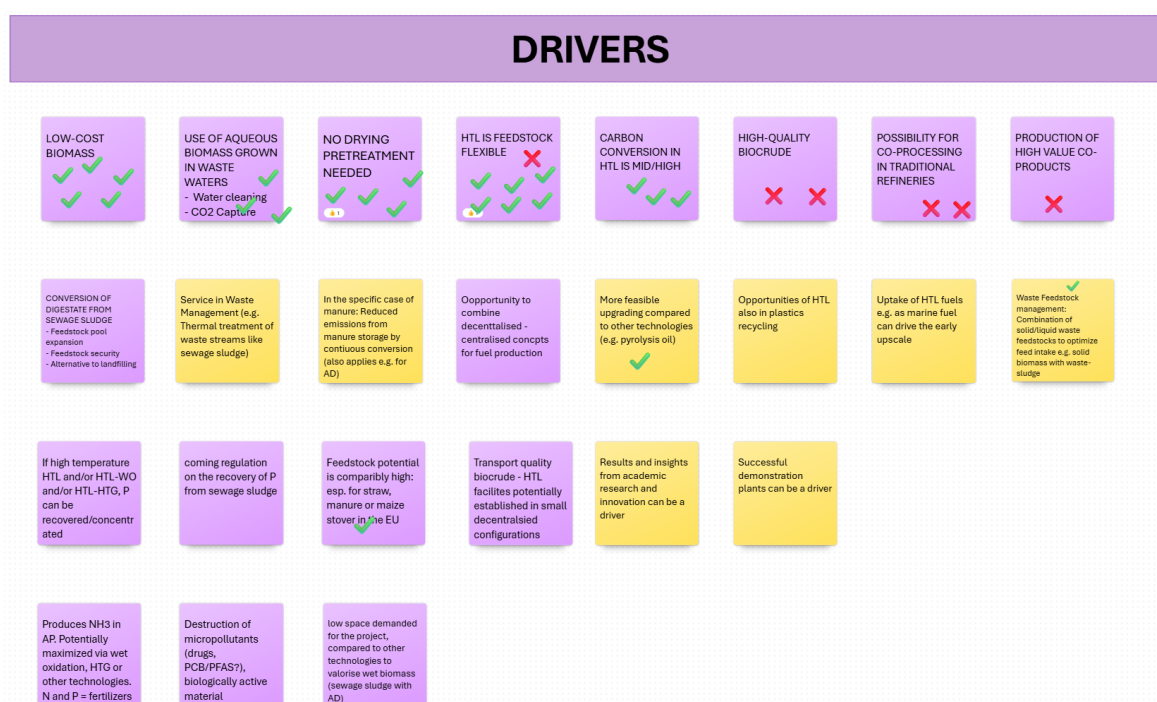


Figure 9.1. Compilation of drivers shaping the *Biocrude oils to SAF* value chain. Green check marks and thumb up icons indicate high relevance, and red crosses indicate less relevance to the participants

³⁶<https://magazin.tu-braunschweig.de/en/pi-post/phosphorus-recycling-from-sewage-sludge-to-plant-fertilise/#:~:text=By%202029%20at%20the%20latest%2C%20operators%20of%20sewage,for%20decades%2C%20will%20then%20no%20longer%20be%20possible.>

The other highlighted drivers encompassed the following:

- successful demonstration plants
- more feasible product upgrading compared to similar processes such as pyrolysis oil
- Results and insights from academic research and innovation

Among all the notes gathered, the following were indicated as highest relevance to the participants:

- HTL is feedstock flexible
- Low-cost biomass
- No drying pre-treatment needed
- Potential utilization of aqueous biomass grown in wastewaters
- Mid/high carbon conversion

On the contrary, the drivers that were given lower priority were:

- Production of high-quality biocrude
- Possibility for co-processing in traditional refineries
- Production of high value co-products

Moving on to **BARRIERS**, the number of inputs grew remarkably, making evident the need for further research and innovation (see Figure 9.2).

Also in this section, a significant number of the opinions mentioned by the participants correlated directly with some of the constraints shared by the selected speakers. The first main group of inputs referred to **feedstock and its contaminants**. Although feedstock flexibility is positive, it comes at a cost. As mentioned before, the HTL product closely reflects the composition of the original feedstock, meaning that contaminants present in the feed not only persist in the resulting biocrude but can also lead to operational issues. As a result, the biocrude oil **upgrading** can be very challenging, necessitating the removal of contaminants either upstream, downstream, or through a combination of both approaches. These upgrading requirements explain why raw HTL bio-oil cannot be simply co-processed in existing oil refineries for transportation fuel. Instead, some pre-conditioning - such as contaminant removal and moderate catalytic upgrading - is essential before integrating into refinery streams. **Fouling and corrosion** related barriers were also identified as critical issues, as they lead to operational troubles too. If not properly addressed, these challenges can impede long-term continuous operation and must be resolved prior to upscaling and achieving stable production.

Concerns were also raised about **management of the water in the process**. Key challenges included the need to treat the water phase. Generically speaking, due to its high contaminants and COD content, the water phase cannot be directly discharged to nature or to wastewater treatment plants. It also contains large amounts of carbon that is lost into the aqueous phase during the HTL process. The chemistry of HTL is highly complex with many reactions involved, which is not completely understood yet. In terms of **phase separation**, two barriers were highlighted, i.e., i) the fact that biocrude oils are not completely hydrophobic and therefore retain certain amounts of water and ii) creation of emulsion with water and phase-flip phenomenon where, under certain conditions, biocrude droplets become encapsulated in the aqueous phase, contributing to carbon loss.

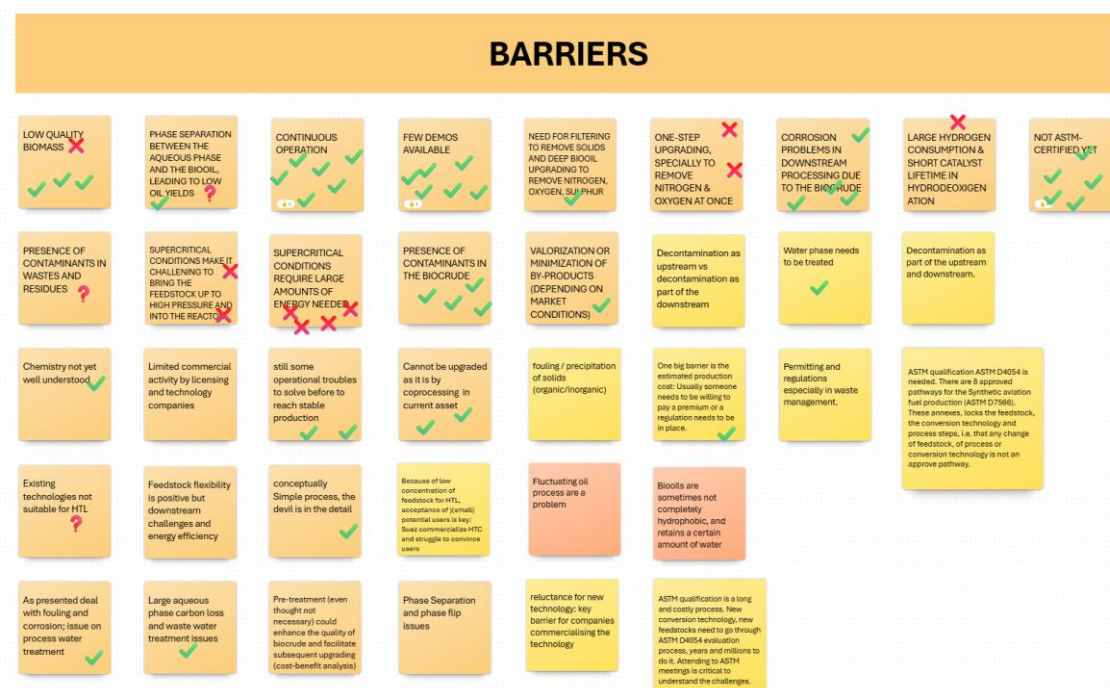


Figure 9.2. Compilation of barriers shaping the *Biocrude oils to SAF* value chain. Green check marks and thumb up icons indicate high relevance, and red crosses indicate less relevance to the participants.

Also, in line with the key messages by the selected speakers, barriers connected to **ASTM-certification** were identified by the crowd. The technological pathway certifications strictly define all elements along the value chain, from feedstock to conversion technology and process steps. Therefore, any modification of any of these elements will require a new certification process. Fuel certification for aviation takes loads of time, huge quantities of fuel products need to be delivered, and the process is very costly, therefore, active participation in ASTM-meetings is critical to understand the challenges and requirements.

Participants shared several new insights, with most discussions centring around the challenges of **commercializing emerging technologies** like HTL which are often hindered by several key factors. A major barrier is the high production costs estimations that often require buyers to either pay a premium or rely on supportive regulatory frameworks to bridge the price gap. Regulatory hurdles were also highlighted with regards to permitting processes in waste management. Another major barrier to commercialization of the biocrude oils to SAF value chain through HTL is the widespread reluctance among companies to adopt new technologies, which significantly slows down their path to market.

The attendees were asked to prioritize the barriers that should be given more attention in the coming years, and to identify those that could be deprioritized.

The most relevant barriers according to our participants were:

- Continuous operation
- Few demos available
- HTL-based SAF not being ASTM-certified yet
- Presence of contaminants in the biocrude
- Corrosion problems in downstream processing
- Low quality biomass

Whereas those least prioritized were:

- Supercritical conditions require large amounts of energy and make it challenging to bring the feedstock up to high pressure and into the reactor

- One-step upgrading to remove nitrogen and oxygen at once

After completing barriers, the group engaged in discussing **INNOVATION POTENTIALS** to effectively overcome such barriers and help accelerate the upscaling of this technological route. Figure 9.3 depicts the inputs gathered during the process.

Also in this category, many of the participants' contributions were well aligned with the perspectives shared by the invited speakers, mainly regarding innovation opportunities in improving HTL process, phase separation, water valorisation and upgrading processes.

Regarding process improvement, promising areas of innovations were identified, notably around novel HTL concepts. A necessary innovation yet to be achieved is the development of a **robust and stable HTL process** capable of producing **biocrude with consistent quality** over extended periods. This would mark significant advancements in overcoming one of the main challenges in bio-oil production, i.e., process variability, which can hinder commercialization and scale-up. Two specific recommendations have been proposed in this respect: i) incorporation of a **feedstock pre-treatment** to remove feedstock contaminants and ii) **salt separation** technologies, where the **integration of supercritical water salt separation** into the HTL process was explicitly mentioned. Salt accumulation has long been a challenge in HTL systems, affecting biocrude quality, equipment durability and process stability. By incorporating salt separation within the process, both the quality of the biocrude and overall operational efficiency can be improved, while also minimizing maintenance requirements. Further, at the interphase between HTL processing and upgrading, **catalytic HTL** has been proposed to “pre-upgrade” the biocrude and hence reduce the burden in downstream processes. In parallel, researchers are also exploring the idea of **hybrid systems** that combine HTL with other technologies such as pyrolysis or fermentation with the purpose of further enhancing carbon efficiency and optimizing the product portfolio.



Figure 9.3. Compilation of innovation potentials shaping the *Biocrude oils to SAF* value chain. Green check marks and thumb up icons indicate high relevance, and red crosses indicate less relevance to the participants

In the area of **phase separation**, one notable proposal involved the use of **in-situ additives** in three-phase separators to avoid emulsion-related challenges. A second innovation addressed the **improvement of the hydrophobicity** of the biocrude.

Regarding **water valorisation**, experts emphasized the importance of **recovering catalysts and organic acids**, alongside strategies for recycling the process water back into the process, highlighting the potential for increased sustainability and resource efficiency.

Several innovations were also identified in the upgrading step. These included **advancements in catalyst development**, specifically the combination of hydrodeoxygenation (HDO) and hydrodenitrogenation (HDN) catalysts in a stacked bed configuration to optimize the overall upgrading performance. Another interesting idea was the co-processing of HTL-derived biocrude in existing central HDO units within HEFA plants, which could effectively reduce feedstock scarcity in those refineries while minimizing capital intensity.

Other innovation potentials highlighted during the co-creation process include:

- **integration of HTL within a broader circularity framework**, not only from a technological standpoint but also in terms of communication strategies. By framing HTL as a circular solution, it becomes more attractive to policymakers, investors, and the public.
- use of **blended waste feedstocks blends**, both liquid and solid
- **co-processing of pyrolysis oil with conventional feedstocks in HTL**, offering new opportunities for valorising diverse biomass streams and improving biocrude yields."
- **Identification of working business cases** to enable a viable commercialization strategy

When asking our participants to indicate the relevance of the compiled innovation potentials, the following results were obtained:

Most relevant

- Aqueous phase valorisation
- Salt separation technologies
- Robust process capable of producing biocrude of consistent quality over long time
- Integration of HTL with green hydrogen
- Valorisation of by-products

Once the three main blocks addressing drivers, barriers and innovation potentials were completed, the experts were invited to share their perspectives on the **ROLE OF BIOCRUDE OILS AND HTL IN FUTURE SAF PRODUCTION**. Initial reflections highlighted concerns around the fact that with a future with limited fossil fuel availability, aviation is likely to become a luxury, and society may prioritize the use of diesel and **marine fuels over SAF**. Along these lines, one participant noted that HTL-derived fuels may find a more suitable entry market in maritime applications. This view was justified by technical and certification challenges in aviation, particularly related to ASTM standards which do not exist yet.

At the same time, several experts expressed a more optimistic perspective. In terms of HTL-based biocrude production, the **potential** lies in its access **to abundant feedstock** and **relatively low production cost**. However, some participants indicated that the volumes of available waste-feedstock may be insufficient and limit scalability. Further, it was also mentioned again that if HTL biocrude could be **co-processed in existing HEFA HDO reactors** at certain blend ratios (i.e., <10%) alongside other renewable feedstocks, it would be beneficial. Similarly, if the biocrude could serve as **blendstock with Fischer-Tropsch liquids**, it would offer further integration opportunities.

Demonstration projects are essential to validate the feasibility of HTL biofuels for aviation and to advance the technology to higher readiness levels.

Figure 9.4 provides an overview of the compiled statements.

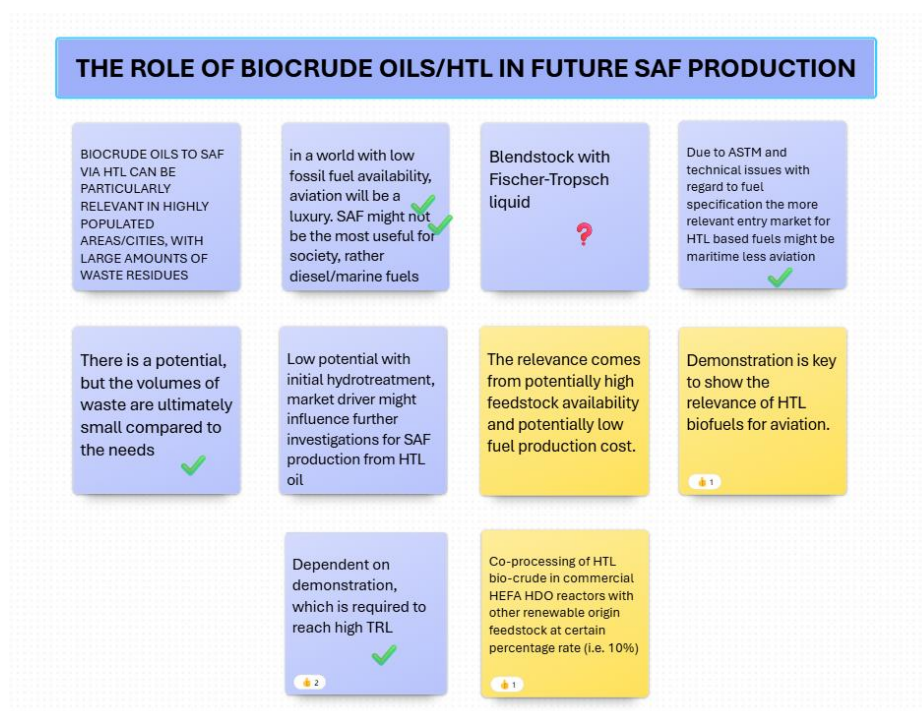


Figure 9.4. Compilation of statements on the role of the *Biocrude oils to SAF* value chain. Green check marks and thumb up icons indicate high relevance, and red crosses indicate less relevance to the participants

Among the above formulations, the need for more demonstration projects and the fact that society might deprioritize SAF over diesel or marine fuels were voted as the most relevant factors defining the future role of HTL-derived biocrude oils to SAF.

Finally, the participants were given the opportunity to provide additional lessons learned and experiences complementing all previous inputs and two concrete observations were noted:

- Large fluctuations on oil prices severely slows the development of alternatives
- In case of high pH feedstock such as black liquor: low Ni content stainless steels are much more resistant – high Ni content steels (hastelloy, Inconel) show very fast corrosion (BL2F project result³⁷)

9.2 Co-creation webinar on syngas to SAF

9.2.1 Insights from the external presentations

The second co-creation webinar focused on syngas to SAF (held on 24th June, 14 -16 CEST, with 34 participants), built on the momentum of the first event on biocrude oils to SAF. Once again, three distinguished speakers, representing both academia and industry, shared their perspectives on the drivers, barriers, and innovation opportunities within the syngas to SAF value chain. The expert panel featured:

- *Philippe Marchand, Independent Biofuels Expert and Consultant, France*
- *Michael Hecquet, Head of R&D Advanced Fuels, TotalEnergies, France*
- *Robert Burton, Principal Process Engineer, Sasol, South Africa*

³⁷ D. Blücher, T. Lange, J. Sandquist, I. Saanum, M. Uusitalo, *Mater. Corros.* 2024, 75, 1258–1271.

The **DRIVERS** that can be extracted from the presentations by the three selected speakers can be gathered around four main blocks, i.e., feedstock, technology, market and partnerships.

Regarding **feedstock**, the syngas converted through Fischer-Tropsch can be derived from a wide range of **low-cost** waste and green streams, including lignocellulosic residues from agriculture and forestry, industrial waste, wastewater treatment sludge and municipal solid waste. This **feedstock diversity** reduces supply risk - a critical factor for scaling SAF production.

In terms of **technology**, the speakers highlighted technology readiness as a key driver. The FT route is already **industrially proven** for coal- and natural gas-derived syngas, and only minor modifications are required to process renewable feedstocks and produce SAF (and other green fuels) from renewable feedstocks. This positions FT as one of the most mature and commercially viable SAF pathways, ahead of alternatives such as the methanol route. Decades of operational experience, combined with ongoing catalyst innovations, will further enhance performance.

For syngas production via gasification, TRLs vary by feedstock. Gasification of MSW, for instance, is at high TRL (8-9) while integrated bio-based gasification and FT processes are at commercial pilot stage, indicating strong momentum toward full-scale deployment.

Beyond maturity, the presenters highlighted that the pathway delivers the best **environmental performance** among the three assessed routes in ICARUS, achieving a life-cycle greenhouse gas (GHG) emissions reduction of around 94%, making it a leading option for decarbonizing aviation.

As for **market**-related factors, a major advantage is that SAF produced via FT has been **ASTM-certified** since 2009, enabling immediate market entry without regulatory barriers.

Multiple insights were shared regarding **partnerships**. Moving toward green solutions is costly and complex, but collaboration can significantly reduce barriers and speed up deployment.

First, stakeholders should leverage **existing know-how** and strengthen **industry-academia** alliances, while actively forming **new partnerships** to fill knowledge gaps. Integration and cooperation across all technology elements - from feedstock supply to catalyst development - will make a lasting difference in achieving commercial maturity. *CARE-O-SENE*, a German - South African research initiative sponsored by the German Government (BMBF) was showcased as a strong example of best practice. This project brings together partners from both countries, each contributing specialized knowledge in catalyst research and technology development. Such international cooperation demonstrates how coordinated efforts can drive innovation and accelerate SAF commercialization.

Turning to the identified **BARRIERS**, the presentations by the selected speakers highlighted three main categories, i.e., feedstock, technology and market.

Securing **feedstock** remains one of the most critical challenges. Key resources for the syngas to SAF value chain, such as lignocellulosic residues and municipal solid waste (MSW), as noted under the drivers section – are widely **scattered**, frequently located in **remote areas** difficult to access, and lack an organized collection and supply infrastructure. This fragmentation creates persistent **logistical obstacles**, as these residues are often managed through diverse and uncoordinated practices.

Beyond these logistical hurdles, **local regulations** add another layer of complexity that, alongside limited biomass availability, require integrated approaches and innovative pathways to ensure a sustainable and reliable feedstock supply.

The **technological** barriers highlighted by the speakers did not only refer to the syngas to SAF process but also to the gasification step prior to the syngas conversion.

Starting with **biomass gasification** - it is **yet to be proven at industrial scale** for syngas production in a relevant scale and despite significant technological progress has been achieved in recent years, persistent technical challenges continue to hinder large-scale deployment. Variations in feedstock composition, moisture, ash chemistry and contaminants can cause operational issues such as agglomeration, slagging, fouling, tar formation, corrosion and demanding gas-cleaning requirements.

In lower-temperature fluidized-bed systems, challenges are often associated with the gasifier and raw-gas handling, whereas high-temperature entrained-flow gasification generally produces a cleaner syngas but requires extensive feedstock preparation. The closure of Fulcrum Sierra BioFuels in 2024³⁸ highlights the importance of reliable feedstock processing, gasification and syngas conditioning when scaling waste-to-fuels technologies.

A key hurdle is the **management of methane, tars and ash**, whose formation is highly dependent on operating conditions. Methane and condensable tars in the syngas stream reduce conversion efficiency for downstream fuel synthesis. Additionally, tars can condense at low gasification temperatures, causing severe clogging and blockages within the reactor system. In parallel, ash derived from alkali species in the biomass introduces additional operational risks, including slagging, fouling, bed agglomeration and corrosion. Preventive strategies to limit ash formation and deposition are therefore essential for process stability and efficiency.

Moving on to the syngas conversion step via FT, additional constraints were identified. First, the complex cocktail of **contaminants in syngas** usually poisons/deactivates the catalysts, reducing activity and shortening their lifetime. Second, **high water partial pressures** further complicate the process, impacting negatively catalyst activity and selectivity.

Building on these barriers, several additional considerations were brought up to the audience regarding Co-Low Temperature **FT catalysts** and reactor **requirements**. Among these it is worth noting that catalyst should:

- Deliver high activity to reduce catalyst consumption and operate at high syngas conversion for small-scale economics
- Ensure selectivity toward jet fuel and middle distillates over 80%
- Provide enhanced stability to maintain yields of wax while enabling a wider operation range
- Limit the formation of fines to ease wax-solid separation
- Produce added-value products such as base oils and hard wax
- Achieve process efficiency with carbon utilization above 95%.

Beyond chemistry the speakers also highlighted systemic challenges when **scaling**, as many factors do **not scale linearly** when moving from lab to pilot and full-scale reactors. Key issues include variations in heat and mass transfer, mixing patterns, undesired temperature gradients, and changes in catalyst performance. In the case of FT, today's commercial reactors designed for coal and gas operate at scales much larger than what is feasible with biomass feedstock, requiring downscaling, while new lab-scale reactor designs demand upscaling. These complexities underscore the critical importance of applying established scale-up methodologies and leveraging industrial know-how to avoid the well-documented *Valley of Death* between pilot and commercial deployment – particularly through semi-commercial facilities for catalyst scale-up and testing.

Finally, one needs to keep in mind that different technology blocks of the value chain are not all at the same technology readiness (industry wide). The entire biomass to SAF chain has not been demonstrated at scale, with components at different TRLs and high financial risk for large-scale deployment.

These factors collectively underscore the need for breakthrough innovations in catalyst design, process integration, and system flexibility to enable commercial viability.

When considering **market** barriers, two key aspects stand out. First, there is a clear need for a significant **product premium** to enable market adoption. Second, the gasification-FT (syngas to SAF) value chain currently ranks relatively **low in terms of merit order** when assessed by the **Minimum Selling Price** (MSP) of SAF³⁹, particularly in the short term (pioneer plants around 2030) and when using

³⁸ <https://cen.acs.org/energy/Fulcrum-BioEnergy-abandons-trashfuel-plant/102/web/2024/06>

³⁹ <https://www.ieabioenergy.com/wp-content/uploads/2024/06/IEA-Bioenergy-Task-39-SAF-report.pdf>

agricultural and forestry residues. In comparison, alternative pathways such as HEFA or Alcohol-to-Jet are more competitive under these conditions. However, the ranking improves when municipal solid waste (MSW) is used as feedstock. Looking ahead to the longer term (nth-of-a-kind plants around 2050), competitiveness improves further, but gasification-FT remains non-competitive compared to the other two pathways except in cases where MSW is utilized. It is important to note that capital expenditure (CAPEX) accounts for approximately 50% of the MSP for Gasification-FT. Therefore, achieving future improvements in this pathway will require substantial reductions in capital costs.

The selected speakers also shared their perspectives on **INNOVATION** opportunities for future developments.

The first speaker highlighted **Methanol Oligomerization**, derived from the methanol-to-olefins process originally developed 50 years ago, as an innovative and alternative route to Fischer-Tropsch (FT) synthesis. This approach offers approximately 10% higher efficiency compared to current FT processes. However, it is important to note that this pathway is not yet commercially implemented and lacks ASTM certification.

A second innovation focused on the **integration of gasification and e-fuels** for SAF production. This concept was illustrated through the well-known French project **BioTfuel**, which combines gasification of natural waste with electrolysis, resulting in an **e-BTL** (electro-based Biomass-to-Liquid) process. Electrolysis generates hydrogen and oxygen: hydrogen enhances carbon availability, while oxygen serves as the gasification agent. This configuration eliminates the need for a Water Gas Shift reaction.

Finally, it was underlined the critical need to develop **next-generation catalysts for SAF production**, aiming to further maximize profitability and process efficiency. For that, selectivity and water tolerance are identified as critical.

To conclude, the speakers were asked to share insights on the **future role of the gasification-FT** value chain for SAF production, and the following reflections were made. In the near term, this pathway is expected to remain limited to demonstration projects and industrial qualification, with commercial deployment unlikely before 2030. However, its mid-term potential is considerable. FT firmly retains a place at the table for sustainable fuels, enabling the conversion of syngas derived from either biomass/waste or from electrolysis. Looking ahead to 2050, gasification-FT alongside e-SAF, could account for close to 50% of global SAF supply, driven by regulated demand and the availability of advantaged feedstocks. This growth will be reinforced by feedstock limitations on HEFA. In short, while gasification-FT will start slowly, its strategic role can expand largely, positioning it as a cornerstone of the SAF landscape in the long term.

9.2.2 Additional gains from the co-creation exercise

The second session in the co-creation series, dedicated to the syngas to SAF value chain, fostered engaging and productive discussions, facilitated by Berend Vreugdenhil, Researcher and Gasification Specialist at TNO, The Netherlands.

Figure 9.5 presents the **DRIVERS** identified during the session. Consistent with the previous session on biocrude oils to SAF, contributions from participants are shown in lower case, while the project's key findings to date are indicated in capital letters for reference.

The outcomes have been structured into three primary categories, i.e., feedstock, products and market, and integration.

Within the **feedstock** domain, three interconnected factors emerged as critical. First, the **limited** availability of **lipid-based feedstocks** constrains the volumes of SAF that can be produced through HEFA processes. With SAF demand increasingly outpacing HEFA's supply capacity, there is a clear need for alternative conversion routes, such as syngas to SAF. Second, the gasification-FT technological pathway offers a high degree of **feedstock flexibility**, thereby improving security of feedstock supply

and, in turn, strengthening the resilience of the entire value chain. Lastly, gasification can process heterogeneous **feedstock mixtures** which have been reported to enhance process efficiency. This improvement is partly attributed to the presence of inorganic components, such as alkali metals, which adopt a catalytic role and increase syngas production.

Regarding **products and market**, multiple drivers stood out. In terms of products, one major advantage is the ability to produce multiple **drop-in products** including SAF, naphtha, LPG, etc., which serve diverse markets and enhance economic viability. This **multiproduct flexibility** allows stakeholders to adapt to market demands and optimize revenue streams.

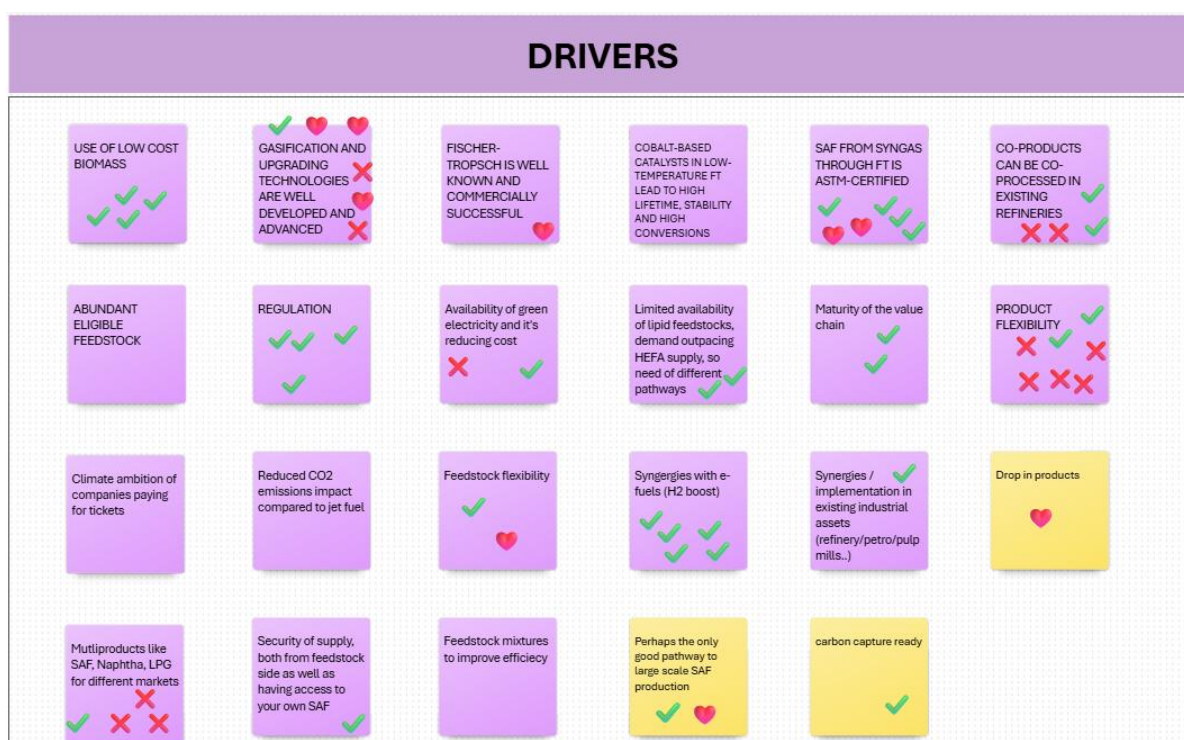


Figure 9.5. Compilation of drivers shaping the *Syngas to SAF* value chain. Green check marks and hearts icons indicate high relevance, and red crosses indicate less relevance to the participants

Several **market**-related aspects were also identified, starting with **growing climate ambitions** – particularly in voluntary markets where companies and consumers are willing to pay premiums for low-carbon travels – which are accelerating SAF uptake and reinforcing the need for scalable solutions. In this context, the participants pinpointed that the syngas to SAF value chain is perhaps the only **viable pathway for large-scale SAF production**, thanks to the significant scalability potential of gasification-FT technologies. This value chain also benefits from **technological maturity** and **carbon capture** readiness, positioning it to meet stringent future emissions regulations. Moreover, compared to conventional jet-fuel, syngas-derived SAF achieves significant **CO₂ emission reductions**, thereby improving its environmental footprint. Finally, the syngas to SAF value chain contributes to **securing access to SAF**, making it critical for long-term preparedness for fuel suppliers and airlines.

The last category of collected drivers focused on **integration** opportunities. Participants highlighted the advantages of creating **synergies with e-fuels** to enhance hydrogen availability and optimize the FT process. Additionally, leveraging existing industrial assets such as refineries, pulp mills, etc., was seen as an enormous benefit to reduce costs and accelerate deployment.

The insights that received the highest relevance among participants were:

- Syngas-to-FT based SAF is ASTM-certified
- Synergies with e-fuels (e.g. H₂ boost)
- Use of low-cost biomass

- Regulation

On the contrary, the drivers that were given lowest priority were:

- Product flexibility
- Multiproducts like SAF, naphtha, LPG, for different markets

After the section on drivers, the discussions concentrated on **BARRIERS**. Figure 9.6 shows the barriers identified during the co-creation session. Contributions from participants are shown in lower case, while the project's key findings to date are indicated in capital letters for reference.

Similar to the insights provided by the invited speakers, the barriers identified can be categorized into three main dimensions: feedstock, technology and economy of scale, and policy and market.

With regards to **feedstock** several critical challenges were highlighted. The first relates to the high **moisture content** of the required feedstock, which poses a significant obstacle, as gasification technology demands dry material. Lowering moisture levels is highly energy-intensive, thereby adding complexity and operational costs. The second challenge concerns **strong competition** for the same type of feedstock across multiple applications – particular emphasis was made on heat power on its use for heat and power generation. Additionally, **logistical constraints** were identified as a third barrier – in line with one of the inputs provided by the selected experts. These challenges become increasingly pronounced at larger scales, as the distance between feedstock sources and the plant must expand to secure sufficient supply, leading to higher transportation costs and operational complexity.



Figure 9.6. Compilation of barriers shaping the *Syngas to SAF* value chain. Green check marks and hearts icons indicate high relevance, and red crosses indicate less relevance to the participants

Multiple challenges related to **technological aspects and economy of scale**. First, the **limited availability of low-cost, non-intermittent renewable energy** sources, such as hydropower, restricts the potential for producing green hydrogen at scale. This is critical because **green hydrogen** is required to minimize carbon losses (~ 50% of the carbon is emitted as CO₂ across the biomass-to-fuel pathway)

during conversion (particular emphasis was made to the Water-Gas-Shift (WGS) step), yet its **production remains prohibitively expensive** due to the high cost of electrolyzers. Additionally, the process demands fine gas cleaning (parts-per-billion levels) to meet FT synthesis requirements, introducing significant cost and complexity to the overall process.

In terms of economy of scale and building on the logistical challenges associated with feedstock and mentioned above, participants insisted in the mismatch between feedstock availability and the scale required for FT operations. They stressed the importance of designing and **scaling FT concepts in alignment with feedstock supply constraints**, considering both upstream and downstream requirements, which vary depending on feedstock quality. **Past experiences** from projects such as **Choren** and **BioTfuel** illustrate these challenges clearly: difficulties in gathering sufficient biomass and the need to scale-down FT units and gas cleaning systems. Additional barriers include the comparatively **high** capital expenditure (and GHG mitigation costs) of this pathway relative to other SAF production value chains, as well as concerns around **societal acceptability**, given the large volumes of biomass required to achieve economies of scale.

The final category addressed a combination of **policy and market** barriers that significantly hinder the deployment of syngas-based SAF. The current **political instability** creates long-term uncertainty around regulations and mandates, discouraging investors from committing capital to new projects. This challenge is reinforced by **insufficient incentives to bridge the price gap** between syngas-based SAF and other production pathways, particularly HEFA, which up to date, remains the only commercially available SAF option. This provides little motivation for end-users (airlines) to pay extra for these fuels. Furthermore, **imports of SAF** are often preferred over domestic production within the EU because they are cheaper and easier to source, further weakening the business case for local projects. Without strong and stable policy signals combined with mechanisms to improve market competitiveness, the deployment of syngas-based SAF remains highly constrained.

Beyond these barriers, the participants identified several **critical needs**. First, regulations should ensure that the **carbon value** - measured as CO₂ avoided - is recognized equally for SAF and its co-products, creating a level playing field across all outputs of the process. Second, **financial support** mechanisms are required to reduce the contribution of **capital costs** to overall production costs, thereby improving project economics and bankability. Finally, targeted **funding** should be provided for **engineering studies, demonstration plants, and First-of-a-Kind (FOAK)** projects to de-risk technology and accelerate commercialization.

The barriers considered most relevant by the participants were:

- High CAPEX across the value chain
- Production cost
- Feedstock competition for multiple uses
- Variation in the chemical composition of the feedstock

On the other hand, those regarded as least relevant were:

- Availability of low-cost green energy which is not intermittent
- Low selectivities to SAF in the FT process
- The level of moisture content of the feedstock and the energy intensity required to reduce such content

After concluding the discussions on barriers, the co-creation process shifted to addressing **INNOVATION POTENTIALS**. The insights collected – primarily around two main topics, i.e., feedstock and technology/new concepts – are depicted in Figure 9.7. Participant contributions are presented in lowercase, while the project's key findings to date are highlighted in uppercase for reference.

Beginning with **feedstock**, further research is required to ensure **flexible feedstock qualities** that support long-term operation of FT facilities, securing both supply and pretreatment processes.

Moreover, innovations should focus on **harmonizing diverse feedstock types** through pretreatment to produce a more uniform and commoditized material.

Most of the innovations and research needs identified during the co-creation process related to technology development and new concepts. In line with the barriers outlined earlier, key priorities include **reducing the energy intensity** of SAF production pathways, **improving contaminants control**, and developing **alternative syngas cleaning** approaches. Innovations in **catalyst design** is another critical area, with promising concepts such as integrating FT catalysts with zeolite phases for hydrotreatment and advancing **materials circularity** through catalyst regeneration to minimize its consumption.

Further research should also target the development and commercialization of **novel gasification methods**, including plasma and supercritical water gasification (SCWG). In addition, strategies for **co-processing** are essential to enable the transformation of fossil-based refineries into renewable facilities. Leveraging **synergies between biomass and e-based technologies**, such as the eBTL-FT concept should also be explored.

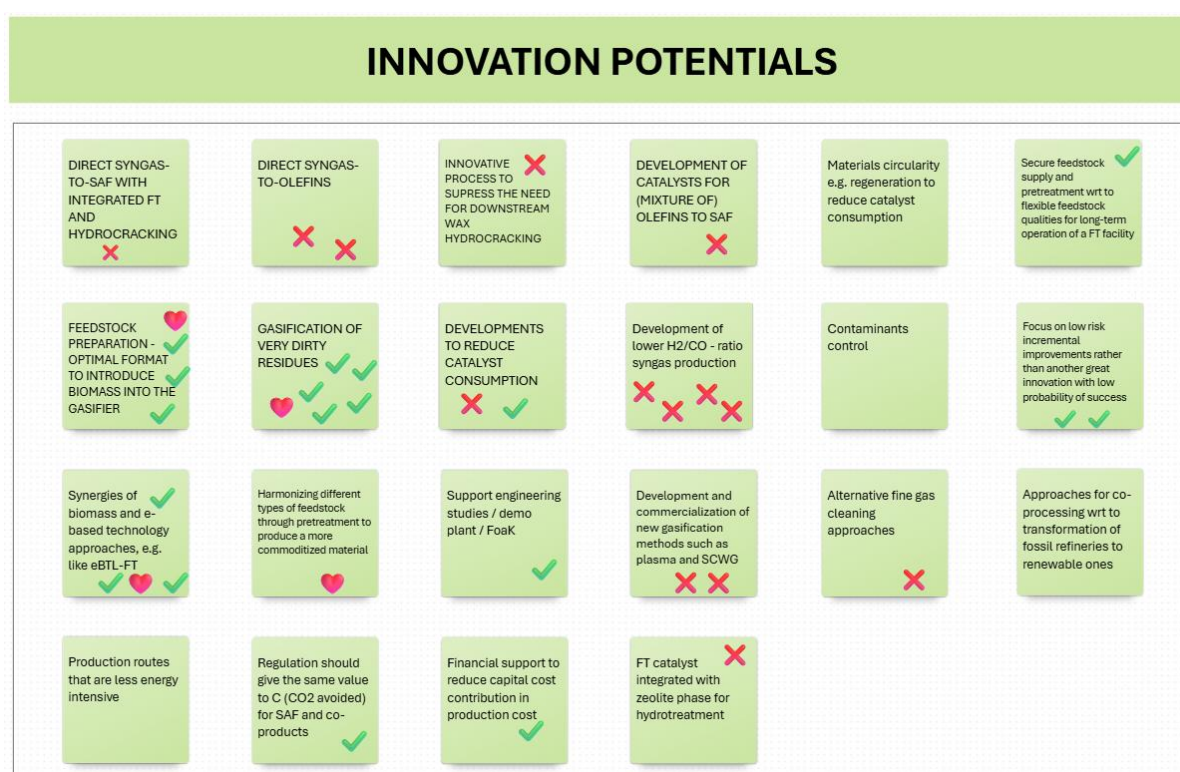


Figure 9.7. Compilation of innovation potentials shaping the *Syngas to SAF* value chain. Green check marks and hearts icons indicate high relevance, and red crosses indicate less relevance to the participants

Finally, participants emphasized – more generally - the importance of prioritizing **low-risk incremental improvements** that deliver practical benefits, rather than pursuing high-risk breakthroughs with limited probability of success.

Of all the innovation opportunities and research needs outlined in Figure 8.7, participants identified the following as most relevant:"

- Gasification of very dirty residues
- Feedstock preparation – optimal format to introduce biomass into the gasifier
- Synergies of biomass and e-based technology approaches such as eBTL-FT

As for the least relevant, participants selected the following aspects:

- Development of lower H₂/CO ratio syngas production

- Direct syngas-to-olefines
- Development and commercialization of new gasification methods such as plasma and SCWG

Towards the end of the co-creation session, participants reflected on the **ROLE OF THE GASIFICATION-TO-SYNGAS-FT PATHWAY IN FUTURE SAF PRODUCTION**, and several perspectives emerged (see Figure 9.8). While some participants expect this route to play a pivotal role in scaling SAF production in Europe, with potential for deployment across multiple countries and regions, others emphasized its relevance as a transitional solution while Power-to-Liquid (PtL) technologies mature and become commercially viable.



Figure 9.8. Compilation of statements on the role of the *Syngas to SAF* value chain. Green check marks icons indicate high relevance.

Another key insight highlighted the importance of integrating the gasification technology into new industrial complexes capable of production not only SAF but a broader portfolio of products, thereby improving economic viability and resource efficiency.

Finally, it was noted that no single pathway will meet future SAF demand. According to IEA Net Zero scenarios, global SAF production must increase tenfold by 2050 compared to today's levels. This underscores the need for all available alternatives, including gasification-based routes, to work in parallel to achieve the required scale. Participants identified this point as the most significant insight of all those collected.

To close the session, a compilation of additional lessons learned, and experiences was made (see Figure 9.9).



Figure 9.9. Compilation of lessons learned/experiences regarding the *Syngas to SAF* value chain. Green check marks icons indicate high relevance.

Past experiences with gasification-based SAF projects reveal that failures have significant consequences. Learning from setbacks - such as the Fulcrum case - is essential, as these failures not only highlight technical and strategic gaps but also make future fundraising more difficult. To prevent repeating mistakes, stakeholders should establish an open framework for sharing experiences and lessons learned, fostering transparency and collaboration across the value chain.

Equally important is the regulatory and policy environment. A long-term, stable legal framework is needed to de-risk investments and provide certainty for project developers. At the same time, reducing regulatory complexity will be critical to enable technology scale-up and continuous improvement, ensuring that innovation can move from pilot to commercial deployment more efficiently.

Additional insights included the need for the EU to focus more on Carbon Intensity (CI) rather than the very strict sustainability criteria existing in the current Renewable Energy Directive (REDIII). Combined with greater pragmatism in project development, these measures will help create the conditions for success.

9.3 Co-creation webinar on alcohols to SAF

9.3.1 Insights from the external presentations

The third co-creation webinar focused on alcohols to SAF (held on 27th October 15 -17 CEST, with 36 participants). For this particular webinar it was decided to extend the scope from isobutanol to jet to a more general alcohols-to-jet to capture as much relevant insights as possible. This time four speakers, representing key industrial players in the value chain, shared their perspectives on the drivers, barriers, and innovation opportunities within the alcohols to SAF value chain. The expert panel consisted of:

- *Andrew J. Ingram, Director Process Chemistry and Catalysis, Gevo, USA*
- *Björn Heijstra, VP Commercial Innovation, LanzaTech, B.V., Netherlands*
- *Juha Anttila, Vice President of Technology, Chempolis Ltd., Finland*
- *Johan Thevelein, Founder & Managing Director, NovelYeast, Belgium*

The **DRIVERS** that can be extracted from the presentations by the three selected speakers can be gathered around SAF mandates, feedstock flexibility and process integration.

The presentations collectively underscored that the primary driver for ATJ deployment is the **scheduled increase in SAF mandates**, especially in Europe and the U.S., which demands a substantial scale-up in production. ATJ is expected to meet a major share of future SAF demand, driven partly by the limited availability of suitable feedstocks for HEFA. The speakers also highlighted that the **growing market for sustainable products** is strengthening demand for carbon-recycling technologies. Rising regulatory pressure, stronger corporate climate targets, and the need for scalable feedstock options together reinforce ATJ's strategic importance within the SAF landscape.

From a **feedstock** perspective, the ATJ process offers considerable **flexibility**, accommodating everything from conventional sugar- and starch-based materials to more advanced lignocellulosic biomass. Although the first-generation, sugar- and starch-based feedstocks are not eligible under EU regulation, SAF produced from them can be cost-competitive outside of EU. ATJ from those feedstocks is expected to have prices below HEFA over time, and even approach fossil jet fuel costs in integrated production systems. Lignocellulosic ATJ pathways can also **achieve cost reductions through process integration**. With global SAF demand projected to rise steeply, the ATJ route represents a significant opportunity. Lignocellulosic biomass stands out as the most abundant long-term resource, giving ATJ pathways utilizing such feedstocks the greatest potential by 2050.

Isobutanol adds further market flexibility because it can be efficiently converted to jet fuel or blended into gasoline, diesel, and marine fuels. Presenters emphasized that isobutanol can be converted **more efficiently to hydrocarbons** than ethanol, strengthening its role as a promising intermediate. Additionally, gas-fermentation pathways using point-source carbon emissions were highlighted as

innovative and potentially more cost-competitive than lignocellulosic routes, owing to the concentrated and consistent nature of gaseous feedstocks. The **scalability of gas fermentation** was highlighted together with illustrations on continuous production exceeding 300-day runs, and the potential for carbon-negative fuels using biogenic and renewable energy inputs

Finally, **integrating green hydrogen** into ATJ processes, which are necessary for alcohol-to-jet conversion, enables producers to access **e-SAF regulatory incentives** for part of their fuel output. This creates an additional opportunity to improve carbon performance and economic viability within future SAF production systems.

Turning to the identified **BARRIERS**, the presentations by the selected speakers highlighted three main categories, i.e., market/regulatory conditions, feedstock and technology bottlenecks.

A major barrier highlighted by the presenters is the **limited availability of lignocellulosic ethanol**, which constrains the ATJ pathway in Europe, where **1G ethanol is not permitted as a SAF feedstock** under current regulation. This regulatory limitation restricts early-stage scale-up, as the sector cannot rely on the mature and abundant 1G ethanol industry to build initial capacity. In parallel, the speakers highlighted an additional regulatory factor: the planned ban on new internal combustion engine vehicles. Since road transport historically served as the large-scale outlet for biofuels production, especially ethanol, this upcoming shift may further hinder production volumes and learning-curve effects that could otherwise benefit ATJ deployment. Market barriers also relate to the **absence of stable long-term demand** signals in some regions, which can deter investment in capital-intensive ATJ facilities.

Feedstock variability emerged as another major challenge for all bio-based routes. Lignocellulosic and agricultural resources are grown across many locations, exposed to different climates, soils, and harvesting methods. The result is that no feedstock arrives at the processing plant with stable and predictable properties over time, requiring conversion technologies to tolerate significant fluctuations in composition and quality. This challenge is especially acute in lignocellulosic ethanol production and was also emphasized in gas-fermentation pathways, which must handle real-world variability in industrial off-gas streams.

The **biological and process engineering challenges** were a category that came into the light under the presentations. For isobutanol, the barriers include low titers, metabolic bottlenecks, formation of unexpected side-products, and pronounced toxicity, all of which **require advanced genetic engineering** as well as continuous in-situ product removal to prevent inhibition during fermentation. Similar biological constraints apply to lignocellulosic ethanol, where enzyme costs, inhibitor tolerance, and multi-sugar utilization remain major hurdles.

On the conversion side, although ATJ catalytic steps are technically mature, with units proven at commercial scale, the presenters stressed that **capital costs and energy requirements remain high**. Even when individual unit operations are commercially demonstrated, integrating them into a streamlined, optimized end-to-end system continues to pose financial and engineering difficulty.

The speakers also outlined a range of **INNOVATION** opportunities within feedstock utilization, genetic engineering and system integration, that could accelerate future development of the ATJ value chain.

A central theme across the presentations was the importance of **improving overall feedstock utilization**. Presenters highlighted that achieving full valorisation of the entire biomass, including lignin and other non-sugar fractions, will be essential for improving cost effectiveness and securing the economic viability of large-scale SAF deployment. One promising approach is **selective fractionation of lignocellulosic biomass**, which separates the feedstock into clean, well-defined streams suitable for producing high-value co-products such as biochemicals, bio-coal, and specialty lignin-derived materials. By enabling multiple product revenue streams, this approach enhances the financial robustness of SAF production while also improving material efficiency. The process CO₂ can further be captured and reused in e-SAF pathways, enabling additional decarbonization and access to regulatory incentives.

A second major innovation area concerns **reducing enzyme costs**, a long-standing barrier in cellulosic ethanol production. Upstream removal of lignin before enzymatic hydrolysis can significantly reduce enzyme demand, improving the economics of biomass conversion. This measure, combined with improved fractionation and co-production approaches, positions lignocellulosic ATJ pathways to become more cost-competitive in the medium term.

Innovations in genetic engineering, especially for isobutanol production were also highlighted as crucial for the value chain. Progress on achieving genetically engineered yeast strains capable of utilizing mixed sugars (xylose, glucose, cellobiose) and achieving higher productivity was pointed out. The development of advanced 2G isobutanol yeasts was presented as a key enabler for expanding feedstock flexibility. Moreover, breakthroughs in in-situ product removal, especially through membrane pervaporation, were identified as critical to mitigate the toxicity constraints of isobutanol and to reach economically viable titers.

Innovation opportunities presented indicate a strong convergence toward **integrated, multi-product biorefinery concepts**. Smarter process design can increase value capture across the supply chain. Next-generation ATJ catalytic systems, improved Ethanol-to-Olefins (ETO) routes, and integrated plant configurations can lower capital expenditure and improve energy efficiency. The system integrations mentioned aim to streamline the ATJ conversion process, reduce the number of steps, and improve overall yields, ultimately enabling faster commercialization of the ATJ route.

9.3.2 Additional gains from the co-creation exercise

The interactive co-creation session in the webinar, devoted to the alcohols to jet value chain, facilitated by Iker Aguirrezabal from the University of the Basque Country, generated collaborative discussions with constructive sharing of perspectives among the participants.

Figure 9.10 presents the **DRIVERS** identified during the session. Consistent with the previous sessions on biocrude oils to SAF and syngas to SAF, contributions from participants are shown in lower case, while the project's key findings to date are indicated in capital letters for reference.

The outcomes have been structured into three primary categories, i.e., feedstock, conversion and process integration as well as regulatory and certification aspects.

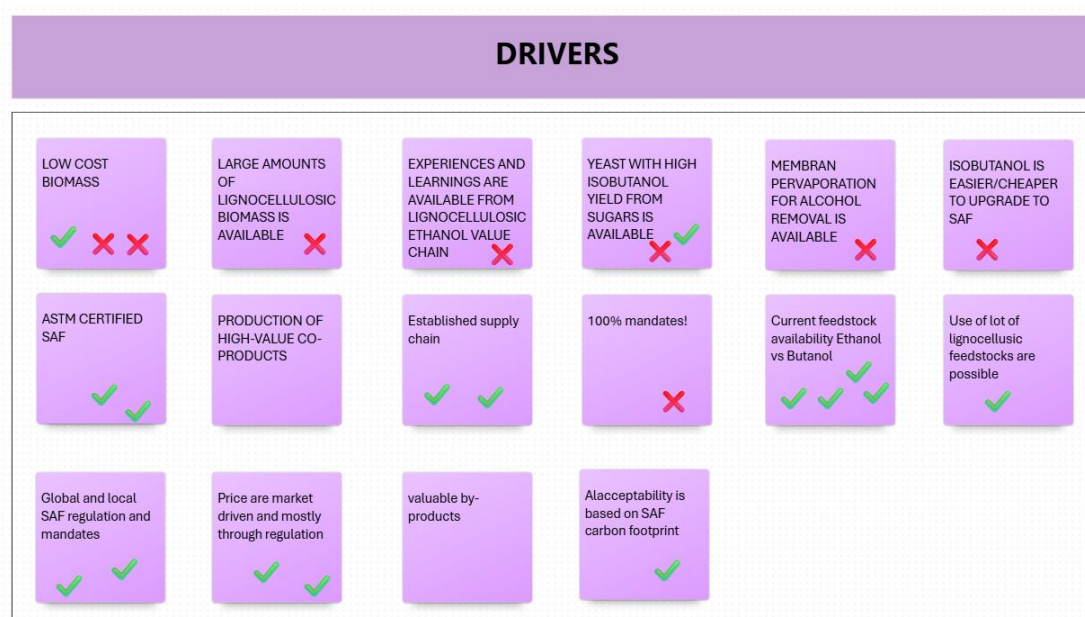


Figure 9.10. Compilation of drivers shaping the *Alcohols to SAF* value chain. Green check marks and hearts icons indicate high relevance, and red crosses indicate less relevance to the participants

Several drivers relate to the availability and nature of biomass and alcohol intermediates. The **use of low-cost biomass** was identified as a potential enabling factor for the ATJ value chain. Closely related to this is the **availability of large amounts of lignocellulosic biomass**, which is considered relevant due to its non-food character and potential to support advanced biofuel production.

The ATJ pathway is also linked to **existing experience within the lignocellulosic ethanol value chain**, including accumulated experience and learnings from previous development and demonstration activities. The possibility of using a wide range of lignocellulosic feedstocks was highlighted, reflecting the flexibility of upstream biomass sourcing options.

Differences between alcohol intermediates were addressed as well. Statements included the current feedstock availability of ethanol compared to butanol, as well as the notion that isobutanol is easier or cheaper to upgrade to sustainable aviation fuel (SAF). In addition, the potential for yeasts with high isobutanol yields from sugars and their availability at scale was included among the identified drivers.

The ATJ value chain was further characterized by statements related to processing and separation technologies. One such aspect is the **availability of membrane pervaporation for alcohol removal**, reflecting interest in advanced separation technologies that could influence process efficiency and costs.

The upgrading of alcohols to SAF was discussed in relation to both ethanol and isobutanol, highlighting the relevance of conversion complexity, yield, and integration into downstream fuel production. The presence of **valuable by-products** was also identified as a relevant factor, as by-product valorisation can contribute to overall process economics and system efficiency.

Several drivers relate to the maturity and structure of the ATJ value chain. The existence of an **established supply chain** was identified as a relevant characteristic, particularly in connection with alcohol production, logistics, and handling infrastructure. This includes links to existing industrial operations and distribution systems.

Regarding the regulatory and certification aspects, the availability of **ASTM-certified SAF** was identified as a key element of the ATJ value chain, reflecting the importance of fuel qualification and compatibility with existing aircraft and infrastructure.

In addition, **global and local SAF regulations and mandates** were identified as influential drivers shaping the development and deployment of ATJ fuels. These include policy instruments that affect demand creation, compliance requirements, and long-term market signals.

The concept of 100% mandates was listed among the discussed drivers, alongside considerations related to policy ambition and implementation pathways. Furthermore, price and market development driven primarily through regulation was identified as a defining feature of the current SAF market context.

Finally, sustainability performance and allocation mechanisms were addressed. The allocability of fuels based on **SAF carbon footprint** was identified as a driver, reflecting the role of lifecycle greenhouse gas performance in determining eligibility, compliance, and market value within SAF frameworks.

Participants identified several drivers as relevant for the development of the Alcohol-to-Jet (ATJ) value chain. Central among these are regulatory and market-related drivers, including global and local SAF regulations and mandates, as well as price and market development being mainly driven through regulation. The availability of ASTM-certified SAF was also highlighted as a key enabling factor, underlining the importance of certification for market access and airline uptake.

From a value-chain perspective, the presence of an established supply chain, namely, the existing ethanol production and logistics, was considered highly relevant. Participants also identified current feedstock availability favouring ethanol over butanol and the possibility to use a wide range of lignocellulosic feedstocks as important drivers. In addition, the role of lifecycle greenhouse gas performance in SAF eligibility and market value was regarded as a significant factor.

Other potential drivers were viewed as less relevant in the current context. These include assumptions related to the large-scale availability of lignocellulosic biomass and the availability of yeasts with high isobutanol yields from sugars at scale. Similarly, statements suggesting that isobutanol is easier or cheaper to upgrade to SAF were not considered a strong driver.

Participants also attributed lower relevance to specific process technologies, such as the availability of membrane pervaporation for alcohol removal, and to policy concepts such as 100% mandates, which were not perceived as a near-term driver for ATJ deployment.

Figure 9.11 presents the **BARRIERS** identified during the session. The barriers have also been structured into three primary categories, i.e., feedstock and its pretreatment, technical barriers identified in the conversion process as well as challenges related to regulatory framework and market conditions.

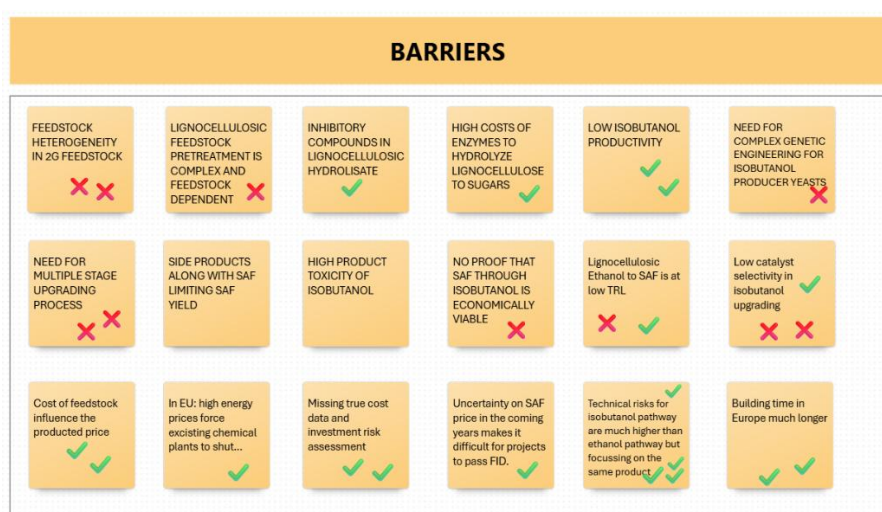


Figure 9.11. Compilation of barriers impeding the wider commercialization of the *Alcohols to SAF* value chain. Green check marks and hearts icons indicate high relevance, and red crosses indicate less relevance to the participants

Several barriers relate to the intrinsic properties of feedstocks used in the ATJ value chain. **Feedstock heterogeneity** in Annex IX part A feedstocks was identified as a challenge, reflecting variability in composition and quality across lignocellulosic materials. Closely linked to this is the barrier that **lignocellulosic feedstock pretreatment is complex** and feedstock-dependent, highlighting the need for tailored pretreatment strategies depending on biomass type.

Barriers related to alcohol production were also prominently identified. The presence of **inhibitory compounds** in lignocellulosic hydrolysates was identified as another barrier, as such compounds can negatively affect downstream fermentation and conversion processes. In addition, high costs of enzymes to hydrolyse lignocellulose to sugars were identified as a significant constraint, affecting overall process economics.

Low isobutanol productivity was included as a limiting factor, reflecting challenges in achieving high yields and productivities in fermentation processes. Related to this, the **need for complex genetic engineering** for isobutanol-producing yeasts was identified as a barrier, pointing to technical complexity and development effort in strain optimization.

Concerns were also raised regarding **high product toxicity of isobutanol**, which can inhibit microbial activity and constrain achievable concentrations during fermentation. These biological constraints were further linked to the **absence of proof that SAF produced through isobutanol is economically viable**, highlighting uncertainty around cost competitiveness.

The ATJ conversion process itself was characterized by several barriers. The need for **multiple-stage upgrading processes** was identified as a challenge, reflecting the number of conversion steps required to transform alcohols into jet-range hydrocarbons. In addition, **low catalyst selectivity** in isobutanol upgrading was identified as a barrier, pointing to challenges in achieving high yields of desired fuel fractions.

Another barrier relates to technology maturity, with the statement that **lignocellulosic ethanol to SAF is at low technology readiness level (TRL)** included among the identified constraints. This reflects the early development stage of certain integrated pathways combining advanced feedstocks with ATJ upgrading.

The role of co-products was also framed as a potential barrier. The production of such co-products alongside SAF is lowering the main product yield, highlighting that by-product formation can reduce the overall fuel yield.

Multiple barriers relate directly to costs and economic conditions. **Feedstock cost influencing the product price** was identified as a key constraint, underlining the sensitivity of ATJ economics to biomass and alcohol pricing.

Region-specific economic challenges were also highlighted, including the statement that in the EU, **high energy prices force existing chemical plants to shut down**, indicating an unfavourable operating environment for energy-intensive processes. Furthermore, **missing true cost data and investment risk assessment** was identified as a barrier, pointing to gaps in reliable economic information for project developers and investors.

Uncertainty about future market conditions was captured by the statement that **uncertainty about SAF prices** in the coming years makes it difficult for projects to pass final investment decision (FID). This reflects the broader challenge of long-term price visibility in emerging SAF markets.

Finally, several barriers relate to technical risk and regional implementation conditions. Technical risks for the isobutanol pathway being much higher than for the ethanol pathway when focusing on the same product was identified, highlighting comparative uncertainty between different alcohol intermediates.

In addition, **building time in Europe being much longer** was identified as a barrier, reflecting regulatory, permitting, and construction timelines that can delay project implementation relative to other regions.

Several barriers were identified as significant constraints on the ATJ value chain. Economic and market-related uncertainties included the uncertainty about future SAF prices, which complicates project bankability and final investment decisions, as well as the lack of robust cost data and investment risk assessments.

Participants also highlighted feedstock cost influencing the final product price as a major barrier, along with high energy prices in Europe, which negatively affect the viability of energy-intensive chemical and fuel production facilities. In addition, longer building and permitting times in Europe were identified as a relevant regional barrier.

From a technical perspective, higher technical risks associated with the isobutanol pathway compared to the ethanol pathway were considered important.

Several technical and biological challenges were perceived as less critical barriers. These include feedstock heterogeneity in second-generation feedstocks, complex and feedstock-dependent pretreatment of lignocellulosic biomass, and the presence of inhibitory compounds in lignocellulosic hydrolysates.

Similarly, low isobutanol productivity, high product toxicity of isobutanol, and the need for complex genetic engineering for isobutanol-producing yeasts were not considered among the most pressing barriers. Other factors receiving lower relevance include low catalyst selectivity in isobutanol

upgrading, side-product formation limiting SAF yield, and the perception that lignocellulosic ethanol-to-SAF pathways are at low technology readiness level.

Figure 9.12 presents the **INNOVATION POTENTIALS** identified during the session. The barriers have also been structured into three primary categories, i.e., process step developments, overall process development and regulatory innovations.

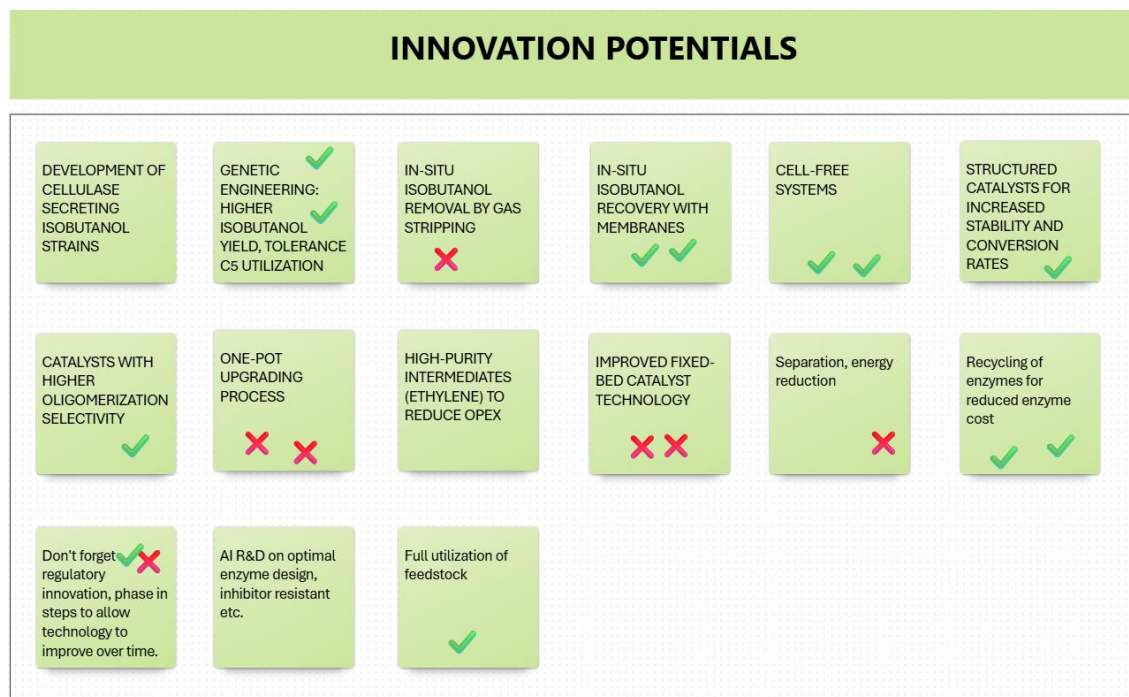


Figure 9.12. Compilation of innovation potentials shaping the *Alcohols to SAF* value chain. Green check marks and hearts icons indicate high relevance, and red crosses indicate less relevance to the participants

During the workshop the participants identified most of the innovation potentials related to individual technological steps. The first group of innovation potentials relates to biological and microbial developments. This includes the **development of cellulase-secreting isobutanol strains**, which could enable more efficient biomass conversion by integrating enzyme production into the microorganism thus the microorganism could hydrolyse its own sugar. In addition, a **cell-free system** concept is mentioned, representing an alternative bioproduction approach that decouples the conversion process from living cells. **Genetic engineering** aimed at achieving higher isobutanol yields, improved tolerance, and enhanced utilization of C5 sugars, addresses current challenges in fermentation performance and substrate use. Furthermore, **AI-supported research and development** for optimal enzyme design and **inhibitor-resistant systems** are identified as potential innovations of future improvements in bioconversion efficiency.

A second group concerns product separation, recovery and upgrading technologies. The participants highlighted options such as **in-situ isobutanol removal** by gas stripping or by using membrane systems, both of which aim to mitigate product inhibition and improve process efficiency. **Catalytic upgrading** is also central to the identified innovation potentials. These include **structured catalysts** designed for increased stability and higher conversion rates, as well as catalysts with **improved oligomerization selectivity**, which are relevant for enhancing the efficiency of converting alcohol intermediates into jet-range hydrocarbons. Additional process concepts include **one-pot upgrading** processes, which seek to integrate multiple reaction steps, and **improved fixed-bed catalyst technologies**, aiming to optimize established reactor configurations.

Another set of innovation potentials focuses on process optimization and cost reduction. For instance, the **production of high-purity intermediates** such as ethylene to reduce the OPEX is identified as a

potential lever for economic improvement. Similarly, **recycling of enzymes** to reduce enzyme costs addresses one of the key cost drivers in lignocellulosic conversion processes. Broader system improvements are reflected in the inclusion of separation and energy reduction measures and the full utilization of feedstock, both targeting increased overall process efficiency and resource use.

Finally, the participants pinpointed the importance of regulatory and systemic innovation, including the notion that regulatory frameworks should allow phasing-in of technologies over time, enabling continuous improvement and gradual scaling rather than requiring immediate full maturity.

Regarding priorities, the most prominent priorities are associated with biotechnological improvements (genetic engineering for higher yields and improved sugar utilization), membrane-based in-situ recovery, cell-free systems, advanced structured catalysts, catalyst selectivity improvements, enzyme recycling, and full utilization of feedstock. These areas reflect a strong focus on improving yields, process efficiency, and cost competitiveness across both the biological and catalytic stages of the ATJ value chain. In contrast, lower priority is attributed to in-situ gas stripping for product removal, one-pot upgrading processes, improved fixed-bed catalyst technology in its current form, and general separation and energy reduction measures. Mixed or moderate attention is given to regulatory innovation, high-purity intermediate production, and AI-driven enzyme development, which are recognized but not highlighted as the most immediate priorities.

As part of the webinar, participants were asked to provide their perspectives on the **ROLE OF ATJ VALUE CHAIN FOR FUTURE SAF PRODUCTION**. The responses consisting of two statements are shown in Figure 9.13.

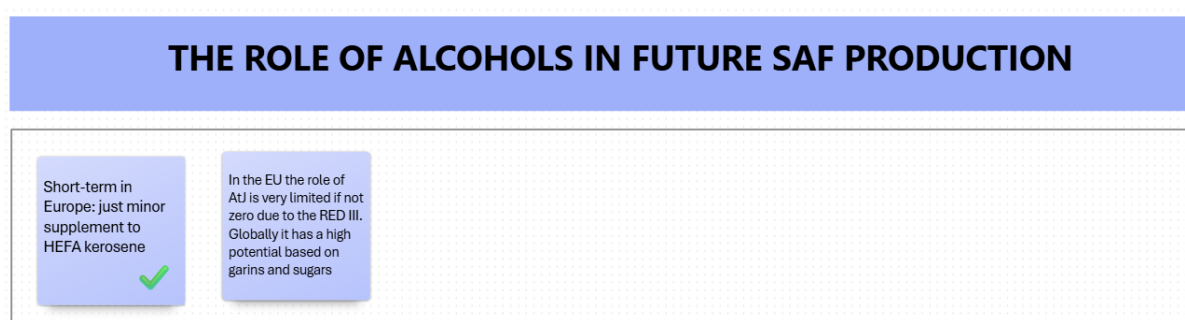


Figure 9.13. Compilation of statements on the role of the *Alcohols to SAF* value chain. Green check marks icons indicate high relevance.

There first statement indicates that in the short term and in Europe, alcohol-based pathways are expected to play only a minor role, primarily as a supplement to HEFA. This reflects the current dominance of HEFA in SAF production and suggests that alcohol-derived fuels are not yet positioned as a primary supply route in the European market. The second statement introduces a local limitation in a global perspective. It specifies that in the European Union, the role of ATJ is very limited or potentially negligible under the current Renewable Energy Directive (RED III), as it requires the alcohol to be produced from Annex IX part A feedstock. At the same time, the statement emphasizes that globally, the ATJ pathway is considered to have high potential, primarily due to the availability of grains and sugars as feedstocks. This reflects the scalability of alcohol production systems outside the European context and their relevance for future SAF production as well as the influence of policy frameworks on the deployment of alcohol-based SAF pathways, particularly in relation to feedstock eligibility and sustainability criteria.



Figure 9.14. Compilation of lessons learned/experiences regarding the *Alcohols to SAF* value chain. Green check marks icons indicate high relevance.

The webinar outcomes in Figure 9.14, reflect insights provided for the discussions about lessons learnt and experiences with the ATJ value chain.

The first key lesson emphasizes that technology can achieve progress and overcoming technical barriers, indicating confidence in the ongoing advancement of the ATJ value chain. At the same time, the statement stresses that technological progress alone is insufficient without supportive policy frameworks, as mentioned before.

A second statement addresses also a policy issue, namely instability and a potential risk factor. The absence of established market players, such as large oil companies contributes to financiers remaining cautious and delaying investment decisions. This reflects perceived risks associated with the ATJ value chain, where uncertainty in policy and market conditions can hinder access to capital and slow down project development.

A third key observation relates to geographical dynamics, indicating that technology development often takes place within Europe, while practical deployment and application occur overseas. This statement highlights a disconnect between innovation and implementation, suggesting that although research and development capabilities are strong in certain regions, more favourable conditions elsewhere may drive commercialization outside the EU.

10 Outcomes from the onsite co-creation workshop

On the 21 May 2026, ICARUS organised an on-site co-creation workshop entitled *SAF Upscaling – Time for Action!* at the 34th European Biomass Conference & Exhibition (EUBCE) in The Hague, serving as the second round of co-creation discussions. Based on the results achieved so far and a comprehensive assessment of suitable conferences, it was concluded that organising a single umbrella workshop would be the most impactful approach. This format, bringing together all three value chains within a unified framework – rather than the three separate workshops initially envisaged during the proposal phase – enabled ICARUS to build more effectively on the successful first round of webinars and to gather further input on best practices and concepts for SAF upscaling. It also facilitated integrated discussions across key horizontal dimensions such as sustainability, policy, and market considerations, while providing a valuable opportunity to engage the broader SAF community in a more cohesive manner. Furthermore, the workshop was designed to complement and align closely with other key SAF-related events at the conference, notably a high-level roundtable and an industrial track.

As Figure 10.1 shows, the workshop was structured around three main blocks. The first block, fully represented by ICARUS partners (SINTEF, CRES, University of the Basque Country, TNO, NTNU & DBFZ), focused on the technology dimension, starting with how innovative feedstock strategies can unlock large-scale SAF deployment and reduce reliance on limited resources. It presented then the latest conversion technology developments to overcome process limitations and accelerate

commercialization, concluding with an analysis of production costs and environmental impacts for the selected pathways.



Figure 10.1. Final programme of the workshop

The second block moved beyond technology to address policy frameworks, market dynamics, and sustainability certification requirements, including financing needs and instruments essential for SAF upscaling. This session engaged both project partners (KM-IIC and RSB) as well as a Maria Georgiadou, senior expert on renewable fuels, biofuels and bioenergy in the European Commission (DG-RTD).

Finally, the third block featured a panel discussion and interactive co-creation session, designed to gather diverse perspectives and integrate them into the ongoing ICARUS work on best-practices and concepts for SAF upscaling. The panel consisted of acknowledgeable leaders/senior representatives from both industry, academia and the European Commission:

- *Bart Suijkerbuijk, Global Head of Partnerships and Technology for Low-Carbon Fuels, Shell, The Netherlands*
- *Claudia Esarte Relanzón, Product Design Technical Advisor - Specialist in renewable liquid fuels, transport decarbonization and energy transition, Repsol, Spain*
- *Glauca Souza, Professor, University of Sao Paulo, Brazil (tbc)*
- *Ib Johanssen, Founder and CTO, Circlia Nordic ApS, Denmark*
- *Maria Georgiadou, Senior expert Renewable Fuels, Biofuels and Bioenergy, European Commission*

This closing session offered participants a unique opportunity to contribute directly to shaping future best practices and supporting the expansion of SAF across Europe and beyond.

The event brought together more than 60 participants from around the world – including Europe, Brazil, the United States, Thailand, and other regions – resulting in a fully packed room (see Figure 10.2) that clearly reflected the strong interest in, and high relevance of SAF upscaling.



Figure 10.2. Fully packed room during the event. On the left side, Berta Matas Güell (SINTEF) is introducing the project. On the right side, Judit Sandquist (SINTEF) is moderating the panel discussion.

10.1 Updates from the European Commission

Maria Georgiadou, Senior Expert on renewable fuels, biofuels, and bioenergy at the European Commission (DG RTD), opened her intervention with an overview of relevant EU policies for SAF, with particular emphasis on the legislative files within the Fit for 55 package.

She then introduced the AccelerateEU Communication, a strategy launched by the European Commission this spring 2026 in response to the energy crisis, with the aim of accelerating Europe's transition to clean energy. In relation to SAF, Ms Georgiadou highlighted that the strategy includes a dedicated section addressing the need to "increase domestic EU production of sustainable biofuels."

Furthermore, she presented key findings from the recent study *Mobilization of Industrial Capacity Building for Advanced Biofuels*, conducted by several organisations on behalf of the European Commission. A central takeaway from this study is that advanced biofuels can be produced sustainably within Europe, without relying on external technologies or feedstock from other regions.

In conclusion, Ms Georgiadou drew attention to two specific EU funding opportunities relevant to scaling up SAF production, encouraging participants to explore these opportunities and share the information with other relevant stakeholders.

10.2 Insights from the panel discussion

The panel discussion highlighted that, despite significant technological progress, the main barriers to large-scale SAF deployment are economic and regulatory rather than technical. Stakeholders broadly agreed that achieving bankability and ensuring stable returns on investment remain the central challenges. Within the current EU regulatory framework – including instruments such as ReFuelEU Aviation – important steps have been taken to stimulate demand and guide market development. However, these measures are not yet sufficient to guarantee predictable revenue streams for producers. This underscores the need for stronger market-stabilizing mechanisms, such as long-term offtake agreements, Contracts for Difference, and other financial instruments to reduce investment risk and enable scaling.

At the same time, the discussion pointed to broader limitations within the EU regulatory approach. The framework is often perceived as overly restrictive and compliance-driven, particularly when compared to more incentive-based systems in regions such as the United States and the United Kingdom. Better alignment between regulatory ambition and practical implementation is needed, finding a balance between robust sustainability and sufficient flexibility to support market uptake.

Another key insight is that scaling up SAF production will require a diversified portfolio of feedstocks, as no single resource can meet future demand. Although substantial biomass resources exist globally – especially in the Global South (e.g. Brazil) – much of this potential remains inaccessible due to complex and demanding certification requirements. Simplification, harmonization, and innovation in biomass certification methodologies, alongside improved traceability systems, are therefore essential.

Structural challenges in the value chain also persist, notably the mismatch between geographically dispersed biomass resources and the centralized nature of existing refining infrastructure, which limits economies of scale. The hydrothermal liquefaction technological pathway illustrates this challenge well, as its deployment remains limited by the relatively small volumes of suitable wet biomass available and therefore volumes of biocrude oils produced compared to the scale of existing refinery capacities.

Although technology itself is not considered the primary barrier, the panellists also agreed on the importance of continued technological innovation, pinpointing improvements in process efficiency, intensification, and flexible conversion pathways as key to enhance both economic performance and scalability. Greater flexibility in production systems, including the blending of intermediate products from different value chains, may also improve overall system efficiency, although this will require further research and regulatory adaptation. More broadly, sustained investment in research and innovation was also underlined as essential to address not only technological challenges but also cross-cutting issues related to sustainability, certification, and market integration.

Finally, the discussion reaffirmed the critical role of public support in advancing SAF deployment. EU funding instruments, particularly those aimed at de-risking FOAK plants, have been instrumental in bringing technologies to maturity. Overall, the panel emphasized that SAF upscaling requires a coordinated approach aligning policy, financial mechanisms, industrial capabilities, and research efforts, with a pragmatic focus on advancing viable solutions at scale.

10.3 Additional gains from the co-creation exercise

After two and a half intensive hours featuring excellent presentations and a lively, engaging panel discussion, the workshop concluded with a 30-minute interactive session designed to gather additional insights from participants. This final segment was organized into three thematic stations: one focused on policy and market-related issues (led by KM-IIC), another on SAF sustainability certification (led by RSB), and a third dedicated to technical innovations (led by DBFZ).

10.3.1 Station on Policy and Market

This station generated a substantial number of inputs covering both policy and market dimensions, identifying key drivers, barriers, and innovations, as presented in Figure 10.3 and detailed in Tables 10.1 and 10.2. Several of these inputs had not emerged from our previous online co-creation webinars, extensive in-depth interviews, or literature review. They therefore complemented and further enriched the findings obtained to date.

With regards to policy, participants identified sustainability and climate change mitigation as overarching **DRIVERS**, alongside the broader energy transition. They also emphasized affordability, socio-economic development, and increased independence as critical factors, while underscoring the need for secure and resilient (domestic) supply chains for stable supply of energy and daily goods.

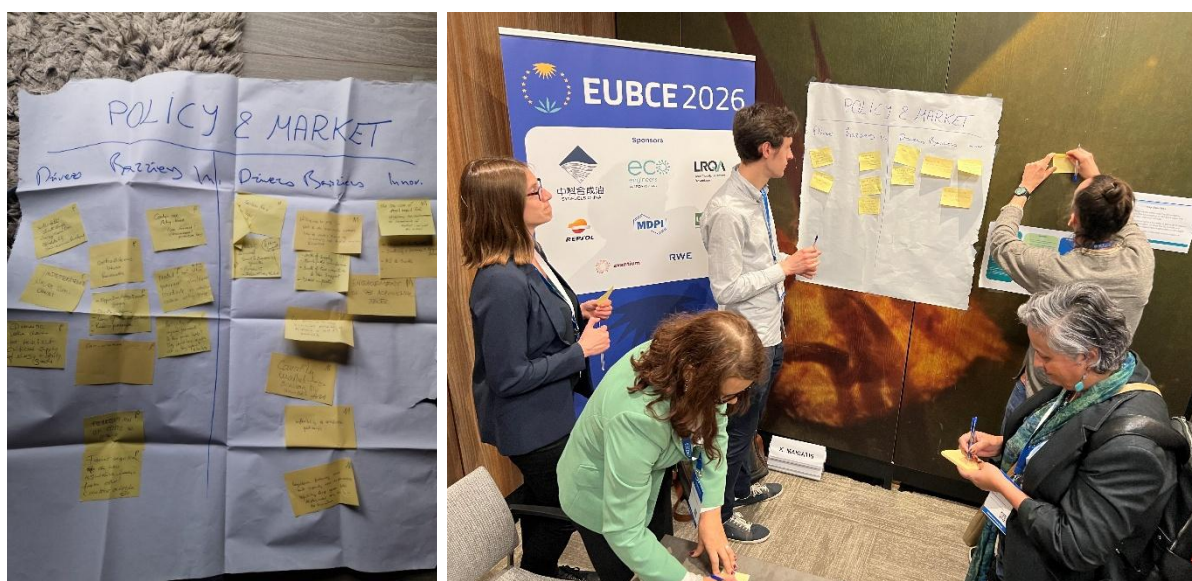


Figure 10.3. On the left side, overview of the compiled inputs from the participants on Policy and Market. On the right side, a picture taken during the co-creation exercise.

Table 10.1. Overview of policy-related drivers, barriers and innovations for SAF-upscaling identified during the co-creation workshop

POLICY		
DRIVERS	BARRIERS	INNOVATIONS
• Sustainability • Climate change • Energy transition • Affordability • Socio-economic development • Independence • Security supply chains • Domestic value chains for resilient critical supply of energy and daily goods •	• Contradictions between frameworks • Carbon tax policy based. Law forced? (environmental protection law) • Opposition/negationist groups • Loss of funds/finance • Public pressure • Communication • Perception of costs in public • Faster reaction on new legislative frame from other countries outside EU	• Needed. Government should probably coordinate an industry centred working group • Participation of regional governments? Do they provide inputs? They should have an active role as they implement technologies

The list of **policy**-related **BARRIERS** was even longer. Participants highlighted contradictions across policy frameworks as well as challenges linked to carbon tax-based approaches. They pointed to potential loss of funding, and resistance from opposition groups as additional constraints. Public pressure, communication gaps, and negative perceptions of costs were also identified as key barriers, alongside the need for faster responses to emerging legislative frameworks in countries outside the EU.

In terms of **INNOVATIONS**, two concrete inputs – both related to governments – were shared. Firstly, the need for stronger coordination, suggesting that governments should take a leading role in facilitating industry-centred working groups and, secondly, the importance of actively involving regional governments, recognizing their key role in providing input and driving the implementation of technologies on the ground.

Moving on to **market** aspects, multiple **DRIVERS** for SAF-upscaling were collected, starting with the role fiscal measures such as carbon tax or taxing fossil fuels to subsidize SAF, in shaping market incentives. Furthermore, participants emphasized profitability and survival as key considerations, alongside broader goals of social and economic growth and long-term prosperity. Expanding access to

new markets and enabling further growth were also identified as important drivers supporting the scale-up of SAF.

Table 10.2. Overview of market-related drivers, barriers and innovations for SAF-upscaling identified during the co-creation workshop

MARKET		
DRIVERS	BARRIERS	INNOVATIONS
• Carbon tax • Tax on fossil fuels to subsidize SAF • Profitability • Survival • Social & economic growth • Prosperity • Access to more markets and more growth	• Willingness to pay for SAF and other sustainable aspects. • Loss of public support by increasing cost through mandates & incentives • Lack of supply • Fossil fuels abundance • Lack of tax incentives and governmental support • World conflicts • The low cost of fossil-based fuel threatens the development or investment of biofuel, as well as e-fuel • EU focuses on the most sustainable feedstocks at the expenses of cost & practicality • Commodity market → scaling by number • Inflexibility of certification pathways • Regulation favouring new built capacity over co-processing, requiring large green field deployment very early in the transition	• Access to the markets • Creativity + science + opportunities • AI & growth • Engagement of the agricultural sector

With regards to **BARRIERS**, the list of factors hindering SAF-upscaling was notably longer – similar to the observations from the policy outcomes – and broad in nature. Participants highlighted the limited willingness to pay for SAF and the risk of losing public support as costs rise due to mandates and incentives. Also, they pointed to insufficient availability of SAF and the continued abundance and low cost of fossil fuels, both weakening the business case for biofuels and e-fuels. Structural and regulatory constraints were also emphasized, including the lack of tax incentives and governmental support, inflexible certification pathways, policy approaches that prioritize highly sustainable feedstocks at the expense of cost and practicality, and regulations favouring new-build capacity over co-processing, requiring early large-scale greenfield investments. Finally, broader market dynamics, such as world conflicts, were identified as additional barriers to SAF deployment.

Although to a more limited extent, participants also identified a small set of market-driven **INNOVATIONS**, including the use of artificial intelligence (AI) and engagement of the agricultural sector, both of which could enable innovative market solutions to support SAF-upscaling.

10.3.2 Station on SAF Sustainability Certification

In addition to the co-creation workshops on policy and market frameworks and technical innovation, a dedicated session focused on sustainability certification for SAF, building upon a 10-minute presentation held earlier during the session.

The discussions in the co-creation exercise were also organised around drivers, barriers, and innovations, as depicted in Figure 10.4. The raw inputs from this session are provided in Table 10.3.



Figure 10.4. On the left side, overview of the compiled inputs from the participants on SAF sustainability certification. On the right side, a picture taken during the co-creation exercise.

Participants reflected on what enables certification to support SAF scale-up, where certification frameworks currently limit or slow deployment, and how certification systems should evolve to better support innovation and market development.

Table 10.3. Overview of drivers, barriers and innovations for SAF-upscaling related to SAF sustainability certification identified during the co-creation workshop

SAF SUSTAINABILITY CERTIFICATION		
DRIVERS	BARRIERS	INNOVATIONS
Policy should be the driver	- Unknown to researchers, farmers and general public; fear of fraud - Alignment with ASTM certification - Feedstock production - Customer understanding of Book & Claim - Traceability for small holders. Mandatory to include small holders - Certify use of final products - Annex IX - Food security narrative - Land integration - Certification bodies not enough capacity building	- Communication to society - Chemical tracers and markers like road transport - Link LCA values to GHG calculations - Blockchain - Make auditing jobs more attractive - Innovation in traceability

Several key insights emerged from the discussion. Participants emphasised the need for clearer and more consistent communication on the role of certification in enabling SAF markets, particularly in distinguishing between compliance requirements and broader system value. Stronger alignment was identified as a priority between sustainability certification frameworks and technical standards, such as ASTM, to ensure a coherent pathway from innovation to market entry.

Participants stressed the need to distinguish clearly between technical fuel approval under ASTM processes and sustainability certification. While ASTM approval is required to confirm that a fuel is suitable for use in aviation, sustainability certification addresses the environmental, social and traceability requirements that determine whether a given SAF pathway can be recognised under regulatory or voluntary sustainability frameworks.

A key lesson from the certification discussion is that certification considerations should be integrated early in project development rather than addressed only at market-entry stage. For novel SAF pathways, early assessment of feedstock eligibility, chain-of-custody options, GHG calculation boundaries, land-related risks, and social safeguards can help avoid delays later in commercialization.

For SAF book and claim systems, participants emphasized that credible governance is essential to avoid double counting, ensure robust claims, and maintain trust among airlines, corporate buyers, and end users.

Participants called for simplification and harmonization of certification approaches, while maintaining the environmental and social integrity required for credible SAF markets.

Traceability requirements for smallholders were identified as a particular challenge. Participants emphasized that certification systems should enable smallholder inclusion through practical group certification, capacity building, and proportionate traceability approaches, while maintaining credible assurance.

Furthermore, participants highlighted the need for further research on implementation challenges, including fraud risks and the treatment of high-risk feedstocks. Traceability was identified as a critical area requiring continued innovation, especially in the context of complex global supply chains and for smallholder participation. More broadly, the discussion pointed to the need for simplification of certification requirements and stronger capacity-building efforts to support scaling, particularly for new market entrants and early-stage projects.

The insights generated through the co-creation workshop directly informed the development of Deliverable 4.3, *“Sustainability Certification Guidance for Novel SAF Pathways”*, led by RSB. The findings contributed to shaping practical recommendations on early-stage integration of certification, system alignment, and approaches to strengthen transparency, credibility, and scalability of SAF certification frameworks.

10.3.3 Station on Technical Innovations

The third parallel station, addressing technical innovations, attracted the greatest level of attention and generated the highest number of inputs, as illustrated in Figures 10.5 and 10.6.

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level); 5) suitable EPC (engineering, procurement and construction) contractors and project developers and 6) further/others.

The first observation from the results is that process integration and scale-up, securing supply of resources and auxiliaries as well as the flexibility of plant operation received the largest number of inputs, indicating that, most likely, these three parameters can be perceived as the most critical ones for SAF-upscaling. These domains encompassed a high number of factors rated as “very important,” highlighting their central role in enabling successful deployment.

Starting with **process integration and scale-up**, the inputs from the participants can be grouped into three main areas. First, process and infrastructure integration was seen as critical, including optimizing the interface between biomass conversion and refining (upgrading) steps such as pretreatment, and integrating SAF production into existing refinery infrastructure, while adapting plant scale to the smaller requirements of bio-based feedstocks as compared to traditional fossil-based refineries. Second, supply chain configuration and system design emerged as essential, with a hub-and-spoke approach enabling localized biomass conversion and centralized upgrading, thereby enhancing both security of supply and economic performance. Third, sustainability and efficiency considerations were emphasized, including retrofitting existing facilities to reduce land use, improving carbon and energy efficiency across processes, and integrating renewable electricity to strengthen overall environmental performance. In addition, participants identified two other factors rated as “important,” namely, the need to ensure long-term profitability and security of revenues, and the importance of maintaining a strong focus on both supply availability and operational flexibility.

With regards to **securing supply of resources and auxiliaries**, the messages collected focused on three main aspects too. Firstly, business viability and investment confidence were seen as fundamental, with a secure and reliable supply – ensuring consistent quantity, quality, and cost – considered essential for building a strong business case and attracting investors. Secondly, supply chain stability and reliability were emphasized, particularly given the fragmented nature of second-generation (scattered) feedstocks, requiring well-organized and resilient supply chains to maintain stable operations, ensure process continuity, and support predictable revenues. Finally, risk mitigation and long-term security of supply were highlighted through the need for diversification strategies and long-term contracts, as well as policy mechanisms such as low-carbon intensity reward systems to incentivize supply, as it is the case in several regions outside the EU. Overall, participants stressed that without secure and sufficient feedstock availability, SAF production cannot be realized. Additional factors to be considered for SAF-upscaling and rated as “important” were on the one hand the seasonality of certain feedstocks, affecting supply consistency, and on the other hand the adaptability of plants to process different feedstocks for operational resilience.

The third critical technical dimension for SAF-upscaling was **flexibility of plant operation in terms of resource and product portfolio**. From a feedstock point of view, with biomass being inhomogeneous, and diverse by nature, and therefore with different feedstock categories (e.g. lignocellulosic materials versus organic waste) requiring distinct processing conditions, this dimension was underlined as crucial. Seasonality further adds to variability in supply and therefore another layer of complexity. Operational and system flexibility was emphasized as essential as well, including the ability to adapt to changing market needs and fluctuations in renewable energy availability. In this context, participants also stressed the importance of stable storage and pretreatment steps to ensure robust plant performance. Overall, flexibility was seen as a key prerequisite for ensuring resilient and scalable SAF production. As for the other factors identified by the participants as “important”, it is worth mentioning the need to optimize and prioritize the use of biomass to maximize its impact.

The other two remaining dimensions, AI-supported plant operation and suitable EPC contractors and project developers, were considered as less critical for the upscaling of SAF.

With regards to **AI-supported plant operation**, the digital transformation associated with the fourth industrial revolution (industry 4.0) was the only factor rated as “very important”. Beyond that, participants raised certain concerns by identifying several factors as “less important” including i) the

fact that AI is considered less critical for continuous processes with low variability, where conventional control systems may already perform adequately, ii) the impact of AI on cost reduction and safety improvements remains to be clearly demonstrated, iii) in the absence of well-established and stable processes, the added value of AI may be limited. In addition, data security was highlighted as a concern.

Concerning **suitable EPC contractors and project developers**, and like the previous domain, also in this case only one factor was identified as “very important”, i.e., the need for sufficient money and ambition to scale-up. Additionally, participants noted that large companies with strong financial capabilities – such as established EPC contractors – can play an important supporting role in SAF deployment. However, while the involvement of EPCs is relevant, it was not considered a central factor in addressing this specific challenge.

Finally, participants were also encouraged to identify **cross-cutting issues** beyond the core dimensions. Among the key themes raised were the need for political incentives for technology development, advancements in technical factors such as the importance of developing novel, robust, and flexible processes, as well as catalyst development. In addition, certification frameworks in terms of the ASTM along the process chain were identified as a constraint, with current criteria perceived as too rigid and not sufficiently adapted to emerging SAF pathways. As an example, participants noted the difficulty of having separate ASTM annexes for the wide variety of feedstocks and processes converted through HTL, which may hinder the adoption and scaling of new technological solutions.

Table 10.4. Complete overview of technical-based inputs of relevance for SAF-upscaling identified during the co-creation workshop

Technical innovation for market uptake	Process integration (e.g. brown/green field) and scale up	Secure supply of resources (biomass, intermediates) and auxiliaries (e.g. catalysts, hydrogen)	Flexibility of plant operation in terms of resource and product portfolio	AI supported plant operation (e.g. on process, market level)	Suitable EPCs/project developer	Further (please add your views)
Very important	• Interface between biomass conversion and refining (upgrading) step; e.g. pretreatment • Downscale of classic refining infrastructure: bio-based feedstock needs much smaller plant than a typical «small» refinery. • Refinery integration • Security and economics • Hub and spoke approach needed • Biomass conversion locally • Reduce land use and foster retrofitting • To improve the carbon and energy efficiency • Integration of renewable electricity to the process	• Needed to have a business case • Secured supplies (quantity/quality/cost) are key to convince investors • Sufficient feedstocks facilitate the fluency of process and reliability of maintenance • 2nd gen feedstock is scattered + reliable supply chain is required to have stable revenue • Diversification and long-time contracts • No supply = no SAF • Supply is secured through low carbon intensity rewards systems	• Key as biomass is by nature irregular, inhomogeneous • Act according to market needs • Different conditions needed to process biomass feedstock from different categories (e.g. lignocellulosic vs. organic waste etc.) • Storage and pretreatment issue to ensure robust operability • Very important to reach flexibility on both seasonality and renewable energy • Very important due to feedstock variety	• Digital transformation is real on 4th industrial revolution	• Money/ambition to scale	• Political incentives for very specific technology • Novel, robust and flexible process • Catalyst Development • Criterion for technical certification of SAF's are too rigid (?) and it's hard to define a new annex for each type of SAF. • For ex. it's difficult to have an annex for each and every feedstock for an HTL process

Important	• Obviously important to reach profitability and security of revenues (long term profitability) (supply, market, demand is key) • Supply and flexibility.	• Seasonality for some feedstock • Question: how adaptable are plants with regard to feedstock? • Supply is king	• Flexibility ensures security of supply as Europe's only one feedstock • We should optimize/prioritize the use of biomass for max impact	• Large companies with strong financial background as EPC's • EPCs is relevant but it is not the key of this question
Less important				• AI is less important for continuous low variability process • The impact on cost/safety is to be demonstrated • Question of liability: actual benefits over current operating methods, data security • If you do not have an established process; what do you want with AI? Important but not problematic

11 Conclusions

This deliverable combined literature assessments, techno-economic, environmental and social sustainability analyses, stakeholder interviews, co-creation webinars and an on-site workshop to identify best practices and concepts for accelerating SAF deployment. Across all activities, a high level of convergence emerged regarding both the opportunities and challenges associated with SAF upscaling.

Among the pathways investigated, gasification followed by Fischer-Tropsch synthesis was consistently identified as the most promising route for large-scale SAF production in Europe due to feedstock availability, technological maturity, ASTM certification, and strong greenhouse gas reduction potential. The biocrude oils to SAF pathway was recognized for its ability to utilize wet waste streams and contribute to circular economy goals, although significant challenges related to upgrading, contaminants and certification remain. Due to the absence of ASTM certification and the lower upgrading requirements for marine fuels, HTL-derived biocrudes may initially be more suited for the maritime sector. Alcohol to jet pathways were considered globally relevant, particularly in regions with abundant alcohol production, but their prospects within Europe are currently constrained by feedstock availability and regulatory requirements. Of the three pathways assessed, isobutanol to SAF was generally viewed as the least commercially mature and the one requiring the greatest advancements before large-scale commercialization can be achieved.

Across all pathways, the findings indicate that the primary barriers to large-scale deployment are no longer technological. Instead, stakeholders highlighted financing, investment risk, feedstock availability, policy stability, certification frameworks in terms of ASTM and sustainability, and the transition from demonstration to commercial deployment as the principal challenges. The lack of support mechanisms capable of bridging the gap between successful demonstration and commercial operation was identified as a critical bottleneck.

The findings further demonstrate that future SAF demand cannot be met through a single feedstock, technology pathway or region. Achieving aviation decarbonization will require a diversified portfolio of sustainable fuel pathways supported by stable policy frameworks, effective financing instruments, continued innovation, and strong collaboration across the value chain.