Framework conditions for SAF development in Europe and MIC

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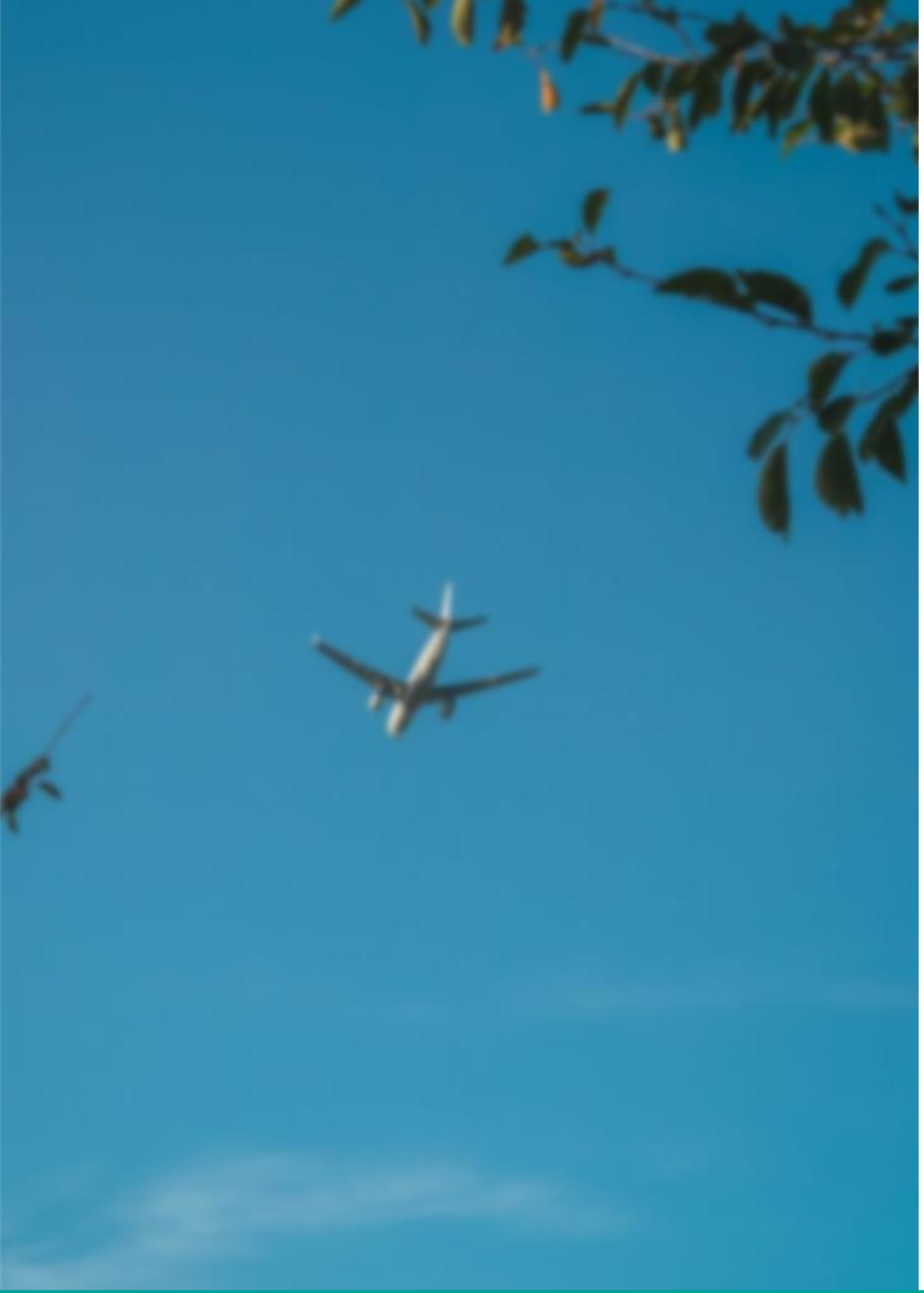
EUBCE, 21 June 2024 (Marseille, France)



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SAF Standards: Defining Fuel Quality

The ASTM D7566-23b annex defines the standards for SAF, including specifications for fuel properties, environmental impact, and sustainability.

Annex	Title	Product name	Manufacture	Max. Blending
A1	Fischer-tropsch hydroprocessed synthesized paraffinic kerosine	FT-SPK	Fischer-Tropsch (FT) process using Iron or Cobalt catalyst with subsequent hydroprocessing.	50%
A2	Synthesized paraffinic kerosine from hydroprocessed esters and fatty acids	HEFA SPK	Hydrogenation and deoxy-genation of fatty acid esters and free fatty acids with subsequent hydroprocessing.	50%
A3	Synthesized iso-paraffins from hydroprocessed fermented sugars	SIP	Hydroprocessed synthesized iso-paraffins wholly derived from farnesene produced from fermentable sugars with subsequent hydroprocessing.	10%
A4	Synthesized kerosine with aromatics derived by alkylation of light aromatics from non-petroleum sources	SPK/A	FT SPK as defined in Annex A1 combined with synthesized aromatics from the alkylation of non-petroleum derived light aromatics (primarily benzene) with subsequent hydroprocessing.	50%
A5	Alcohol-to-jet synthetic paraffinic kerosene (atj-spk)	ATJ-SPK	Synthesized paraffinic kerosene wholly derived from either ethanol or isobutanol through oligomerization, hydrogenation, and fractionation.	50%
A6	Synthesized kerosine from hydrothermal conversion of fatty acid esters and fatty acids	CHJ (Catalytic Hydrothermolysis Jet)	Hydrothermal conversion of fatty acid esters and free fatty acids with subsequent hydroprocessing.	50%
A7	Synthesized paraffinic kerosine from hydroprocessed hydrocarbons, esters and fatty acids	HC-HEFA SPK	Paraffins derived from hydrogenation and deoxy-genation of bio-derived hydrocarbons (Botryococcus braunii species of algae), fatty acid esters, and free fatty acids.	10%
A8	Alcohol-to-jet synthetic paraffinic kerosene with aromatics (atj-ska)	ATJ-SKA	Addition to ATJ-SPK of an aromatic product stream comprising dehydration, aromatization, hydrogenation, and fractionation.	50%

Regulatory Framework for SAF

The regulatory landscape for SAF is evolving rapidly. Governments and aviation authorities are implementing policies to promote SAF production and use.

EU Green Deal

The EU Green Deal targets a 50% reduction in aviation emissions by 2050, promoting SAF as a key solution.

CORSIA

The Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) encourages airlines to invest in SAF and other sustainability initiatives.

National Policies

Several countries, including the UK, France, and Germany, have introduced national policies to stimulate SAF production and deployment.

Mandates applied to the production and use of SAF

Country/Area	Policy	Commitments	refs
Europe	EU Renewable Energy Directive (RED II)	Mandates increasing the share of renewable energy in the EU's energy mix, including a sub-target for advanced biofuels and SAF. It sets sustainability criteria for biofuels used in the aviation sector.	(1)
	European Commission's ReFuelEU Aviation Initiative and RED III	Proposes a SAF (including biofuels and e-fuels) blending mandate starting at **2% in 2025**, gradually increasing to **70% by 2050**, to boost the supply and demand for SAF in aviation across EU member states.	
Canada	Clean Fuel Standard (CFS)	Aims to reduce the carbon intensity of fuels used in Canada, including aviation fuels. It encourages the use of lower carbon fuels, energy sources, and technologies. Industry-led initiatives and governmental regulations, including British Columbia's mandates to increase renewable fuel percentage in jet fuel, aimed at scaling up SAF usage.	(2)
India	SAF Mandate for Airlines	A forthcoming mandate for the use of **1% SAF in domestic airl**ines by 2025 to align with emissions reduction goals.	(3)
Brazil	National SAF Program (PROBIOQAV)	A policy targeting the inclusion of SAF into the Brazilian energy matrix **from January 2027** to curb airline emissions.	(4)
US	Sustainable Aviation Fuel Grand Challenge	Aims to produce **3 billion gallons of SAF per year by 2030** and reduce aviation emissions by 20% by 2035. The initiative involves collaboration between various federal agencies to support SAF development and deployment.	(5)

Challenges to SAF Market Deployment

Despite the potential of SAF, **significant barriers hinder** its widespread adoption and market penetration.

1

Cost

SAF currently costs significantly more than conventional jet fuel, making it a challenge for airlines to adopt.

2

Scale

Production capacity for SAF needs to be scaled up significantly to meet the growing demand from the aviation sector.

3

Infrastructure

Adapting existing airport infrastructure and supply chains to handle SAF presents a logistical challenge.

4

Sustainability

Ensuring the sustainable sourcing of feedstocks for SAF is crucial to avoid unintended environmental consequences.

ICARUS Project: a collaborative **Horizon Europe** initiative for SAF market development

addressing the technical and economic challenges of SAF production.

1 Technology Development

The project focuses on the development of innovative technologies for the production of SAF from various feedstocks.

2 Life Cycle Assessment

A comprehensive life cycle assessment is conducted to evaluate the environmental impact of the developed technologies and identify areas for improvement.

3 Pilot Scale Implementation

The project aims to implement the developed solutions on a pilot scale to demonstrate their feasibility and scalability for commercial production.

4 Market Analysis

A thorough market analysis is conducted to identify potential barriers and opportunities for the deployment of the developed SAF technologies.

Three chosen SAF routes

ICARUS focuses on evaluating the **three most promising pathways for SAF development** in both Europe and MIC, considering their technical feasibility, economic viability, and environmental impact.

1

Biocrude Oils to SAF

Evaluating and analyzing innovative and promising catalytic hydrotreatment approaches for biocrudes produced through Hydrothermal Liquefaction (HTL).

2

Alcohols to SAF

Exploring various methods for converting alcohols, such as ethanol and methanol, into sustainable aviation fuels, taking into account technological advancements and economic considerations.

3

Syngas to SAF

Assessing the current and emerging technologies for syngas production from gasification, gas conditioning, and upgrading, as well as analyzing the relevant policy developments and regulatory frameworks.

1-Biocrude oils to SAF (1/2)

- Feedstock Sourcing
- Biocrude Production
- Upgrading
- Hydroprocessing
- SAF Production

Removal of particulate matter/solids (before upgrading)

Process	Advantages	Disadvantages	Source
Centrifugation & Filtration	- Capable of recovering high yields of bio-oil - Simple and scalable	- May not effectively remove the finest particles	(Mujahid et al., 2020b)
Microfiltration	- Can target specific sizes of particles for removal - Beneficial for improving bio-oil purity	- Lack of established technologies for particles <10µm - Potential for high operational costs	(Elliot et al., 2016; Javaid et al., 2010),
Two-step separations	- Enhances bio-oil purity by employing sequential refinement - Effective for complex feedstock bio-oils (microalgae)	- Potentially resource-intensive due to multiple processes	(Grigorenko et al., 2018)
Biomass filter aids	- Utilizes biomass-derived materials, enhancing sustainability - Efficient in aiding the filtration process	- Requirement for subsequent disposal or processing of spent filter aids	(Biller et al., 2018; Johannsen et al., 2019; Lin, 2015)
Advanced membranes technologies	- High effectiveness in particle and oil separation - Reduced fouling compared to other membranes	- Costs associated with ceramic membranes can be high - Potential for ceramic membrane fouling in long-term operations	(Sayegh et al., 2022)

1-Biocrude oils to SAF (2/2)

Comparison of main methods for N removal

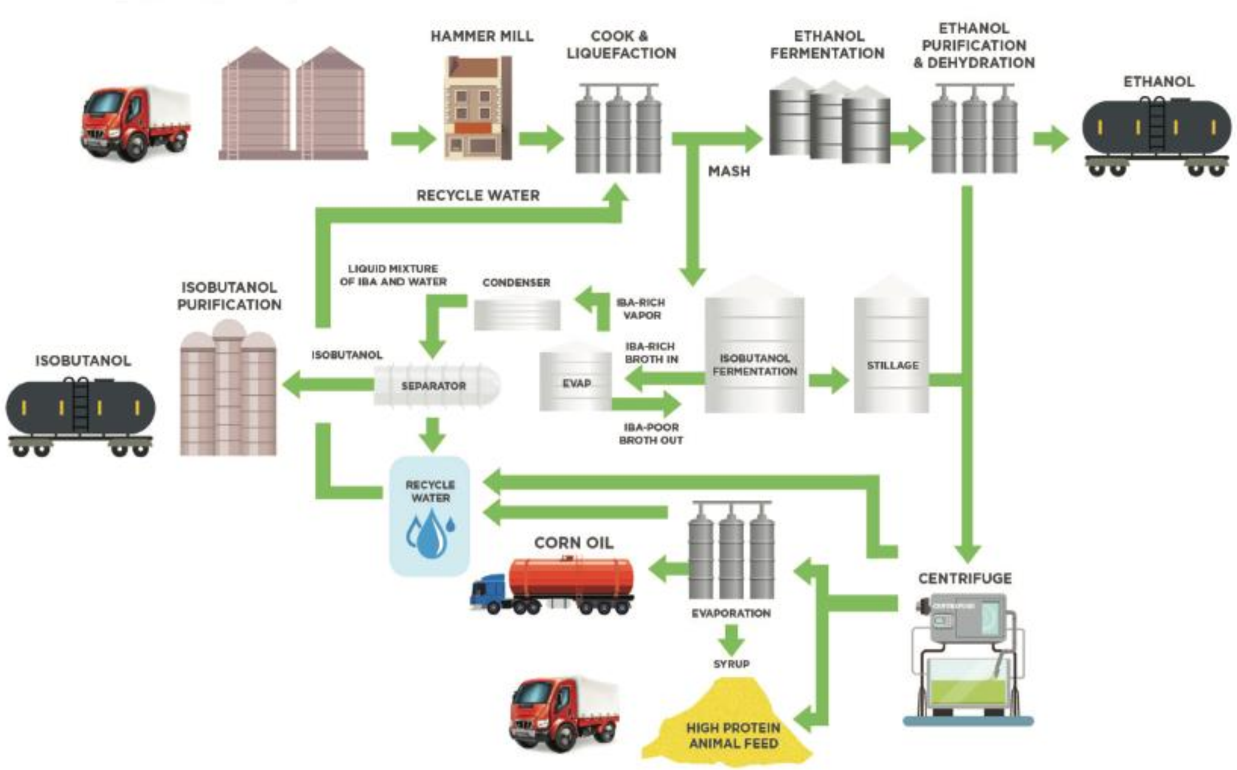
Method	Advantages	Disadvantages	Technology readiness
Hydrotreating	- Industrially proven method for nitrogen removal - Effective in removing nitrogen as ammonia	- Not a selective nitrogen removal process - Other hydroprocessing reactions occur simultaneously	industrially proven and widely used
Liquid-Liquid Phase Partitioning	- Selective extraction of nitrogen-containing compounds based on solubility parameters - Potential for efficient separation of nitrogen compounds	- Limited by solubility parameters and selectivity of extracting liquid - Process complexity and solvent recovery challenges	requires further optimization for industrial application
Solvent Deasphalting	- Effective in removing heavier components like asphaltenes containing nitrogen - Can improve oil quality by reducing nitrogen content	- Not capable of deep nitrogen removal from oil - Process may not eliminate all nitrogen-containing compounds	requires further optimization for industrial application
Adsorption	- Selective adsorption of nitrogen-containing compounds based on interactions with adsorbent - Potential for high selectivity and capacity	- Regeneration of adsorbent for reuse can be challenging - Adsorbent capacity and selectivity may vary based on the type of adsorbent	requires further optimization for industrial application
Chemical Conversion and separation (2 step)	- Transformation of nitrogen compounds to facilitate separation - Potential for modifying chemical structure of nitrogen compounds	- Process complexity and optimization required for effective conversion and separation - May require specific catalysts and conditions	requires further optimization for industrial application
Microbial Conversion	- Potential for biological removal of nitrogen compounds from oils - Environmentally friendly approach	- Limited application and research compared to other methods - Effectiveness may vary based on microbial strains used	low

Operation conditions for HDO

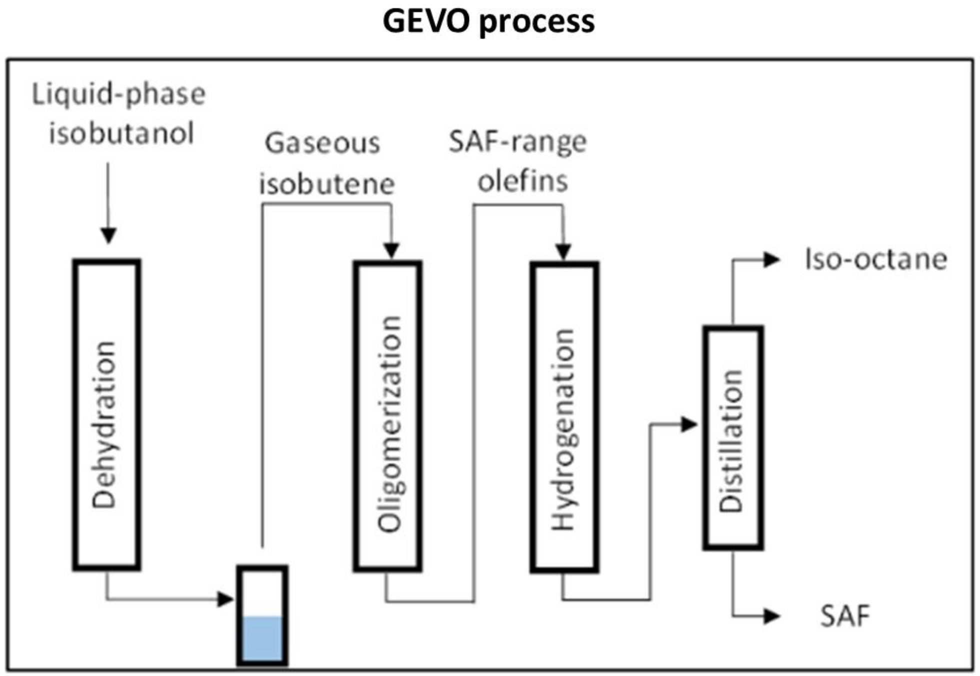
Parameter	Range of values	Efects
Temperature	250ºC and 400ºC (higher efficiency between 300 and 350ºC)	Temperatures above 450ºC are not favorable for upgrading due to the exothermic nature of the HDO process and the increased formation of coke deposits and consequently catalysts deactivation.
H_2 Pressure	10-30MPa	High pressures ensure good solubility of H_2 in the reaction medium and promote the stabilization of unstable precursors derived from bio-oil (i.e., high molecular weight intermediate compounds). These conditions reduce the formation of solid deposits and increase the lifetime of the catalysts; some studies have demonstrated that lower H_2 pressures can achieve good deoxygenation efficiencies with catalysts
Solvent	Use of H_2 donor solvents such as methanol, ethanol, propan-2-ol, tetralin and formic acid.	The use of solvents influences the heterogeneous catalysts activity in HDO through competition for active centres. The possible formation of oxides on the surface of the catalysts and of intermediate compounds specific to each solvent can interfere with the activation energy of the process. The promotion of parallel hydrolysis and esterification reactions is also a problem.
Residence time	Residence times between 0.5 – 8 h (defined as the contact time between the raw material and the catalyst).	High feeding rates and hourly mass space velocity. Short residence times result in low HDO efficiencies.

2-Isobutanol to SAF (1/2)

- Gevo - dominant player in isobutanol production technologies
- Implements integrated system of isobutanol production with the existing corn ethanol plant.



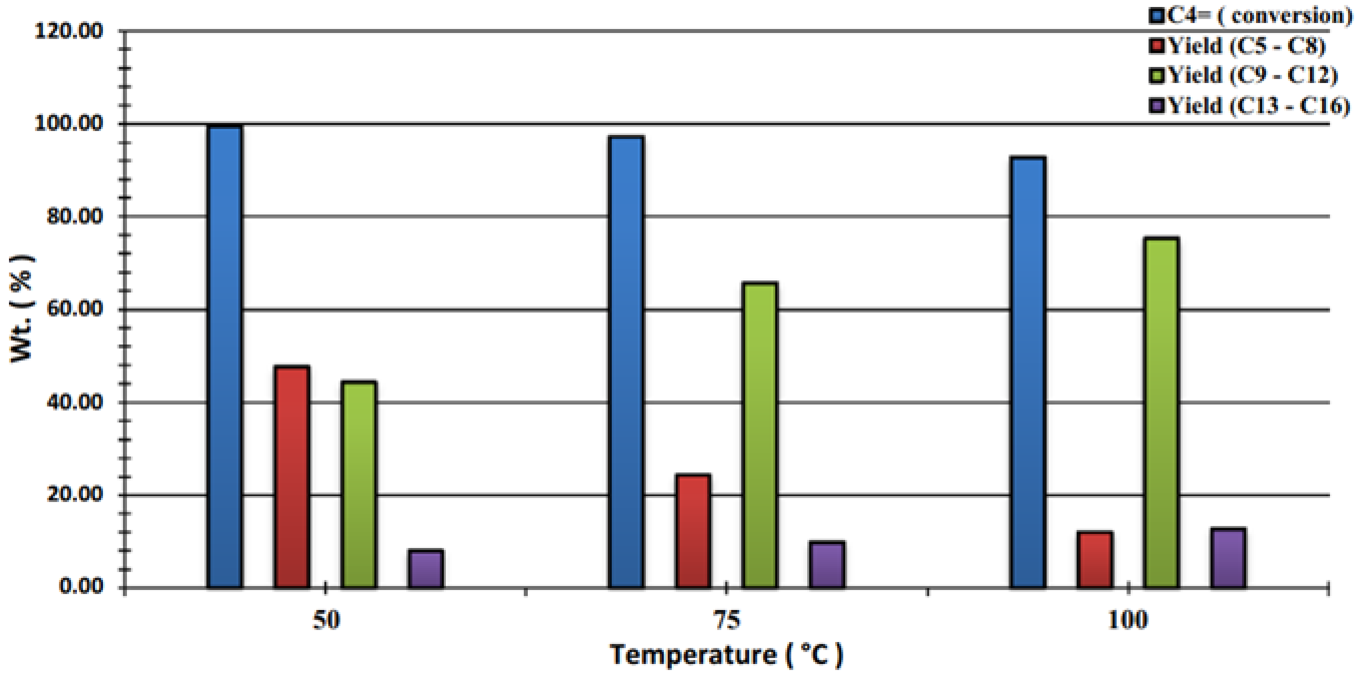
(https://gevo.com/wp-content/uploads/2023/03/Gevo-Whitepaper-Overview-of-Gevos-Biobased-Isobutanol-Production-Process.pdf)



GEVO´s commercial process for SAF production from isobutanol.

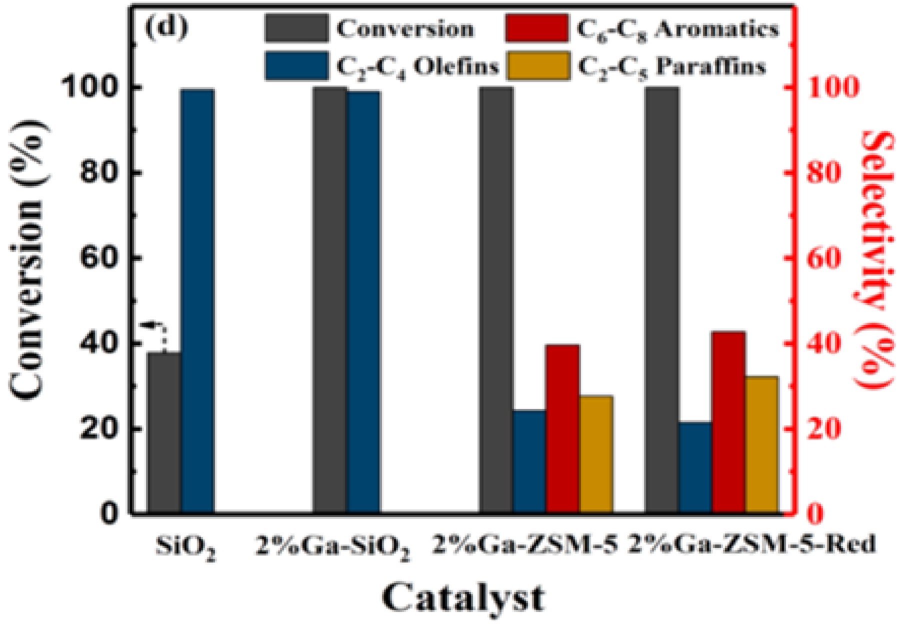
2-Isobutanol to SAF (2/2)

Isobutene oligomerization as a function of T



Conversion of C4 and yield of C5-C8, C9-C12 and C13-C16 at different temperatures using Phosphoric HZSM-5-Y

Catalysts comparison



Main factors to influence SAF performance and selectivity:

- Catalyst type
- Reaction temperature
- Reaction time

3-Syngas to SAF (1/2)

The syngas-to-SAF pathway holds significant promise for the future of sustainable aviation, offering a flexible and versatile approach to producing high-quality SAF from diverse feedstocks.

Direct Syngas-to-Jet

An integrated FT-based catalyst design to deviate from the ASF distribution and produce jet fuel in one step;

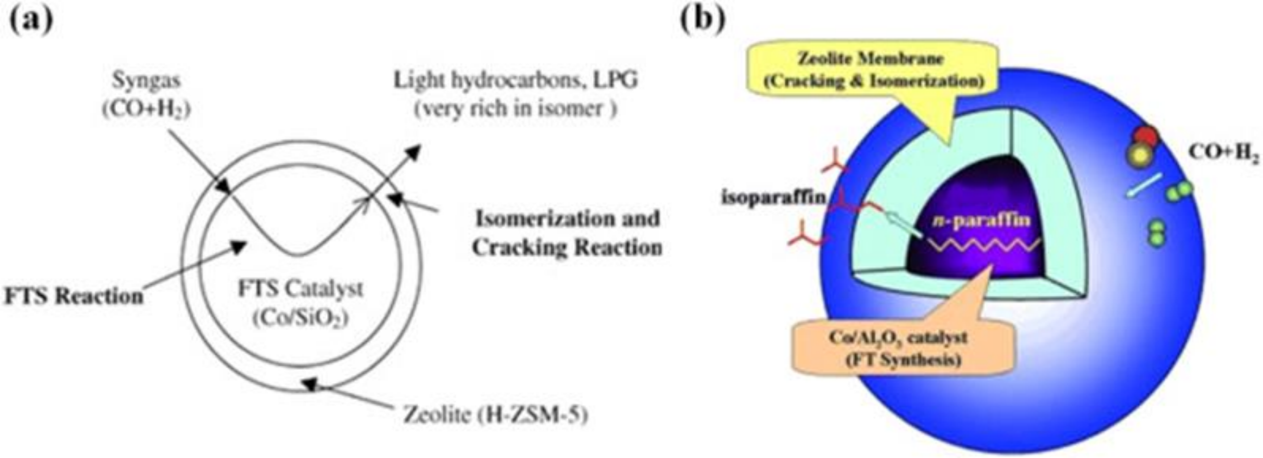
Syngas-to-Olefins(-to-Jet)

A more alternative pathway with a potentially higher carbon selectivity to SAF compared to traditional FTS. The required oligomerization and hydrogenation to produce jet-grade SAF is considered

Syngas-to-Alcohols(-to-Jet)

Pathway for the conversion of syngas into alcohols, followed by a series of subsequent steps to produce SAF. The alcohol-to-jet (ATJ) pathway is a well-established approach, but further research is ongoing to optimize the process and reduce production costs.

New capsule catalyst for direct synthesis of isoparaffins



3-Syngas to SAF (2/2)

	First syngas conversion step		*Overall Syngas-to-Jet Process*	
Approach / process	**Selectivity (max.)**	**Catalyst production (commercial feasibility)**	***Total conversion units***	***Final Jet fuel grade (branched C8-C16)***
Commercial SAF				
SMDS process (conventional)	45% C8-C16 from syngas	Good	*2*	*Good*
ATJ “commercial” fermentation based	40% to C8-C16 from alcohol (ethanol)	Good	*4*	*Good*
Syngas-to-SAF (direct)				
Co / La-meso-Y (Li et al., 2018)[39]	72% C8-C16	Poor	*1*	*Good*
Confined Co / SiO2 (Cheng et al, 2018)[65]	65% C8-C16	Good	*1-2*	*Unknown*
Core-shell Co@C@Void@CeO2 (Safari et al., 2023)[46]	65% C8-C16	Poor	*1-2*	*Unknown*
Ru / CNT (Kang et al., 2009)[62]	65% C8-C16	Poor	*1-2*	*Medium*
Syngas-to-olefins				
Na-Ru / SiO2 (Yu et al., 2022)[80]	80% C2-C20 olefins, 3% CO2	Medium	*2-3*	*Good*
ZnCrOx – mSAPO (Jiao et al., 2016)[79]	80% C2-C4 olefins, 45% CO2	Medium	*3*	*Good*
ZnZrOx – SAPO (Cheng et al., 2016)[81]	74% C2-C4 olefins, 40% CO2	Medium	*3*	*Good*
Syngas-to-alcohol				
Cu/ZnO/Al2O3 for syngas-to-methanol	99.9%	Very good	*4*	*Good*
RhMn@S-1 (Wang et al., 2020)[108]	27.3%	Medium	*4*	*Good*
K-NiMo$_3$S$_x$ (Wang et al., 2018)[115]	42%	Medium	4	*Good*

Direct Syngas-to-Jet

- Promising catalysts include La-stabilized Co/meso-Y and confined Co/SiO2, achieving up to 72% and 65% selectivity to C8-C16 hydrocarbons, respectively.
- Advantages: Requires only one conversion unit.
- Challenges: Catalyst production complexity and stability remain uncertain.

Syngas-to-Olefins(-to-Jet)

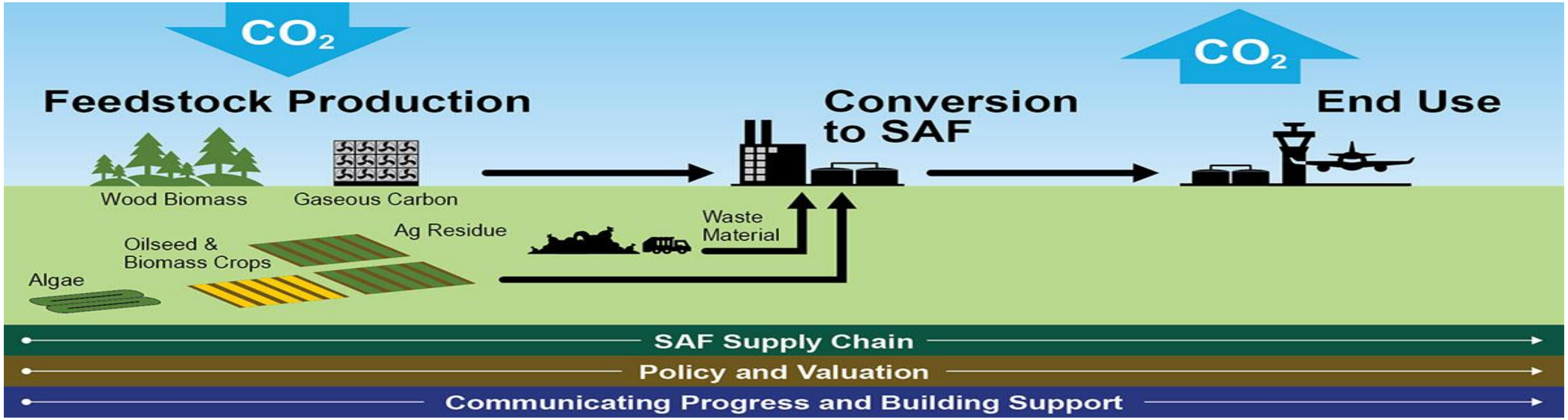
- Recent work with Na-Ru/SiO2 achieved 80% C2-C20 olefin selectivity.
- Challenges: Overall carbon selectivity lower than direct syngas-to-SAF due to subsequent steps.

Syngas-to-Alcohols(-to-Jet)

- Ethanol production faces limitations in activity and selectivity.
- Noble metal catalysts (e.g., Mn-O-Rh) show promise, but alternatives like MoS2/K-Ni are being explored.

Next steps

- Accurate identification of of potential barriers affecting the VC evolution
- To write an action plan with recomendations for best practises and concepts
- To prepare a guidance for accelerating the upscale of SAF
- To prepare a guidance for SAF certification (new routes)
- Amongst others…



Workshop on SAF policies (hybrid)

ICARUS Public Workshop

Sustainable Aviation Fuel (SAF) Policies

9 July 2024 (10:30 – 16:30)

Premises of the European Commission DG RTD, Brussels

Confirmed speakers:

From EC: *Maria Georgiadou*, DGRTD; *Ewa Oney,* DG MOVE

IATA: *Preeti Jain*

Brazil: *Daniel Lira, Instituto Senai de Energias Renováveis*

Canada: *Warren Mabee, Queen's University, Kingston*

China: *Shizhong Li, Tsinghua University*

USA: *Zia Abdullah, NREL*

Still to confirm: UK and India

Confirmed Moderator:

Kees Kwant, NL Enterprise Agency

icarus

Thank you

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ICARUS has received funding from the European Union’s Horizon Europe research and innovation programme under grant agreement no. 101122303