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# The Portfolio of SAF Production Pathways: Technologies, Maturity, Relevant Players and Projects

**How to become SAF ready? How to make SAF happen?**

**SAF Training for ACI Africa & AFRAA**

23.-25.04.2025, Arusha, Tanzania

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## Topic

# The Portfolio of SAF Production Pathways: Technologies, Maturity, Relevant Players and Projects


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Technology Expert


Dr. Fabian Schmitt is a professional in green chemicals such as sustainable aviation fuels with profound knowledge in chemical conversion technologies with expertise in electrochemical processes, electrochemical and thermochemical conversion of carbon dioxide to produce base chemicals, as well as methanol and FT-synthesis. Convinced, that green transition is an interdisciplinary and international effort that needs to be holistically and jointly addressed from technology, business and regulatory perspective.

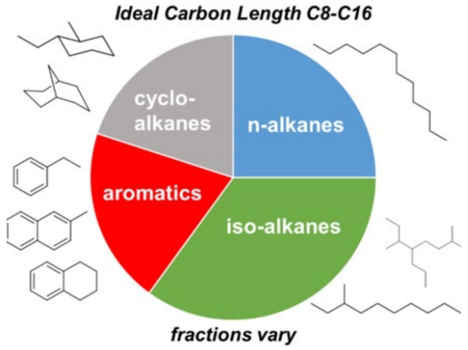
***Consulting Focus @ CBR Sustainability Partners***

- Technology assessments, feasibility studies and techno-economic analysis in the field of renewable gases and liquids, hydrogen, Power-to-X, sustainable fuels (SAF) and green chemicals
- Expertise in regulatory policies with focus on renewable fuels, such as SAF
- Focus on renewable fuel production technologies, feedstock availabilities and $CO_2$ reduction potentials

***Education***

- PhD in Chemical Engineering, TU Darmstadt, Germany
- Master in Chemical Engineering, TU Darmstadt, Germany / Aalto University Espoo, Finland
- Bachelor in Chemistry, TU Darmstadt, Germany

# Guiding questions




What are the **differences between fossil Jet fuel and SAF**?

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Which **SAF production routes** are **approved** by **ASTM**? Which are future candidates?

1. HEFA
2. Power-to-Liquid
3. Waste-to-Liquid
4. Biomass-to-Liquid
5. Alcohol-to-Jet
6. Hybrid fuels, e.g. PBtL

Which **technologies** are applied? How **technically mature** are they?

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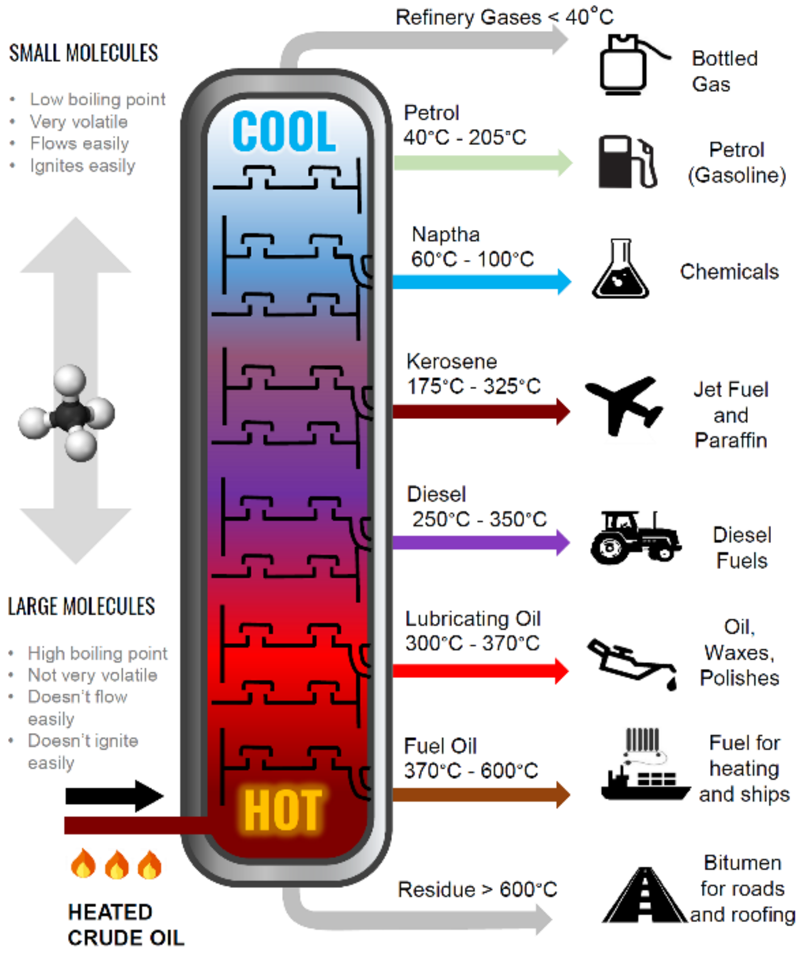
Which are **leading examples** for each **production route**?

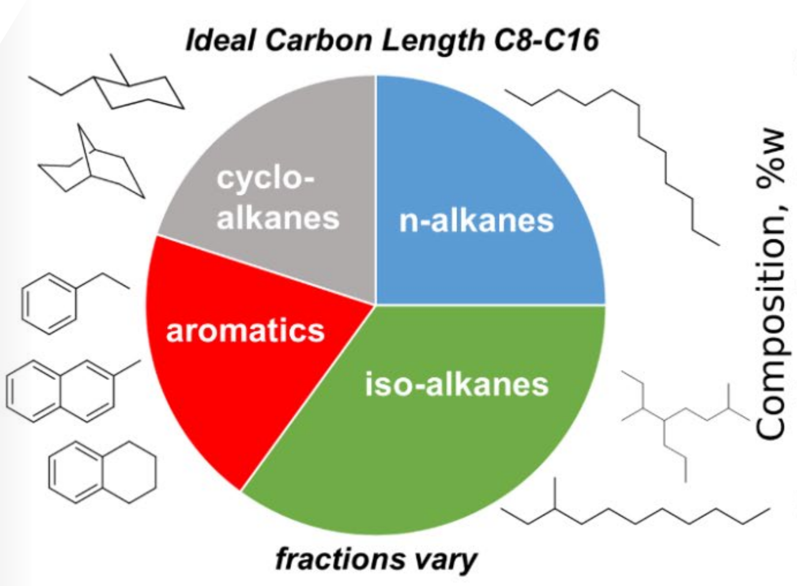
# Characteristics of jet fuel composition derived from fossil sources must be mimicked by SAF drop-in solutions.

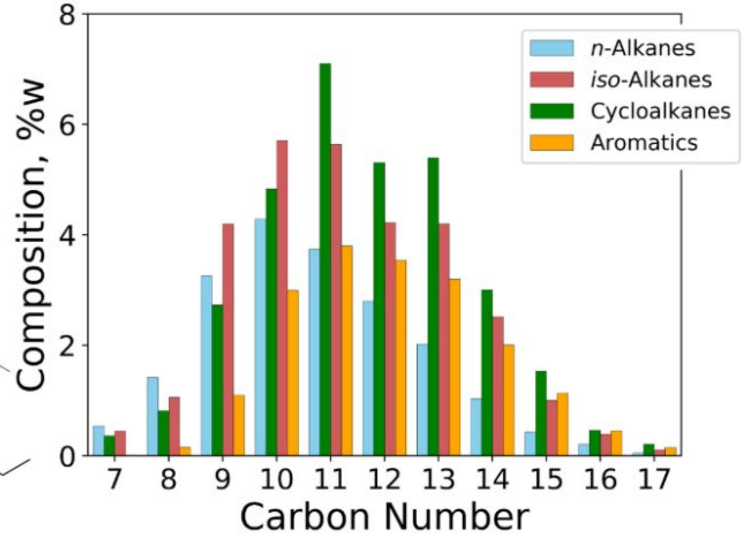
## Crude oil fractionation column




Source: Enerpac, Holladay et al.

## Fossil Jet fuel composition




**Aromatics are limited to 25%**
**Olefins and heteroatoms are limited (not allowed)**
- Olefins (<1%) (gum formation)
- S, N, O containing (limited allowance)

Pie chart adapted from Tim Edwards
Composition/Carbon number from Josh Heyne

**To be a drop-in solution, SAF** must have a **similar composition to fossil jet fuel**. Note: SAF composition depends on production route.

# High variety of SAF production routes in terms of feedstocks and technologies are leading to different eligible blending rates.

| | | Feedstocks | Process | Carbon intermediate | Process | | Chemical composition |
|---|---|---|---|---|---|---|---|
| Bio-SAF | Fats, oils and grease (FOGS) | Used Cooking Oil (UCO) | Neutralization | Lipids | Co-processed in conventional refinery | | Paraffins and aromatics* |
| | | Oilseed crops | Neutralization | Lipids | Hydroprocessing & distillation | | Paraffins, no aromatics |
| | | Animal fats | Rendering | Lipids | Hydrothermolysis | | Paraffins, no aromatics |
| | | Algae | Oil extraction | Lipids | Hydroprocessing & distillation | | Paraffins, no aromatics |
| | Lignocellulosic waste & residues | Sugar & starch crops | Fermentation | Farnesane (15C hydrocarbon) | Hydro processing & distillation | | Paraffins, no aromatics |
| | | | | Alcohol | Dehydration / Oligomerization | Distillation | Paraffins, no aromatics |
| | | Other agricultural waste | Gasification | Synthesis gas ($CO + H_2$) | Fischer-Tropsch (FT) catalytic synthesis | Co-processed in conventional refinery | Paraffins, no aromatics |
| | | Forest residues | | | | Hydro-processing & distillation | LT: Paraffins, no aromatics<br>HT: paraffins and aromatics |
| | | Municipal solid waste (MSW) | | | | | |
| Synthetic SAF | | (Green) $H_2$ | Electrolysis, rWGS | Synthesis gas ($CO + H_2$) | Fischer-Tropsch (FT) catalytic synthesis | Hydro-processing & distillation | LT: Paraffins, no aromatics<br>HT: paraffins and aromatics |
| | | $CO_2$ | | | | | |

Most SAF routes produce predominantly paraffins with **limited or no aromatics.**

**Aromatics** have a great impact to secure **leak free aircraft sealings** (swelling effect).

**How to guarantee that SAF meets the requirements for a safe flight?**

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*For coprocessing aromatics are contained in the fossil jet fuels and not in the renewable component
Source: Barclays Research, 2022; CBR, 2023

# Certifications differ in underlying property: „chemical“ vs. „green“ to meet safety, performance and environmental standards.

## ASTM certification for SAF

**Technical certification** assuring that the **chemical properties** of the fuel are adequate and compliant with the use as jet fuel.

**ASTM D1655**: key specification for JetA/A-1.

**ASTM D7566**: quality standard required for each SAF production pathway, defining which feedstock must be used, the associated process and the properties and the output of each pathway.

**ASTM D4054**: the process for approval of new SAF production pathways.

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## Sustainability certification for SAF

Certification about **compliance towards sustainable criteria** according to specific sustainability programs (e.g., CORSIA).

**Key sustainable criteria for SAF production:**

- Sustainable feedstock availability
- Direct / Indirect Land Use Change
- GHG Emissions
- Labour / Human rights
- Food security
- Traceability.

CORSIA

RSB CERTIFIED

ISCC International Sustainability & Carbon Certification

# ASTM Standards to ensure SAF production pathways meet specifications and requirements in Aviation Turbine Fuels.

| | Exemplary feedstock | Group | ASTM qualified conversion process (D7566, D1655) | Max. blend | Chemical composition | Technology used | ASTM |
|---|---|---|---|---|---|---|---|
| 1 | **Fatty acids or fatty acid esters** (from virgin or used fats and oils) | HEFA & Co-Processing | **HEFA-SPK**: Synthesized paraffinic kerosene from hydroprocessed esters and fatty acids | 50% | Paraffins, no aromatics | Hydroprocessing for HEFA | D7566 |
| 2 | **Fatty acids or fatty acid esters** (co-processed with fossil petroleum) | HEFA & Co-Processing | **Co-processed HEFA**: Co-hydroprocessing of esters and fatty acids in a conventional petroleum refinery | 5% | Paraffins and aromatics contained in the jet fuels | Co-hydroprocessing | D1655 |
| 3 | **Algae** | HEFA & Co-Processing | **HC-HEFA-SPK**: Synthesized paraffinic kerosene from hydrocarbon - hydroprocessed esters and fatty acids | 10% | Paraffins, no aromatics | Hydroprocessing for HEFA | D7566 |
| 4 | **Hydrocarbons** derived from **triglycerides or their derivates** | HEFA & Co-Processing | **Co-fractionation** using maximum 24% of bio-material, with result of maximum 10% bio-share in the jet fuel. | 10% | Paraffins and aromatics contained in the jet fuels | Hydroprocessing for HEFA | D1655 |
| 5 | **Syngas** (via gasification or from $H_2/CO_2$) | Fischer-Tropsch | **FT-SPK**: Fischer-Tropsch hydro-processed synthetic paraffinic kerosene | 50% | Paraffins, no aromatics | Fischer-Tropsch synthesis | D7566 |
| 6 | **Syngas** (via gasification or from $H_2/CO_2$) | Fischer-Tropsch | **FT-SKA**: Synth. kerosene with aromatics derived by alkylation of light aromatics from non-petr. sources | 50% | Paraffins and aromatics | Fischer-Tropsch synthesis | D7566 |
| 7 | **FT hydrocarbons** (co-processed with fossil petroleum) | Fischer-Tropsch | **Co-processed FT**: Co-hydroprocessing of Fischer-Tropsch hydrocarbons in a conventional petroleum refinery | 5% | Paraffins and aromatics contained in the jet fuels | Co-hydroprocessing | D1655 |
| 8 | **C2-C5 Alcohols** (various feedstocks) | Oligomerisation | **ATJ-SKA:** Alcohol to jet synthetic paraffinic kerosene with aromatics (Pure SAFSM) | 50% - 100% | Paraffins and aromatics | Fermentation to alcohol, dehydration and oligorimerisation | D7566 |
| 9 | **Ethanol, Iso/n-butanol, Isobutene** (from crops, 2G biomass, $H_2/CO_2$) | Oligomerisation | **ATJ-SPK**: Alcohol to jet synthetic paraffinic kerosene | 50% | Paraffins, no aromatics | Fermentation to alcohol, dehydration and oligorimerisation | D7566 |
| 10 | **Sugars** (from crops or 2G biomass) | Oligomerisation | **SIP**: Synthesised iso-paraffins from hydroprocessed fermented sugars | 10% | Paraffins, no aromatics | Fermentation | D7566 |
| 11 | **Fatty acids or fatty acid esters** (from virgin or used fats and oils) | other | **CHJ**: Catalytic hydrothermolysis jet fuel | 50% | Paraffins and aromatics | Hydrothermal synthesis | D7566 |

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Source: ASTM

Other process in the pipeline for ASTM approval: **Methanol-to-Jet**, **Synthesised Aromatic Kerosene** (Virent), **Integrated Hydropyrolysis and -conversion IH2** (Shell), **Pyrolysis of non-recyclable plastics** (OMV), **Coprocessing** of **pyrolysis oil**, **certification for flying with 100% SAF.**

# Large differences within SAF technology pathways: Short comparison of HEFA, AtJ and PtL

## Hydrotreated Esters and Fatty Acids (HEFA)

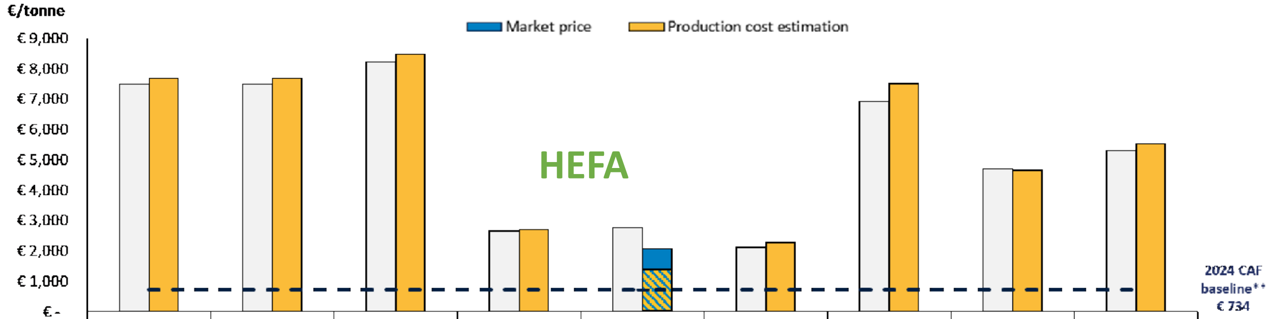
- Almost all of today's SAF with plant capacities up to 1 Mt/a
- Established players, brownfield projects (revamp)
- Feedstock hurdles: Challenging collection, limited availability

## Alcohol-to-Jet (AtJ)

- Few plants running with capacities around 40 kt/a
- Dedicated project developers
- Established alcohol markets, well defined feed

## Power-to-Liquid (PtL)

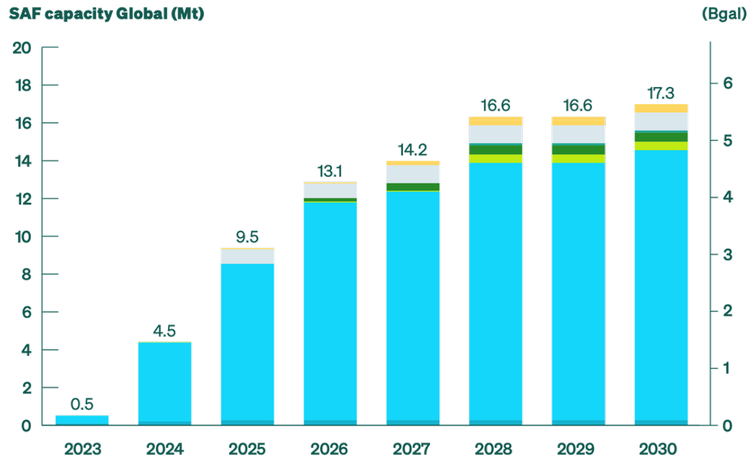
- Minor shares today with plant capacities up to 0.4 kt/a
- Dedicated project developers, greenfield projects
- Feedstock hurdles: Low energy molecules




| | Synthetic aviation fuels from industrial $CO_2$ | Synthetic aviation fuels from biogenic $CO_2$ | Synthetic aviation fuels from atmospheric $CO_2$ | Advanced aviation biofuels | Aviation biofuels * | Recycled carbon aviation fuels | Renewable $H_2$ aviation fuels | Low-carbon $H_2$ aviation fuels | Synthetic low-carbon aviation fuels |
|---|---|---|---|---|---|---|---|---|---|
| 2023 | € 7,500 | € 7,500 | € 8,225 | € 2,675 | € 2,768 | € 2,125 | € 6,925 | € 4,700 | € 5,300 |
| 2024 | € 7,695 | € 7,695 | € 8,470 | € 2,715 | € 2,085 | € 2,280 | € 7,520 | € 4,655 | € 5,525 |

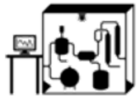
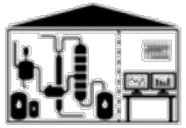
*The bar with blue and yellow stripes represents the 2024 production cost estimation for aviation biofuels (provided for informational purposes).*

*** For reference: The 2023 CAF price was 816 €/tonne.*




Sources: SkyNRG 2024

# The current First-of-a-Kind nature of SAF plants is a key barrier to transition the business cases to growth stage.

| | | | | | |
|---|---|---|---|---|---|
| **Phase** | **Early Stage** | | **Growth Stage** | | **Profit Stage** |
| **Focus** | **Technology Development & Proof** | | **Commercialisation & Expansion** | | **Scaling & Optimisation** |
| **Plant design** | Lab level and individual components | Prototyping / Pilot plants | First-of-its-kind plants (commercial plant) | Second generation / (commercial roll-out) | Mature and optimised plant design |
| **Maturity** | TRL 1-4 | TRL 5-7 | TRL 7-9 | TRL 9 | TRL 9 |
| **Scale** | n/a | Test volumes | Small to middle scale | Middle to large scale | Large industrial scale |
| **TRL** |  Laboratory bench |  Mini plant |  Pilot plant |  Demo plant |  Full-scale plant |
| | | | | |  Full-scale plant |
| **Typical tasks and goal** | Kinetic and thermodynamic study | Connecting processes (incl. recirculating flow, product separation) | Process optimization, dynamic behaviour (start-up, shut down), catalyst lifetime, logistics of feed, products, samples | Obtain general proof that a technology is suitable for the targeted (economic) purpose. | Producing product that is sold, answering the market demand |
| | | | | | Same type of plants of the previous described, with higher experiences and trustability due to the installation of different units. |
| **Further characteristic elements** | Lab scale (small quantity) and manual labor | Usually steel equipment and semi-automatised | Increase of plant size and usually a specific location is chosen. | Products to Initial market. Integration in an industrial value-chain. | Contributed to the economic sustainability of an economic entity (i.e. market profit) |
| | | | | | Fully commercial system |

Sources: Buchner et al.2019

# State-of-the-art and expected development of SAF technologies

## Early Stage
Technology Development & Proof

Pilot plant

## Growth Stage
Commercialisation & Expansion

Demo plant

## Profit Stage
Scaling & Optimisation

Full-scale plant

TRL 5 | TRL 6 | TRL 7-8 | TRL 9

### Hybrid fuel (e.g. Methanol-to-Jet)
Competitive factors: Technology proof, feedstock access (e.g. biogas) and funding for roll-out.

Pro:
- Abundant feedstock
- Low cost of production

Cons:
- TRL4 (TRL8-9 indv. processes)
- High specific CAPEX
- Feedstock / process dependent

### Waste to Liquid
Competitive factors: MSW sourcing and pre-treatment capabilities

Pro:
- Wide range of feedstock
- Low GHG emissions
- Feedstock/process dependent

Cons:
- not yet commercialized
- High specific CAPEX

### Power to Liquid
Competitive factors: Access to renewable energy (Green H2) and CO2.

Pro:
- Hardly any restrictions
- Low GHG emissions

Cons:
- Not yet commercialized
- High specific CAPEX
- High cost of production

### Alcohol to Jet
Competitive factors: Sustain-able Ethanol access and technological integration.

Pro:
- Low specific CAPEX
- Several feedstock available
- Depending on feedstock

Cons:
- Not yet commercialized
- Depending on feedstock

### Biomass to Liquid
Competitive factors: Abundant, reliable biomass feedstock, e.g. forest residues.

Pro:
- Wide range of feedstock
- Low cost of production

Cons:
- Depending on feedstock
- Not yet commercialized
- High specific CAPEX

### Hybrid fuels (e.g. PBtL)
Competitive factors: Technology proof, feedstock access (e.g. biogas) and funding for roll-out.

Pro:
- Abundant feedstock
- Low cost of production

Cons:
- TRL8-9 individual processes
- High specific CAPEX
- Feedstock / process dependent

### HEFA
Competitive factors: **Feedstock access** and **large-scale refinery infrastructure**.

Pro:
- State of the art technology
- Low specific CAPEX
- Low cost of production

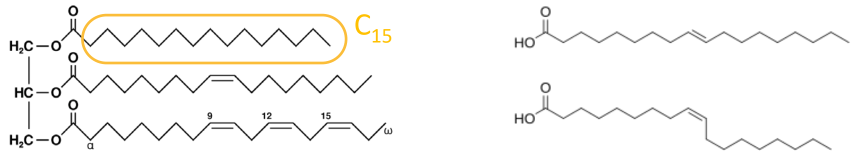
Cons:
- Limited oils / fatty acids supply
- Depending on feedstock

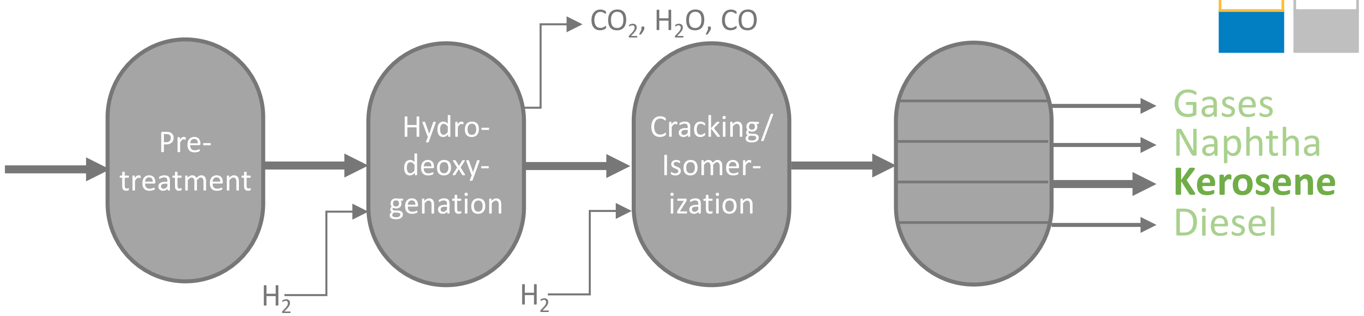
Source: CBR, 2024

# Chemical degree of diversity of feed defines synthesis effort to SAF.

HEFA

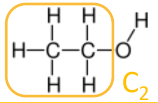
**Esters and fatty acids**
Contain structures very similar to Jet fuel components, that need to be split and upgraded.

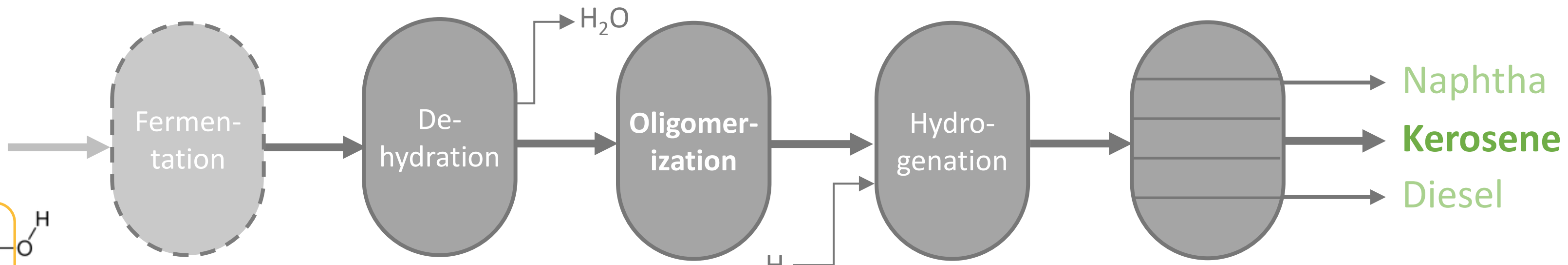



AtJ

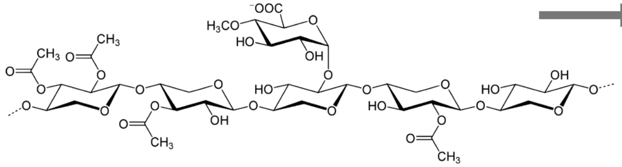
**Alcohol** (ethanol, butanol)
Well defined feedstock from fermentation ($1^{st}$G sugars, $2^{nd}$G lignocellulosic biomass, woody crops, agricultural residues/waste).
C-chain-length needs to be increased (oligomerization).



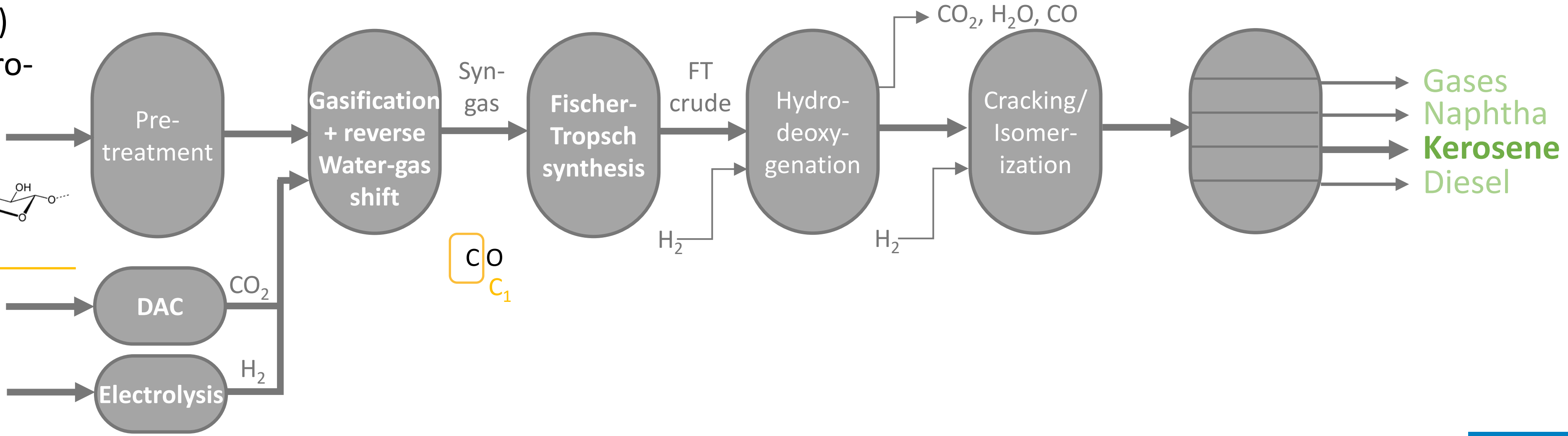

BtL

**Lignocellulosic biomass** (Xylan)
Chemically diverse, solid, hetero-geneous feedstock.

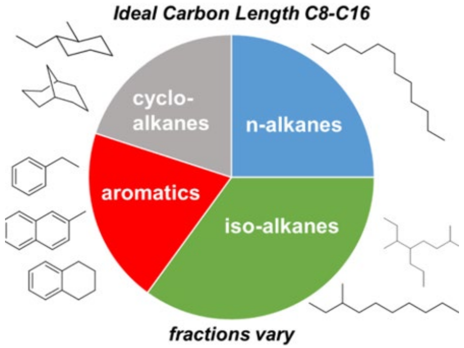


PtL

**Direct Air Capture** of $CO_2$ and **Electrolysis** of water running on electrical power



# Key take-aways




SAF are a drop-in solution, but the composition differs from fossil fuels. SAF are used up to **50% blend.**

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**ASTM certification** is a requirement to commercialize a SAF and use it in an airplane engine.

1. HEFA
2. Power-to-Liquid
3. Waste-to-Liquid
4. Biomass-to-Liquid
5. Alcohol-to-Jet
6. Hybrid fuels, e.g. PBtL

**HEFA** as **most mature** technology (TRL 9), but **limited feedstock**. Other **technologies emerge**.

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Insights on **exemplary SAF projects** showed the **state of the art** of each **technology route**.

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# Summary

| | Project Developers | Eni | LanzaJet | Uniper |
|---|---|---|---|---|
| 1 | Who is that player? What is the player's **background**? | Established, Oil&Gas | Technology developer | Established, energy supplier |
| 2 | Where / in which **phase** does the project stand and what is the **timeline**? | Fully operational Jan. 2025;<br>2014-19 HVO (300 Mio EUR),<br>2023-25 SAF | Officially opened in Jan. 2024;<br>2018-20 Technology development,<br>2021-24 Construction | Discontinued Oct. 2024;<br>2021: Announced, 2022: Feasibility phase, 2025: Planned FID |
| 3 | Which **location** is chosen for the plant? Why? | Gela, Italy;<br>Existing asset | Soperton, Georgia, US;<br>Feedstock supply, regulatory | Långsele, Sollefteå, Sweden;<br>feedstock supply, electricity |
| 4 | Which **feedstock** shall be used? | UCO, animal fats, by-products from vegetable oil processing | Ethanol from sugarcane, novel waste sources in the future | Biomass, electricity ($H_2$) |
| 5 | Which **technology** is used and is there an according ASTM pathway? | Ecofining™ Diesel (HVO), SAF (HEFA) | Dehydration and Oligomerization | PBtL: Gasification, Fischer-Tropsch |
| 6 | What is the technological **readiness** level? What is the target **capacity**? | TRL 9; 736 kta biomass, 1 Mio ton SAF by 2026 | TRL 8-9; 300 kta | TRL 7-8 (islands potentially higher); 100 kta |
| 7 | Who are the **partners**? Who are these partners/sponsors? | Enilive, Honeywell UOP (for technology development) | Pacific Northwest National Laboratory (PNNL); Shareholder: International Airlines Group (IAG), LanzaTech, Mitsui & Co., Shell, and Suncor Energy. Investors: Microsoft Climate Innovation Fund, Breakthrough Energy, British Airways, and All Nippon Airways (ANA) | Sasol ecoFT (technology provider) |
| 8 | What are potential **risks** and **limitations** to this project? Why? | Supply of waste-based feedstocks, regulatory uncertainty | Supply of ethanol feedstocks, regulatory uncertainty | Market dynamics, regulatory uncertainty, cost escalation |
| 9 | What is **unique** about this project? How do the aspects fit together? | Revamp of existing refinery, constant adaptations | World's first ethanol-to-jet (AtJ) | First-of-a-kind (FOAK) PBtL |

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