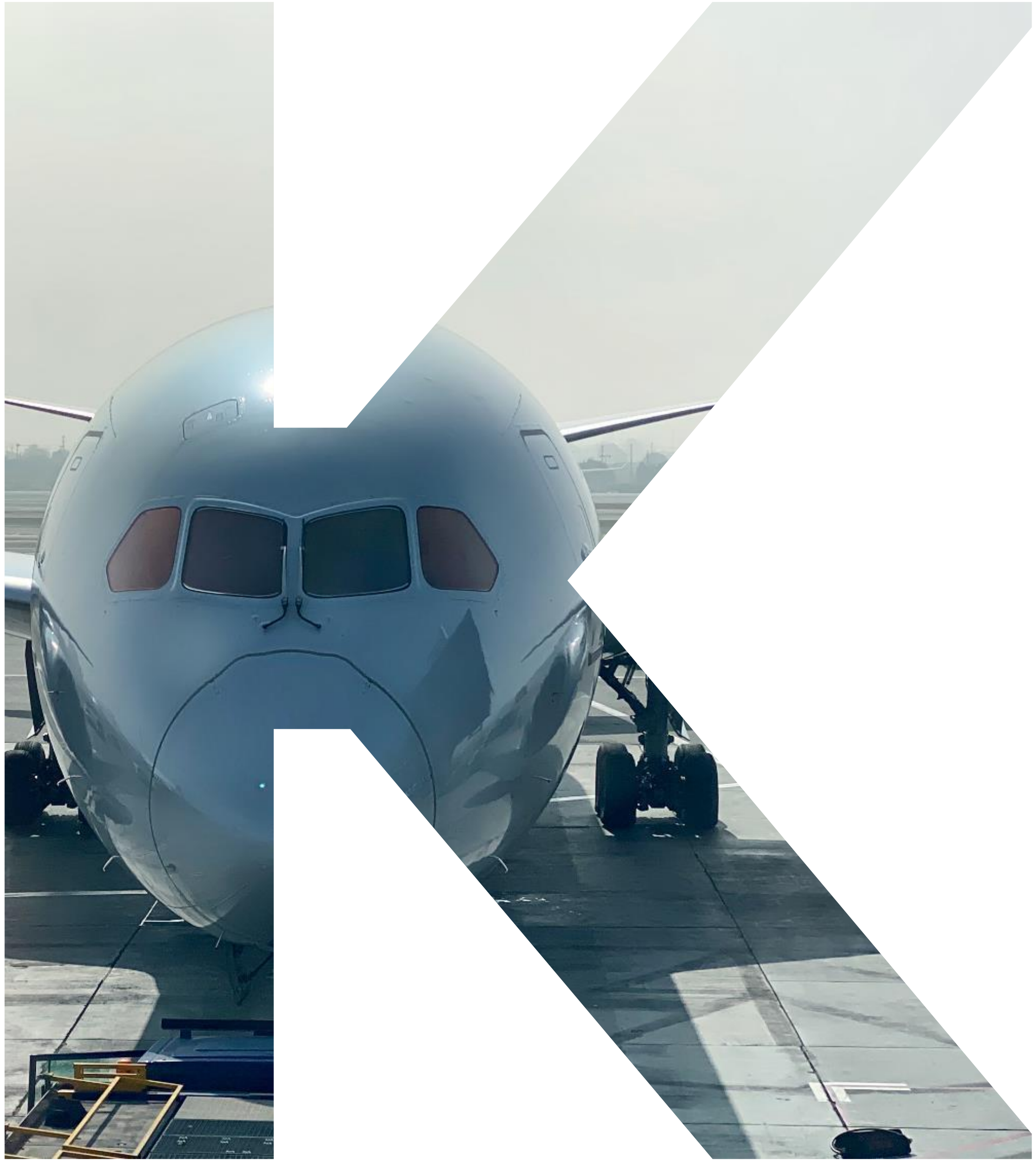
# Sustainable Aviation Fuel (SAF)

**IC**
August 2022



KEARNEY

# Sustainable Aviation Fuel offers significant emissions reduction opportunities & improved fuel efficiency – however cost is still high & blending is limited to 50%

## Overview: SAF advantages & drawbacks

### Advantages

- Significant **overall** lifecycle **$CO_2$ emission reduction** possible (80-100%)
- Currently **readily available** decarbonization option based on a **variety** of different **biomass sources**
- Offers the **possibility** of **extending** the **lifespan** of **older aircraft** while **decreasing** their specific **emissions**
- Offers an **improved fuel efficiency** (1.5 – 3%) as well as a slightly **higher energy density** than conventional fuel
- Produces **90% less particle** emissions & **100% less SOx** emissions compared to JetA1

### Drawbacks

- **Additional cost** due to **complex synthesis** route (currently ~3x higher cost than conventional kerosene)
- **$CO_2$, NOx, $H_2O$** and **particles still** locally **emitted**
- Current **tech. limitation** of **50% due** to **missing aromatics** (required for proper sealing, deep-dive on next slide)
- **Bio-based SAF potential limited** due to global **feedstock availability**



Sources: SkyNRG, Kearney

# The current SAF-Blend is limited to 50% mainly due to the aromatics within jet fuel being responsible for sealing properties of hydraulic nitrile O-rings in the aircraft

## Explanation of technical limitations

SAF[1] = Jet Fuel — **Aromatics**

- **Aromatics** cause **swelling** of **nitrile O-rings** within fuel system of aircraft and **ensure sealing,** but also cause **increased particulate emissions** (less efficient burning)
- **Maximum SAF-blends** are thus set at **50%** for most production pathways[2] (Notable exception: 10% for HH-SPK[3], HC-HEFA[3] and synthesized Iso-Paraffin)
- **Aircraft** can be operated with **pure SAF** if they were **never powered** by **aromatic-rich fuels** before
- **Research** is looking into **molecules** as **SAF additives** to provide **sealing properties** (aromatics, cycloalkanes)

## SAF-blending capabilities for different aircraft types

### Conventional O-ring sealings in **existing aircraft**

**Combined JF[4]-SAF use**: 50% max. SAF[5] | 50% min. jet fuel

### Conventional O-ring sealings in **new aircraft (purchase <2030)**

**Combined JF[4]-SAF use**: 50% max. SAF[5] | 50% min. jet fuel

Likely case due to the limited SAF availability

**Pure SAF use**: 100% SAF capable

### Upgraded sealing technology in **new aircraft (purchase 2030+)**

**JF[4]-SAF flexible**: 100% SAF or JF capable

EU Taxonomy: 100% SAF certification required in 2028+

1. Simplified illustration | 2. FT & FT-SKA (Fischer-Tropsch containing aromatics), HEFA (Hydro-processed esters and fatty acids), ATJ (Alcohol-to-jet), CHJ (Catalytic hydro-thermolysis jet fuel)
3. HH-SPK or HC-HEFA = Hydro-processed hydrocarbons | 4. JF = Jet fuel | 5. Without additives such as synthetic aromatics or cycloalkanes or sealing retrofit

Source: WEF, IATA, U.S. DOE, Kearney

# Most SAF production routes are bio-based and have max. blend ratios of 50% - Power-to-Liquid (PtL) uses $CO_2$ from point sources or Direct Air Capture

## Overview: SAF production routes

Deep-Dive next Slide

| | Technology | Max. blend | Raw materials | Description |
|---|---|---|---|---|
| Power-to-Liquid | Power-to-Liquids (PtL) | 50 % | Electricity, $CO_2$ & $H_2O$ | $H_2O$ is split to **$H_2$** in an electrolyzer & processed with **$CO_2$ into syngas** which is **converted** into **liquid SAF** |
| Bio-based | Hydro-processed Esters & Fatty Acids (HEFA) | 50 % | Vegetable oils, used cooking oil | **Feedstock** is **deoxygenated** and consequently **hydro-processed** to produce the blending fuel |
| Bio-based | FT (Fischer-Tropsch) & FT-SKA (FT containing aromatics) | 50 % | Wastes (MSW), agricultural residues, lignocellulosic | The **feed** is **gasified** into **syngas** (CO + $H_2$), which is **catalytically converted** to liquid hydrocarbon fuels |
| Bio-based | Alcohol-to-Jet (ATJ, Isobutanol & Ethanol) | 50 % | Sugarcane & -beet, agricultural residues, lignocellulosic | The process consists of **alcohol conversion** through **dehydration**, **oligomerization** & **hydro-processing** |
| Bio-based | Catalytic Hydrothermolysis Jet fuel (CHJ) | 50 % | Waste oils or energy oils | **Hydrothermal conversion** & **hydrotreating** of the **feedstock** towards fuel like jet fuel (incl. aromatics) |
| Bio-based | Hydro-processed Hydrocarbons (HH-SPK or HC-HEFA) | 10 % | Oils produced from algae | **Hydro-processing** of bio-derived hydrocarbons unlike fatty acids (from algae botryococcus braunii) |
| Bio-based | Synthesized Iso-Paraffin (SIP) | 10 % | Sugarcane, sugar beet | A **fermentation process** converts the **feedstock** into hydro-carbon molecules to mix with jet fuel |

Power-to-Liquid SAF production | Bio-based SAF production

Sources: IATA, WEF, Biofueldigest, ICCT, Kearney

# SAF based on Power-to-Liquid are the best option for scale-up as they are not limited by feedstock availability, require less space & enable full decarbonization

## Potentials: Production routes

Even **exploiting total** available **feedstock** in the **EU** for SAF would only cover **~25% of total fuel**

Purely **hypothetical consideration without feasibility** assessment

| Process | Max. feedstock available in the EU | Global 2050 jet fuel demand[1]: Space | Additional sustainability aspects | Potential | | Cost | |
|---|---|---|---|---|---|---|---|
| | | | | TRL[2] | Feed[3] | Today | Future |
| Power-to-Liquids (PtL) | Total potential not limited | **0.1 – 0.5%** of habitable land required | – **Must** be operated using **green energy**<br>– Very **low water** demand: **4 $L_{H2O}/L_{SAF}$**<br>– **$CO_2$** WTW **reduction** potential: **100%** | | | | |
| Hydro-processed Esters & Fatty Acids (HEFA) | **~2%** of total aviation fuel demand **in 2030** | **4 – 19%** of habitable land required[5] | – Spec. **yield** of **feedstock not favorable**<br>– **High** max. **$H_2O$** demand[2]: **22 000 $L/L_{SAF}$**<br>– **$CO_2$** WTW **reduction** potential: **~80%** | | | | |
| Fischer-Tropsch (FT) w/ gasific. | **~16%** of total aviation fuel demand **in 2030** | **3 – 7%** of habitable land required | – **Must** use **sustainable feedstocks**<br>– **$CO_2$** WTW **reduction** potential: **~90%** | | | | |
| Alcohol-to-Jet (ATJ) | **~7%** of total aviation fuel demand **in 2030** | **2 – 4%** of habitable land required | – **Competition** with **road traffic**<br>– **High** max. **$H_2O$** demand:[4] **6 000 $L/L_{SAF}$**<br>– **$CO_2$** WTW **reduction** potential: **~90%** | | | | |

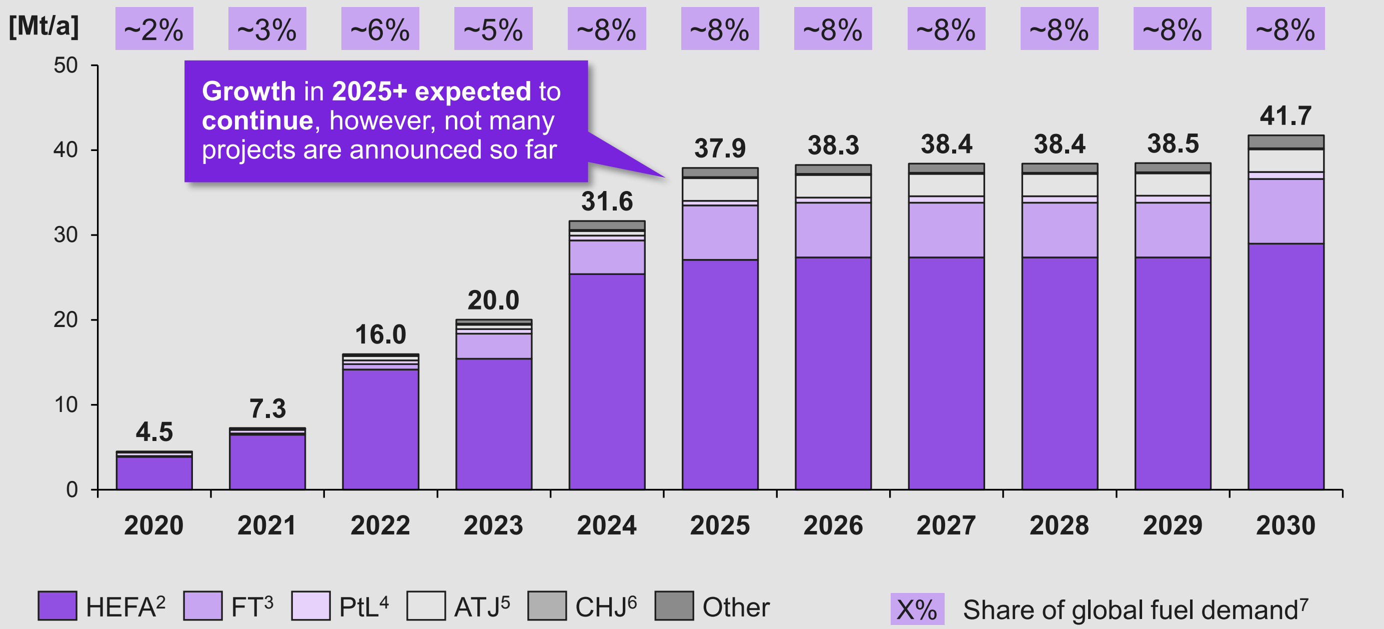
Low potential   High potential

1. Required land depending on feedstock type; 2. TRL – Technology Readiness Level; 3. Feedstock availability potential; 4 $H_2O$ demand depending on feedstock ; 5. Excl. palm oil
Source: ICCT, ICAO, Umweltbundesamt, WEF, Kearney

# Most currently announced SAF production facilities are based on the bio-based HEFA process – global market share until 2030 would currently not reach 10%

Situation as of April 2022

## Overview: Cumulative global SAF production capacity by technology [Mt/a][1]




## Key insights

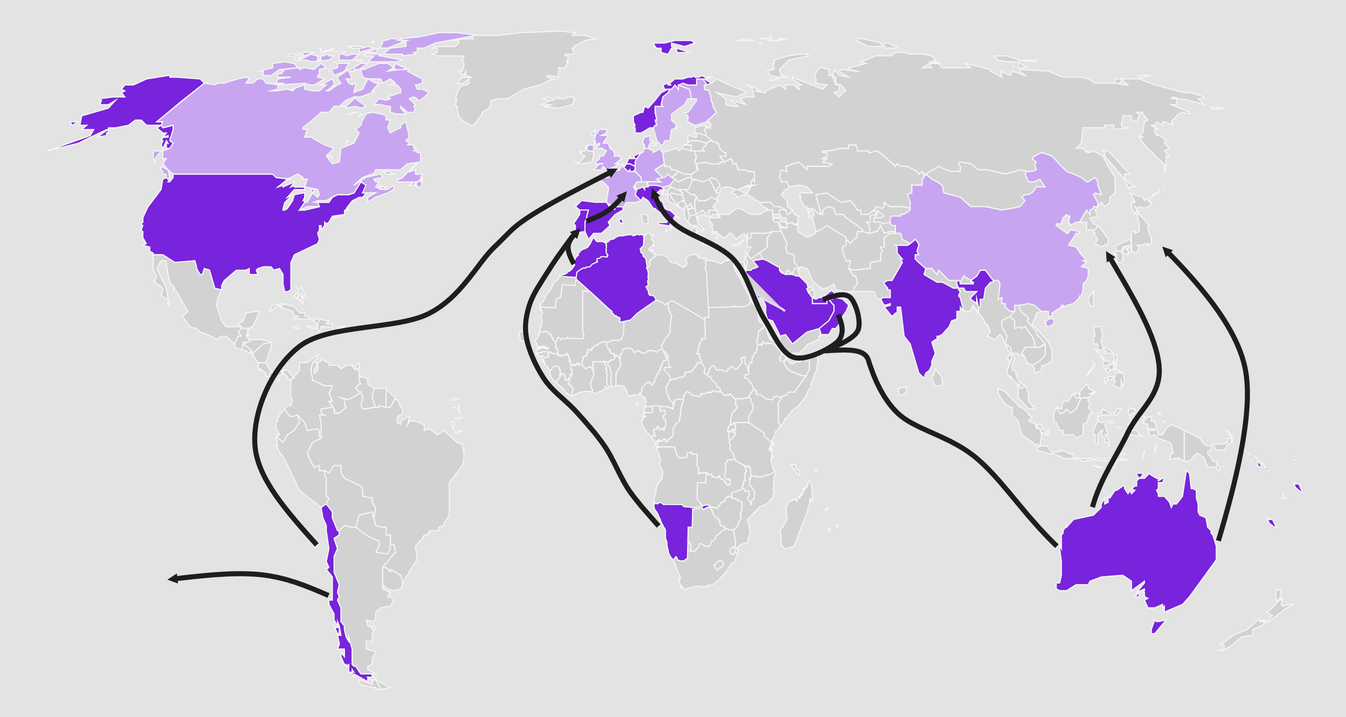
- Currently **announced production capacities** until **2025** are projected to **increase** supply almost **10-fold**
- **Only few projects** are **announced** for **2025+** (number is expected to increase significantly in the next years)
- **Most** the current **activities** still **focuses** on **HEFA-based processes**
- **FT-based** processes utilizing **municipal waste** start **gaining** traction towards **2025**
- **More PtL-based production expected** to be developed & announced **soon** to cover a larger part of the global fuel market

1. Based on databases from ICAO & WEF; 2. HEFA – Hydro-processed Esters & Fatty Acids; 3. FT – Fischer-Tropsch; 4. PtL – Power-to-Liquid; 5. ATJ – Alcohol to Liquid; 6. CHJ – Catalytic Hydrothermolysis Jet fuel; 7. Based on aviation growth projections from IEA; Sources: ICAO, WEF, Kearney

# Economic competitiveness of Power-to-Liquid synthetic fuels can be improved by focusing on large-scale production in low energy cost regions

Situation as of August 2022

## Overview: Potential low energy cost regions & import pathways (selection)



## Key insights

- **Cost** for **electricity** & **energy** input **decisive** for **economic competitiveness** of Power-to-liquid fuels
- **Regions** with **high availability** of **cheap renewable electricity positioned well** to support **large-scale production**
- **Import/Export** of liquid fuels **possible** using **established networks** compared to more complex $H_2$ transport

## Legend

- Low energy cost region
- Other potential production region
- Potential import routes



Source: IEA, BDI, Kearney

# PtL SAF production in Saudi Arabia is expected to be significantly cheaper than local $CO_2$ direct air capture and $H_2$ production in Germany …

Example country Saudi Arabia

Alternative pathways (e.g. Methanol) for synthetic fuels exist and deserve further analysis as well

## Comparison of possible production value chains for PtL SAFs for 2030 [€/$Liter_{SAF}$]

| | A Renewable energy | B $H_2$ production | C Direct air capture | D RWGS[1] | E Fischer-Tropsch[2] | F Transport & Conversion | G Sustainable aviation fuel |
|---|---|---|---|---|---|---|---|
| | Electricity | Electrolysis | $CO_2$ | CO + $H_2$ | SAF | Ship | End use (Germany) |
| Germany | 1.90 -2.20 €/$L_{SAF}$ | | | | | | |
| Saudi Arabia | 1.00 – 1.10€/$L_{SAF}$ | | | | | | |
| Cost trends | ↓↓ | ↓ | ↓↓ | → | → | → | |

**Electricity prices** are a **key factor** of the total cost of green hydrogen. Saudi Arabia has reported the lowest electricity cost worldwide with 1.04 US ct/kWh from renewable energies.[4]

**Direct air capture** is a promising yet still capital extensive technology to filter $CO_2$ directly from the atmosphere. As such, it represents a **significant cost component** within the value chain of SAF production.

Depending on the **production site of $H_2$ and SAF** itself, **transport** from Saudi Arabia to Germany may constitutes an **additional cost** position to consider

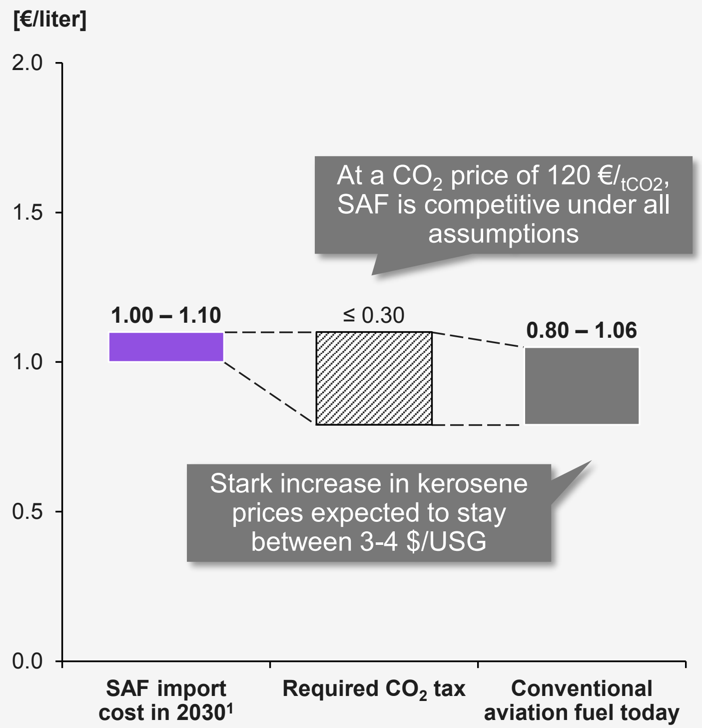
1. RWGS = Reverse water-gas shift reaction; 2. Simplified assumption $CO_2$ conversion ~ 85%; 3. Including conversion, transport and reconversion via the ammonia route
4. See joint Uniper-Kearney study on green hydrogen import pathway competitiveness in 2025; Option B assumes green ammonia imports to Germany
Source: Kearney

↑ Small cost increase; → Cost stable; ↓ Small cost decrease; ↓↓ Significant cost decrease; ○ Insufficient current cost information

# … and looking at 2030 economics, PtL SAF imports could become a viable option

Situation as of June 2022

## PtL SAF cost perspective 2030




## Insights

- **PtL SAF** will most likely become a **cost-effective alternative** in **2030+**
- **Currently high kerosene cost** due to the energy crisis are **likely** to **stay long-term**
- Depending on price development & technology improvement, **SAF could be** economically **competitive without** $CO_2$ **taxes** in **2030**
- Carbon price of ≤ **120 €/$t_{CO2}$** or SAF subsidies are **sure** to **break even** with conventional aviation fuel cost - EU ETS $CO_2$ price is expected to reach 150-200 €/$t_{CO2}$ **by 2030**[4]

## Assumptions

- Current EU ETS $CO_2$ price of 80 €/$t_{CO2}$ considered
- Specific $CO_2$ emissions of Kerosene of 2.56 $kg_{CO2}$/Liter

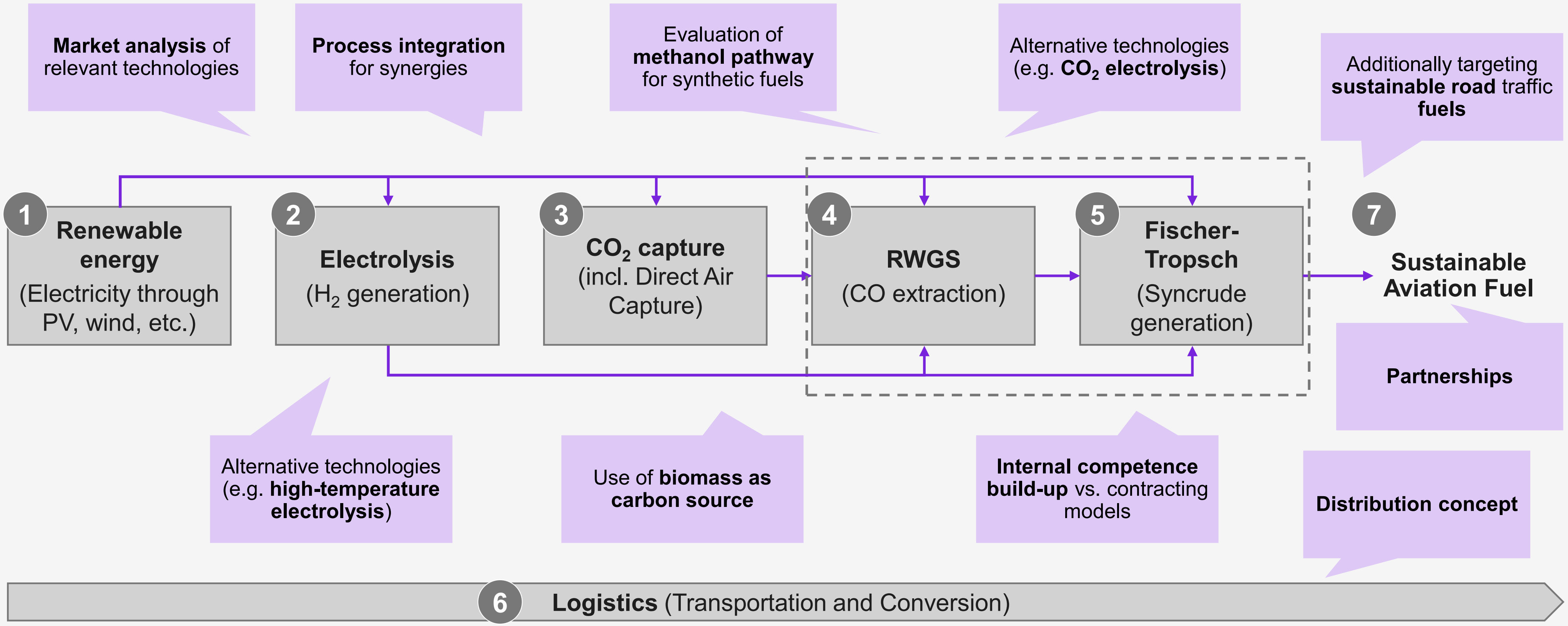
**While not yet competitive with conventional fuels, SAF will become a cost-effective alternative by 2030.**

1. SAF production via PtL assumed to reduce 100% of $CO_2$ emissions; 2. May 2022: $CO_2$ tax of 80 €/$t_{CO2}$ emitted; 3. Specific $CO_2$ emissions of Kerosene of 3.39 $kg_{CO2}/kg_{JetA1}$; Sources: IATA, WEF, Clean Skies for Tomorrow, Kearney

# We suggest to investigate additional opportunities and technologies across the value chain of sustainable fuels

**Overview:** **Additional PtL opportunities**

Use case example






Source: Kearney