Low temperature CO_2 electrolysis for synthetic fuel production

Evaluating the potential of a new technology for decentralized CO_2 sources utilization

Capgemini invent

in collaboration with

carboneo | Naldeo

Executive summary

The aviation industry faces a critical challenge: how to decarbonize a sector expected to double in traffic by 2050 while meeting net-zero emissions targets. Sustainable Aviation Fuels (SAF), particularly synthetic fuels produced from captured CO_2 and green hydrogen (e-fuels), are central to this transition. However, current production methods are costly, complex, and difficult to scale.

This joint study by Capgemini, Carboneo, and Naldeo explores a breakthrough solution: ***low-temperature CO_2 electrolysis*** —a promising alternative to the conventional Reverse Water Gas Shift (RWGS) process targeted to be used in synthetic fuel production. This emerging technology directly converts CO_2 into carbon monoxide (CO) using electricity, simplifying the production process and reducing hydrogen consumption by 26%. The result is a projected 15% cost reduction in synthetic fuel production by 2030.Beyond cost savings, CO_2 electrolysis offers strategic advantages:

Modularity:
Unlike RWGS, it can be deployed at small to mid-scale CO_2 sources (e.g., cement plants, biogas units), enabling decentralized fuel production.

Flexibility:
Fully electrified and compatible with intermittent renewable power, it improves the overall energy balance of the Power-to-Liquid (PtL) pathway.

Industrial Sovereignty:
Carboneo's molecular catalyst technology reduces reliance on critical metals and supports a European clean-tech supply chain. With a technology readiness level of 3–4 and pilot demonstrations planned by 2026, CO_2 electrolysis is on track to become a cornerstone of Europe's synthetic fuel ecosystem. Its development aligns with EU climate goals and industrial policy, offering a scalable, sovereign solution to decarbonize hard-to-abate sectors such as aviation.

Introduction: The current stakes around SAF production require further exploration on new production technologies

Civil aviation is a rapidly growing sector which relies primarily on Sustainable Aviation Fuels (SAF) to achieve its climate targets: net-zero by 2050

Aviation plays a significant role in global emissions, and its rapid growth makes it particularly challenging to decarbonize.

- In 2019, aviation-related CO_2 emissions reached approximately **1 Gt,** equivalent to the total annual emissions of Japan[1]. This represented around **2.5% of global GHG emissions** from fossil fuel combustion[2]
- When non-CO_2 effects (such as contrails and nitrogen oxides) are included, the **climate impact could be twice as high**[3]
- Following a temporary drop during the COVID-19 crisis, **air traffic is expected to double by 2050,** which could push emissions beyond **2 Gt/year** in a business-as-usual scenario where traffic growth is forecasted at +3%/year[4]

[1] IEA, Tracking Aviation 2021 / ICAO
[2] ICAO, Environmental Report 2019
[3] IPCC AR6 / EASA, 2020
[4] ICAO, Long-Term Traffic Forecast 2021

To align with global climate goals, aviation must reach net-zero emissions by 2050. The sector relies on a mix of five main decarbonization levers[5].

Among these, SAF represents more than half of the levers and stands out as one of the **most immediately actionable technical solution** (apart from demand reduction, a especially since SAF are drop-in-fuels[6], and do not require significant technological changes to the aircraft engines. Moreover, maintaining the same energy density as conventional jet fuels allow the SAF to bring a ready-to-use solution for the long-haul flights, for which electric, hybrid and hydrogen propulsion will not be variable in the short term, nor will the modal shift to trains, cars, buses, ships.

As the **SAF stakes** are not mainly linked to usage and integration[7], they are **strongly driven by a skyrocketing demand from airlines** seeking to decarbonize, enhance their image, and comply with regulations.

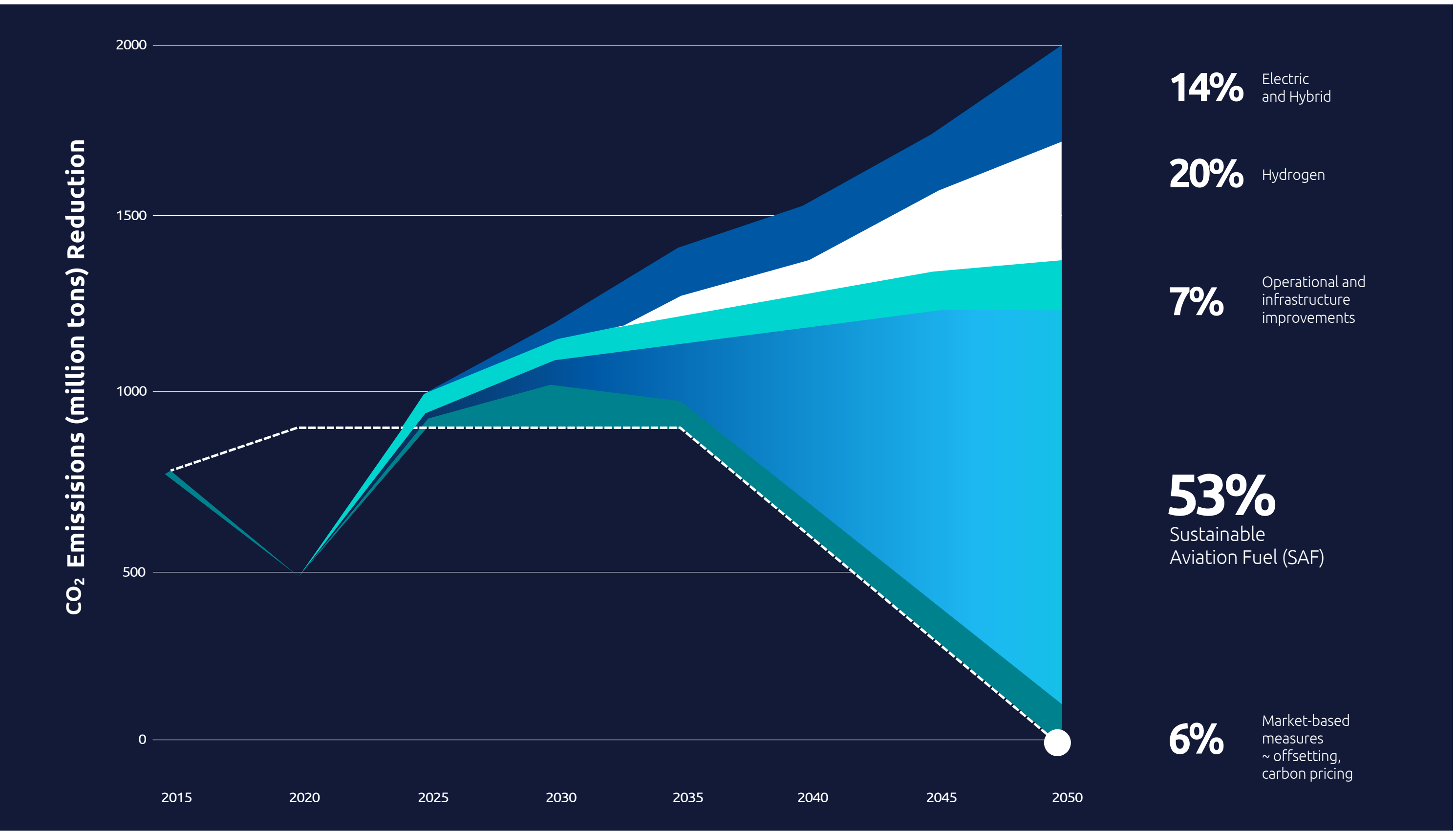


Figure 1: *Civil aviation sector path to net zero by 2050 (source: Capgemini SAF report adapted from Waypoint 2050)*

[5] Waypoint 2050 report

[6] Alternative fuel used in current aviation engines without requiring modifications. It is chemically similar to traditional fossil fuels.

[7] Aircrafts are certified to fly with 50% SAF blended with conventional jet fuel, and first essay flights with 100% SAF have been performed and was successful.

Among SAF types, synthetic fuels can unlock the fuel decarbonization needs for the global aviation sector facing several production scaling challenges

According to industry projections[8], global SAF demand could reach 450B liters by 2050, fulfilling 53% of the decarbonization target. This necessitates a 350-fold increase in production capacity over the next 25 years, raising concerns about scalability. This unlocks a potential market of 225B liters of synthetic fuels (produced by Power-to-Liquid pathways) by 2050 based on the extrapolation of the European sub-mandates on synthetic fuels.

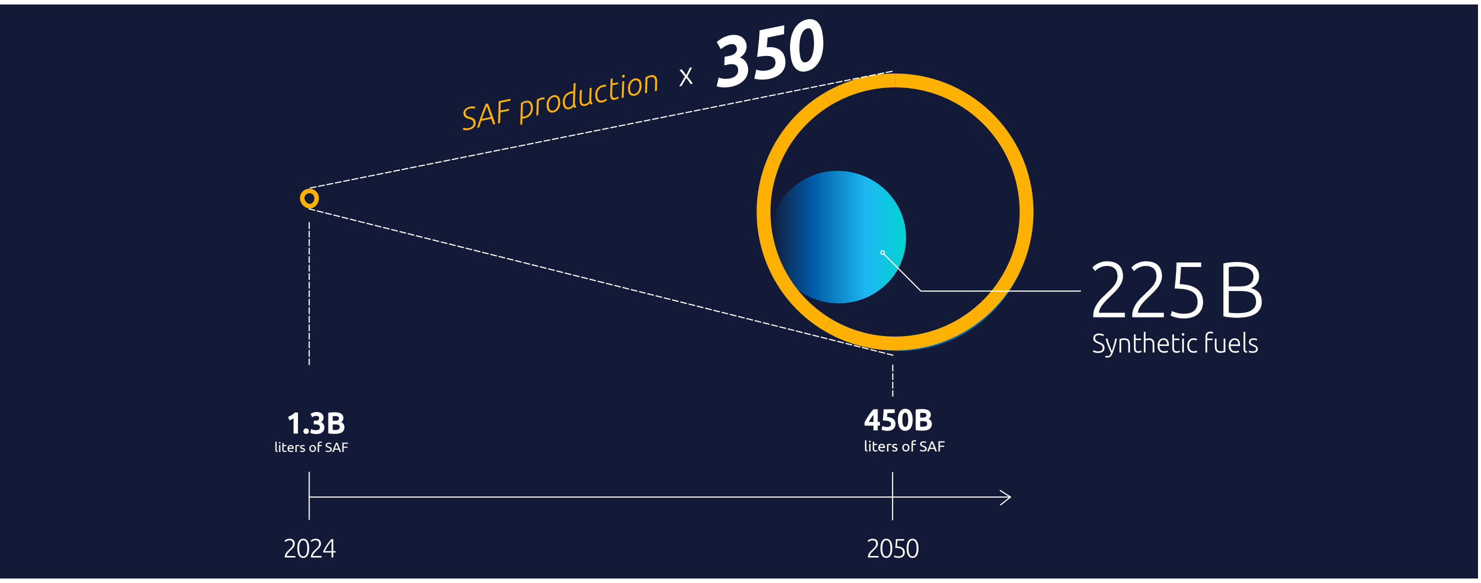


Figure 2: *Evolution of the necessary global SAF production from 2024 to 2050 in the aviation sector* [9]

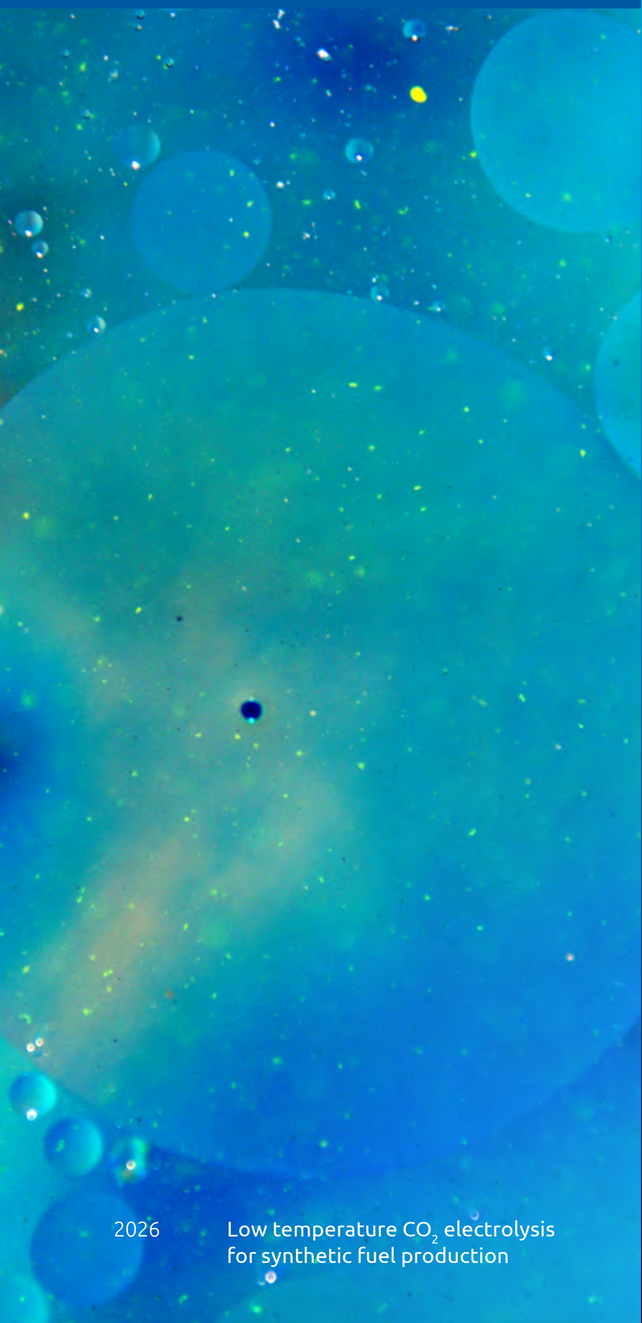
This document focuses only on PtL pathways for synthetic fuel production (bio-based production out of scope), leveraging thermochemical and/or electrochemical processes. **Synthetic fuels** from CO_2 captured and combined with hydrogen (preferably from water electrolysis with electricity from renewable or low-carbon sources – RFNBO / LCFNBO) will be called **e-fuels (or e-SAF)** in this document.

Although the gradual and large-scale deployment of synthetic fuels in the market represents a major strategic lever for the decarbonization of aviation and is driven by regulations such as the ReFuelEU Aviation[10], it also raises significant technological, economic, and industrial challenges to be addressed in the coming decades, as well as resource constraints for the inputs (H_2 subject to energy constraints and CO_2 subject to compliance and dispersion).

The development of synthetic fuels also aims to ensure demand-driven production and ultimately minimize the overall environmental footprint of aviation fuels.

[8] IATA, Net zero 2050: sustainable aviation fuels, June 2023
[9] IATA, SAF Deployment Policy, 2023
[10] Official Journal of the EU, ReFuelEU Aviation, L239/1, 22 Sept 2023

Focus on ReFuelEU Aviation initiative



Brought under the Fit for 55 package, the objective is to increase demand for and supply of sustainable aviation fuels, reducing CO_2 emissions and ensuring a level playing field across the EU air transport market:

- **Mandates for Aircraft Operators:** progressive increase in SAF blending by 2050 with 70% SAF, including at least 35% synthetic fuels.
- **Infrastructure Development:** encourage the enhancement of airport infrastructure to support the production, storage, and use of SAF.
- **Investment Promotion:** thriving financial incentives to airlines, airports, and fuel producers with public-private partnerships or direct funding mechanisms. For example, the integration of SAF into the EU Emissions Trading System (EU ETS) to support SAF uptake, to bridge the cost gap and incentivize early adoption by airlines (€20M EU allowances).

	General	Specific to synthetic fuels
Strengths	SAF drop-in capability for existing aircrafts (certification for 50% of blended SAF) and infrastructures, no	Immediate near-zero GHG emissions potential well-to-wake if using renewable or low-carbon H_2 and captured CO_2 No or paltry land use vs bio-fuels: no competition with agriculture (~90% lower land intensity compared to biofuels production) Lower water demand than bio-fuels pathways (~30–50% less depending on electrolysis method)
Weaknesses	SAF must meet strict regulatory and certification standards to be used in aircraft, which can be a lengthy and complex process for new pathways	Lower level of maturity of the synthetic fuels pathways compared to bio-fuels production, especially for the industrial carbon capture and RWGS bricks High production costs: synthetic fuels currently 3–5 times more expensive than fossil jet fuels (depending on electricity price and plant scale) Massive electricity demand for hydrogen production required for e-fuels: 15–20 kWh of renewable /low-carbon electricity needed per liter of product No guarantee of zero-pollutant emissions during production if using fossil-heavy electricity grids (outside European scope)
Opportunities	Strong regulatory driver: ReFuelEU mandates — 2% SAF by 2025, 6% by 2030 (sub-mandate of 1.2% synthetic fuel), 70% by 2050 (sub-mandate of 35% Boost to local economies through renewable energy projects and SAF production hubs, enhancing European energy sovereignty	Enabler of the development of a profitable hydrogen value chain (electrolyzer market expected to reach €50 billion globally by 2030 – IEA) Cleaner combustion: 90% reduction in sulfur and aromatic emissions compared to conventional jet fuel according to ICAO
Threats	Important production ramp-up expected to reach the sector's ambitions and the regulatory mandates of different regions Technological lock-in risk: SAF-based aircraft fleets will dominate beyond 2050, potentially delaying adoption of disruptive alternatives (e.g. H_2 or electrical aircraft).	Fossil CO_2 sources banned for RFNBO eligibility after 2041, increasing reliance on a diffuse biogenically CO_2 ecosystem and a costly Direct Air Capture (DAC estimated at €300–600/tCO_2 today according to IEA) Low European sovereignty: ~70% of electrolyzer manufacturing capacity (for water electrolysis) currently based outside the EU according to Hydrogen Europe Deployment risk: EU electricity generation must increase by +25–30% to meet hydrogen and e-fuels needs by 2030, according to the European Commission, increasing competition for renewable electricity with other industries (green steel, chemical sector, electric mobility).

Figure 3: *SAF and synthetic fuels sectors' overview of strengths, weaknesses, opportunities and threats*

Synthetic Aviation Fuels Production pathways

The **Fischer-Tropsch pathway** is currently the most widespread production route for producing synthetic fuels. It combines **electrochemical (water electrolysis) and thermochemical (RWGS) conversions to produce syngas, the precursor for Fischer-Tropsch synthesis**. Both rely on the same technological bricks of water electrolysis and CO_2 from carbon capture supply to the hydrocarbon transformation into fuel. These processes use low carbon or renewable electricity at transformation steps to reduce environmental impact of syntheses.

The Fischer-Tropsch pathway is the most preferred pathway for the first projects announced for synthetic fuel production

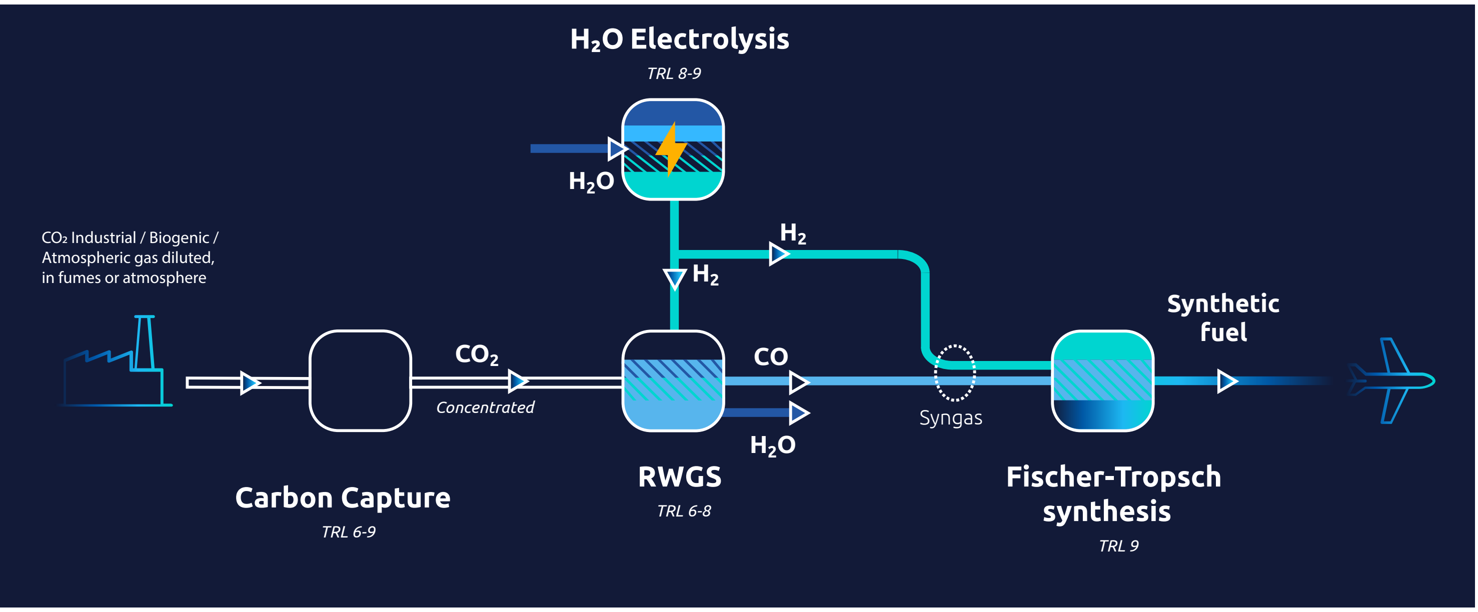


Figure 4: *Fischer-Tropsch pathway for synthetic fuel production* [11]

[11] Power-to-Liquids : A scalable and sustainable fuel supply perspective for aviation, 2022

The FT pathway (or FT-SKA) is currently the most mature and widely adopted route for synthetic fuel production projects, offering high compatibility with existing fuel infrastructure. This pathway involves three main stages:

- **An electrochemical conversion**, where green hydrogen is generated via water electrolysis using renewable electricity
- **A first thermochemical conversion**, where captured CO_2, combined with a fraction of green hydrogen, is converted into CO and H_2O through a Reverse Water Gas Shift (RWGS) reaction. The CO is then mixed with green hydrogen to form a syngas
- **A second thermochemical conversion**, where the syngas is converted into long-chain hydrocarbons through the Fischer-Tropsch synthesis, which are subsequently upgraded into synthetic kerosene, compliant with aviation fuel standards (ASTM D7566[12]).

However, RWGS remains the least mature brick in the pathway (apart from the upstream carbon capture brick), with **TRLs ranging from 6 to 8** depending on different demonstrators and industrial pilots. The pathway overall currently reaches a **Fuel Readiness Level (FRL) of 6 to 7,** with ongoing industrial efforts aimed at full-scale deployment[13]. For example, based on this technology, Ineratec recently opened on June 2025, the largest PtL plant in Europe with 2,500 tons/year of e-fuels production capacity.

[12]ASTM D7566 is the international certification standard for synthetic and alternative aviation fuels. It defines the technical requirements and testing protocols that synthetic fuels (such as Fischer-Tropsch SPK or HEFA-SPK) must meet to be blended with conventional jet fuel for commercial aviation use.

[13] An overview of the Sustainable Aviation Fuel: LCA, TEA, and the Sustainability Analysis, 2024

Low temperature CO_2 electrolysis can boost the FT pathway

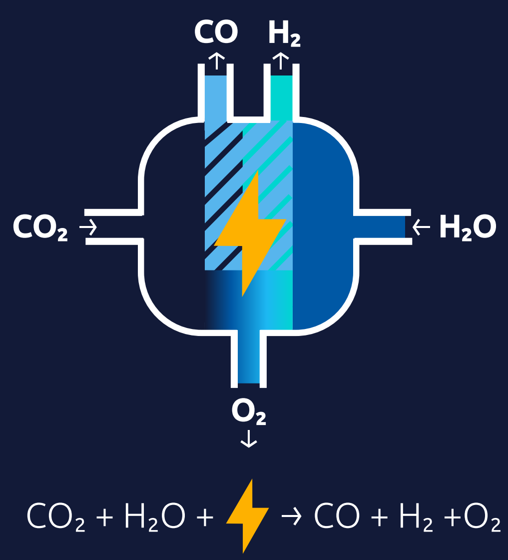


Figure 5: *CO_2 electrolysis process*

Low temperature CO_2 electrolysis

CO_2 electrolysis (electrochemical conversion) offers an alternative to the RWGS step (thermochemical conversion) by enabling the direct production of CO for captured CO_2 using electricity. Using the same principle as water electrolysis: in a CO_2 electrolyzer, electricity is used to break CO_2 into CO and oxygen.

The reaction requires CO_2, water and electricity and as with green hydrogen production, low-carbon electricity is used to lower the footprint of the electrolysis process.

As outputs of the reaction, CO (desired product) has co-generated byproducts such as O_2 but also $H_{2\,2}$ in a relatively small quantity.

Low temperature CO_2 electrolysis could facilitate the production of synthetic fuels

Low-temperature CO_2 electrolysis could offer an alternative to RWGS technology brick by enabling the direct production of CO from captured CO_2 using electricity. This electrified process simplifies the FT pathway by eliminating more complex (size and system) RWGS technology brick, reducing the overall hydrogen consumption and moving the CO_2-to-syngas conversion from a combination of electrochemical & thermochemical routes to a 100% electrochemical route (except the last Fischer-Tropsch brick which is common to the 2 pathways). The integration of CO_2 electrolysis in the PtL pathway allows for an improvement in the energy balance and noticeable reduction of the production costs.

Compared to RWGS, CO_2 electrolysis would require 26% less hydrogen to produce synthetic fuel. Even assuming a high CAPEX for CO_2 in 2030 (estimated at four times the CAPEX of the water electrolyzers), the reduction in hydrogen consumption leads to overall CAPEX savings. As a result, synthetic fuel produced via CO_2 electrolysis is expected to be 15% cheaper than produced through RWGS.

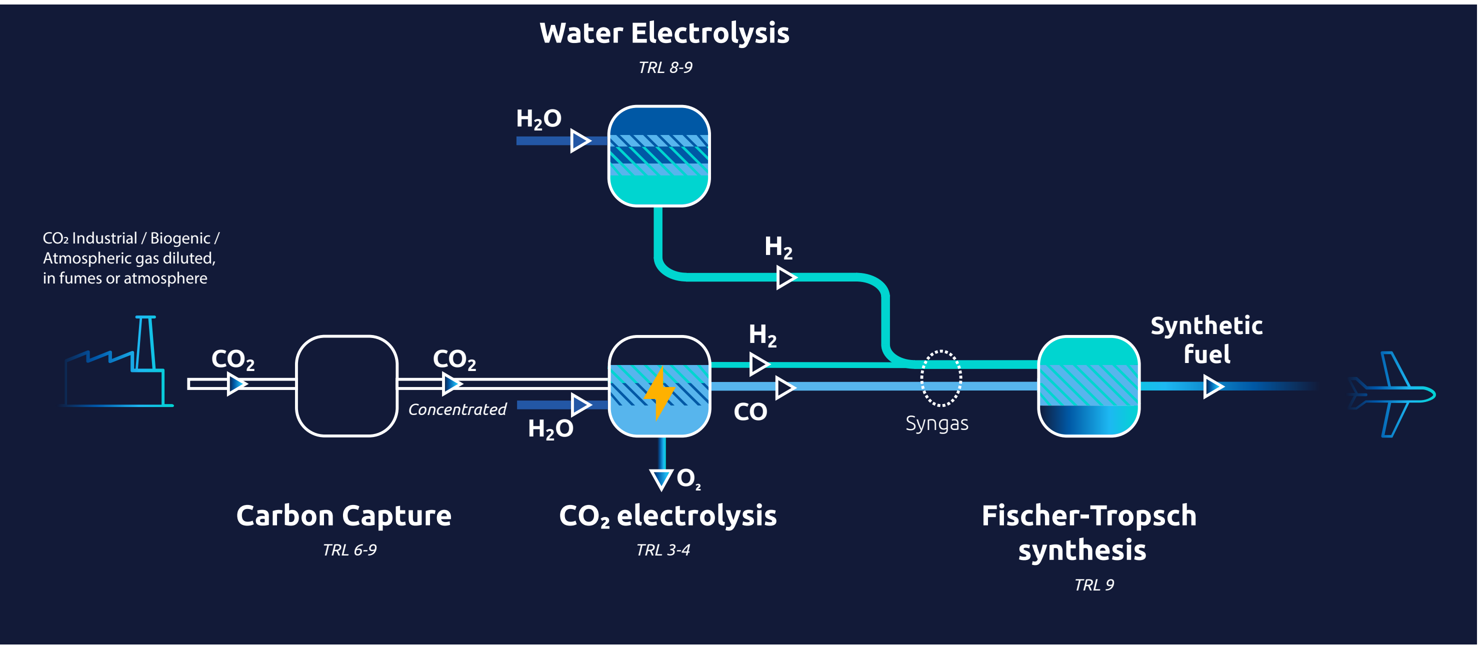


Figure 6: *Fischer-Tropsch pathway with CO_2 electrolysis for synthetic fuel production*

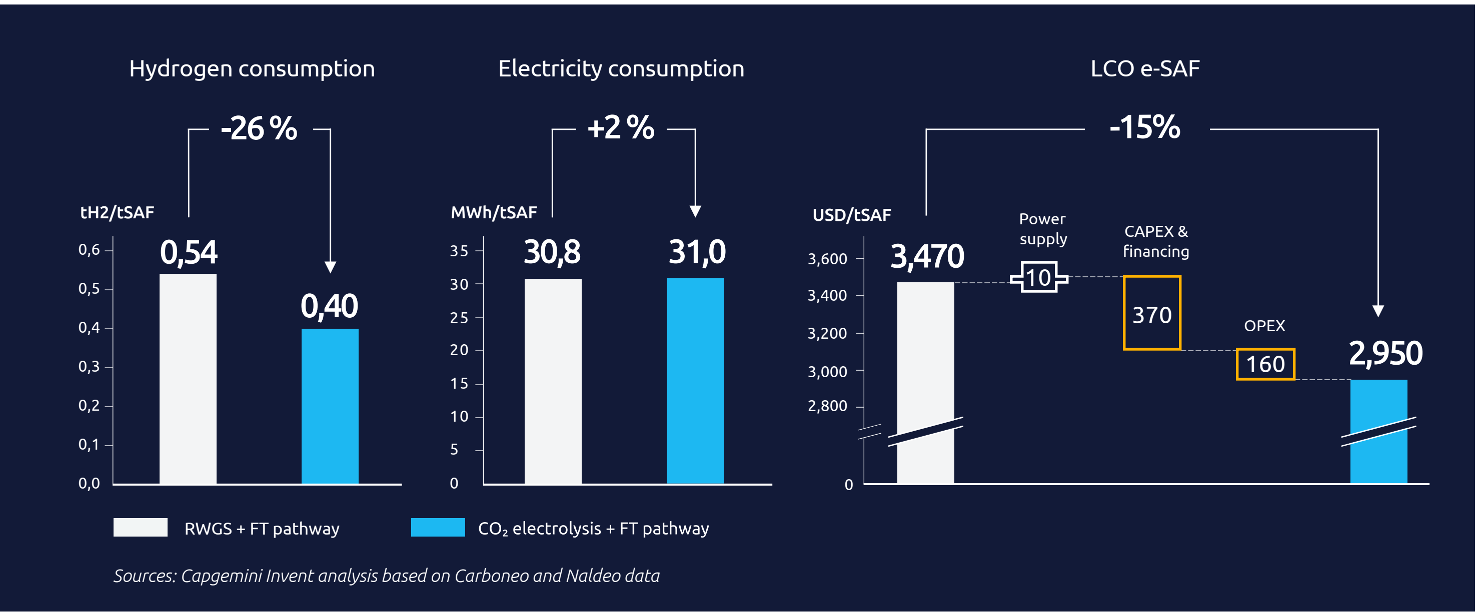


Figure 7: *Comparison of energy consumption and production costs between CO_2 Electrolysis & RWGS* [14]

A comparison of the levelized cost of e-fuel (LCO) between the two pathways reveals clear differences in cost structures, primarily driven by the lower hydrogen requirement in CO_2 electrolysis:

- **CO_2 supply** accounts, in both cases, for less than 5% of the LCO.
- **Power supply** is the dominant cost driver, representing over 45% of the LCO in the RWGS pathway, compared to 55% in the CO_2 electrolysis route.
- **Capital expenditures and related financing costs** make up approximately 35% in RWGS, versus 30% for CO_2 electrolysis.
- **Operational expenditures** account for around 15% in RWGS and 10% in CO_2 electrolysis.

Looking ahead, with technology maturity increase and deployment, CO_2 electrolysis technology could benefit from an accelerated cost reduction by leveraging the learning curve of water electrolysis, given the technological similarities.

Furthermore, by being modular by design (based on stackable cells to fit the required capacity) CO_2 electrolysis enables the flexible deployment of units tailored to local, small- and mid-scale CO_2 sources, something RWGS cannot achieve as effectively, since it is primarily suited for large-scale applications.

[14] Results based on a biogas plant case study at horizon 2030, with a conversion ratio of 3,3 tCO_2/tSAF using 5 $ktCO_2$ per year at 60 €/tCO_2 and a low-carbon electricity supply priced at 50 €/MWh. For comparison purpose, the thermal requirement of the RWGS process is supposed to be supplied from electricity

Case studies

Modular by design

Based on cells, CO_2 electrolysis is modular by design and can easily fit with different sizes of systems including small to medium-sized CO_2 sources which are not directly connected to CO_2 collection pipes. CO_2 electrolysis could offer these sources a valuable CO_2 conversion pathway with an additional revenue stream.

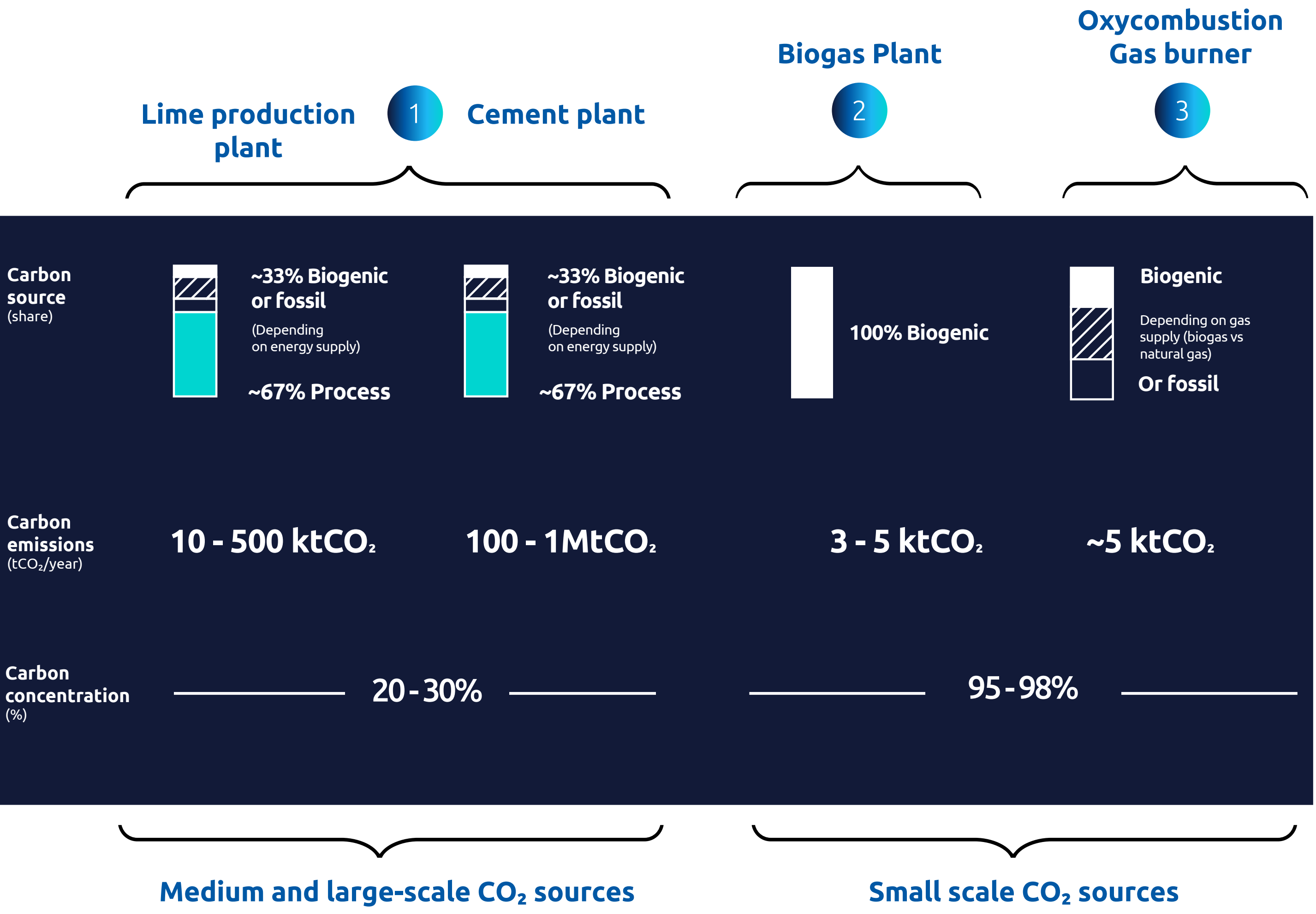


Figure 8: *Use cases overview*

1 Cement plants (and lime production plant)

Cement and lime production processes emits large amounts of CO_2:

– 2/3 from decarbonation $CaCO_3 \rightarrow CO_2 + CaO$)

– 1/3 from combustion for decarbonation process heating

Cement plants in France emit between 100 ktCO_2 /year and 1 MtCO_2/year, totaling about 10 MtCO_2/year. On average, around 10% of total CO_2 emissions are currently biogenic, equivalent to 25% of biogenic CO_2 from combustion. With decarbonization through biomass, biogas, or solid recovered fuels, this percentage might rise. However, resource availability could limit some plants to a few dozen kt of biogenic CO_2 per year.

Lime production plants in France emit between 10 ktCO_2/year to 500 ktCO_2/year, totaling about 2 MtCCO_2 /year. On average, only part of this CO_2 is currently biogenic, but this could increase with future decarbonization efforts, allowing several plants to offer a few dozen kilotons of biogenic CO_2 annually.

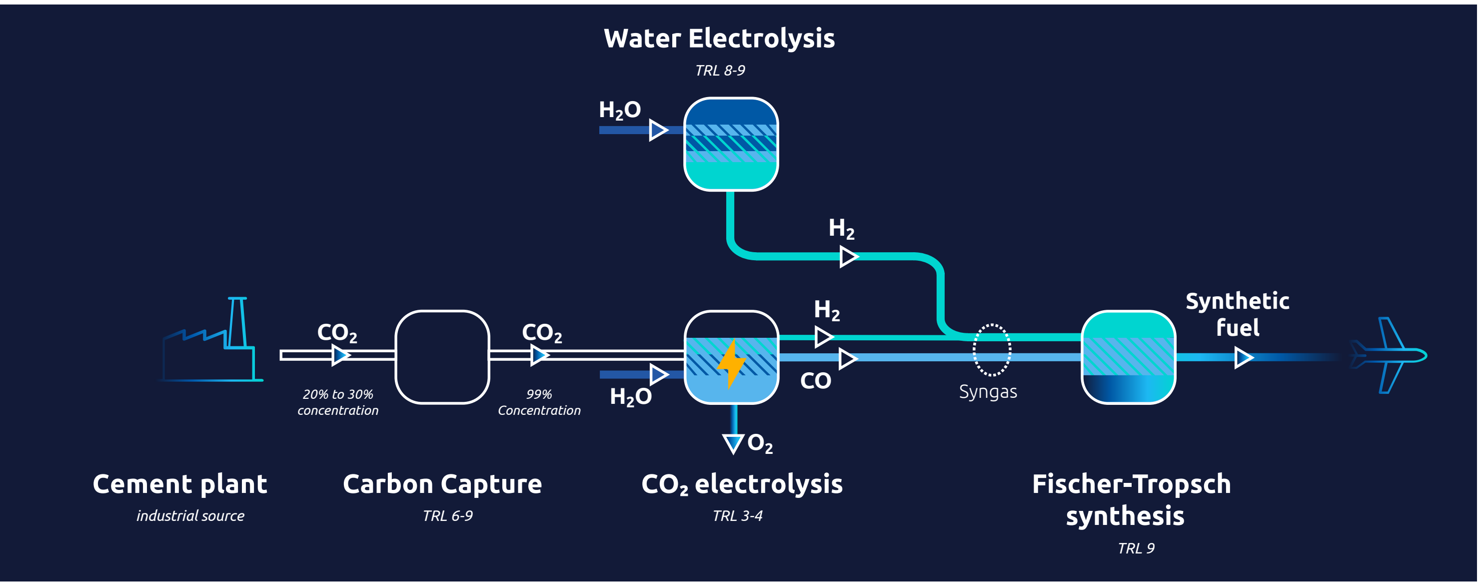


Figure 9: *Cements plant use case overview*

In the cement and lime industries, a significant share of process heat can be supplied through biomass combustion, offering a partial decarbonization lever. Today, many cement plants already integrate 10% to 40% biomass in their fuel mix, which corresponds to 10,000 to 50,000 tons of biogenic CO_2 emissions per year, depending on the plant size. These mid-scales, concentrated biogenic CO_2 sources are ideally suited for low-temperature CO_2 electrolysis, enabling their conversion into SAF directly on-site.

In addition, many cement and lime facilities are located in geographically isolated or off-grid industrial zones, where connecting to large CO_2 pipelines or fuel distribution infrastructure can be challenging or economically unviable. Deploying modular e-fuel production units based on CO_2 electrolysis provides a local, circular solution—converting waste CO_2 into valuable energy carriers while reducing transport emissions. Furthermore, the oxygen co-produced during electrolysis can be reused for oxycombustion in the same facility, enhancing the CO_2 concentration in flue gases and improving the overall cost-efficiency of carbon capture.

2 Biogas plants

A medium-size biogas plant producing 400 Nm3/h biogas and 1,700 tons of biogenic CO_2 per year could produce 500 tons of synthetic fuel per year thanks to CO_2 electrolysis.

Today, except for a few tests, CO_2 from biogas is not captured and used. In France, only 2% of CO_2 from biogas is utilized in the food industry.

The total biogenic CO_2 emissions of the 18,000 biogas plants in Europe represent 12MtCO_2 /year and could lead to 3.6 Mt of synthetic fuels/year with a large adoption of distributed on-site fuels production.

This CO_2 electrolysis combined with a modular Fischer-Tropsch module, like the French manufacturer Khimod, could answer the needs of deployment at a small scale.

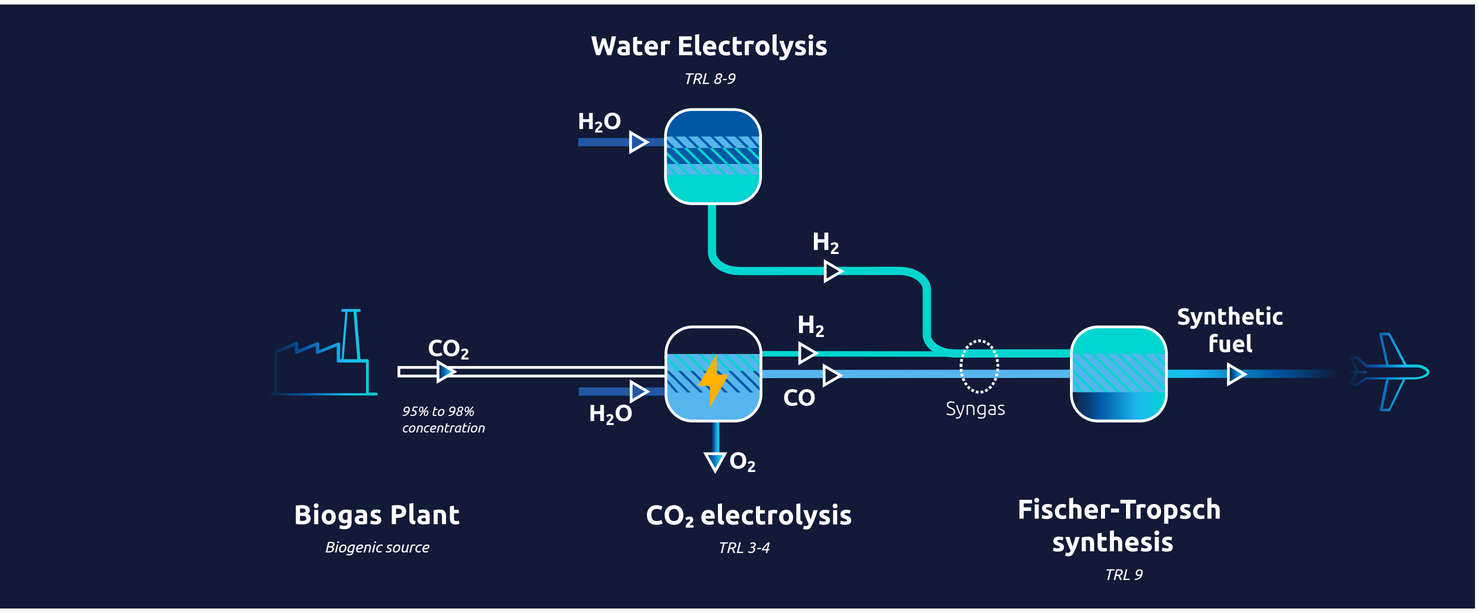


Figure 10: *Biogas plant use case overview*

3 Oxycombustion gas burner

Many industrial sites in Europe are equipped with small to mid-sized gas combustion systems—typically ranging from a few megawatts up to several tens of megawatts—which generate CO_2 emissions from a few thousand to several tens of kilotons per year. The European market for such boilers is estimated at around 20,000 installations.

In a future where natural gas networks will be increasingly decarbonized through a higher share of biomethane, a new generation of oxycombustion-equipped gas burners could enable the production of highly concentrated biogenic CO_2. This CO_2 could then be efficiently converted into e-fuels using Carboneo's low-temperature CO_2 electrolysis technology, offering a pathway to further decarbonize industrial heat while utilizing on-site carbon streams.

The oxygen co-produced through electrolysis could be directly reintegrated into the oxycombustion process, thus enabling a closed-loop and energy-efficient system.

Such technologies are already under development. In France, the "Ch0C" project [15] aims to develop a low-carbon industrial gas boiler using oxycombustion, designed for heating capacities in the range of a few megawatts. The technology is expected **to enable significant CO_2 emission reductions** - potentially in the range of several million tons per year if widely deployed. An industrial demonstrator is currently being commissioned and is expected to enter the performance testing phase in 2026, on an industrial chemical platform in France.

[15] The project is led by a consortium including Naldeo, Babcock Wanson, ENGIE Solutions, Fives Pillard, GRDF, NaTran, TotalEnergies, VERDEMOBIL BIOGAZ, and Carboneo as observer with the support from the ADEME (French Agency for Ecological Transition) via the France 2030 program..

Future perspectives

CO_2-to-CO electrolysis players for e-fuels production

Globally, only a handful of players are developing CO_2 -to-CO electrolysis compatible with e-fuels and e-SAF production: **Technology provider 1** (USA), **Technology provider 2** (Hungary) and Carboneo (France).

While Carboneo's approach is centered on ultra-low metal loading and cost-effective molecular catalysts, other companies primarily focus on metallic catalysts (silver and copper mainly). Carboneo concentrates its efforts on the electrode (catalyst and catalytic layer) betting on economies of scale with water electrolysis, thanks to the proximity of the two technologies. In the other hand, **Technology provider 1** and **Technology provider 2** are mainly developing CO_2 stacks and electrolyzer systems.

Companies developing CO_2 electrolysis but targeting other products such as methanol or ethylene are out of scope of the comparison below, as they do not target CO as a product (required for e-fuels production).

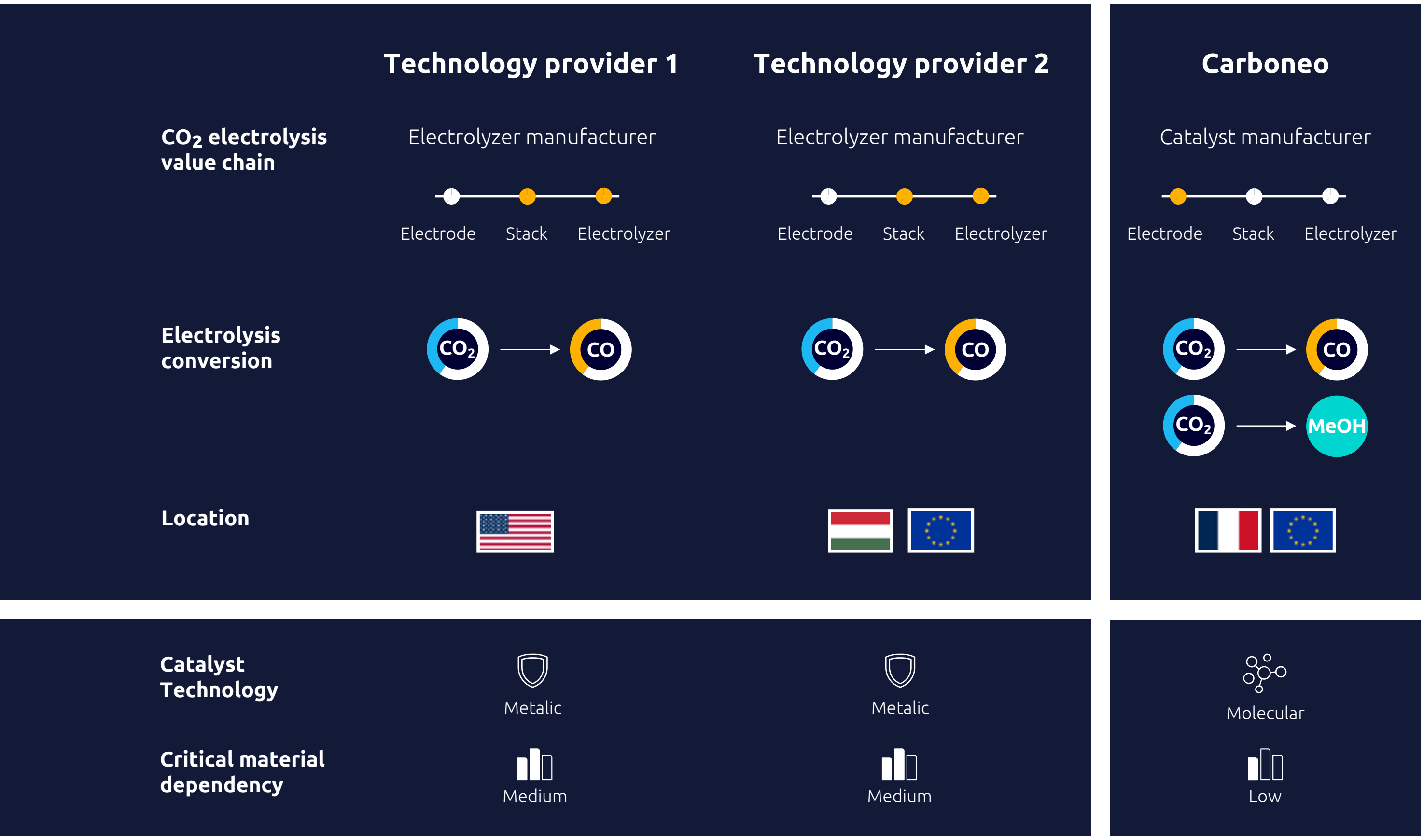
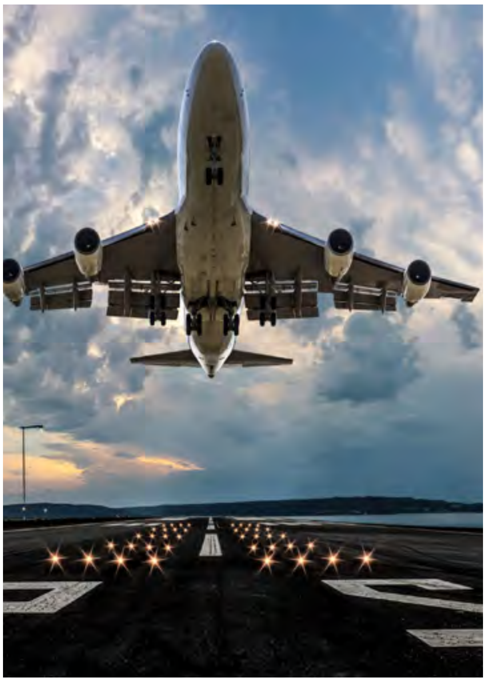


Figure 11: *CO_2 electrolysis players and their position*



Presentation of Carboneo

Carboneo is a French startup focused on developing CO_2 electrolysis for various applications, including synthetic fuel production.

Currently developing a new class of catalyst able to convert efficiently CO_2 into CO: molecular catalysts consisting of a single metallic atom surrounded by a larger molecule. Molecular catalysts could easily be engineered and customized to improve catalyst's performance. As they rely on a single atom, molecular catalysts require 100 times less critical metals and are 10 times cheaper compared to other metallic catalysts.

Carboneo's ambitious technology development roadmap

Low temperature CO_2 electrolysis has now reached TRL 3-4 maturity level in its technological development. Over the last 10 years, academic research efforts have validated the technical viability of the process at laboratory scale (1-5 cm^2 electrodes), with significant progress in current density (x100 from 2012) and lifespan (up to 240 hours). Carboneo, spin-off from Université Paris Cité and Sorbonne University, has accelerated the development focused on electrodes size scale-up (100+ cm^2 in 2025) and electrodes lifespan. This positions the technology at a readiness level

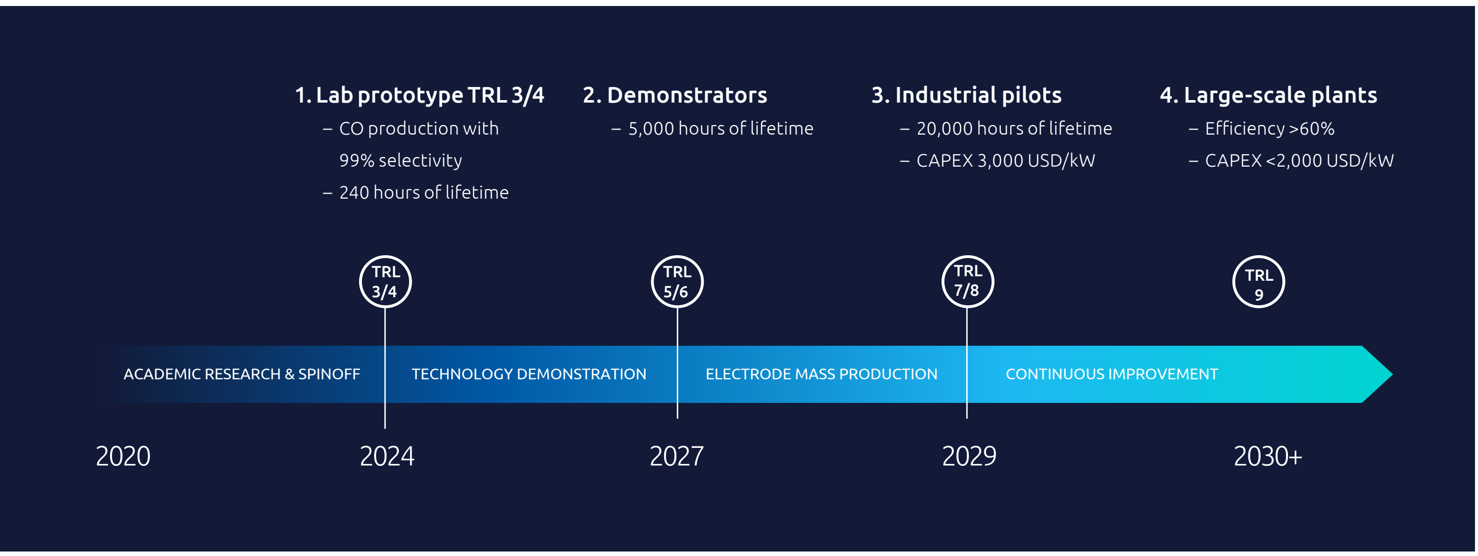


Figure 12: *Carboneo's technology deployment roadmap*

that allows its integration into first demonstrator to be installed in real conditions by 2026.

The next five years will be decisive to unlock the industrial potential of CO_2 electrolysis. Scaling from industrial pilot to commercial scale will require increased durability, mass manufacturing of key components, and further cost reductions. Players targeting maturity by 2030 will need to demonstrate systems reaching at least 20,000 hours of operation, at capital costs aligned with competitive hydrogen electrolysis benchmarks.

With partners, Carboneo targets an end-to-end CO_2 to synthetic fuel demonstrator by 2026 including a CO_2 electrolyzer able to convert a few several dozen tons of CO_2 per year and reach TRL 5-6 maturity level. Such demonstrator will require 5 to 10 m^2 of electrodes and targets to demonstrate 5,000 hours lifespan.

At this stage, industrial pilot would be running in 2028, able to convert 5,000 tons of CO_2 per year. Hence, Carboneo will have to create a capable and resilient ecosystem at European level to reach its target.

CO_2 electrolysis is a catalyst for a broad range of new opportunities

Alongside its development in the synthetic fuel market, Carboneo is actively advancing its R&D on direct CO_2 -to-Methanol electrolysis, targeting both existing methanol markets and the emerging sector of green shipping fuels. Notably, **Carboneo's molecular catalysts can directly convert CO_2 into methanol with high efficiency**, which is not the case for the metallic catalysts. At the moment, only one other company, (USA), is also developing CO_2-to-Methanol electrolysis based on a similar approach.

Given the technological proximity between CO_2 and water electrolysis at system level, low temperature CO_2 electrolysis presents a compelling growth opportunity for the electrolyzer industry. This also enables a transition to a **fully electrochemical CO_2-to-syngas pathway** by eliminating the RWGS process, thereby increasing resilience and simplification. **CO_2 electrolysis could stand to benefit from the economies of scale and learning curves to be achieved in water electrolysis, driving down CAPEX more rapidly**.

By focusing on the manufacturing of catalysts and electrodes, high value-added components for CO_2 electrolysis, **Carboneo offers a strategic opportunity for the PtL sector in France and Europe to reduce dependence on critical metals and secure technological sovereignty**. This stands in contrast to much of the Greentech sector, where key components such as electrodes, membranes, and critical-metal catalysts are often imported from abroad.

Conclusion

The decarbonization of aviation is one of the most demanding climate challenges of the next decades. With a projected demand of SAF multiplicated by 350 by 2050, synthetic fuels will represent the backbone of the sector's net-zero pathway. Synthetic fuels (particularly produced from CO_2 and green hydrogen) offers a viable solution, particularly for long-haul aviation, where alternative propulsion systems (battery-electric, hydrogen) face structural limits. The ReFuelEU regulation confirms this trajectory with ambitious incorporation targets.

Achieving this ambition requires the rapid industrialization of a complex and evolving value chain. Key technologies such as water electrolysis, CO_2 capture, RWGS, and FT or MTJ synthesis, are progressing at different maturity levels and costs. While hydrogen and carbon capture systems are reaching commercial readiness, intermediate synthesis steps still face cost and scalability challenges. Scaling up synthetic fuel production will therefore rely on assembling a flexible mix of technological bricks, not just the most mature, but also emerging ones adapted to diverse contexts and use cases. A one-size-fits-all model is unlikely to succeed.

In this context, low-temperature CO_2 electrolysis represents a catalytic breakthrough. As a fully electrified and modular alternative to RWGS, it enhances the Fischer-Tropsch pathway by enabling direct CO production from captured CO_2. This approach reduces hydrogen demand, lowers system complexity, and offers promising cost savings, especially when benefiting from shared learning with water electrolysis. This CO_2 electrolysis technology could serve as a booster for the synthetic fuels value chain, especially in decentralized configurations where mid-scale CO_2 sources are available but underused. Early demonstrators are gaining maturity, with pilot-scale projects expected before 2030.

Beyond its technical potential, CO_2 electrolysis also opens the way for a strategic European industrial segment. Its deployment could anchor a broader clean-tech ecosystem, involving membrane design, catalyst innovation, and electrolyzer manufacturing, not limited to CO_2 electrolysis alone but extending to other forms of electrochemical conversion. The Draghi Report and the European Competitiveness Compass point in this direction, explicitly calling for strengthening industrial leadership in green technologies to protect Europe's climate and economic sovereignty.

To seize this opportunity, Europe must now act with strategic clarity and industrial resolve. This includes long-term policy visibility, coordinated investment, public-private risk sharing, and targeted support for emerging technologies. Beyond specific tools like CfDs or PPAs, the EU needs a broader framework to enable market deployment, accelerate certification, and de-risk early-stage projects, particularly in hard-to-abate industrial sectors with local CO_2 availability. Political drive and support efforts should consider not only equipment, but also critical components involved such as catalysts, electrodes, and membranes to develop a robust supply chain able to lower European dependency, especially to critical resources.

The coming decade will be decisive. The technologies are advancing, regulatory ambition is rising, and the momentum is here. What remains is to channel this momentum into action. By mobilizing industrial leaders, public authorities, and investors around a shared ambition, Europe can build a competitive, resilient, and sovereign synthetic fuel ecosystem, capable of driving the aviation transition and anchoring the next generation of clean industrial value chains.

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ICAO, Long-Term Traffic Forecast 2021 - *https://www.icao.int/Meetings/STA11/Documents/STA.11%20-%20WP.004%20-%20 ICAO%20LONG-TERM%20TRAFFIC%20FORECASTS%20AND%20POST-COVID-19%20SCENARIOS.pdf*

Waypoint 2050 report - *https://aviationbenefits.org/FlyNetZero?web=1&wdLOR=cEFF871A0-B19E-4595-9BF0-266B941BA972*

Alternative fuel used in current aviation engines without requiring modifications. It is chemically similar to traditional fossil fuels. - *https://www.iata.org/en/programs/sustainability/sustainable-aviation-fuels/*

Aircrafts are certified to fly with 50% SAF blended with conventional jet fuel, and first essay flights with 100% SAF have been performed and was successful -
https://www.iata.org/en/iata-repository/pressroom/fact-sheets/fact-sheet-sustainable-aviation-fuels/

IATA, Net zero 2050: sustainable aviation fuels, June 2023 -
https://www.iata.org/en/iata-repository/pressroom/fact-sheets/fact-sheet-sustainable-aviation-fuels/

IATA, SAF Deployment Policy, 2023 -
https://www.iata.org/contentassets/d13875e9ed784f75bac90f000760e998/saf-policy-2023.pdf

Official Journal of the EU, ReFuelEU Aviation, L239/1, 22 Sept 2023 - *https://eur-lex.europa.eu/eli/reg/2023/2405/oj/eng*

ASTM D7566 is the international certification standard for synthetic and alternative aviation fuels. It defines the technical requirements and testing protocols that synthetic fuels (such as Fischer-Tropsch SPK or HEFA-SPK) must meet to be blended with conventional jet fuel for commercial aviation use. - *https://www.astm.org/d7566-24d.html*

Results based on a biogas plant case study at horizon 2030, with a conversion ratio of 3,3 tCO_2/tSAF using 5 $ktCO_2$ per year at 60 €/tCO_2 and a low-carbon electricity supply priced at 50 €/MWh. For comparison purpose, the thermal requirement of the RWGS process is supposed to be supplied from power.
- *https://www.ieabioenergy.com/wp-content/uploads/2024/10/IEA-Bioenergy-Task-37-case-story_CO2-092024.pdf*

The project is led by a consortium including Carboneo, Engie Solutions, and Axelera, with support from the ADEME (French Agency for Ecological Transition) - *https://bioenergyinternational.com/engie-partners-with-cma-cgm-and-air-france-klm/*

Glossary

ASTM D7566: *International certification standard for synthetic and alternative aviation fuels. Defines technical requirements and testing protocols for SAF blends (e.g., FT-SPK, HEFA-SPK) to be used in commercial aviation.*

Biogenic CO_2: *Carbon dioxide emitted from the combustion or degradation of biomass. Considered carbon-neutral if sourced sustainably.*

CFD (Contract for Difference): *A financial support mechanism that guarantees a fixed price for producers. If the market price falls below the contract price, the difference is compensated through public funding.*

CO_2 Electrolysis: *An electrochemical process that directly converts captured CO_2 into carbon monoxide (CO) and oxygen (O_2) using electricity, typically from renewable sources. Can replace RWGS in synthetic fuel production chains.*

DAC (Direct Air Capture): *Technology that captures CO_2 directly from ambient air. Still emerging, it is expected to play a key role in long-term carbon neutrality strategies.*

e-SAF (Electro-synthetic Aviation Fuel): *Synthetic aviation fuel produced by combining green hydrogen (from water electrolysis) with captured CO_2, via pathways such as Fischer-Tropsch or Methanol-to-Jet.*

FT (Fischer-Tropsch): *A thermochemical process that converts syngas (CO + H_2) into hydrocarbons. Used in gas-to-liquid (GTL) and coal-to-liquid (CTL) fuel production, including synthetic jet fuel.*

FRL (Fuel Readiness Level): *Scale used to assess the operational readiness of a fuel for aviation, from 1 (concept) to 9 (fully certified and commercially used).*

FT-SPK / FT-SPK/A: *Synthetic Paraffinic Kerosene produced from the FT process.*

FT-SPK: *contains no aromatics; certified for up to 50% blending.*

FT-SPK/A (or FT-SKA): *includes aromatics; developed for 100% drop-in use.*

GHG (Greenhouse Gases): *Gases that contribute to climate change, including CO_2, CH_4, and N_2O.*

HEFA (Hydroprocessed Esters and Fatty Acids): *The most mature SAF production pathway today, based on used cooking oil or animal fats. Limited by feedstock availability.*

LCO (Levelized Cost of Output): *The average cost of producing a fuel or energy output over its lifetime, often expressed in €/MWh or €/ton.*

LT-CO_2E (Low-Temperature CO_2 Electrolysis): *An electrolysis process operating at low temperatures (<100 °C), converting CO_2 into CO with low energy input, suitable for modular and renewable-powered systems.*

MTJ (Methanol-to-Jet): *A synthetic fuel production pathway converting methanol into jet fuel. Not yet certified for commercial aviation use.*

PPA (Power Purchase Agreement): *Long-term contract securing the price and delivery of renewable electricity, typically used to support green hydrogen production.*

PtL (Power-to-Liquid): *A value chain that converts electricity into liquid fuels, combining water electrolysis, CO_2 capture, and hydrocarbon synthesis (e.g., via FT).*

RFNBO (Renewable Fuel of Non-Biological Origin): *A regulatory term referring to fuels made from renewable electricity and captured CO_2, not from biomass. Recognized under EU climate regulations.*

RWGS (Reverse Water Gas Shift): *A thermochemical reaction that converts CO_2 and hydrogen into carbon monoxide (CO) and water (H_2O), often used as the first step before Fischer-Tropsch synthesis.*

SAF (Sustainable Aviation Fuel): *Low-carbon alternative to fossil jet fuel, produced from sustainable sources such as biomass (bio-SAF) or CO_2 and green hydrogen (e-SAF).*

Syngas: *A synthetic gas mixture of carbon monoxide (CO) and hydrogen (H_2) used as a precursor for producing synthetic hydrocarbons.*

TRL (Technology Readiness Level): *A scale from 1 to 9 assessing the maturity of a technology, with TRL 9 indicating full commercial deployment*

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About Carboneo

Founded in 2020 by Professor Marc Robert, a globally recognized expert in CO_2 electrolysis, Carboneo is a French industrial deeptech spin-off from Sorbonne University, developing a breakthrough technology to transform CO_2 into value-added molecules for chemistry and low-carbon fuels for aviation (e-SAF) and shipping (e-methanol), markets expected to see significant growth in the coming years.

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