WHITE PAPER

Meeting the Midterm Aviation Decarbonization Challenge

The SAF dilemma for A&D companies – a need and an opportunity

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Why does SAF matters?

SAF—sustainable aviation fuels—are liquid fuels chemically similar to fossil-made kerosene (A1 jet fuel), but made from biological feedstocks (such as plants) or synthetic feedstocks (in other words: renewable electricity). SAF reduces lifecycle carbon emissions by up to 99%[1]. While burning this fuel still releases carbon, the carbon has been recently captured, artificially or by plants, and therefore has low net emissions.

SAF has two major benefits over other new aircraft technologies such as hydrogen or electricity. It can be used as a drop-in fuel by existing aircraft without modification, and it can use existing airport refueling infrastructure. As a result, SAF is the most promising technology to decarbonize aviation in the next several decades, poised to cover 70% of emissions reduction of the aviation industry by 2050.

SAF demand: Where are we headed?

Worldwide operational SAF production capacity was less than 2Mt in 2022, two-thirds of which was in North America[2]. This accounts for around 0.5% of 2022 global jet fuel demand. While still small, when compared with only 0.1Mt of SAF production capacity in 2020, it illustrates the positive trend in SAF development over the past few years.

Public policies—mostly in Europe and the US—will contribute to a steady growth of SAF demand by 2030. In the EU, ReFuelEU targets a 6%[3] share of SAF by 2030 on commercial air traffic operated from airports located on EU territory. In the US, in September 2021, the Biden Administration announced support for an SAF tax credit, and issued an executive order to increase SAF production. Combined with supportive public policies in other geographies[4] and announcements of voluntary commitment from airlines and corporates, SAF demand is expected to reach 22Mt in 2030 (6% share of global jet fuel demand) and more than 110Mt in 2050 (24% share of global jet fuel demand).

While promising, SAF demand forecasts remain significantly short of meeting the decarbonization requirements of the aviation sector. To meet the IEA net-zero scenario, SAF demand must reach about 40Mt in 2030, and 250Mt in 2050, or there will be a demand gap of 18Mt in 2030, and more than 100Mt in 2050.

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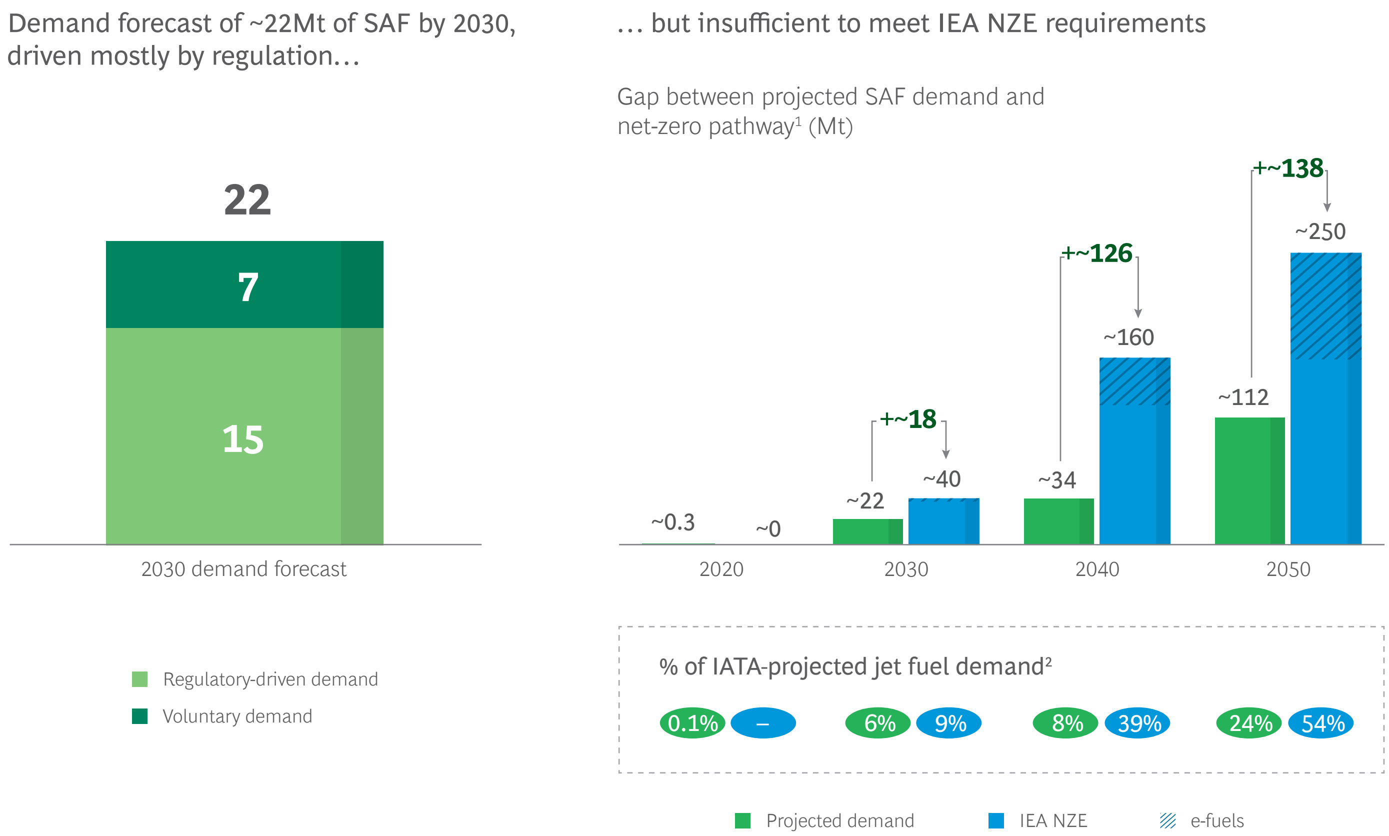
[1] Almost 40% to 80% emissions reduction achieved in most mature HEFA technology today.

[2] Fuel synthesis processes yield both SAF and renewable diesel (RD). SAF supply was estimated providing production capacities are optimized toward SAF (50% SAF/50% RD yield for HEFA). Incentive schemes in North America however often favor RD over SAF today.

[3] On April 25, 2023, ReFuelUE Aviation was adopted raising the SAF target to 2% in 2025, then 6% in 2030 (followed by 20% in 2035, 34% in 2040, 42% in 2045, and 70% in 2050).

[4] Notably in the UK, Japan, Norway, Sweden, and Indonesia.

Exhibit 1 - SAF demand, mainly driven by public policies, is expected to remain insufficient to meet IEA NZE requirements: extra ~20Mt SAF needed by 2030


Demand forecast of ~22Mt of SAF by 2030, driven mostly by regulation…

… but insufficient to meet IEA NZE requirements

Sources: IEA “Net Zero by 2050: A roadmap for the Global Energy Sector” report; BCG analysis.

[1] Based on IEA NZE2050 scenario – estimation for 2040, assuming similar energy content per ton for biofuels and synfuels resulting in ~10% share of synfuels over total SAF consumption in 2030, ~30% in 2040 and ~35% in 2050.

[2] No behavioral change assumed.

SAF supply: What is on the table today and tomorrow?

To assess our solutions to close the gap, let’s take a step back. What technologies exist today (or will exist tomorrow) to produce SAF? Among the numerous routes to produce low-carbon fuels, four SAF pathways stand out: HEFA, GFT, ATJ, and PTL.

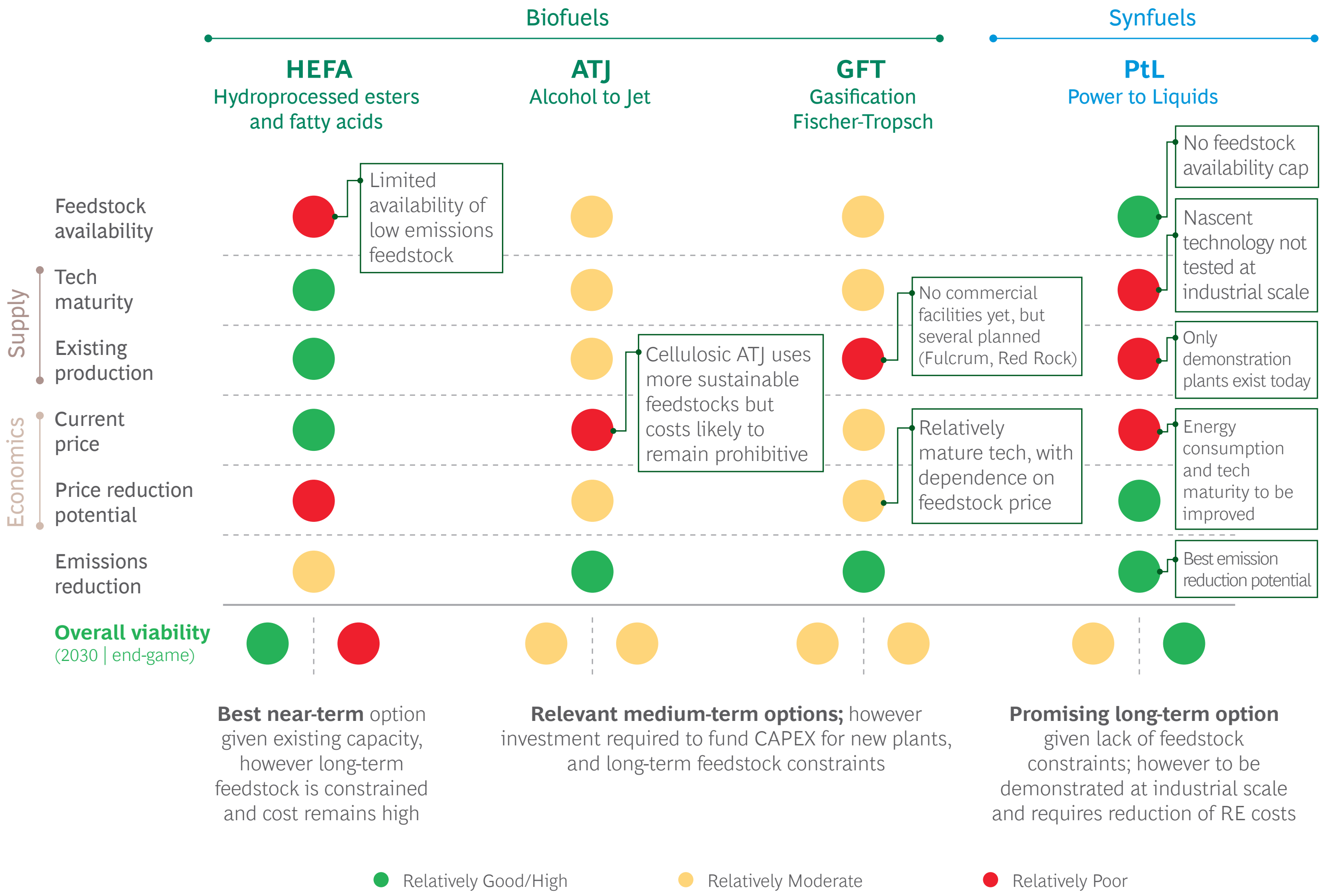
- HEFA (hydroprocessed esters and fatty acids). The most mature of all SAF pathways, HEFA produces SAF from used cooking or vegetable oil. The vast majority of SAF is produced through the HEFA pathway today.

- GFT (gasification Fischer-Tropsch). GFT gasifies biomass feedstock to generate hydrocarbons. The GFT pathway accepts a wider (and cheaper) variety of biomass feedstock than HEFA, ranging from municipal solid waste to agricultural and woody residues. The GFT pathway is in an early commercialization phase today and feedstock collection systems are still nascent.

- ATJ (alcohol to jet). ATJ works through fermentation and hydrocarbon upgrade of biomass feedstock. Like GFT, it accepts a wider variety of feedstock than HEFA (ethanol, isobutanol, starch crops), but is still in the early commercialization phase.

- PTL (power to liquid). Unlike the three previous pathways, PTL does not rely on biomass feedstock but produces SAF out of low-carbon hydrogen and CO2. Low-carbon hydrogen can notably be produced by electrolysis using renewable energy (green hydrogen) or nuclear power (pink hydrogen)[5], while CO2 will be captured through industrial-point-source fossil or biogenic carbon capture, or direct air capture. The PTL pathway is still in the pilot phase today

Exhibit 2 - Out of the four most mature SAF pathways, HEFA is closest to full commercial maturity, but has mid-term constraints – PtL has low maturity but appears promising



		Biofuels			Synfuels
		HEFA Hydroprocessed esters and fatty acids	**ATJ** Alcohol to Jet	**GFT** Gasification Fischer-Tropsch	**PtL** Power to Liquids
	Feedstock availability	🔴	🟡	🟡	🟢
Supply	Tech maturity	🟢	🟡	🟡	🔴
Supply	Existing production	🟢	🟡	🔴	🔴
Economics	Current price	🟢	🔴	🟡	🔴
Economics	Price reduction potential	🔴	🟡	🟡	🟢
	Emissions reduction	🟡	🟢	🟢	🟢
	Overall viability (2030 | end-game)	🟢 | 🔴	🟡 | 🟡	🟡 | 🟡	🟡 | 🟢

HEFA: Limited availability of low emissions feedstock

ATJ: Cellulosic ATJ uses more sustainable feedstocks but costs likely to remain prohibitive

GFT: No commercial facilities yet, but several planned (Fulcrum, Red Rock)

GFT: Relatively mature tech, with dependence on feedstock price

PtL: No feedstock availability cap

PtL: Nascent technology not tested at industrial scale

PtL: Only demonstration plants exist today

PtL: Energy consumption and tech maturity to be improved

PtL: Best emission reduction potential

Best near-term option given existing capacity, however long-term feedstock is constrained and cost remains high

Relevant medium-term options; however investment required to fund CAPEX for new plants, and long-term feedstock constraints

Promising long-term option given lack of feedstock constraints; however to be demonstrated at industrial scale and requires reduction of RE costs

🟢 Relatively Good/High 🟡 Relatively Moderate 🔴 Relatively Poor

Sources: CAAFI, ICCT, IEA, Expert Interviews, BCG analysis.

Note: Max output blend of 50% for all selected pathways.

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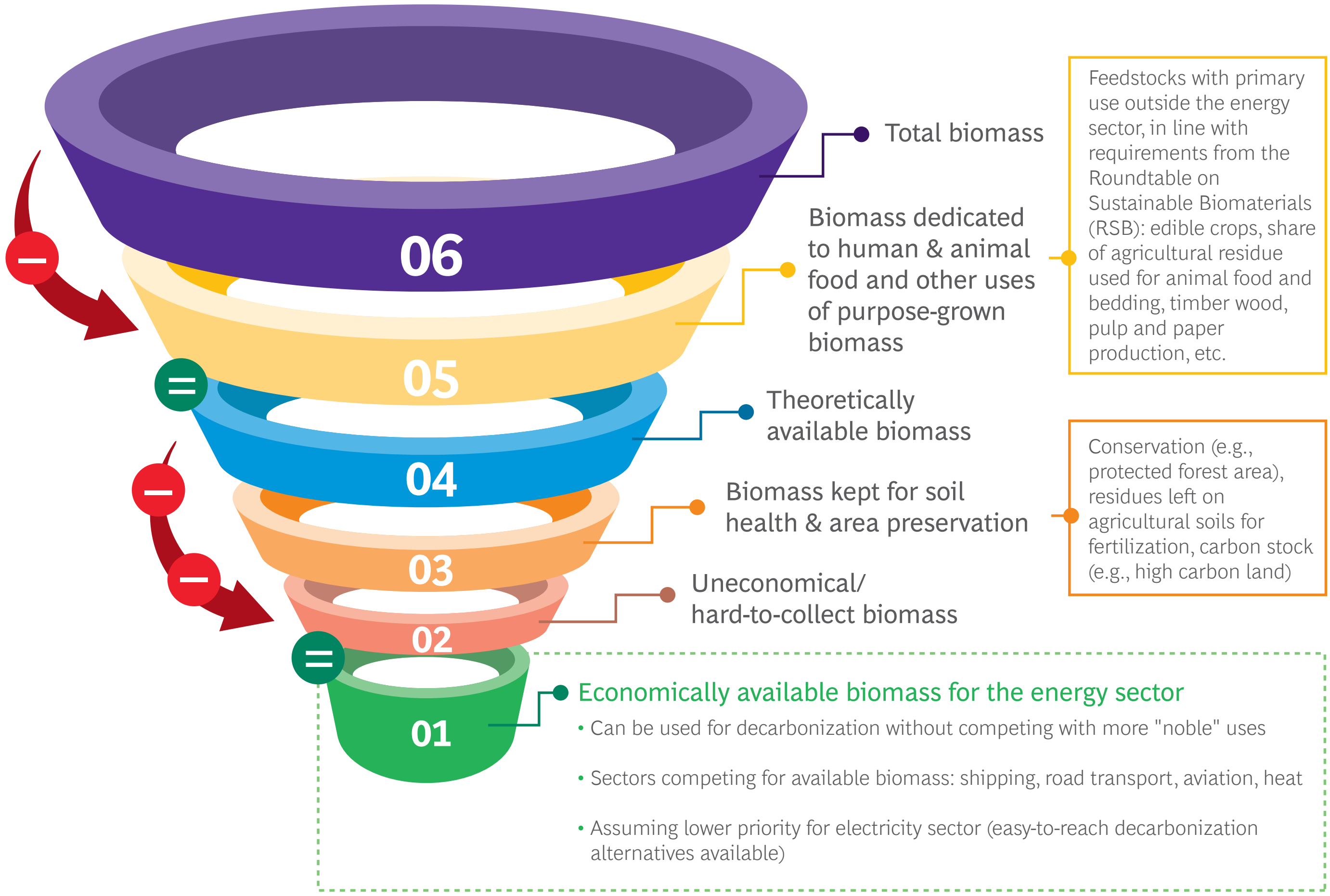
[5] Other low-carbon hydrogen production methods exist: blue hydrogen (reforming and fossil fuels with CCUS), turquoise hydrogen (pyrolysis of fossil fuels or bioenergy), or orange hydrogen (reforming of biogas or biomethane). For obvious reasons, any low-carbon hydrogen production relying on biomass feedstock would have limited relevance for PTL.

While HEFA is the most mature pathway today, it also has the highest constraints on biomass feedstock availability. To avoid competition for land use (no extra land artificialization, no competition with edible crops, etc.), only waste and residue lipids, oil trees on degraded lands, and oil cover crops are deemed eligible for SAF production through HEFA pathway, leading to a global production cap of 50-80Mt of SAF per year.

GFT and ATJ pathways can rely on cellulosic biomass, broadening potential feedstock sources for SAF production to cellulosic cover crops, agricultural residues, forest residues, wood-processing waste and municipal solid waste. Accounting for higher priority biomass usage (animal feed and bedding, natural soil fertilization, etc.) and economical availability, GFT and ATJ can yield up to around 250Mt of SAF per year[6].

While computed biomass availability for SAF production through HEFA, GFT, and ATJ theoretically far exceeds SAF demand from the IEA net-zero scenario, it should be noted other transport and energy sectors will be competing for the same feedstock. Accounting for forecasted demand for biofuels (for shipping and road transport), for biogas (for electricity and heating), and for solid biomass (for heating[7]), global biomass demand could exceed economical availability as soon as 2030 and exceed it by more than 60% in 2050[8].

Exhibit 3 - Feedstock availability | Only a portion of biomass eligible to produce biofuels



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[6] While excluded from the assessment, it's worth asking whether part of the cellulosic biomass available for SAF production might not be better used for natural sequestration of carbon in soils.

[7] Solid biomass needs for electricity were deemed of lower priority since other decarbonization alternatives are available, and were not included in the calculation.

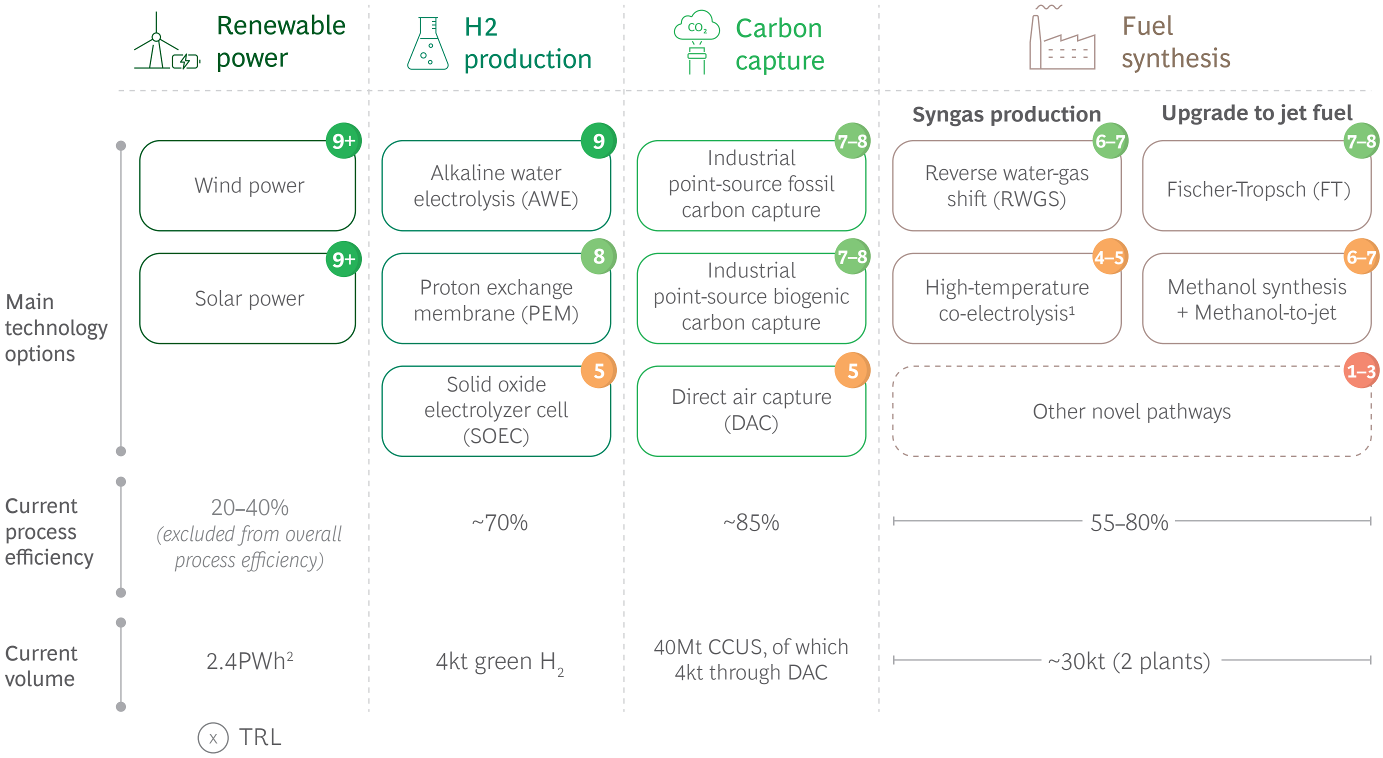
[8] Looking at theoretical availability instead of economical availability, limits would be reached around 2050.

For securing SAF requirements for a net-zero scenario while abiding by biomass feedstock availability constraints, PTL appears to be the perfect solution: no dependency on biomass availability and better decarbonization potential than biomass-based SAF. However, PTL production volumes are close to zero today. To notably contribute to SAF production in the next decade, the pace of development of the PTL pathway must pick up dramatically.

As described earlier, PTL produces SAF from low-carbon hydrogen and CO2, with both hydrogen production and CO2 capture requiring substantial amounts of energy. Three interlinked dimensions explain the limited development of PTL today:

- **Technology:** Neither H2 electrolysis, carbon capture, nor fuel synthesis technologies have yet reached full technology maturity[9] and will require further developments and investments in the coming years.

Exhibit 4 - Several technology options coexist for each process brick



	Renewable power	H2 production	Carbon capture	Fuel synthesis	
				Syngas production	**Upgrade to jet fuel**
Main technology options	Wind power (9+)	Alkaline water electrolysis (AWE) (9)	Industrial point-source fossil carbon capture (7–8)	Reverse water-gas shift (RWGS) (6–7)	Fischer-Tropsch (FT) (7–8)
	Solar power (9+)	Proton exchange membrane (PEM) (8)	Industrial point-source biogenic carbon capture (7–8)	High-temperature co-electrolysis[1] (4–5)	Methanol synthesis + Methanol-to-jet (6–7)
		Solid oxide electrolyzer cell (SOEC) (5)	Direct air capture (DAC) (5)	Other novel pathways (1–3)	
Current process efficiency	20–40% *(excluded from overall process efficiency)*	~70%	~85%	55–80%	
Current volume	2.4PWh[2]	4kt green H_2	40Mt CCUS, of which 4kt through DAC	~30kt (2 plants)	

(x) TRL

Source: BCG analysis.

[1] Co-electrolysis of water and carbon dioxide.

[2] Excluding other renewables sources (e.g., hydro), less relevant for PtL use cases.

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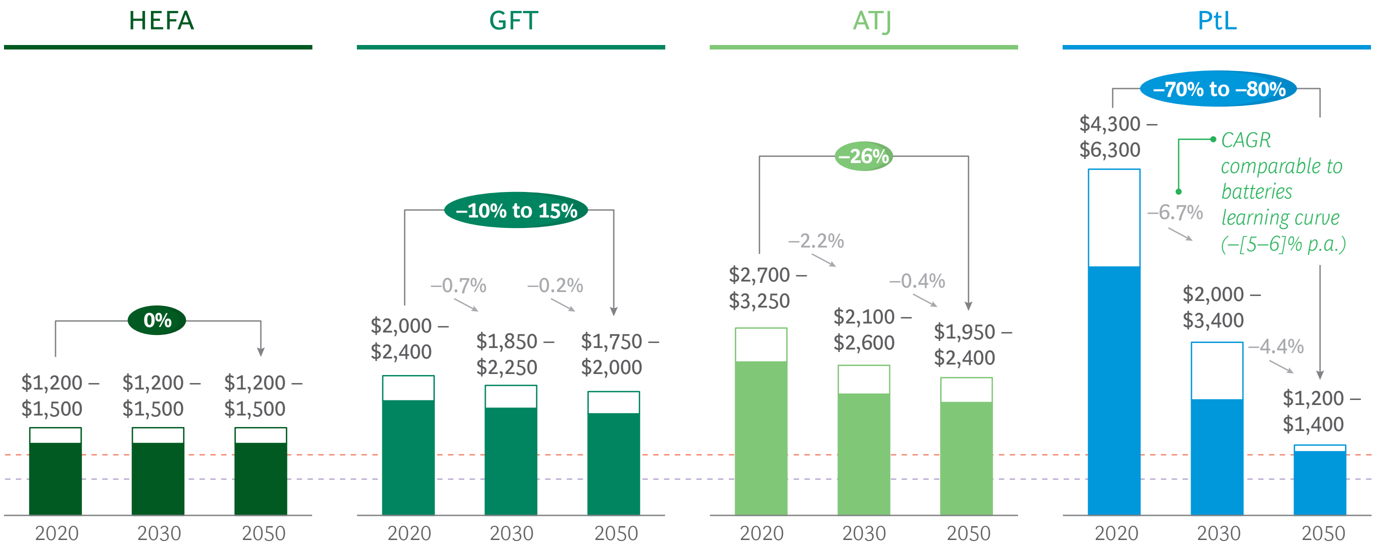
9. Except Alkaline Water Electrolysis (AWE) technology for H2 production (with a TRL or Technology Readiness Level of 9), all H2 electrolysis, carbon capture and fuel synthesis technologies have a TRL of 8 or below.

- **Economics:** SAF produced through the PTL pathway today costs from $4,300 to $6,300/t, five to six times more than A1 jet fuel and three to four times more than SAF produced through the HEFA pathway. With proper technological improvements, the PTL pathway, however, shows the biggest cost reduction potential in the coming years, expected to reach $2,000 to $3,400/t by 2030 and $1,200 to $1,400/t by 2050, bringing it close to parity, provided there is proper regulatory support.

Exhibit 5 - PtL to become the most affordable SAF in 2050, still higher than A1 jet fuel cost but close to parity with proper regulatory support



◆ Small changes in CAPEX expected as HEFA is at scale and has been used for 20+ years (3% learning rate anticipated)

◆ Feedstock is 50% of cost, expected to slightly increase with demand and supply constraints, offsetting potential CAPEX reductions

◆ GFT CAPEX to come down cost curve with commercialization (learning effect assumed to reduce CAPEX cost by 10%–20%)

◆ Lower cost of feedstock as inputs include MSW (trash) as well as waste agricultural residues

◆ CAPEX will decrease with commercialization but will still be significant as ethanol and jet production are CAPEX intensive

◆ Feedstock (ethanol, isobutanol, corn) costs are unlikely to decrease

◆ High cost today driven by cost to produce green H2 and cost of carbon from direct air capture (OPEX costs)

◆ Range in OPEX driven by uncertainty in DAC cost[3]

◆ PtL cost expected to decline as green hydrogen and DAC cost declines

---- 2021 Jet fuel A1 cost: $600/t

---- Virtual jet fuel A1 cost[1]: $1100/t

xx% ↘ 2020–2030 and 2030–2050 CAGR

Sources: Brynolf et al., 2017; NREL, S&P Platts Jet Fuel Price Index, CAAFI, ICCT, Clean Skies for Tomorrow "Sustainable Aviation Fuels as a Pathway to Net-Zero Aviation" report, BCG analysis.

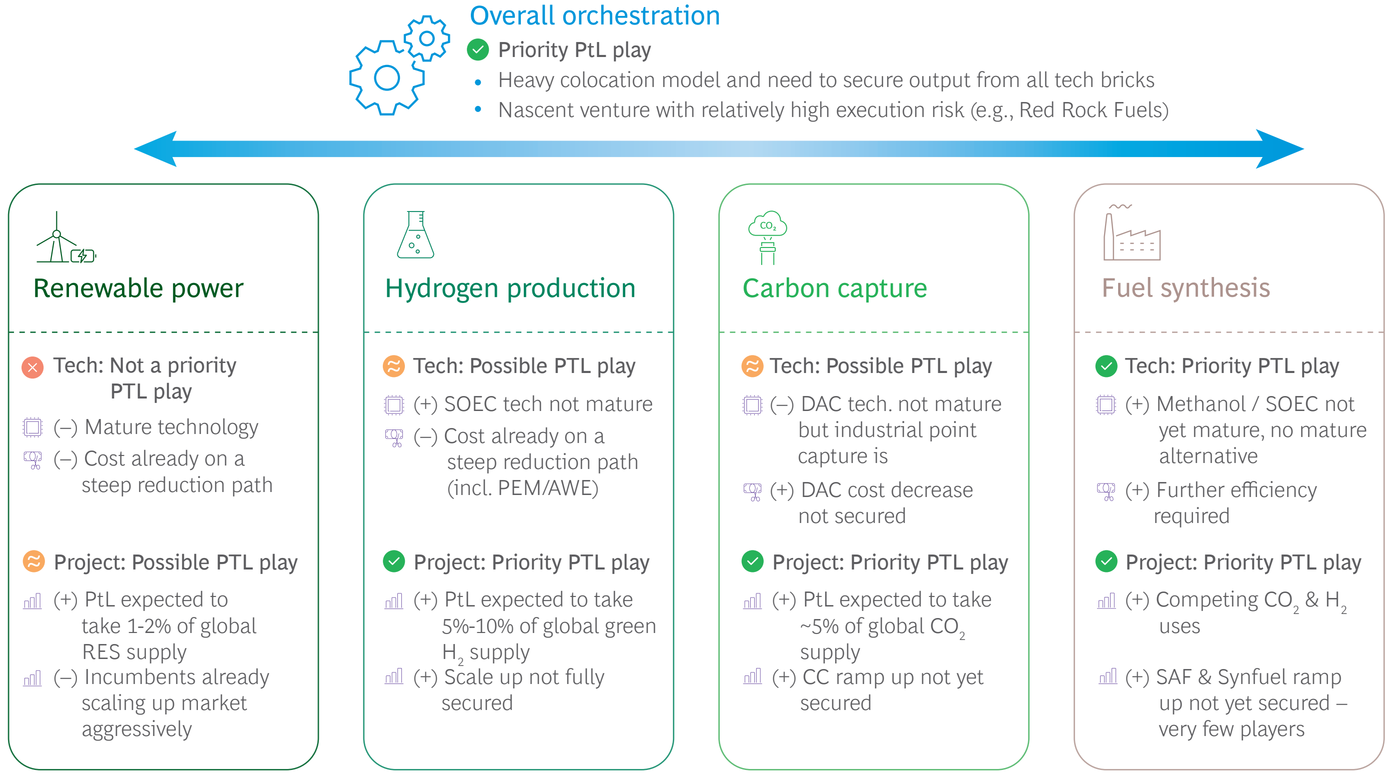
[1] Regulations virtually impact A1 jet fuel cost by +$500/t on average > US incentives for SAF: ~$850/t through BTC ($300/t), RFS ($250–300/t) and LCFS ($250–300/t); EU's ETS (penalties on A1 jet fuel): +$200/t increase on Jet fuel A1 (excl. impact of ETD from 2025 onwards).

- **Scale:** Scaling PTL production volumes to meet net-zero requirements (3Mt in 2030, 90Mt in 2050) requires major renewable power, green hydrogen, and CO2 inputs–likely to reach several percentage points of worldwide production by 2050, while production pipelines for renewable power, hydrogen, and carbon capture already fall short of existing 2030 demand forecasts, and fewer than ten small-scale PTL projects have been announced so far—representing approximately 200kt of supply by 2030.

How aviation players can get us back on track

To get the aviation sector back on track to meet net zero, the SAF market must accelerate by five to ten years, bolstering SAF adoption by two to three times in 2030. To do this, aviation players must combine actions to increase SAF supply and activate SAF demand, as both dimensions are intrinsically linked today: increased demand contributing to de-risk supply, and increased supply contributing to meeting demand.

Exhibit 6 - How to accelerate scale-up of PtL pathway by 2030



Overall orchestration

✓ Priority PtL play
- Heavy colocation model and need to secure output from all tech bricks
- Nascent venture with relatively high execution risk (e.g., Red Rock Fuels)

Renewable power

✗ Tech: Not a priority PTL play
- (–) Mature technology
- (–) Cost already on a steep reduction path

≈ Project: Possible PTL play
- (+) PtL expected to take 1-2% of global RES supply
- (–) Incumbents already scaling up market aggressively

Hydrogen production

≈ Tech: Possible PTL play
- (+) SOEC tech not mature
- (–) Cost already on a steep reduction path (incl. PEM/AWE)

✓ Project: Priority PTL play
- (+) PtL expected to take 5%-10% of global green H_2 supply
- (+) Scale up not fully secured

Carbon capture

≈ Tech: Possible PTL play
- (–) DAC tech. not mature but industrial point capture is
- (+) DAC cost decrease not secured

✓ Project: Priority PTL play
- (+) PtL expected to take ~5% of global CO_2 supply
- (+) CC ramp up not yet secured

Fuel synthesis

✓ Tech: Priority PTL play
- (+) Methanol / SOEC not yet mature, no mature alternative
- (+) Further efficiency required

✓ Project: Priority PTL play
- (+) Competing CO_2 & H_2 uses
- (+) SAF & Synfuel ramp up not yet secured – very few players

Accelerate supply

Because of its built-in advantages and low relative maturity, players considering bolstering SAF supply acceleration should look into supporting PTL project development. As previously stated, accelerating PTL development involves technology improvements as well as renewable power, H2 production, carbon capture, and fuel synthesis production ramp-up. While an increasing number of players are positioning on the individual technology developments, they too often approach the problem alone or in bilateral agreements. However, successfully developing PTL requires setting up ecosystem-wide partnerships—ideally several players with complementary skills joining forces, and a strong orchestrator willing to take the first step and lead the partnership toward a shared goal of developing several PTL production facilities at scale in the next decade. The orchestrator must bring together technology and product development know-how from partners on renewable power, H2 production, carbon-capture, and fuel synthesis, as well as securing offtakes and financing.

Exhibit 7 - Marketplace | 3 options depending on desired involvement level

Involvement level

	Spot OTC transactions	**Virtual venue**	**Exchange platform**
Description	Bilateral transactions, monitored by a price reporting agency	Virtual venue, channeling and standardizing orders from off-takers to producers	Platform taking over titles from producers, bearing goods on their balance sheet before selling to offtakers
Key features	• Price reporting agency in charge of an index to report transactions	• Standardization of exchanged goods (e.g., grading based on environmental attributes) • Index logic to report transactions	• Complex infrastructure setup (banks, exchange licenses, ...) • Need to leverage a player with existing infrastructure
Profit/risk profile	• Very low risk and costs • No recurring revenue	• Low risk and costs • Small pass-through fee taken by match-maker	• Substantial liquidity and credit risk (10%+ margin calls) • Reduces supply/demand risks from market players' failure
Examples	Electricity PPAs	Voluntary carbon credits	Oil, gas, electricity markets
Relevance for A&D players today	◔ (–) No in-house SAF production, role relevant for large SAF producer	◕ (+) Requires major player able to take up the orchestrator role (+) Relevant for low to medium maturity markets	◑ (+) Requires major player able to take up the orchestrator role (–) Requires market maturity not yet reached by SAF

Source: BCG analysis.

Activate demand

Along with supply acceleration, aviation players must activate SAF demand. Demand activation can take many forms or combinations of forms. We identified three priority demand activation actions:

- **Create offtake liquidity.** Current (often peer-to-peer) offtake agreements are not sufficient to de-risk supply. Contract frameworks lack consistency, off-takers lack credit credibility, and peer-to-peer agreements increase risk of default by either party. As a result, access to financing remains difficult. Increasing market liquidity must then be a priority, for instance through the creation of a marketplace. Such a marketplace can take several forms over time, from spot OTC transactions monitored by a price reporting agency to a virtual venue channeling and standardizing orders from off-takers to producers, up to a full-fledged exchange platform. All options require one or several players ready to take up the role of market maker.

- **Unlock demand:** Aviation players must–each from its unique market position–contribute to more SAF demand by incentivizing its clients and suppliers toward SAF usage. For instance, an OEM can package an SAF offering with its products, an airport can offer specific advantages in exchange for increased SAF usage, an airline can require higher SAF compatibility from its suppliers' products, etc.

- **Advocate:** Accelerating demand for SAF will to a large extent depend on future public policies incentivizing SAF or disincentivizing non-sustainable fuels. Aviation players can contribute to it by supporting adequate policies, notably raising the bar for minimum share of SAF in Europe and the US, but also in emerging geographies, or securing access to feedstock (for instance, against lower priority sectors like road transport).

By acting now to accelerate supply or activate demand (or ideally, both), aviation players have a unique opportunity to accelerate the sector's decarbonization, bringing it back on track to meet its 2050 net-zero requirements. This must be a priority for all aviation players across the value chain—even those that historically did not consider SAF as part of their role in the supply chain—because eventually the sector's right to exist in the future is at stake.

The good news is momentum is growing, reflected in the number of recent announcements from players willing to contribute to challenging the status quo. For instance, Airbus and Neste joining forces on production and uptake of SAF in November 2022, United Airlines launching a $100 million SAF venture fund in February 2023, and Airbus and Qantas investing jointly to develop SAF in Australia.

It is far from scale yet, and many more efforts are needed at the ecosystem level, but these are definitely steps in the right direction.

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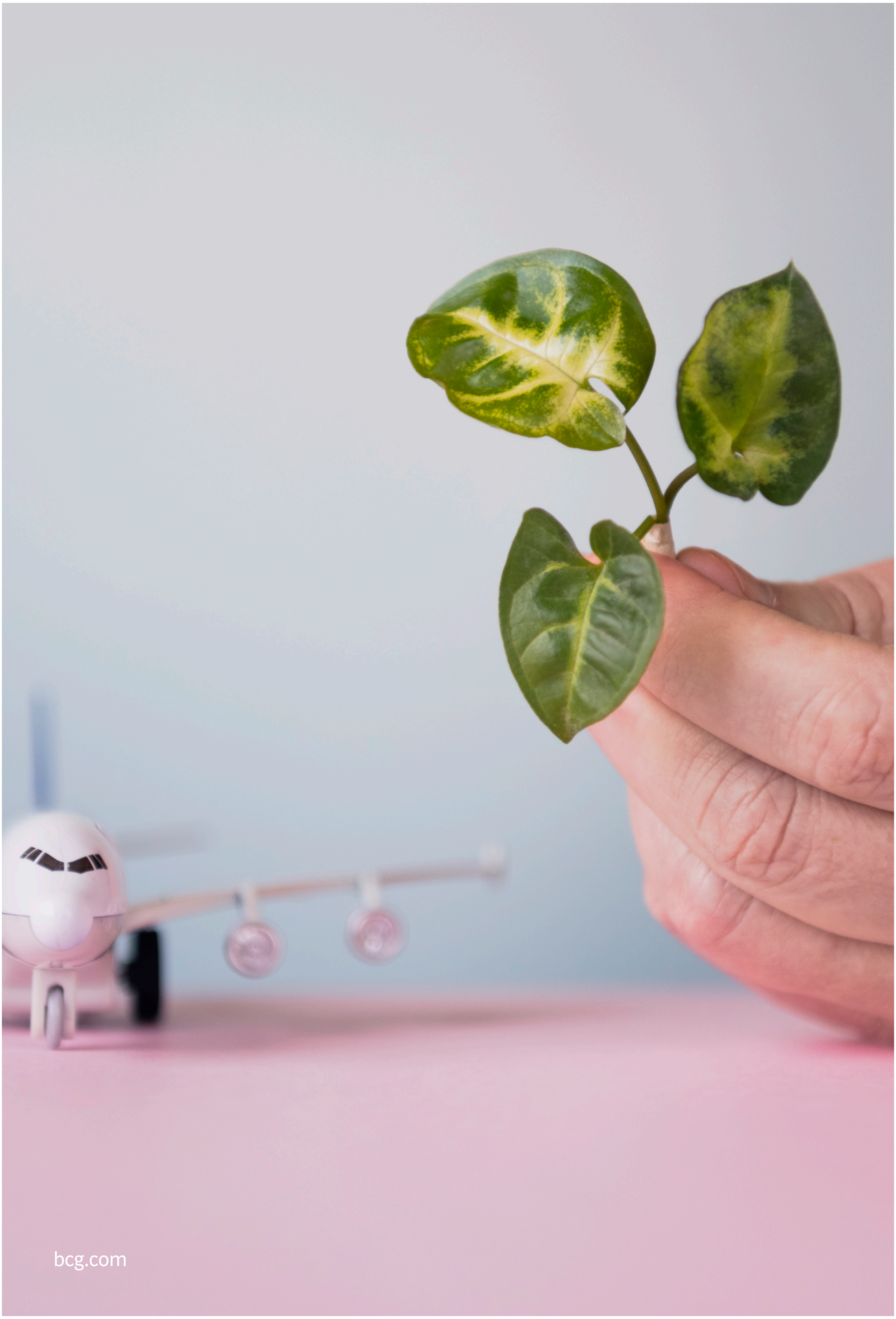
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