Clean Skies for Tomorrow

WORLD ECONOMIC FORUM

In knowledge partnership
with McKinsey & Company

Clean Skies for Tomorrow: Delivering on the Global Power-to-Liquid Ambition

INSIGHT REPORT

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Foreword

Pedro Gomez
Head of Shaping the Future of Mobility, member of the Executive Committee, World Economic Forum

Robin Riedel
Partner, McKinsey & Company

Reducing carbon emissions will provide enormous economic and health benefits across industries and societies, improve sustainability and help keep the planet liveable for future generations. The aviation industry must play a major role in this effort, which is why the World Economic Forum launched the Clean Skies for Tomorrow (CST) initiative in 2019. The CST public-private partnership is working closely with stakeholders across industry, government and civil society to help the aviation industry transition to net-zero emissions by 2050 using sustainable aviation fuels (SAFs) and other clean propulsion technologies.

Sustainable fuels are already in use and progress is under way. Europe has released its Fit for 55 and ReFuelEU package to mandate the use of SAF, and the US launched the Sustainable Aviation Fuel Grand Challenge, which aims to fully decarbonize aviation by 2050. The Clean Skies for Tomorrow initiative, with support from the Mission Possible Partnership, has brought together almost 100 organizations – including leading airlines, airports, fuel suppliers, aircraft manufacturers, frequent corporate flyers and freight forwarders – which have committed to accelerating the use of SAF to meet 10% of global aviation fuel demand by 2030 and reach the net-zero goal by 2050.

While this momentum is encouraging, major new commitments, investments and innovation will be required. This report explains how power-to-liquid (PtL), a promising SAF pathway, could be scaled in the decade ahead, including how production could unfold in a range of scenarios. Companies have already announced plans to manufacture nearly 4 million tonnes of PtL fuels annually by 2030, although this represents only 1% of global jet fuel demand. Clearly, this is just the beginning.

Stakeholders across the aviation industry, from the largest companies to the individual air traveller, will need to raise their game to achieve the world's decarbonization goals.

We welcome you on the journey to a cleaner future and a more sustainable economy.

Preface

The World Economic Forum's Clean Skies for Tomorrow initiative, supported by the broader Mission Possible Partnership, in cooperation with knowledge partner McKinsey & Company, has undertaken this thorough investigation into power-to-liquid (PtL) fuel that builds on the sustainable aviation fuel (SAF) analytics report published in 2020.[1] While that paper looked at a variety of SAF production pathways, this report aims to provide a more detailed account of PtL technology, the challenges and what is needed regionally and globally to scale up PtL fuel production and uptake.

It is intended to inform the decisions of governments, policy-makers, industry and investors, all of whom will be critical in seizing opportunities, overcoming challenges and taking action to scale the production and use of PtL to reach net-zero emissions goals by 2050. While the report is focused on the global aviation emissions challenge, the learnings can be applied to other sectors such as road transport, marine and chemicals, which could require similar sustainable low-carbon fuels.

The report is also designed to reflect the diversity of national contexts and varying stages of sectoral decarbonization by providing examples and analyses from across regions. It presents findings in three sections:

- The case for PtL and mapping the current value chain and stakeholders
- The challenges of scaling PtL, including how to overcome complex technical and infrastructure requirements
- Scenarios for how the technology could be adopted in the context of other sustainable aviation fuels, including the actions a global coalition will need to take to make the promise of PtL a reality by 2050

Clean Skies for Tomorrow

The Clean Skies for Tomorrow (CST) Coalition provides a crucial global mechanism for top executives and public leaders, across and beyond the aviation value chain, to align on a transition to sustainable aviation fuels as part of a meaningful and proactive pathway for the industry to achieve carbon-neutral flying. The CST vision is to accelerate commercially viable SAF production at scale for industry-wide adoption by 2030 to support aviation's overall net-zero pathway by 2050 through public-private collaboration and cross-sectoral partnerships. The World Economic Forum leads the CST Coalition, supported by the Mission Possible Partnership.

MISSION POSSIBLE PARTNERSHIP

The Mission Possible Partnership is an alliance of climate leaders focused on supercharging efforts to decarbonize some of the world's highest-emitting industries in the next 10 years. The four core partners are the Energy Transitions Commission, RMI, the We Mean Business Coalition and the World Economic Forum.

Executive Summary

As aviation shifts from fossil to sustainable fuels, power-to-liquid could emerge as a critical pathway, with reductions in greenhouse gas emissions of up to 100%.

As climate change accelerates, along with demand for air travel, aviation must decarbonize. The industry, through the Air Transport Action Group (ATAG) and the International Air Transport Association (IATA), other associations and an increasing number of nation states, has now committed to the ambitious target of net-zero emissions in aviation by 2050.

This transition to lower emissions is under way, but reaching the 2050 target will require a combination of solutions and technologies as well as the cooperation of investors, industry, innovators, government, academia and citizens. Sustainable aviation fuel (SAF), which produces 50–100% less net CO_2 than fossil jet fuel on a life-cycle basis, is the most promising option today to reduce aviation's carbon emissions.[2] About 400,000 commercial flights have already been partially fuelled by SAF.[3] Production costs will decline with market interventions, while the costs of climate change rise. Grants and low-cost loans, offtake agreements, blending mandates and other programmes and policies can help the SAF industry achieve economies of scale.

This report explains how one conversion concept within the different SAF production pathways, power-to-liquid (PtL), could be scaled up for commercial use using renewable electricity from wind, solar, hydropower and other green sources along with captured carbon dioxide. The report makes the case for PtL as a solution to aviation emissions, describes how to overcome complex technical and operational production challenges, and outlines actions that could help scale PtL regionally and globally.

Scaling the PtL value chain will mean: addressing the financial and political challenges; expanding the production of low-cost renewable electricity; producing low-cost clean hydrogen on-site or close to fuel-synthesis facilities; capturing sufficient sustainable carbon; optimizing fuel synthesis for efficiency; and balancing the relative proportions of output products to commercialize the by-products of jet fuel such as diesel and naphtha.

While the challenges are many, so are the opportunities. PtL fuel can be produced in deserts far from major electric grids, unlocking "stranded renewables" that could not otherwise be tapped for green electricity production. A solar farm in Chile or the Sahara, for example, could not sell electricity to Asia, the US or Europe, but it could easily transport PtL by train or tanker to any airport in the world. Lowering the cost of renewable electricity and hydrogen in desert economies could enable PtL production costs as low as $1,600 per tonne using direct air capture by 2030. While this would still be more expensive than fossil jet fuel, it would be within the range of other SAF production pathways and achieve nearly 100% decarbonization.

The road to PtL commercialization in the coming decades will need to achieve three main milestones: 1) renewable electricity cost reductions of around 30%; 2) electrolyzer technology cost reductions of about 50%; and 3) efficient direct air capture of carbon with cost reductions of 50–80%.

These targets can be reached if academic institutions, citizens, government, industry, innovators and investors join forces now.

! PtL production uses low-cost renewable electricity, efficient supplies of carbon dioxide and hydrogen synthesized to yield liquid jet fuel and other valuable by-products.

Introduction

The transition to sustainable aviation fuel is under way – and must accelerate.

In 2019, the aviation sector accounted for about 3% of total CO_2 emissions,[4] 12% of transportation emissions and an even higher climate impact when nitrogen dioxide, water vapour and other non-CO_2 emissions are considered. Air travel declined sharply during the COVID-19 pandemic and passenger miles may take several years to recover, particularly if today's higher fuel prices mean more expensive tickets. But, as global wealth rises and billions of people enter the consuming classes, demand for jet fuel is likely to rise to about 500 million tonnes by 2050, even with ongoing efficiency improvements. For example, the industry is reducing greenhouse gas (GHG) emissions through newer aircraft that are up to 20% more fuel-efficient per passenger, technological and operational efficiency improvements, and shifts to intermodal transportation. These efforts, while laudable, will not be enough to decarbonize the sector. More ambitious and concrete action will be needed to reach the target of net-zero by 2050.

This transition is already under way. In July 2021, EU member states unveiled the Fit for 55 package, with targets to cut emissions by at least 55% below 1990 levels by 2030 and reach net-zero emissions by 2050. The US followed, announcing a raft of initiatives and funding aimed to incentivize decarbonization. Other nations have since announced similar net-zero targets and interim goals. In October 2021, the International Air Transport Association (IATA), followed by the broader Air Transport Action Group (ATAG), formally adopted a commitment endorsed by its members to reach net-zero carbon emissions by 2050 for the aviation sector.

Meeting these ambitious emissions reduction targets will require a combination of solutions and technologies and an unprecedented level of cooperation among academic institutions, citizens, governments, industry, innovators and investors.

Choosing a transition path

New hybrid-electric and hydrogen-powered aircraft under development could help the industry reach the next efficiency horizon, but deployment at scale will take time. Given the weight of batteries limiting maximum flight distances to 600 km and the development needed for hydrogen aircraft, these solutions are unlikely to reduce the bulk of aviation emissions in the coming decade. (Today, 75% of CO_2 emissions from aviation are caused by medium- and long-range flights.)[5]

Sustainable aviation fuel (SAF) produces 70–100% less net CO_2 than fossil kerosene depending on the production pathway. The deployment of SAF is therefore the most promising option to significantly reduce the aviation industry's carbon emissions in the near term and for long-haul flying even beyond 2050.

SAF can be synthesized from biomass feedstocks ranging from used cooking oils to municipal, agricultural and forestry waste. It can also be produced as synfuel from renewable electricity, hydrogen and recycled CO_2 from industrial plants or other point sources, and eventually from direct air capture of carbon.

Seven SAF production pathways – combinations of feedstock and conversion processes – are approved for use today when blended up to 50% by volume with conventional jet fuel. About 400,000 commercial flights have been partially fuelled by SAF so far. Full approval of 100% SAF in the next few years is possible as flight testing has already begun. Leading engine and aircraft manufacturers are already engaged with stakeholders to enable commercial flights on 100% SAF. Manufacturers are committed to producing aircraft fuel tanks, onboard distribution systems and engines that can handle 100% SAF by 2030.

Moving SAF forward

The biggest challenge in scaling up SAF production and use is the cost. Depending on the pathway and geography, SAF costs at least two times more to produce than fossil fuel.[6] Bridging this gap will require market support on both supply and demand.

The US and EU stand out as early government supporters of SAF by providing incentives and adopting regulations to stimulate SAF demand and production to close the price gap between fossil and sustainable fuels. In the EU, a blending mandate is under discussion that would require increasing levels of SAF to be blended with conventional jet fuel, and taxes are rising on fossil fuels.[7] In the US, the proposed Sustainable Skies Act would provide energy producers with a $1.50 per gallon tax credit for SAF that reduces GHG

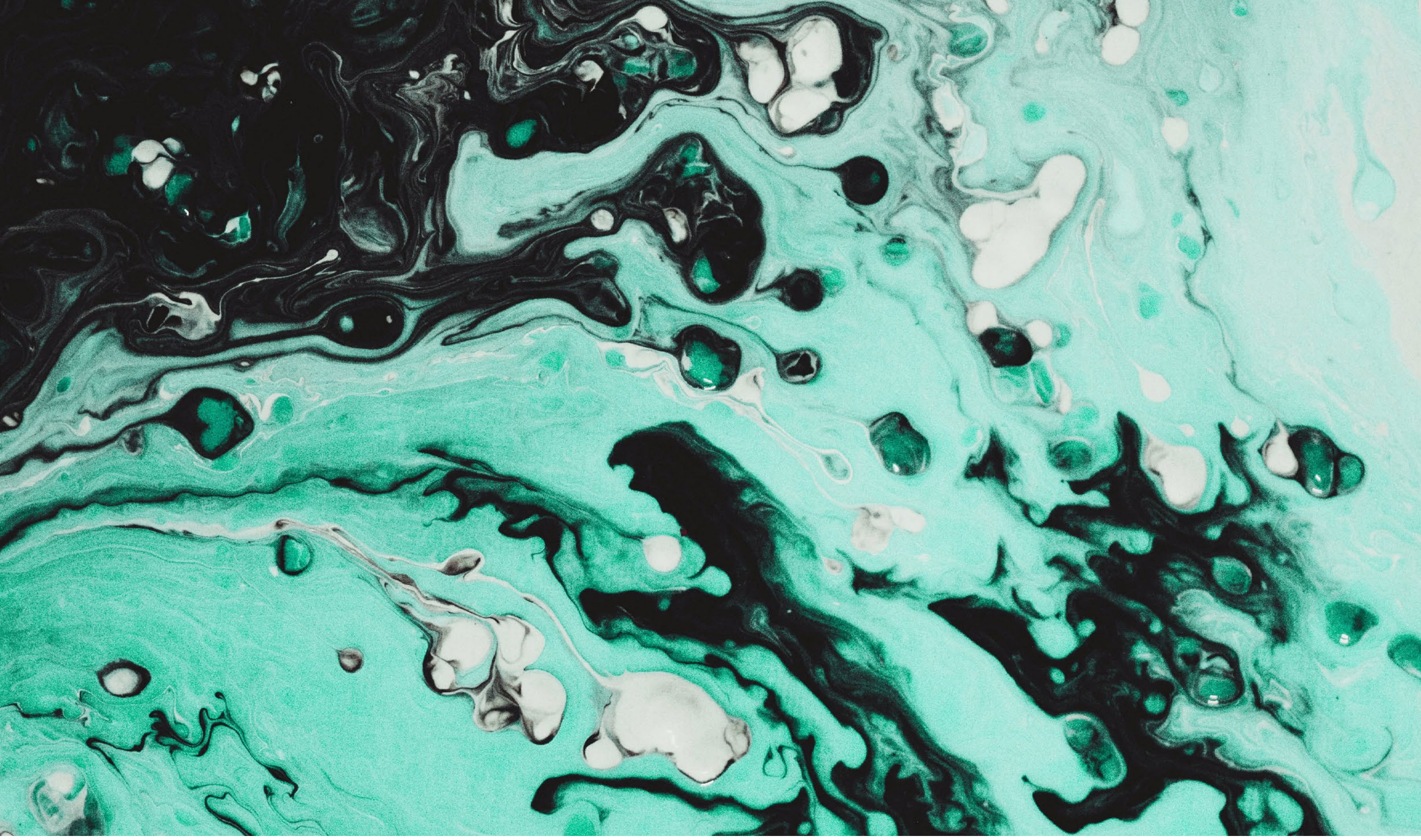
FIGURE 1 **The US, EU and others are proposing a range of incentives and regulations to increase SAF demand and supply and ramp up production**

Demand and supply mechanisms to incentivize scale-up of SAF[1]

	Demand side		Supply side	
	Direct demand for SAF	Increase cost of fossil fuel	Subsidies for SAF production	Low-cost loans /green bonds
Description	A certain minimum share of sustainable jet fuels is prescribed. Minimum penalty for non-compliance with blending requirements	Price discovery via predetermined maximum of allowances Additional taxation of fossil jet fuel	Tax credits for SAF that reduce GHG (by at least 50%)	Grants or low-cost loans (or possibly loan guarantees) to support sustainable infrastructure, innovation, research and development
SAF incentivization	Achieving large-scale SAF production and supply at competitive cost, thereby lowering production cost	"Zero-emissions rating" for SAF portion of jet fuel usage Taxation of fossil jet fuel results in reduced price differential between SAF and fossil jet fuel	Tax exemption/credit for SAF portion of jet fuel usage results in reduced price differential between SAF and fossil jet fuel	Promotion of SAF uptake and production by reducing the investment risk, increasing investment returns and demonstrating government support to help secure third-party investment
	ReFuelEU Aviation Initiative[2] Blend mandate GHG reduction mandate	EU ETS Energy Taxation Directive[3]	Low Carbon Fuel Standard Sustainable Skies Act[4] Sustainable Aviation Fuels Act[5]	Horizon Europe, InvestEU, etc. Green Fuels, Green Skies Blender's Tax Credit Sustainable Aviation Fuel Grand Challenge

Notes: 1 Mechanisms are not mutually exclusive and can be combined, ideally with coherent sustainability criteria and reporting requirements. **2** Legislative proposal of EU Commission; yet to be approved by the European Parliament. **3** Part of EU "Fit for 55"; in discussion. **4** Introduced to Congress only; yet to be approved, after which it will be sent to the Senate. **5** Supports the tax credit provided as per the Sustainable Skies Act; yet to be approved by all of the Houses

Sources: Government websites, ReFuelEU, web search



“ The ReFuelEU package proposes a 28% ‘RFNBO’ mandate by 2050, representing up to 22 million tonnes PtL demand.

emissions by 50% or more, along with a credit of 1 cent per gallon for each percentage point the fuel reduces emissions over 50%. In addition, the proposed Sustainable Aviation Fuels Act would establish an aviation-only low-carbon fuel standard and provide $1 billion over five years to expand the number of facilities producing SAF and build supporting infrastructure.[8] (All financial figures are in US dollars except where noted.)

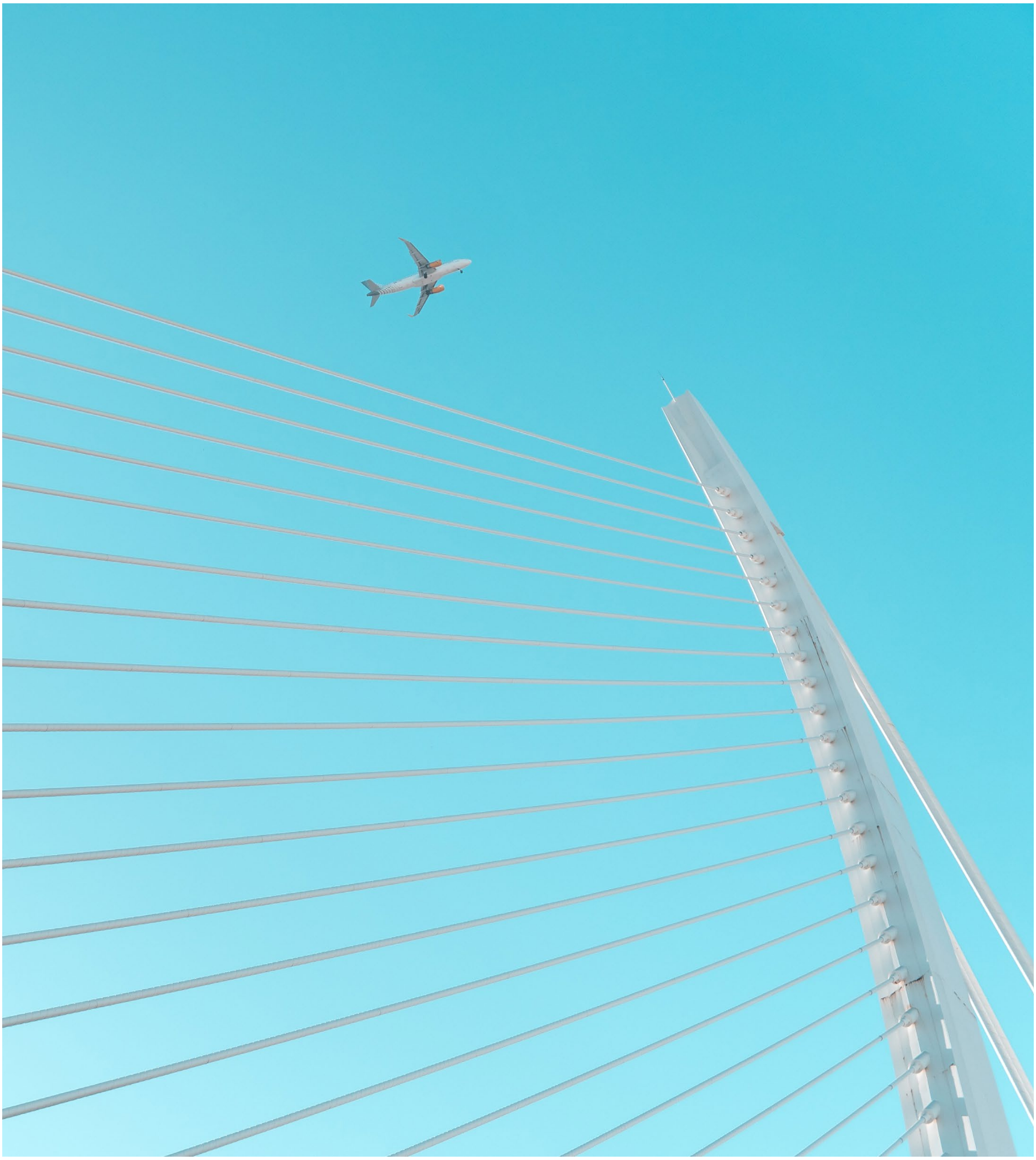
In the UK, EU and US, grants, low-cost loans or loan guarantees are in place or have recently been proposed to support sustainable infrastructure and research and development (R&D). Emissions reduction requirements and SAF blending mandates differ by region and country (see Figure 1). The ReFuelEU package proposes a 5% SAF blending rate target for 2030, with the latest regulation specifying not only the blending rate for SAF overall but also a specific sub-mandate for renewable fuel of non-biologic origin (RFNBO). The proposal includes a ramp-up to 63% SAF blend by 2050, of which 28% will need to stem from RFNBO production. This translates to approximately 4 million tonnes by 2030 and 50 million tonnes of SAF by 2050, of which approximately 0.5 million tonnes and 22 million tonnes, respectively, could be PtL to fulfil the RFNBO sub-mandate. Other regions are ramping up even more aggressively. Norway and Sweden are aiming for nearly 30% SAF by 2030, while the US is targeting 3 billion gallons of SAF production, equal to around 10–15% of expected US aviation fuel demand in 2030. A combination of policies will be needed to achieve the SAF ambition for which action on both the supply and demand sides must accelerate (see Figure 1).

What is clear is that no single production pathway will meet global SAF needs in the long term. A parallel scale-up of different SAF pathways will be required to alleviate feedstock challenges, reduce technology risks and ensure SAF is available in all regions. Mobilizing each pathway will require concerted efforts to build feedstock-collection systems, end-to-end supply chains and production infrastructure.

To support governments, industry and stakeholders along the supply chain, this report focuses specifically on the PtL production pathway. PtL is produced using captured CO_2 and renewable electricity from wind, solar, nuclear, hydropower and other green sources. Given the potential declining cost of hydrogen and CO_2 capture technologies, PtL could grow more quickly than other SAF pathways and will likely play a vital role in aviation decarbonization over the coming decades.

1 Decarbonizing aviation at scale

PtL fuel diversifies SAF supply using 'unlimited' feedstocks that are becoming increasingly viable with cross-industry momentum.



Announced investment in renewable and low-carbon hydrogen is about $540 billion globally and is expected to produce more than 18 million tonnes of SAF annually by 2030.

The aviation industry is investing in more efficient aircraft and other decarbonization efforts, but these will not be enough to meet emissions reduction goals, even when alternative technologies such as hydrogen and batteries begin to power short flights by smaller aircraft. Batteries are currently too heavy to be practical for longer flights; and hydrogen-powered aircraft will not be in service this decade and will require new airport fuelling infrastructure.

While other SAF production pathways are more mature, with some production and supply chains already in place, PtL can help diversify and expand SAF supply to meet future demand while engaging parts of the world without large reserves of sustainable biomass. Scaling PtL globally will mean overcoming considerable technical, financial and political challenges, which will require innovation and cooperation across the industry. Among the seven known SAF pathways, four are most likely to scale and attract industry attention, with PtL the least technically and commercially ready (see Figure 2).

The PtL pathway has historically been challenged by the high cost of inputs, primarily renewable electricity, hydrogen and CO_2. However, the momentum in global hydrogen production, and indirectly renewable electricity, is changing the game for PtL. In June 2021, for example, the US Department of Energy announced its first "Energy Earthshot" to reduce the costs of renewable and low-carbon hydrogen from about $3–$5 per kilogram to $1 by 2030. Globally, renewable and low-carbon hydrogen projects with associated investments of about $540 billion are expected to produce more than 18 million tonnes of hydrogen annually by 2030, enough to meet almost half of the expected demand growth across all hydrogen consumption sectors globally.[9] This includes almost 100 GW of electrolysis investment – a critical input step for PtL production. With lower costs of hydrogen come improved economics for PtL.

The PtL pathway takes advantage of the cross-industry momentum in hydrogen but uses existing aviation infrastructure. If PtL technology can mature and overcome some important challenges of its own, including well-to-wheel efficiency and competing demands for renewable electricity, it will be easier to scale and more flexible than some other pathways because its feedstocks are theoretically unlimited.

FIGURE 2

PtL is the least technically and commercially ready pathway, but offers high GHG reduction potential




	HEFA	Alcohol-to-jet[1]	Gasification/FT	Power-to-liquid
Description	Safe, proven and scalable technology	← Potential in the mid term; however, significant techno-economical uncertainty →		Proof of concept, primarily where cheap high-volume electricity is available
Technology maturity	Mature	← Commercial pilot →		In development
Capacity 2025[2]	42.1 Mt p.a. (of which 11.6 Mt operational and 22.8 Mt with announced SAF ambition)	0.4 Mt	1.1 Mt	0.3 Mt
Feedstocks	Waste and residue lipids, purposely grown oil energy plants[3] Transportable and with existing supply chains Potential to cover 5–10% of total jet fuel demand	← Agricultural and forestry residues, municipal sold waste, purposely grown rotational cellulosic energy crops → High availability of cheap feedstock; however, fragmented collection		CO_2, renewable electricity, hydrogen Unlimited potential via direct air capture Point source capture as bridging technology
Greenhouse gas reduction vs. fossil jet[4]	70–85%[5]	← 82–94%[5] →		85–100%[6]

Notes: 1 Ethanol route. **2** Estimated total fuel output per year of facilities at the end of 2025; excludes production capacity of non-liquids (e.g. RNG/SNG and hydrogen). **3** Oilseed-bearing trees on low-ILUC degraded land or as rotational oil cover crops. **4** Average range for given pathway; modifications such as CCS possible to achieve >100% in some pathways. **5** Some waste feedstock may also have lower GHG savings; excluding all edible oil crop; high share of plastic in MSW may result in lower GHG savings. **6** Based on CO_2 from direct air capture; emissions reduction can be up to 100% with a fully decarbonized supply chain

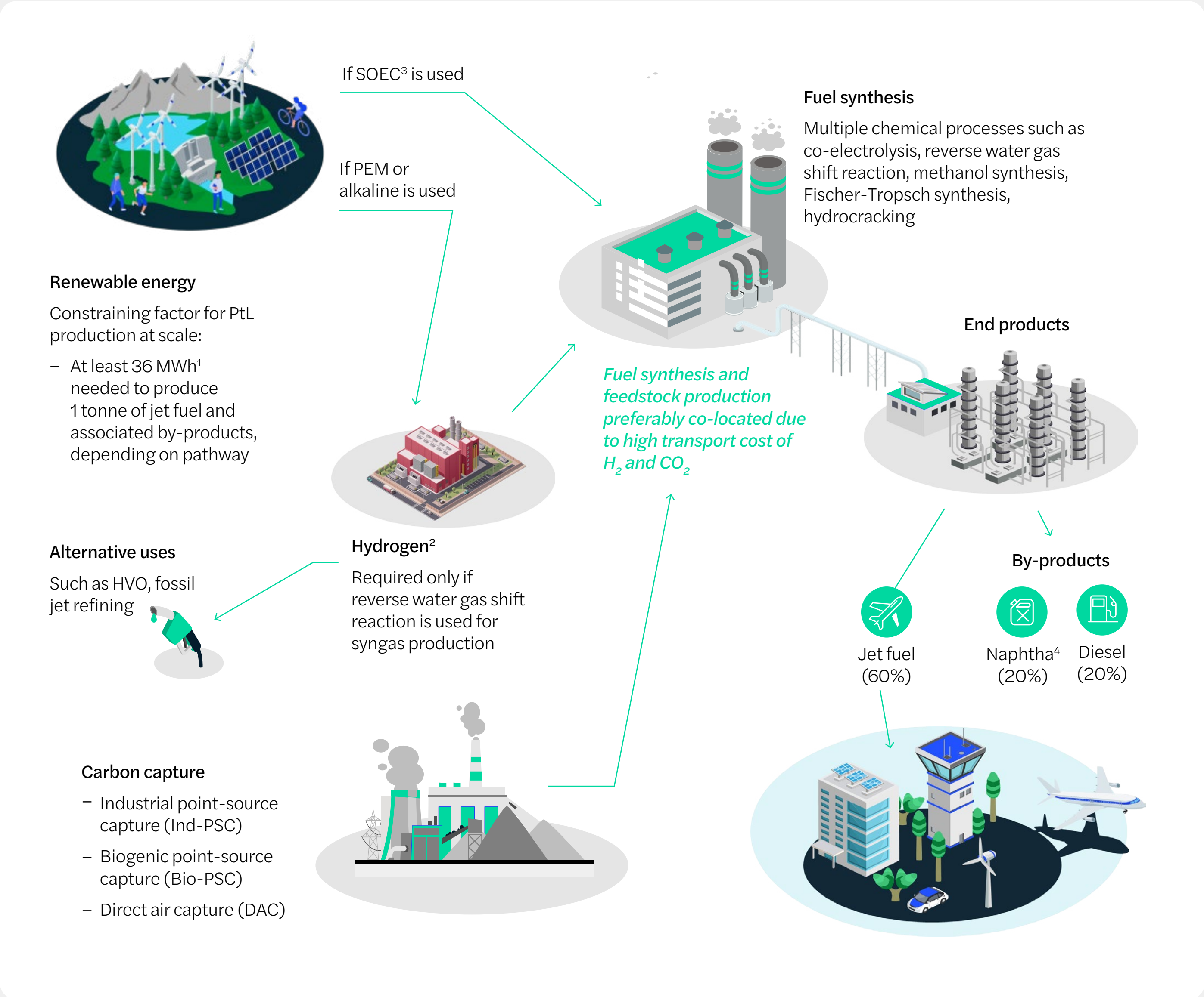
Sources: CORSIA, World Economic Forum Clean Skies for Tomorrow 2020, web search, McKinsey sustainable fuel supply database

1.1 The PtL value chain and stakeholders

Along the PtL value chain, facilities convert renewable electricity, hydrogen and carbon into synthetic fuels (including jet fuel and by-products such as renewable diesel or naphtha) that can be used to decarbonize other modes of transportation and the chemical sector. Producing PtL requires several steps: producing renewable electricity and hydrogen; capturing carbon; and synthesizing the fuel (see Figure 3).

Given the nascency and complexity of constructing the PtL value chain, no mature, fully integrated PtL player is yet operating at scale. Of the more than 450 companies identified as potential participants in the PtL ecosystem, about a third focus on hydrogen and another 20% on carbon capture, with few companies specifically focused on PtL (see Figure 4). An emerging set of companies active in PtL-based methanol are exploring hydrogen and carbon capture technologies. This indicates that the capability to develop more integrated solutions is increasing. That said, the market for companies specializing in conversion to jet fuel appears to be underdeveloped.

FIGURE 3 **The PtL production process relies primarily on renewable energy, hydrogen and recycled carbon**



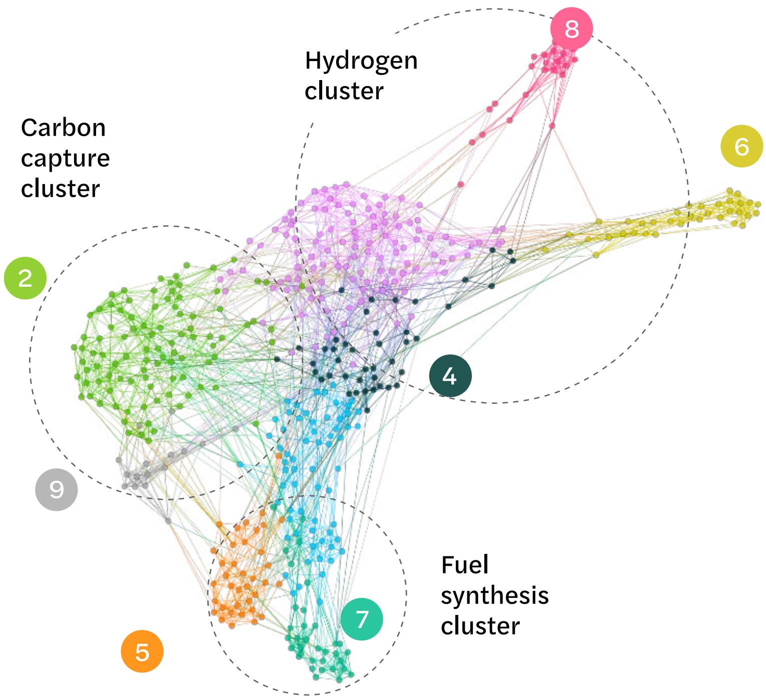
Notes: 1 Up to 45–52 MWh if using direct air capture. **2** Blue hydrogen likely required until sufficient renewable energy is available to produce necessary amounts of green hydrogen. **3** Solid oxide electrolyzer cell. **4** Petrol or chemical feedstock

Sources: Expert interviews, web search

FIGURE 4 | **The PtL ecosystem illustrates the limited overlap of activities across hydrogen, carbon capture and fuel-synthesis companies; few PtL players are fully integrated**

PtL ecosystem[1]

N = ~464 companies



Ecosystem segments

Cluster name	Share of total	Number of companies
1 Hydrogen	32%	149
2 Carbon capture	21%	97
3 Methanol synthesis	14%	64
4 Renewable energy	9%	43
5 Synthesis gas	8%	37
6 Electrolysis	8%	35
7 Fuel synthesis plus end products (jet fuel)	4%	18
8 SOEC	5%	24
9 Carbon capture and storage[2]	3%	16

Notes: 1 Each point represents a single company with activity in the PtL ecosystem; adjacency of points indicates overlap in activity among companies, whereas further distance indicates limited overlap in activity among companies. **2** Cluster 9 identified as less relevant in the context of PtL

Sources: McKinsey Growth Analytics, S&CF Insights

> Of more than 450 companies identified as potential participants in the PtL ecosystem, about a third focus on hydrogen and another 20% on carbon capture, with few companies specifically focused on PtL.

Today, PtL is at the intersection of renewable electricity and low-carbon fuels where few players have internal capabilities to cover both facets. In a number of industries, more stakeholders are forming consortiums to reduce the risks of investment and integrate knowledge from across the value chain. In Norway, for example, companies are forging early links in a PtL ecosystem. Norsk e-fuel (Sunfire), along with Climeworks, Paul Wurth and Valinor, aims to use alkaline and solid oxide technologies to convert CO_2, water steam and renewable electricity into syngas (a mixture of hydrogen and carbon monoxide) by 2023.[10] The consortium plans to use Fischer-Tropsch (FT) synthesis to process the syngas into a sustainable substitute for crude oil that can be refined into SAF, diesel, petrol and other sustainable fuels.

In France, Infinium and Engie have formed a partnership to produce PtL, capturing CO_2 from ArcelorMittal's steel-production facilities. The potential $550 million investment includes a 400 MW electrolyzer to produce renewable hydrogen and capture 300,000 tonnes of CO_2 annually.[11]

In Chile, a consortium of companies led by HIF Global and including Porsche, Siemens Energy, Enel, ENAP, Empresas Gasco and ExxonMobil is building a demonstration plant to produce PtL using direct air capture. It is aiming for industrial-scale production by 2026.[12]

In the United Arab Emirates, a consortium led by Masdar, Siemens Energy and TotalEnergies is demonstrating PtL production from renewable hydrogen and captured CO_2, and aims to proceed to the front-end engineering design (FEED) stage in late 2022.[13]

These are just a few of the projects under way that have been announced. More partnerships across the value chain are likely to materialize as the industry matures and the demand outlook takes shape.

2 The challenges of scaling PtL

Innovation, cooperation and investment will be required.

Scaling the PtL value chain will require major changes:

1. Greatly expanding the production of low-cost renewable electricity
2. Producing low-cost clean hydrogen on-site or close to fuel-synthesis facilities
3. Capturing or supplying sufficient sustainable carbon
4. Optimizing fuel synthesis for efficiency
5. Balancing the relative proportions of output products to commercialize the by-products of jet fuel such as diesel and naphtha

While sources of renewable electricity, hydrogen and carbon to produce PtL are theoretically unlimited, obtaining all inputs in a single site in large quantities can be a challenge. A typical commercial-scale PtL plant (based on recent announcements) is around 50,000 tonnes of PtL fuel per year, but is expected to reach up to 500,000 tonnes once fully deployed at scale. Using today's technology, the 50,000-tonne facility would require 1.1 terawatt hours of energy, or more than 2,700 acres of photovoltaics (see Figure 5). Put another way, producing 10 tonnes of PtL jet fuel in a typical set-up yields enough fuel to power an Airbus A320 or Boeing 737 for four to five hours, as well as by-product diesel to drive a round trip from Berlin to Madrid twice and by-product naphtha to produce 500,000 plastic bottles, among other high value-add petrochemicals. This requires 360 megawatt hours of electricity, enough to power about 400 American homes for a month.

FIGURE 5 **Producing PtL requires enormous amounts of energy**

A large-scale 50,000-tonne PtL plant could produce...

30,000 tonnes jet fuel

+

10,000 tonnes diesel fuel

+

10,000 tonnes naphtha

... which yields

3,000 flights on an Airbus A320 or Boeing 737 for four to five hours

+

7,000+ round trips from Berlin to Madrid in a heavy-duty truck

+

1.5 million plastic bottles and other high value-add petrochemicals

... and requires

1.1 terawatt hours of electricity

or

2,700 acres of solar park

+

160 kilotonnes of CO_2

... which equals

Enough to power 1.2 million American homes for a month

or

2,100 football fields of solar arrays

+

The annual emissions of 36,000 cars

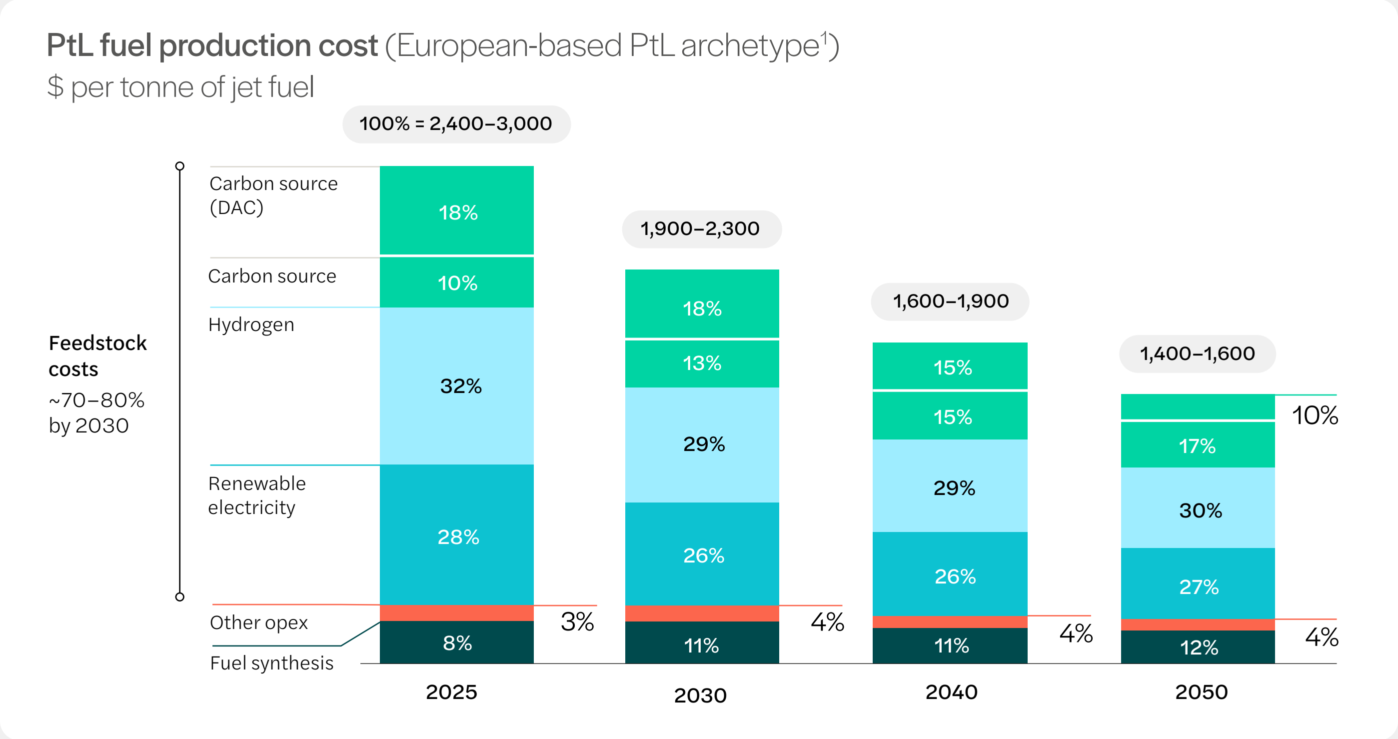
Assumptions: Average fuel economy of A320 of 2.4 tonnes/hour; heavy-duty diesel truck of 6.5 miles per gallon; 20 grams of PET per bottle; an average US residential home consumes 893 kWh/month; an average solar park produces 95,000 MWh/km² per year; an average passenger vehicle emits 4.6 tonnes CO_2 per year; 1 tonne of jet fuel (and by-products) requires 36.2 MWh energy and 5.4 tonnes of CO_2

Source: Team analysis

From a total cost perspective (see Figure 6), renewable electricity, hydrogen and carbon inputs should account for more than three-quarters of the cost of producing PtL in 2030, renewable electricity about a quarter, hydrogen capital cost about 30%, with carbon capture representing 15–30% depending on whether the carbon is captured from point-source emissions or directly from the air. The fuel-synthesis process represents only about 12% of the cost. These costs will need to come down significantly if PtL is to scale.

FIGURE 6

PtL fuel production cost is driven mainly by feedstock cost



Notes: 1 Assuming offshore wind-based renewables and H_2 produced in Europe for \$2.7/kg H_2 in 2030, declining to \$1.8/kg H_2 by 2050; additional \$0.2/kg H_2 included for storage; carbon cost based on industrial point source at \$95/t CO_2 capture with \$5/t CO_2 intermediate storage; DAC cost assumed \$220/t CO_2 in 2030, declining to \$135/t CO_2 by 2050; reverse water gas shift + Fischer-Tropsch technology configuration

Source: McKinsey Sustainable Fuel Model

2.1 Greatly expanding the production of low-cost renewable electricity

Producing PtL is not the most efficient use of renewable electricity where there are alternatives uses for the electricity – its well-to-wake efficiency could be under 20%. But its portability changes the equation.

Renewable electricity generation is rising faster than ever before. Today, roughly 28% of the world's energy is produced from renewable sources, up from 19.8% in 2010.[14] Many experts believe this share will exceed 75% by 2050.[15]

Over the past decade, the cost of renewable energy from solar and onshore and offshore wind declined by 48–85%. Today, the levelized cost of electricity (LCOE) from renewables in many countries is lower than the cost of electricity produced from coal, gas and other fossil fuels.[16] Renewable energy costs vary by region: for example, by 2030, the LCOE from solar in Chile should fall to $18 per megawatt hour, down from $30 today, but remain as high as $32 in Germany, which gets far less sun per acre.

Optimizing the location and set-up of PtL production is therefore key to reducing its cost. Producing PtL is not the most efficient use of electricity – its well-to-wake or life-cycle efficiency could be under 20% (see Figure 7). This compares to 60–75% for battery-powered electric vehicles. Critics suggest that green electricity providers, and indeed policy-makers, may consider PtL a low priority compared to other uses, such as heating and cooling buildings and powering electric vehicles.

The portability of PtL changes the equation. PtL can be produced far from major electric grids, unlocking "stranded renewables" that could not otherwise be tapped for green electricity production. A solar farm in Chile, for example, could not sell electricity to Asia, the US or Europe, but it could easily ship PtL by tanker to any market in the world. Shipping routes are well established using conventional tankers, although transport costs and the additional carbon impacts of shipping need to be considered for a full life-cycle reduction of carbon emissions.

FIGURE 7 **PtL has only 12–15% conversion efficiency from well-to-wake**

Notes: 1 Produced on-site; not taking into account the differing full-load factors and electricity yields. **2** Assuming continuous supply of H_2; thereby, no storage losses. **3** Energy required to capture CO_2 from industrial point source; capture efficiency varies between 80 and 90% depending on the CO_2 concentration of the carbon source; usage rate assumed to be 100% (i.e. supply matches synthesis demand); DAC efficiency lower due to lower CO_2 concentration **4** Efficiency can be increased when recuperating the waste heat into the front end (e.g. high-temperature electrolysis or covering energy demand for DAC) **5** Assumption; 70% assumed on the basis of Quintel Intelligence and Kalavasta's Synthetic Kerosene Production Model **6** Depends on distance and calculation method

Source: Transport & Environment, Centre for Transportation Research, Frontier Economics (2020), Global Alliance, PowerFuels, Quintel Intelligence, Siemens Energy

Complementary solar and wind resources can lower fuel cost by as much as 10%, with further reductions if small amounts of grid energy are used to enable continuous operations.

Typical PtL providers are likely to purpose-build large-scale renewable electricity-production sites to ensure a continuous supply of hydrogen for the FT process, the most common PtL pathway to obtain SAF. (For more on the FT process, see Section 2.4 on fuel-synthesis technology.) Since solar and wind are intermittent and the FT process requires near-continuous production, a successful system will need to gather and store enough power to use when the sun isn't shining or the wind isn't blowing. This storage will likely take the form of hydrogen, at least until battery technology improves enough to bring down costs. Co-locating hydrogen production and electricity generation can improve the economics of a project by using hydrogen pipeline transportation and storage while avoiding the need for costly transmission networks.

A continuous operation is beneficial for the FT process, but this puts a premium on electricity generation and therefore hydrogen production. Strategies such as combining wind and solar and tapping small amounts of grid energy (where applicable and, ideally, clean) can stabilize generation and reduce costs. Analyses by McKinsey & Company show that complementary solar and wind resources can lower the cost of fuel by as much as 10%, and that using the electric grid for less than 5% of total electrolyzer energy can reduce production costs by another 10%, depending on the cost of electricity. Regions in the Americas particularly suited for this type of FT production range from Uruguay, Colombia and north-eastern Brazil to Texas, where solar and wind are complementary and co-located, and the grids are increasingly clean.

How to fuel every flight with wind and sunshine by 2030

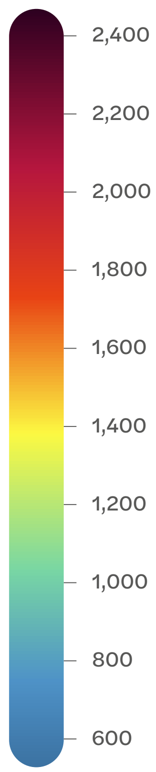
Renewable resources such as solar and wind will play a major role in the energy transition, including decarbonizing the grid and producing green hydrogen and PtL fuel. Large renewable projects require huge amounts of land that is sparsely populated and gets plenty of sunshine or wind. Producing 10 million tonnes of PtL jet fuel, for example – enough to meet the needs of a large airline group for a year – would require a solar farm covering about 1 million acres, about one-third the size of Los Angeles County.

The ease and low cost of shipping PtL solves the land challenge by opening the possibility of global trade. Billions of sparsely populated, non-arable acres in Chile, the Middle East, North Africa and Australia receive exceptional amounts of sunshine and are adjacent to communities that would welcome green economic development and new job opportunities. Building solar developments in these regions on just 1–2% of desert land would provide enough PtL fuel to decarbonize the entire aviation sector in 2030 (see Figure 8). Other constraints, such as water availability, can be addressed through infrastructure developments; for instance, desalination facilities that transport water to the hydrogen production site and have a limited impact on the final total costs (<5%).

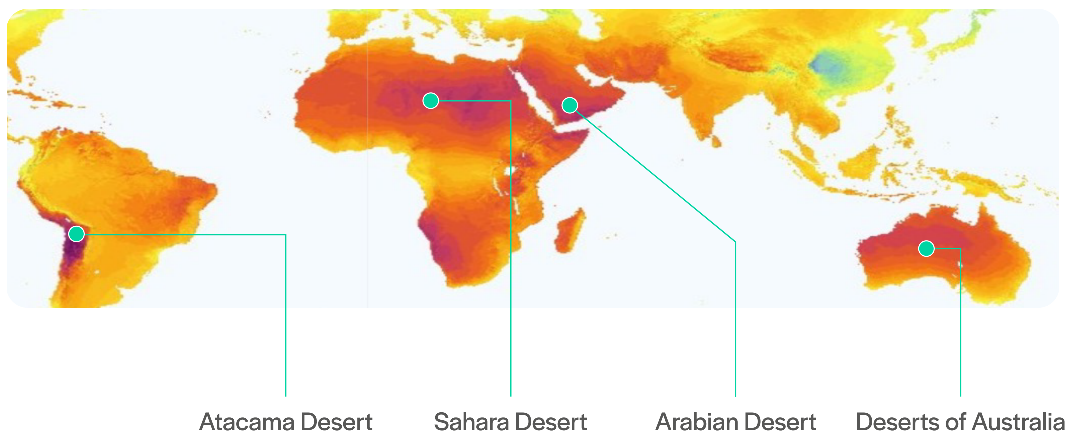
Producing PtL in remote sunny areas also makes economic sense because the higher solar irradiance lowers production costs, even when considering the need for a more expensive water source from desalination plants located on the coast. The cost of creating PtL in desert regions using direct air capture and a desalinated water source could be as low as $1,600–$1,800 per tonne of jet fuel in 2030 – 25% lower than if produced in Europe with the same configuration. It would then add another 5–8% to the cost of shipping PtL fuel to land-constrained, high-demand areas using the legacy infrastructure built for fossil fuels. In this way, creating a global PtL trade network can generate economic and environmental benefits for all countries and eliminate land as a constraining factor for at-scale PtL production.

FIGURE 8 **Four major deserts could supply PtL to the world**

KWh/kWp



Producing PtL using only 1–2%[1] of the land in four regions could meet 100% of aviation fuel needs[2] in 2030



	Atacama Desert	Sahara Desert	Arabian Desert	Deserts of Australia
Total land[3] (km²)	95,000	8,300,000	1,650,000	2,050,000
Capacity factor[4] (%)	30–34	27–31	26–30	25–29

Notes: 1 Includes land required for direct air capture. **2** Includes an additional ~800–900 $MtCO_2$/y emissions avoided from PtL by products (naphtha and diesel) by 2030. **3** Estimated land available for renewables development. **4** Considers bifacial, single-axis tracking technology in 2030 at 33 MW/km²; includes land required for direct air capture

Source: Map obtained from the Global Solar Atlas 2.0, a free, web-based application developed and operated by Solargis on behalf of the World Bank Group, using Solargis data, with funding from the Energy Sector Management Assistance Program (ESMAP). For more information: https://globalsolaratlas.info

2.2 The falling costs of hydrogen could improve PtL's cost-competitiveness

Lowering the cost of renewable hydrogen to below \$1 per kilogram would reduce the cost of PtL by up to 40% in 2030.

Advances in low-carbon and renewable hydrogen production efficiency will also be crucial to the maturity of the PtL value chain. Lowering the levelized cost of hydrogen (which includes renewable electricity input but excludes transport and distribution) to below \$1 per kilogram would reduce the cost of PtL to \$1,200–\$1,800 per tonne, depending on the carbon source, equating to a 40% reduction in average cost in 2030. While this cost is still higher than that of fossil jet fuel, it is within range of alternative sustainable aviation fuels. Low-carbon hydrogen, sometimes referred to as "blue", is derived primarily from natural gas using carbon capture and storage, while renewable or "green" hydrogen is made with renewable electricity.

Low-carbon hydrogen is more cost-competitive than renewable hydrogen today and can be used as a transition technology to scale PtL faster. Although low-carbon hydrogen can be a lower-cost production route, it requires capturing CO_2 twice to produce PtL – once in the hydrogen production route and again in the fuel-synthesis step – an inherently inefficient system.

In the long run, renewable hydrogen is a lower-CO_2 production route that should be prioritized for PtL production. Three primary renewable hydrogen-production technologies are available today, each of which requires large amounts of renewable electricity and clean water. Alkaline water electrolysis (AWE) and proton exchange membrane (PEM) are the most mature. Solid oxide electrolyzer cell (SOEC) may be better suited for PtL due to the integration of high-temperature heat recovery in the production process, but the technology is less mature today.

The costs of renewable hydrogen production will fall as innovative companies – including many outside the realm of aviation – learn about and scale all three technologies. Based on discussions with industry stakeholders and the strengths of initiatives such as the US government's Earthshot, the capital investment per kilowatt required for the technologies should fall by more than 50% from 2020 costs, reflecting learning rates of 9–13% for each cumulative doubling of production capacity.[17] Current activities to develop hydrogen technologies and the manufacturing process are showing great potential to achieve economies of scale. The aviation industry can benefit from the industrialization of renewable hydrogen production in other sectors.

Meeting hydrogen growth ambitions will require a diverse new global value chain, and scaling renewable hydrogen-production technology to meet the needs of PtL will be a challenge. Today, the largest renewable hydrogen facility produces 20 megawatts,[18] while a 100,000-tonne PtL facility producing around 60,000 tonnes of jet fuel would require almost 400 megawatts of electrolyzer capacity alone. Building this much renewable hydrogen-production capacity in a single location would be unprecedented. Many projects have been announced, however, to build gigawatts (thousands of megawatts) of electrolyzer capacity in the coming years. InterContinental Energy, a large renewable hydrogen project developer, plans for multiple 10-plus gigawatt electrolyzer installations at sites across Australia and the Middle East. Such projects represent a potential archetype for PtL players to emulate as the industry tries to achieve large-scale production.

2.3 Biogenic carbon sources can play a bridging role

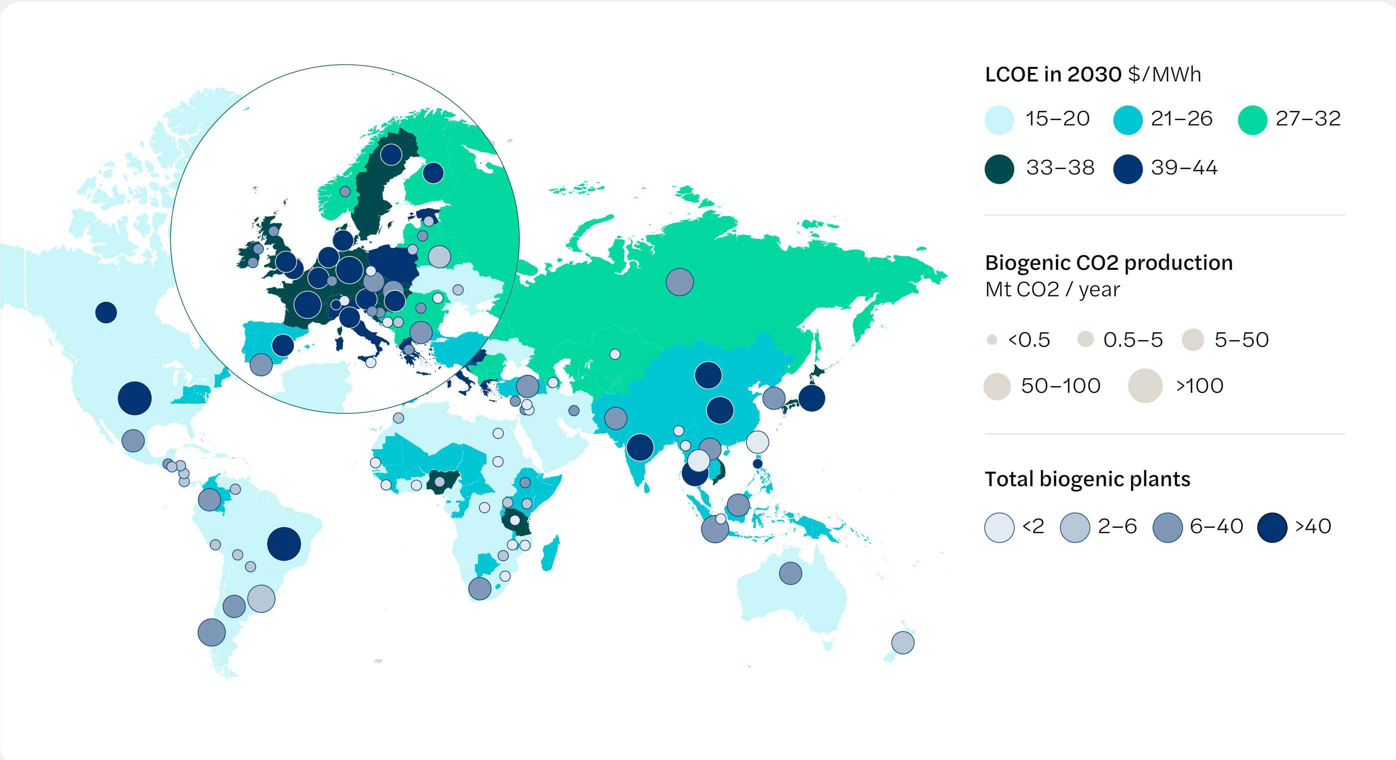
❗ Biogenic carbon could yield about 88 million tonnes of PtL jet fuel annually.

Producing PtL fuels requires CO_2. Potential sources include industrial point-source emissions, either fossil or biogenic-based, and direct air capture. Capturing carbon from industrial sources is a viable bridging solution until direct air capture technology is available at scale. Industrial facilities that generate CO_2 from fossil sources, such as steel mills, cement kilns and coal plants, will be useful in the short term to help scale and mature the industry. Yet, because the CO_2 originates from fossil sources, it cannot fully decarbonize the fuel. There is a potential risk that PtL produced from fossil-based industrial sources will not meet sustainability criteria in future legislation and energy accounting systems. Furthermore, as steel and other major industries decarbonize, fewer emission sources will be available to capture and produce PtL – something to consider before investing in CO_2 capture equipment based entirely on fossil sources.

Fossil sources of carbon should be replaced by more sustainable streams of biogenic carbon from waste and sustainable biomass. Biogenic CO_2 comes from similar industrial processes but was originally sequestered from the atmosphere by photosynthesis and stored within solid biomass. Burning or using biomass during industrial processes leads to biogenic CO_2 emissions, which is part of the carbon cycle and does not contribute to the anthropogenic greenhouse effect. Therefore, biogenic CO_2 can achieve a closed carbon cycle with sustainable cultivation and environmentally compatible processing of the biomass in industrial sources.[19]

Biogenic point sources, such as pulp and paper mills, biogas production facilities, waste incineration and bio-based heat and electric plants, can serve as biogenic CO_2 sources until their limits are reached. Brazil, Uruguay, Chile, Sweden, Spain, Portugal, parts of China and the US have large biogenic carbon sources in renewable electricity generation locations ideal for PtL production (see Figure 9).

FIGURE 9 **South America and regions in the US and China have biogenic carbon sources in locations suited to PtL production**



Notes: 1 Levelized cost of energy; lowest-cost available energy source (e.g. solar, wind onshore/offshore)

The presentation of maps does not imply any opinion on the part of the World Economic Forum concerning the legal status of any country, territory or area of its authorities or concerning the delimitation of its frontiers or boundaries.

Source: McKinsey Energy Insights Global Energy Perspective, Solargis, IEA Bioenergy, European Commission Joint Research Centre

Analysis of global point-source emissions from biogenic sources suggests that almost 0.5 gigatonnes of biogenic CO_2 are emitted today. This carbon potential could yield around 88 million tonnes[20] of PtL jet fuel annually, representing 20–30% of global jet fuel demand in the next 10 years if used exclusively for PtL. Most biogenic carbon sources fall outside carbon trading mechanisms and can be used to produce PtL jet fuel. The biogenic carbon for PtL will also compete for consumption in the maritime, heating and chemicals sectors, often in the form of PtL methanol or power-to-gas. Some of this biogenic CO_2 will also be used for storage to create "negative" emissions, called biogenic carbon capture and storage. The optimal use for the biogenic carbon will depend on its proximity to carbon storage, renewable electricity and hydrogen, and demand centres. As global decarbonization accelerates, sustainable, biogenic carbon, particularly from large point-source facilities, will become increasingly scarce.

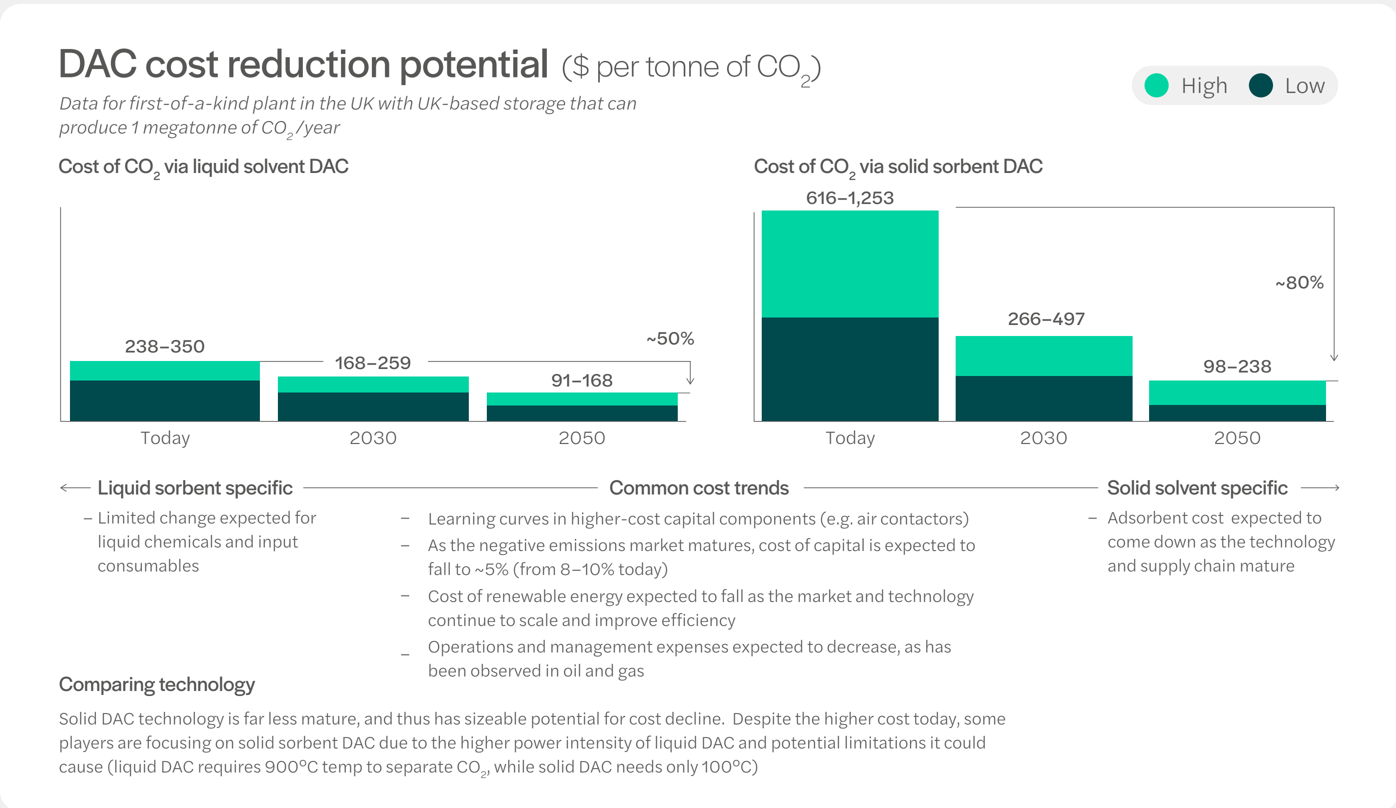
PtL-production facilities will have to optimize production size based on the amount of biogenic carbon available. The facilities with the largest individual point sources of biogenic CO_2, from waste incineration-to-energy, ethanol or pulp and paper mills, would yield 50,000–100,000 tonnes of PtL jet fuel. Scaling beyond this capacity would require aggregating CO_2 sources to a single location, as exemplified by the carbon capture clusters currently emerging in industrial centres around the world.[21] Clustering biogenic carbon will add operational costs and complexity, a consideration when sizing the optimal PtL facility.

The cost of carbon capture today varies significantly by source. More than 130 commercial-scale carbon capture facilities are in development, mostly for electricity generation and natural gas processing.[22] Additional deployment is required and will need to shift to more novel biogenic sources such as waste-to-energy. Industrial point-source capture will likely cost as little as \$25 per tonne of CO_2 in some industries such as bioethanol, and more than \$100 in hard-to-abate industries such as cement production.

In the long run, as the technology matures, direct air capture (DAC) can provide unlimited CO_2 and entirely close the carbon cycle. DAC today costs \$250–\$600 per tonne of CO_2.[23] Nineteen DAC plants are now in operation worldwide, capturing more than 9,000 tonnes of CO_2 per year,[24] but no DAC technology is ready to scale beyond a few thousand tonnes per annum today.

The cost of DAC depends on the technology deployed. By 2030, for example, 1 tonne of CO_2 from liquid solvent DAC could cost \$170–\$260 and 1 tonne from solid sorbent DAC could cost \$270–\$500. Those costs could fall to \$90–\$240 for both technologies as companies scale the learning curve and reduce capital and energy costs. By 2050, the cost of DAC could decline by 50–80% from today's levels as the technology matures and the cost of renewable electricity to power DAC facilities declines (see Figure 10).

FIGURE 10 **The cost of direct air capture could decline by 50–80% by 2050**



Source: Coalition for Negative Emission: coalitionfornegativeemissions.com

Unlocking the potential of DAC will require advances in four main areas:

– **Innovative carbon monetization**: Some niche carbon use applications, such as drinking water purification, ground and municipal water treatment, carbon fibre and injection into concrete, could provide early use cases for carbon.

– **Strategic funding and investment partnerships**: Investors and project developers will need to form coalitions to develop and scale promising technologies. Bringing in offtakers, such as airlines and leading software companies, is critical to reduce project risk.

– **Accelerated technology scaling**: Established companies and start-ups are developing the next generation of technologies with the potential to significantly increase process efficiency. Government grants and funding for R&D will help accelerate cost-reduction in CO_2 removal technologies.

– **New regulatory incentives**: Carbon-pricing instruments are gaining global momentum; in some programmes such as the EU Emissions Trading System, the value has exceeded $100 per tonne. The California Low Carbon Fuel Standard allows for DAC facilities anywhere in the world to generate credits, with the price often exceeding $150 per tonne.

Many small-scale players are pursuing DAC technology today, but it could take more than a decade before enough air-sourced CO_2 is available for at-scale synthetic fuel production. In the meantime, many biogenic plants will be needed to scale PtL jet fuel production. The industry must not wait for DAC to start building PtL facilities – the integrated PtL value chain needs to be tested at scale to advance fuel-synthesis technologies and test the full end-to-end production process.

2.4 Fuel-synthesis technology is at varying levels of maturity

Power-to-liquid fuels can be created in two primary pathways: FT and methanol-to-jet. Both require a first step to create synthesis gas, or “syngas”, which is primarily a mixture of carbon monoxide and hydrogen.

Syngas production

Syngas can be produced using either co-electrolysis (SOEC) or reverse water gas shift (RWGS). The co-electrolysis step eliminates the discrete production of hydrogen and creates syngas in a single step, whereas RWGS requires renewable or low-carbon hydrogen as a precursor to syngas generation. If co-electrolysis can mature as a syngas-generation step, it will have several advantages over RWGS, including lower levelized fuel-production costs due to capital cost savings from the combined hydrogen and syngas production steps. Co-electrolysis is potentially a more efficient process due to heat recovery and integration with the fuel synthesis (FT) step.

In the near term, while electricity is relatively expensive, the choice of SOEC or RWGS will have a major bearing on PtL cost. The SOEC process can use waste heat to reduce electricity needs and overall production costs by about 20%. This assumes waste heat at very high temperatures is produced and available in excess on-site, which often limits the SOEC process to select locations. Without heat integration, SOEC yields fewer savings. Another consideration in choosing SOEC or RWGS is the type of renewable electricity supply. SOEC requires a more stable supply of renewable electricity and is less suitable for highly volatile sources, such as pure solar photovoltaic. Options such as batteries can reduce volatility but add cost. Optimizing renewable electricity to provide a steady flow to fuel-synthesis units is a new concept for both technologies and needs to be addressed. In the longer term, when renewable electricity has a lower levelized cost and hence less impact on overall PtL cost, affordable access to sustainable sources of carbon will become a bigger cost driver for PtL (see Figure 11).

FIGURE 11 **Commercializing SOEC technology could cut production costs by more than 20%**

PtL production cost in 2030, RWGS vs. SOEC

$/t of jet fuel

SOEC cost advantage

SOEC requires more capital investment and consumes more energy than RWGS alone. However, capex and electricity requirements associated with RWGS-FT are higher when hydrogen production is taken into consideration

Source: McKinsey Sustainable Fuel Cost Model

The FT pathway

Stakeholders contemplating the FT pathway should consider integrating operations with oil refineries. Additional hydroprocessing is needed after the FT step to meet the specifications of jet fuel. Hydroprocessing units are common at oil refineries around the world. Indeed, as oil demand declines, spare hydroprocessing capacity will likely become available for PtL fuels. Synergies may arise where higher transportation costs can be recovered through lower capital expenses. Current standards allow for up to 50% blending via the FT pathway, but this share should rise as additional testing and certifications are completed.

The methanol-to-jet pathway

The methanol-to-jet pathway, which uses PtL methanol as an intermediate feedstock, is not yet approved to produce fuel for jet engines. The process, which converts methanol to olefins and olefins to distillates, has not yet demonstrated the same selectivity to kerosene range molecules (C10–C12) as achieved for gasoline (C6–C8). Additional R&D is needed to commercialize this technology pathway. That said, producing PtL methanol is proven today and could offer a wider array of applications in addition to jet fuel, such as marine bunker fuel and chemical feedstock. These applications can support a positive business case until the methanol-to-jet pathway is commercially available. Many companies, such as HIF in Chile and Carbon Recycling International in Iceland, are currently going directly to methanol to commercialize the PtL process. Indeed, more than half of the announced PtL capacity to 2030 will use the methanol pathway, highlighting the importance of commercializing the methanol-to-jet pathway to meet SAF demand (see Figure 12).

Other novel pathways

Several companies are experimenting with novel and potentially breakthrough technologies, blurring the line between PtL and other SAF pathways. These companies can change the landscape by providing potentially lower-cost and higher-efficiency solutions to capturing and using CO_2 for jet fuel:

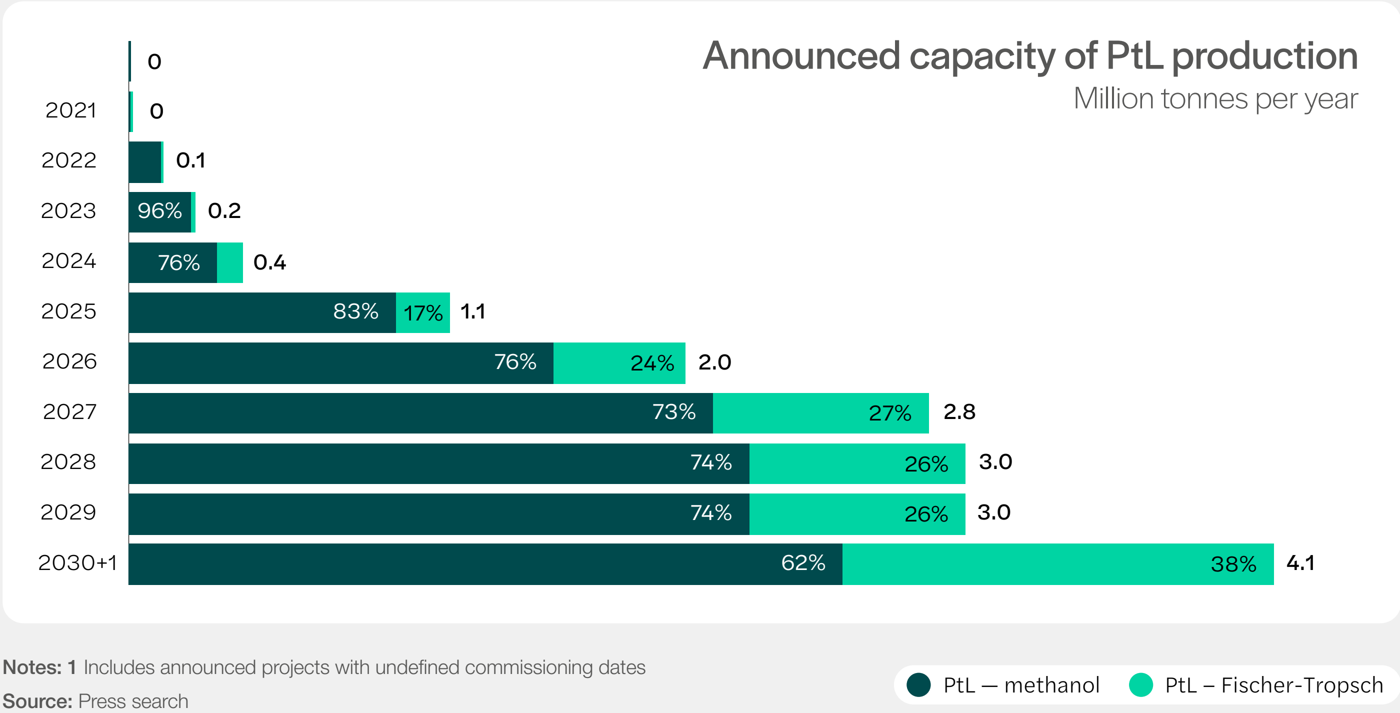
– Prometheus Fuels, based in the US, is using renewable electricity and direct air capture to produce sustainable fuels with long-chain alcohols as the intermediate fuel.

– Synhelion, based in Switzerland, is using solar power from a mirror field to produce synthetic fuel for aviation and other industries with high carbon emissions, such as steel and cement.

– Caphenia, based in Germany, is generating synthesis gas (carbon monoxide and hydrogen) in a novel manner in a three-in-one reactor zone.

– LanzaTech, based in the US, has developed a carbon recycling technology that enlists bacteria to sustainably convert emissions from steel mills or landfills, for example, to fuels and chemicals.

FIGURE 12 **Over half of the announced PtL capacity is planning to produce methanol**



Notes: 1 Includes announced projects with undefined commissioning dates

Source: Press search

2.5 By-product markets need to be considered when scaling PtL

By-products of PtL will help decarbonize other applications besides aviation. Trucking fleets around the world can use synthetic diesel from the PtL process as a sustainable substitute with very little modification to the fleet. The diesel, for example, could also be used in heavy-duty applications with few decarbonization alternatives, such as to power mining equipment in remote regions. Synthetic naphtha can be provided to petrochemical companies, building the circular economy without requiring any changes to existing production processes (see Figure 13).

Balancing the output ratio of PtL and other by-products (i.e. the product slate) can maximize the commercial value of PtL facilities. Producers will need to seek out high-value end markets for the by-products to make a positive business case given most of the incentive for sustainable fuels today is in road transport. So far, companies have few near-term regulatory incentives to produce PtL jet fuel. As demand shifts and legislation is enacted to support aviation decarbonization, players will need to carefully shift production from diesel and petrol fuels to kerosene without leaving road transport applications short of low-carbon fuel.

FIGURE 13

Cost-competitive jet fuel production requires a strong by-product market

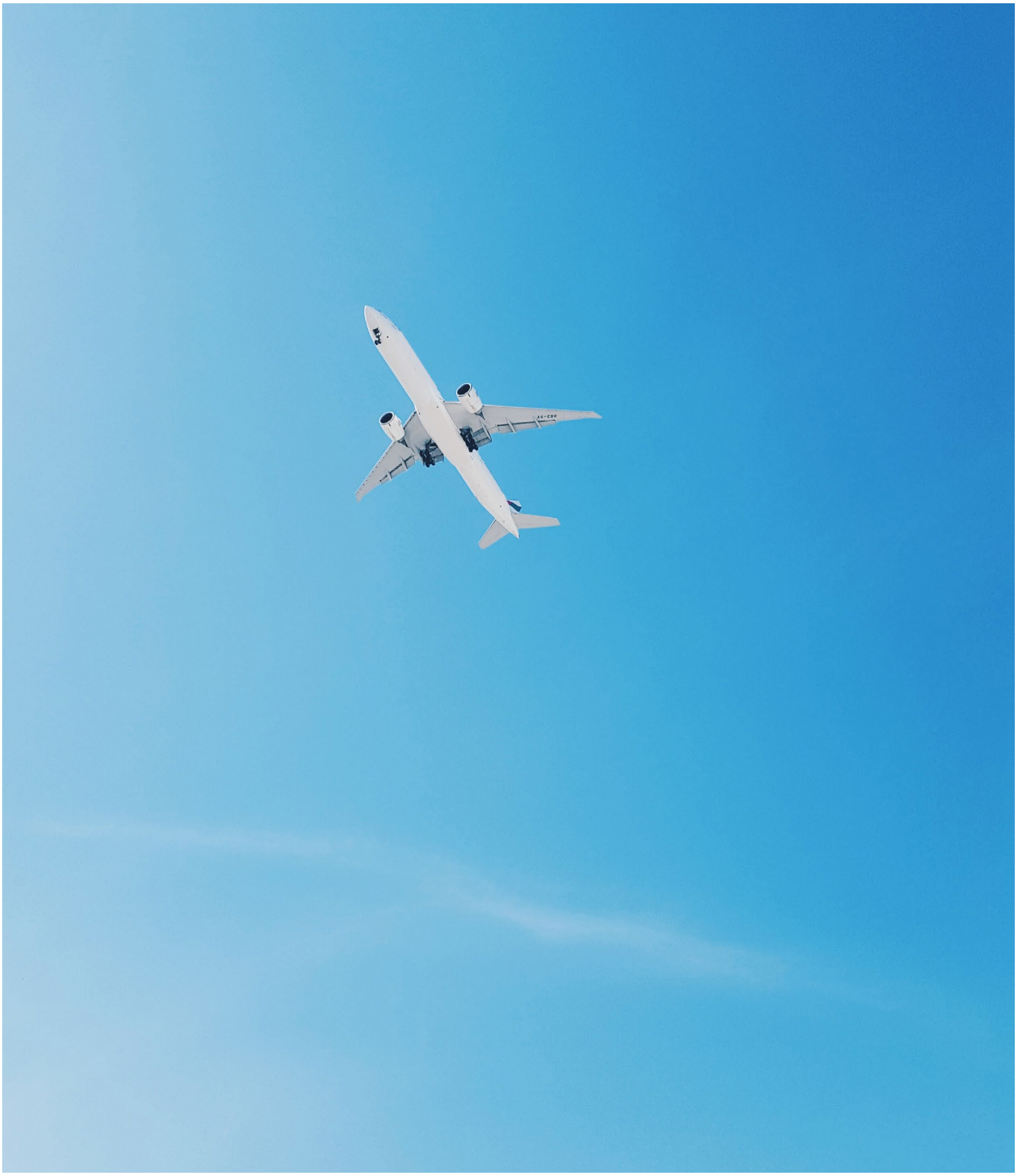
End products of Fischer-Tropsch	Relative production yield		Customer/ end user	Commercialization options
Jet Fuel	1 t	About 60% of product slate (up to 80% possible[1])	Fuel suppliers, airlines	– Increasing demand for synthetic jet fuel driven by regulations – High-margin product; high end market prices
Diesel	0.33 t	About 20% of product slate (possible to reduce to 0%)	Fuel suppliers, transport companies, shipping	– Rapid decarbonization option for existing assets such as articulated lorry fleets or blended into petrol, or for developing countries without the infrastructure to support fleet electrification – Fit for 55 sets a European targeted share of hydrogen and synthetic drop in fuels of 2.6% in the transportation sector
Naphtha	0.33 t	About 20% of product slate	Petrochemical industrials, plastics producers	– Synthetic naphtha can be provided to petrochemical players as a decarbonization lever without changing the production process – Incentives for decarbonization of petrochemical feedstock not yet in place

Notes: 1 Such as Sasol technology optimizing for jet fuel output, reducing diesel output to 0%

Source: Expert interviews, web search

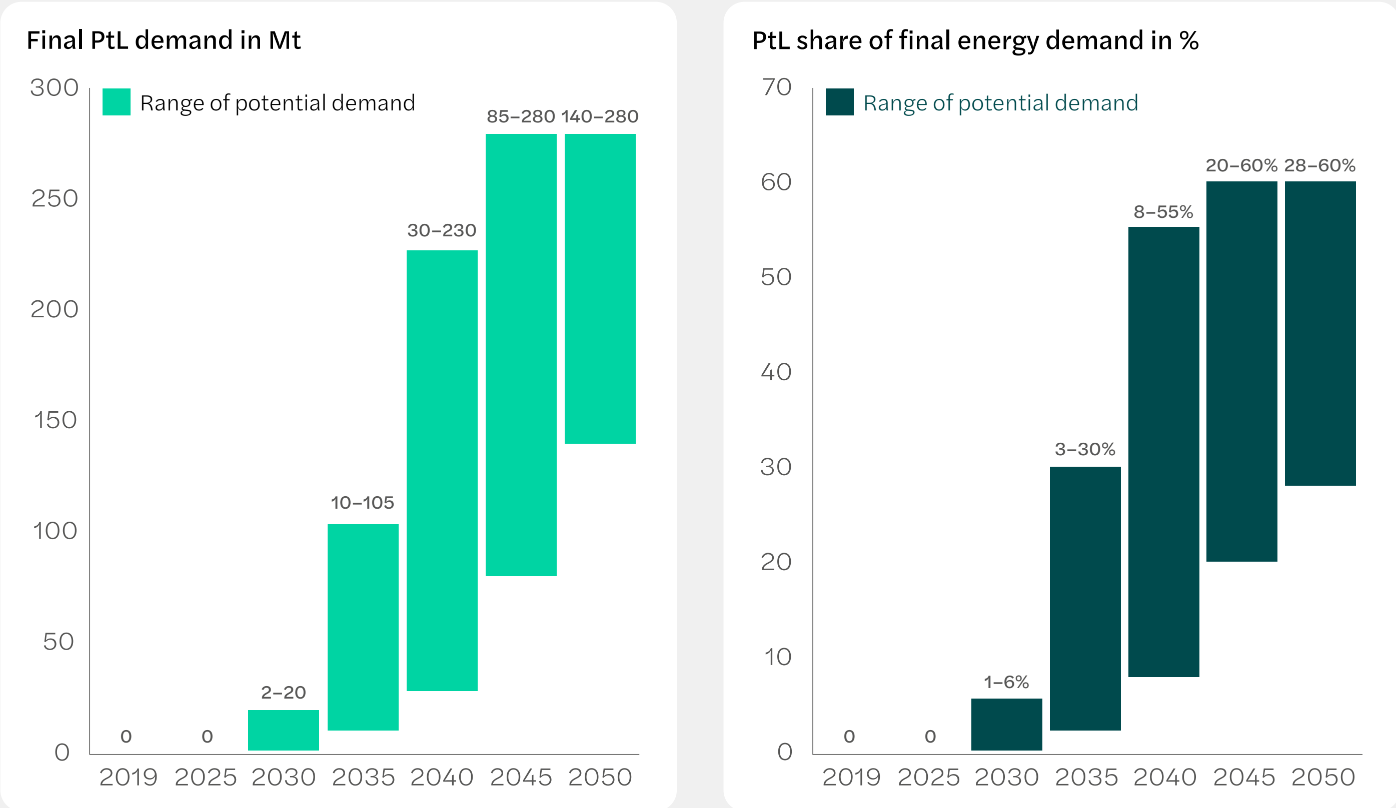
3 How PtL could scale by 2050

Anticipating SAF production in the decades ahead.



Work is under way to understand how the aviation industry may achieve its sustainability ambitions as annual jet fuel demand rises towards 500 million tonnes in 2050. (The Mission Possible Partnership and Clean Skies for Tomorrow will publish an Aviation Transition Strategy report later this year. Provisional data was provided for this report that may not reflect the finalized transition strategy.) Meeting future demand will almost certainly require a mix of SAF production technologies in addition to PtL, including hydrotreated esters and fatty acids (HEFA), alcohol-to-jet (AtJ), gasification plus Fischer-Tropsch (G-FT) and potentially novel pathways such as pyrolysis conversion to jet fuel.

FIGURE 14 **PtL could meet ~30–60% of energy demand in 2050**



Source: Mission Possible Partnership provisional data

❗ $3–4 trillion in cumulative investment in PtL will be required in 2022–2050 to scale PtL to 30–60% of all SAF production.

In Figure 14, the lower-bound projection for potential demand relies on technologies currently available or likely to enter the market over the coming decades according to industry consensus. This includes the aforementioned cost decline in renewable electricity and hydrogen, as well as moderate improvements in the technology performance of the FT and methanol-to-jet pathway. The lower bound assumes PtL remains relatively subscale in the coming decade, representing only 3% of final energy demand in aviation by 2035, but would scale rapidly afterwards as other SAF pathways reach biofeedstock limitations. Given the potential competition for biogenic CO_2 from other sectors, the industrialization of DAC should be achieved by 2035, but PtL production could require almost all of the CO_2 that DAC generates. Sufficient biogenic CO_2 from both DAC and point-source capture should be available to allow PtL to scale unconstrained beyond 2045.

The upper bound simulates a net-zero trajectory by 2050, driven by cheap, abundant renewable electricity. Rapid R&D is needed now and in the coming years, along with faster-than-anticipated cost declines for renewable electricity, to deliver sustained PtL input costs below $15–20 per megawatt-hour. Furthermore, limited quantities of biogenic CO_2 mean that global deployment of DAC is needed well before 2035. Regulations, especially blending mandates specific to PtL, need to come into force in the next five years to spur industry development. Additional demand from other sectors such as the maritime or petrochemical spheres must materialize to create a positive business case for scaling PtL jet fuel.

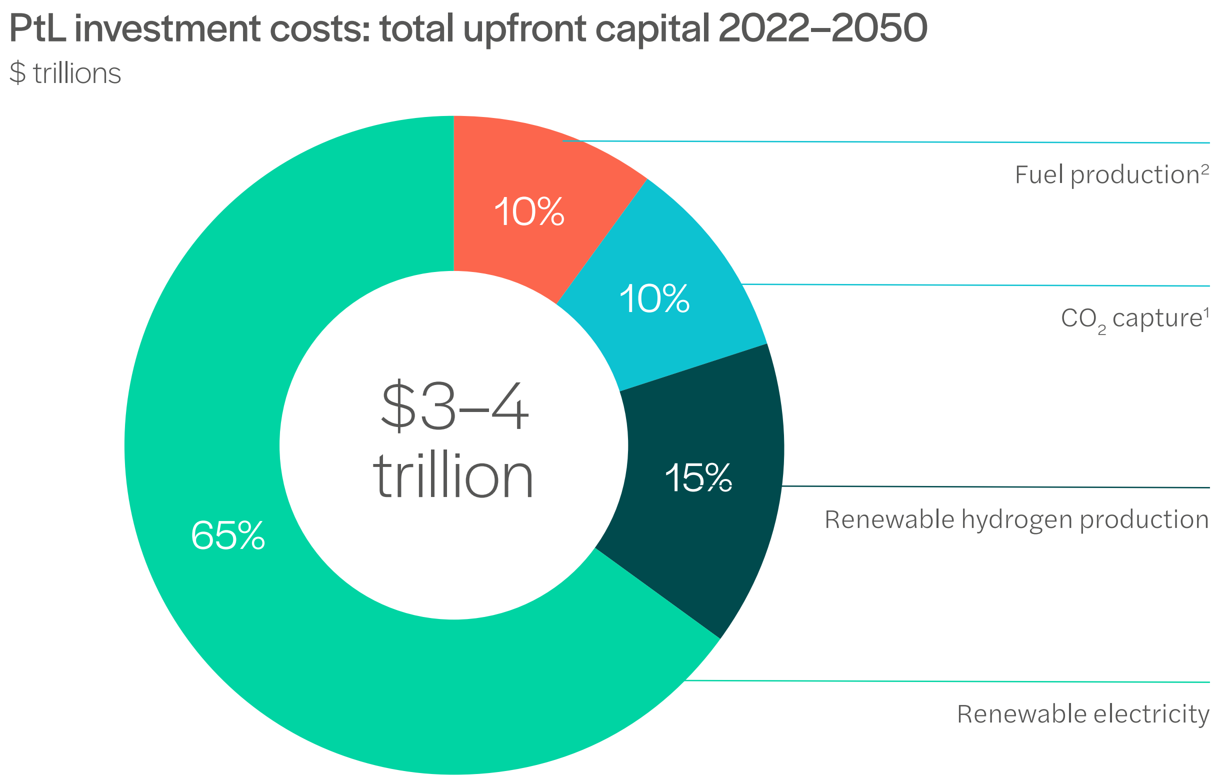
Annual PtL jet fuel production will need to rise from the roughly 100,000 tonnes of capacity announced through 2025 to 10–105 million tonnes by 2035 – a potential thousand-fold increase in 10 years. Scaling up PtL inputs, renewable electricity and hydrogen, will be orders of magnitude lower. As noted, much of this investment could be made in renewable energy-rich regions where competition for alternative uses of renewable electricity is low, meaning PtL would be less likely to "crowd out" other sectors in need of renewable electricity. Announced capacity in renewable hydrogen, including non-PtL use cases, is around 9 million tonnes to 2030,[25] implying an 50% increase in global renewable hydrogen capacity required for PtL by 2035 to meet the lower bound. Given that announced clean hydrogen capacity more than doubled in 2021, many observers expect hydrogen roll-out to continue to scale, preventing it from becoming a constraint in achieving PtL ambitions.

Substantial capital will be required to meet PtL demand – potentially, a cumulative total of $3–4 trillion between 2022 and 2050. Two-thirds of investments in PtL production are likely to be upstream renewable electricity capital costs, followed by investments in hydrogen-production capacity (15%), CO_2 capture (10%) and fuel synthesis (10%) (see Figure 15). This represents an indicative allocation of upfront capital requirements across the whole value chain for the PtL production route via low-temperature electrolysis and RWGS.

The capital intensity of PtL means investors will need to play a significant role in production expansion. Investment vehicles can be designed to allocate risk and returns across the value chain, such that renewable electricity and hydrogen are financed like traditional power agreements, while fuel production and associated marketing can earn potentially higher returns while assuming different risk profiles.

Each region will play a unique role in scaling PtL. In the near term, while DAC is still subscale, regions with high biogenic carbon will have an outsized role in supplying global PtL demand. Those with concentrated point-source emissions should act now to lock in access for PtL producers. Chile, Brazil and Uruguay, and regions in North America, Northern Europe and China, stand out as potential early adopters. New production needs to shift to regions with low-cost renewable electricity where direct air capture is most suited, at the latest by 2040. Parts of Asia, the Middle East and Africa, with few biogenic sources available, need to prioritize DAC investment to become long-term suppliers of PtL. In these regions, hydrogen and renewable electricity must be scaled to meet not only domestic needs but also overseas PtL demand to 2050.

FIGURE 15 **Two-thirds of capital investments in PtL are in renewable electricity generation**



Notes: 1 "CO_2 capture" includes estimated split between point source and direct air capture **2** "Fuel production" includes the final step, such as Fischer-Tropsch synthesis capex for PtL

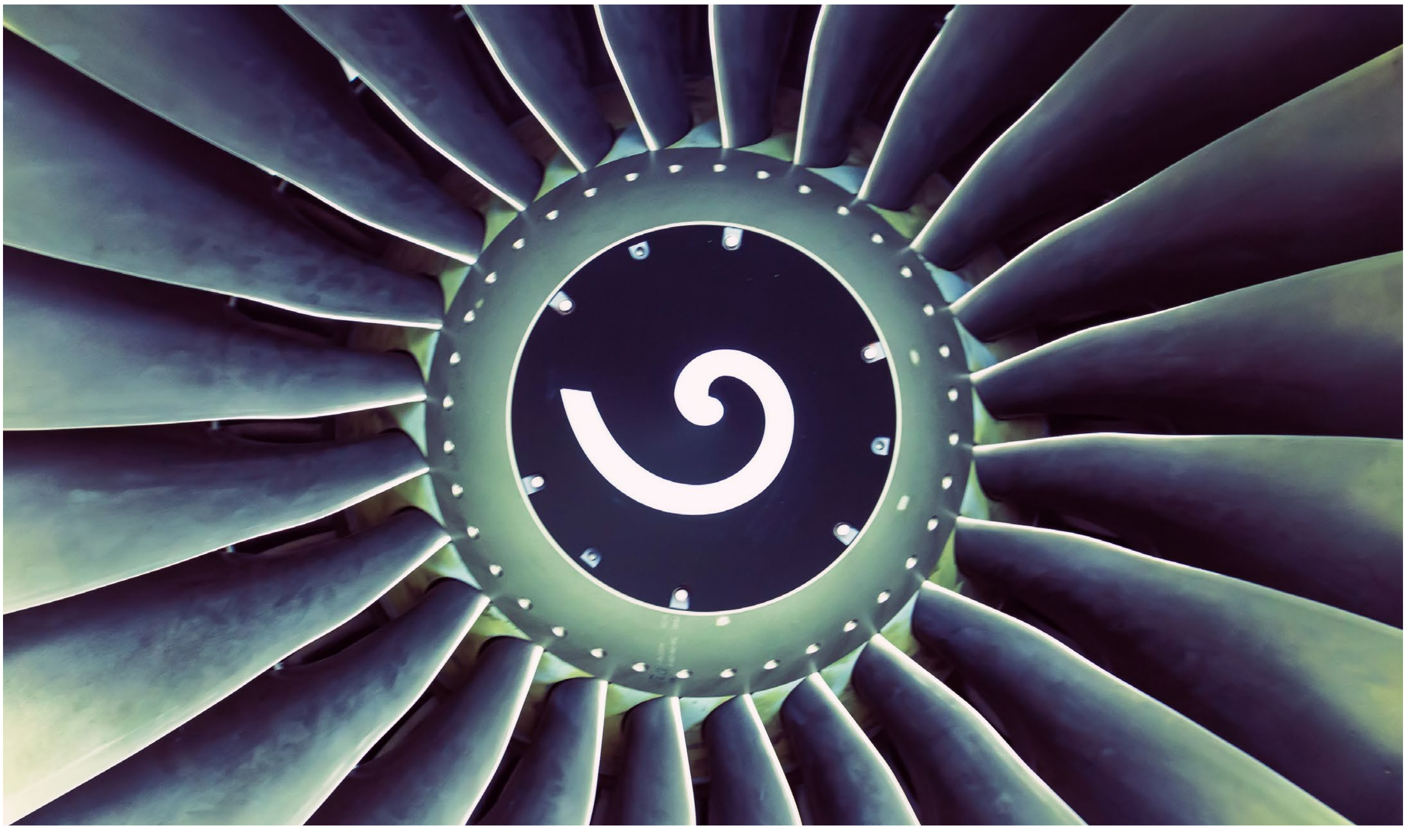
Source: Mission Possible Partnership provisional data

4 Recognizing the signposts of progress

Power-to-liquids must accelerate.

The two biggest priorities in scaling PtL are related to production inputs: lowering the cost of renewable hydrogen and collecting enough carbon (first from biogenic and industry point sources and eventually from DAC, to achieve near-zero net carbon emissions). Delivering on these two priorities will require large investments over decades, as noted, along with regulation to drive demand and provide incentives to expand production of the necessary inputs.

Development of PtL trade flows will determine how quickly each region adopts PtL. Given the likely constraints on renewable electricity generation buildout in developed economies, PtL adoption will require substantial investment in renewable-rich regions of the world. Ramping up PtL production in regions such as the Middle East, South America and Australia will require coordinated efforts among investors, regulators and companies with expertise along the value chain. Stakeholders will need to see clear demand and regulatory signals for SAF in Europe, for example, and in some regions specific demand for PtL, to de-risk investments. Producing countries can make land and other inputs available to consortiums of investors to speed the establishment of integrated PtL facilities. If this global supply chain matures quickly, PtL will become the majority source for aviation fuel.



4.1 The three most important milestones to PtL success

Three main milestones appear on the road to scaling PtL to the required volumes by 2050:

- Renewable electricity cost reductions of about 30% with additional scaling and efficiencies
- Wider commercial availability of high-efficiency PtL technology, such as SOEC, with cost reductions of about 50%
- Efficient DAC of carbon with cost reductions of 50–80%

These three milestones will have to be reached in almost any scenario where PtL plays a significant role in aviation decarbonization. Further renewable electricity cost reductions will be critical to enable PtL regardless of the technology pathway. Likewise, increasing the efficiency of the PtL pathway will help reduce the required installation of renewable electricity, thereby saving capital costs. Advances in DAC will also be vitally important if PtL is to achieve its full potential, especially in deserts and other areas without biogenic carbon sources.

Even with the aforementioned cost reductions along the PtL production chain, PtL, like other forms of SAF, will likely remain more expensive than conventional jet fuel in the decades to come. Thus, market-based interventions and policies that help bridge this cost differential will remain an essential parallel objective to see PtL and other forms of SAF scale in the orders of magnitude needed to reach net zero by 2050.

4.2 How stakeholders can support the scaling of PtL

Like overall sectoral decarbonization efforts, scaling up PtL will require resolute action and investment across the entire value chain. Technology, policy and market-based measures, as well as voluntary actions and commitments by the private sector, will all play important roles, as no single measure or actor will be able to reach the 2050 targets alone.

Regulators can contribute by clearly defining the energy and life-cycle carbon accounting by which PtL will be assessed. Treatment of fossil-based, biogenic and direct air capture carbon needs to be clarified in most climate regulations. Regulators need to set the right incentives so the limited supply of biogenic carbon, and in some cases renewable electricity, is used most efficiently to achieve decarbonization. They may also need to consider policies and regulations that directly help to bridge the price gap between SAF and traditional jet fuels. In some regions, PtL-specific policies may be useful; in others, market dynamics and feedstock availability may mean that general SAF policy will be sufficient to increase PtL production and demand. Additionally, common standards on PtL (both technical and accounting) must be incorporated within SAF certification frameworks. The treatment of CO_2 feedstock stands out as a uniquely PtL challenge that must be addressed for widescale adoption. (For broader SAF policy guidance, the CST SAF Policy toolkit aims to support governments and policy-makers as they develop and implement national strategies.[26])

Investors should recognize that regardless of which scenario unfolds, PtL will be part of the decarbonization landscape. Without it, it is unlikely that sectoral decarbonization by 2050 will be possible. Therefore, even in the absence of specific regulations mandating the use of PtL, investors should see the potential in this production pathway and work closely with industry to develop funding mechanisms to support market development. Investors could structure financing for PtL such that project risk is tiered, whereby construction of renewables such as wind and solar are financed with low-cost capital and the downstream fuel-synthesis facility takes on higher risk with higher-return investment profiles. Critically, developing first-of-a-kind PtL plants will be a necessary step to demonstrate success and scalability; it will take several years to move from demonstration to full-scale production. Producing enough volume to meet anticipated demand by 2030 (based on the prudent improvement and deployment of known technologies) would require 100–200 large-scale PtL facilities – up from zero at the moment.

Suppliers and producers need to increase cooperation across the value chain, bringing together renewable electricity and fuel production, distribution and marketing capabilities. Large standalone companies could try to do everything, from feedstock production to fuel production and commercialization, but they would require vast amounts of capital and could face operational challenges if they lack focus or expertise in specific areas. A process integrator could help specialized players – such as renewables developers and fuel marketers – collaborate and increase speed to market. Partnerships across regions will be critical: technology providers in developed economies will need to work closely with landowners, regulators and project developers in developing economies to build a global supply chain in PtL.

Customers need to signal willingness to purchase PtL. Many aircraft operators, airlines, corporate buyers and individuals have pledged their desire to fly without carbon emissions and accordingly invest in carbon offsetting schemes. With appropriate certification frameworks in place, consumers can indicate their desire for SAF regardless of its availability in their location. These demand signals may indicate the wish to purchase SAF more generally or PtL specifically, and can provide certainty to investors and producers alike.

TABLE 1 | **Among stakeholders, six potential cooperative steps can support the scale-up of PtL**

Potential cooperative steps to scale PtL	Examples today
Promote ecosystems: Regulators could work with airlines and other industries to fund technology development, expand renewable electricity and make it available for PtL production, among other vital uses. By supporting cooperation across industries, they could also help some players specialize in the most promising technologies.	Denmark's Climate Partnership for Aviation recommends creating a master plan for "Power-to-X" infrastructure to produce PtL for aviation, maritime and heavy transport.
Stimulate demand: Airlines and airports can craft long-term offtake agreements to support SAF and PtL production and benefit from declining costs	Air Canada and Carbon Engineering have joined forces to advance aviation decarbonization and create SAF for Air Canada consumption, including using Carbon Engineering's proprietary technology to produce PtL.
Reduce barriers to entry: Landowners can make areas available to co-locate PtL production facilities in low-cost energy locations.	Masdar, a leading renewable energy company, is working with TotalEnergies and Siemens Energy to produce SAF in a demonstrator plant in Masdar City, Abu Dhabi's sustainable urban development flagship.
Generate awareness: Airlines, governments and other stakeholders can educate the public and business community about the importance of scaling sustainable fuels from all pathways, including PtL, and the value of a diverse and global supply of sustainable aviation fuel.	A number of airlines offer passengers the option to purchase SAF directly during the booking process. Swiss/Lufthansa offers travellers the ability to buy SAF in amounts appropriate to their flight, regardless of the airline on which the traveller is flying. United Airlines offers travellers the option to make a donation to its SAF purchase programme.
Stimulate supply: To bolster supply, regulators can design mechanisms that guarantee demand for PtL fuels, thereby providing certainty to investors and producers to invest in first-of-a-kind facilities.	The European Commission ReFuelEU initiative proposes a PtL (RFNBO) sub-mandate to help overcome the high production costs and low technological maturity of PtL.
Support R&D: Governments can accelerate production by offering loan guarantees and tax exemptions and subsidizing PtL facility operations. They can also lead by supporting research to overcome barriers to PtL production.	Under the Biden administration, the US has launched the Sustainable Aviation Fuel Grand Challenge to reduce the cost and expand the production of SAF that cuts life-cycle GHG emissions in half compared to conventional fuel and meets 100% of aviation fuel demand by 2050. The programme offers grant funding for novel SAF pathways and establishes the government as a major consumer of SAF.

Next steps

To meet net-zero targets, the aviation industry, regulators, investors, suppliers and producers all need to take action.

Among the known SAF pathways, PtL is the least technically and commercially mature, but it offers the potential to provide more availability for airlines and consumers as its feedstocks are abundant in CO_2, hydrogen and renewable electricity. The major changes needed to scale PtL involve a combination of technology developments, supportive policies, market-based measures and private-sector initiatives. To support the significant contribution PtL needs to make to the net-zero target, the aviation industry, regulators, investors, suppliers and producers will need to address the following:

Feedstock availability

1. **Renewable electricity**: Stakeholders can help expand the global production of low-cost renewable electricity, which represents two-thirds of the capital cost of PtL. PtL is best produced in remote areas where land is sparsely populated and sunshine or wind is abundant. In these locations, production costs can be minimized and a global trade network created. International collaboration, appropriate policy design and investment will be critical to the success of these innovative facilities, and in the early stages partners can work together to help identify best practices to be incorporated in future production facilities.

2. **Hydrogen:** Hydrogen-production efficiency and scale are keys to PtL maturity. Industrialization of clean hydrogen is needed to serve many industries, including PtL. The scale of development required is unprecedented, but the necessary facilities can feasibly be developed in the next 5–10 years.

3. **CO_2:** Carbon capture technology, while commercially proven, has not yet been integrated in a full-scale fuel-synthesis facility. Investment and industrialization of DAC is needed for PtL to achieve its long-term potential.

Production facilities

4. **Fuel synthesis:** Demonstration plants are required to prove feasibility and optimize overall PtL design. Optimizing renewable electricity and hydrogen to provide a steady flow to fuel-synthesis units is a new concept. Technology innovation in fuel synthesis that can better integrate DAC and renewable electricity is needed to lower the overall system cost of PtL.

Market demand and pricing

5. **Commercialization of production:** Mature and liquid markets are critical not only for SAF but also for sustainable diesel and naphtha. In addition to airlines and airports, trucking fleets, maritime shippers and chemical companies can pledge their long-term support for PtL production to secure the market and improve investor confidence. Since PtL and other forms of SAF are likely to remain more expensive than conventional jet fuel, market-based interventions, government policies and green premiums will be necessary to bridge the price gap.

6. **Accounting for the true demand:** Robust life-cycle assessments and carbon-accounting frameworks are required that consider all aspects of PtL, from the generation of renewable electricity to the production of fuels. Aircraft operators and their customers can then record their sustainability impacts in a traceable and useable manner. This in turn enables more direct carbon offsetting within the aviation industry and clearer evidence of the demand for SAF, both in regions where it is readily available and in those in which supply chains will take longer to develop.

The world must begin the PtL journey now. With enough foresight and responsible planning, PtL could become a critical sustainable aviation fuel pathway to a cleaner world.

Contributors

World Economic Forum

Anne Carnall
Policy Lead, Clean Skies for Tomorrow

Adrienne Gibbs
Policy Lead, Clean Skies for Tomorrow

Lauren Uppink Calderwood
Head of Aviation, Travel and Tourism Industries

McKinsey & Company

Sarah Coupland
Associate Partner

Margret Dupslaff
Associate

Bernd Heid
Senior Partner

Nathan Lash
Associate Partner

Lexie Li
Business Analyst

Robin Riedel
Platform Fellow, World Economic Forum, Partner

Daniel Riefer
Associate Partner

Jonathan Steinbach
Engagement Manager

Antonia Watzinger
Fellow

Mission Possible Partnership

Maximilian Held
Aviation Lead, Energy Transitions Commission Consultant, Mission Possible Partnership

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Endnotes

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World Economic Forum
91–93 route de la Capite
CH-1223 Cologny/Geneva
Switzerland

Tel.: +41 (0) 22 869 1212
Fax: +41 (0) 22 786 2744
contact@weforum.org
www.weforum.org