Decarbonizing Aviation

A Climate Technology White Paper

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Decarbonizing aviation: an introduction

Introduction

Decarbonizing aviation

In this paper we show that there are some important and urgent challenges to decarbonizing aviation. Emissions from the aviation industry in 2019 were 1.06Gt, accounting for 2% of annual global CO_2 emissions. That number is set to increase to 2.05Gt in 2050.

Specifically, we analyze technology innovations, and the early-stage companies developing them. The paper contains the following sections:

1. **Low-emission propulsion technologies:** How can we produce fully low-emission planes in the future? Which technologies have the best potential use cases? (slides 10-22)
2. **Sustainable aviation fuels:** What methods can be used to produce SAFs? What needs to be done to bring the price down compared to conventional jet fuel? (slides 23-33)
3. **Optimization of operations and aircraft:** In what ways can we decrease aviation emissions today? What improvements can be made in aviation management and aircraft design? (slides 34-40)

This paper provides data and context on the challenges, evaluates some of the proposed innovations and suggests ways to overcome potential blockers. In the introduction, we explain why the challenge of decarbonizing aviation is important and unsolved, what makes a good technology and then highlight 65 companies leading the charge in these areas.

BNEF Pioneers: hunting for innovation

This is one of three reports to be published following the 2022 BNEF Pioneers awards.

BloombergNEF's annual Pioneers competition identifies and recognizes innovators developing new technologies to tackle some of the most important challenges in the fight against climate change.

Each year, the Pioneers competition focuses on three innovation challenges.

For the 2022 program the challenges were:

1. Providing round-the-clock zero-emissions power (research note available **here**)
2. Scaling long-term carbon removal technologies (research note available **here**)
3. **Decarbonizing aviation (the focus of this research note)**

For more information about the Pioneers competition, please visit https://about.bnef.com/bnefpioneers/

Why did BNEF choose decarbonizing aviation as a challenge for this year's Pioneers?

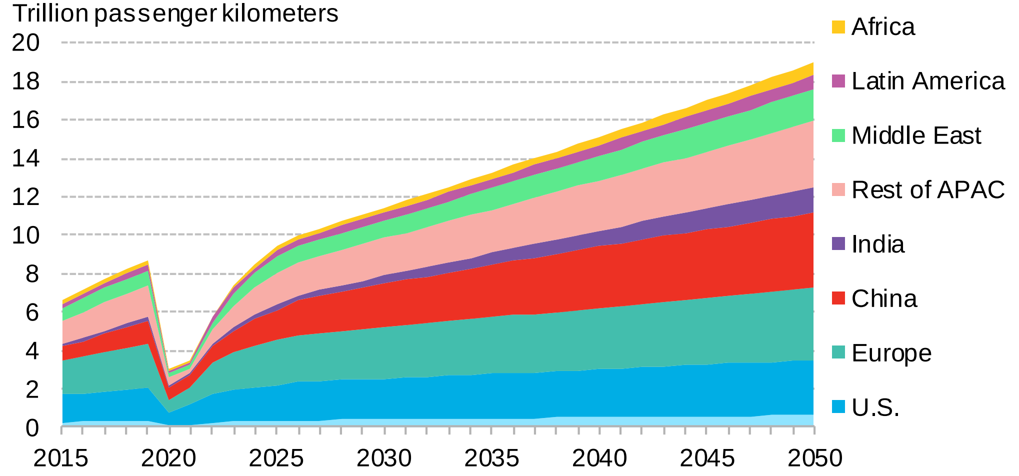
Aviation is perhaps the hardest transport sector to decarbonize. The industry body, IATA, has a target to reach net-zero emissions by 2050, but there are currently no commercially available methods to do this. In 2019 the sector produced around 1Gt of CO_2e, accounting for 2% of annual global CO_2 emissions.

As air travel becomes more affordable for an increasing share of the world's population, BNEF predicts demand for air miles is set to more than double between 2019 and 2050. Pre-Covid, in 2019, the aviation sector consumed almost 8% of oil products globally, equivalent to 7 million barrels a day. This is predicted to rise to 13.9 million by 2050, similar to China's total oil consumption in 2021.

Aviation is a high-polluting and hard-to-abate sector for a number of reasons. These include: stringent regulations for aircraft, making implementation of new low-emission technologies extremely difficult; alternative low-carbon fuels are expensive; and slim airline profit margins leave little room for airlines to pay green premiums. Because of this, and the rapidly increasing demand for aviation, strong investment into potential decarbonization technologies must happen now. The IATA has set a goal for the aviation industry to reach net-zero emissions by 2050.

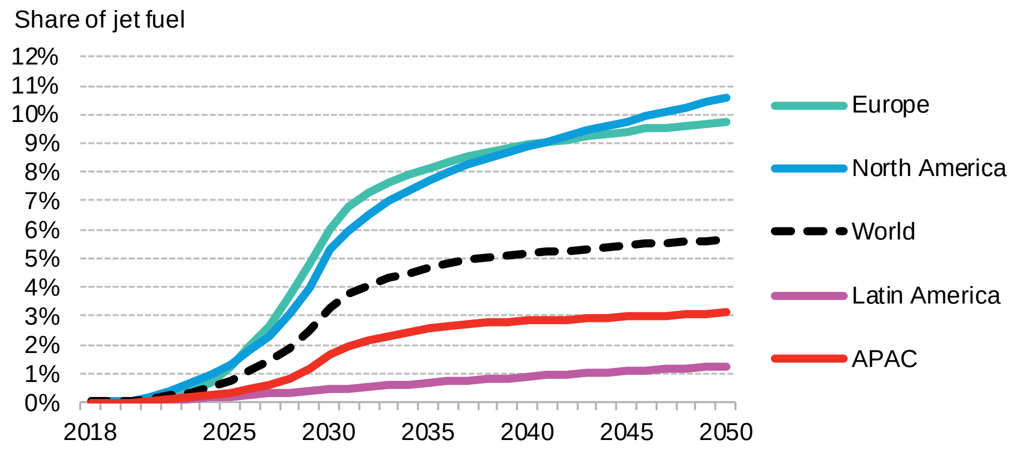
While there is no one obvious route to decarbonization, many technology options exist, each serving different parts of the aviation sector. This report highlights these key technologies, and profiles the most important technology developers working on them. As one of the most difficult industries to decarbonize, a combination of many different technologies will likely be implemented, depending on the specific use cases.

Passenger demand by region, 2015-2050



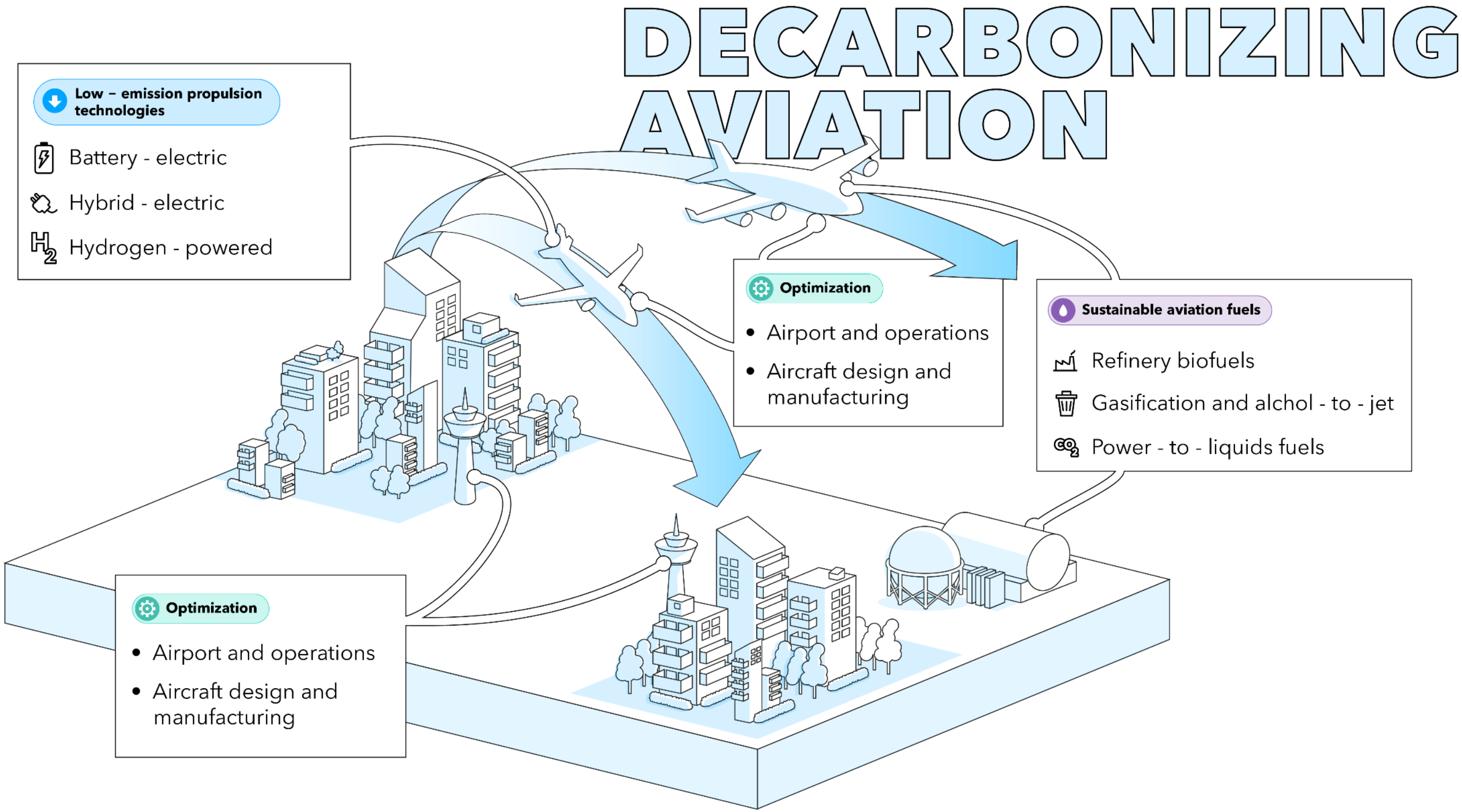
Source: ICAO, World Bank, BloombergNEF

Sustainable aviation fuel consumption by region, 2018-2050



Source: IEA, BloombergNEF

Overview of technologies covered in this note



Source: BloombergNEF

Innovation map of aviation decarbonization technologies

Low-emissions propulsion technologies

Battery-electric propulsion

Electric-aircraft manufacturers

Heart Aerospace, H55, Wright, Eviation, Bye Aerospace

System elements

Addionics, H3X, Sion Power, Group14, Magnix, Sila, StoreDot, Sylphaero

Hybrid-electric propulsion

Ampaire, Rolls-Royce, Pipistrel, Hybrid Air Vehicles, Faradair

Hydrogen-powered propulsion

Hydrogen-aircraft manufacturers

APUS Zero Emission, ZeroAvia, Airbus

System elements

PowerCell, GTL, hypoint, Universal Hydrogen, Kubagen

Sustainable aviation fuels

Refinery biofuels

Neste, World Energy, bp, OMV, TotalEnergies, Renewable Energy Group

Gasification and alcohol-to-jet

Gasification

Enerkem, Fulcrum Bioenergy, Inentec

Alcohol-to-jet

LanzaTech, LanzaJet, Gevo, Byogy Renewables

Power-to-liquids fuels

Prometheus, Twelve, SeeO2 Energy, Synhelion, Arcadia eFuels, NCF New CO2 Fuels, Sunfire, Carbon Engineering, Dimensional Energy

Optimizing operations and aircraft

Airport and operations

Flight operations

Skygrid, Signol, Airspace Intelligence

Ground operations

AirExpert, Cargometer, Moonware, i6 Group

Aircraft design and manufacturing

Aircraft

BASF, cfm, Rolls-Royce, Pratt & Whitney, Lufthansa, GE

Manufacturing

iComat, Supercool Metals, 9T Labs, Productive Machines, Veelo Technologies

Source: BloombergNEF

What makes a technology good for decarbonizing aviation?

The table below scores various decarbonizing aviation technologies described in this note across the following metrics:

Energy density: The energy density of fuels is key for aviation, as aircraft must carry their own weight into the air, and then stay aloft. Range and payload severely decrease with fuel density decreases for aircraft, compared with ground vehicles.

Power density: Aircraft take-off requires a significant amount of energy in a very short time. For electric motors this is an issue because power density decreases with size. For new propulsion technologies, it is essential to increase power density to decarbonize longer-haul aviation.

Cost: The cost of each technology varies largely. Some are still extremely expensive, and will require significant investment to become cost competitive with standard jet fuel. Generally, the higher the current cost of the approach the higher its emissions savings potential when at scale.

Current scale: Establishing how scaled up the technology is, what effect it is having currently and how far implemented it is into the current aviation market.

Implementation time: Clarifying how long each technology is going to take to be used regularly in the aviation market. Some technologies can be easily implemented soon after investment, while others will take decades to be used in the aviation industry.

Emissions savings potential: The potential emissions savings that the technologies represent if they were to be used at their maximum theoretical capacity.

Qualitative ranking of decarbonizing aviation technologies described in this report

		Energy density	Power density	Cost	Current scale	Implementation time	Emission savings potential
Low-emission propulsion technologies	Battery-electric propulsion						
	Hybrid-electric propulsion						
	Hydrogen-powered propulsion						
Sustainable aviation fuels	Biofuel refineries						
	Gasification and alcohol-to-jet						
	Power-to-liquids						
Optimization of operations and aircraft	Airport and operations	N/A	N/A				
	Aircraft design and manufacturing	N/A	N/A				

Source: BloombergNEF. Note: Darker green indicate solution performs better on this metric. Ratings are qualitative relative to others.

BNEF Pioneers 2022 winners

Challenge 3: Decarbonizing aviation

Twelve transforms captured CO2 into critical chemicals, which can be made into materials and fuels, using a patented CO2 PEM electrolyzer

ZeroAvia designs and develops zero-emission, hydrogen-electric aviation powertrains, targeting a 500-mile range in 10–20 seat aircraft

For more information on this year's winners please see *Climate-Tech Startups to Watch in 2022: BNEF Pioneers Winners*

Technology challenges

Routes to decarbonizing aviation

Low-emission propulsion technologies

Low-emission propulsion technologies

Low-emission flight technologies refer to new forms of aircraft propulsion, paired with low-carbon energy sources. These include battery-electric, hybrid-electric and hydrogen-powered propulsion systems. They are all nascent technologies, with low gravimetric and volumetric energy densities when stored, and may require a re-design to extend range. This also means short-haul flight (<500km) is the most obvious sector for them to decarbonize in the near to medium term, but these only comprise 6% of passenger aircraft emissions. New systems like these require significant time to be certified. Because planes have a 30-year operating life, the implementation process will likely be long.

What is it?

Low-emissions flight technology refers to aviation drivetrains that incorporate new propulsion methods and energy sources. These are battery-electric, hybrid-electric and hydrogen-powered propulsion. They are preferable environmentally over fossil fuels as they emit fewer CO_2 emissions in flight, although they require the use of rare or expensive metals. Low-emissions flight technologies have long-term decarbonization potential if the correct fuels are used, i.e. renewable electricity and green hydrogen; however, due to various technological limitations, wide-scale implementation of the technologies is likely decades away. To date, only maiden flights or ground tests with these technologies have been made. There is still debate over technology options and configurations, meaning many variations of electric, hybrid and hydrogen planes will compete before any emerge as winners.

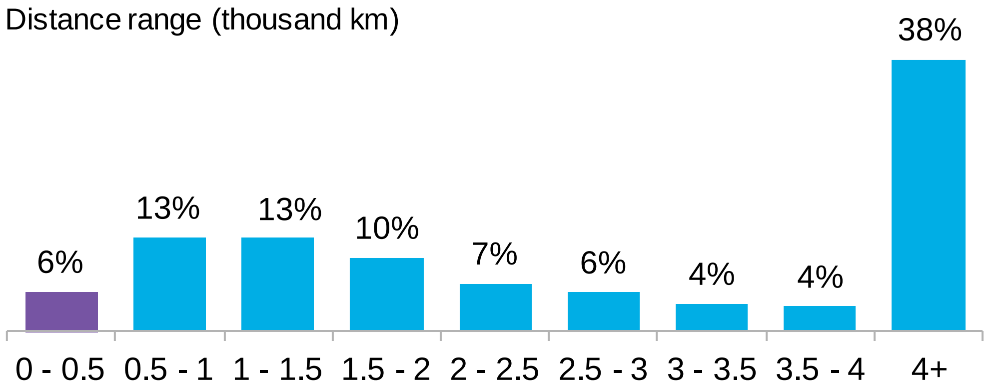
What should we tackle first?

The best use cases for these technologies currently are short-haul flights (mostly <500km) due to the low volumetric and gravimetric energy densities of battery − and hydrogen − energy storage, although technology developers plan to scale to long-haul in the future. Innovation should focus on optimizing efficient fuel storage (within lithium-ion batteries or hydrogen tanks), both by volume and weight. Improving power density is also essential for allowing scale-up of these technologies to heavier longer-haul aviation. Building refueling infrastructure is essential to supply green renewable electricity and hydrogen to aircraft safely and effectively.

Why is it difficult to solve?

Low-emission aviation technologies have larger and heavier drivetrains than conventional aircraft, and lower fuel-specific energy and power density. Alterations to plane design and systems architecture will be required to enable safe and effective flight. This makes retro-fitting aircraft difficult, and limits range/payload of an aircraft. Aviation regulations are incredibly stringent compared to other transport industries, and aircraft lifetimes are up to 30 years. Adoption and integration of new aircraft is therefore slow. Comparing economics is difficult as there is no commercially available low-emission aircraft. Some developers claim battery-electric aircraft could have lower opex than conventional planes, as proven in EVs versus ICE cars, though little to no data exists for aircraft.

Percentage of passenger aircraft CO_2 emissions by flight distance



Source: BloombergNEF

Battery-electric propulsion

Battery-electric aviation, while still nascent, has already gained significant investment. The main expertise of most electric aircraft companies is in electric powertrain assembly and plane re-design, using pre-bought individual elements for the system. Some companies however focus on specific aspects, such as increasing battery gravimetric energy density, or electric motor power density, both of which must increase 4x in order to electrify heavier aircraft. Necessary plane re-design, and low performance metrics for battery-electric systems, mean certification of new electric aircraft is hard to acquire, and new systems are expensive. Battery technology breakthroughs within ground transport, and the growth of electric-powered short-haul flight, could increase investment into long-haul electric flight.

New approaches and technologies

New aircraft configurations: These are key to electric aircraft becoming viable. Putting a powertrain together efficiently, in limited space, is important (rather than improving individual elements themselves, though these are still important).

High power density electric motors (HPDMs): For longer-haul flights, electric motors need to be >12kW/kg, as stated by ARPA-E for a Boeing 737. For this, we need new motor materials and architectures.

Battery innovation: For electric aircraft, increasing the gravimetric energy density of batteries, at 250Wh/kg currently, is essential. Around 1,000Wh/kg is needed for near-jet-fuel parity. This could be done through multiple innovations, including silicon /lithium anodes, solid-state electrolyte, etc.

New electric propulsion methods: Current research includes a focus on electric plasma jets, though it is still extremely early stage.

Limitations

Expensive custom design/capex: Custom aircraft designs with no manufacturing line will be expensive, and will have to be certified to be approved for flight. Combining this with expensive batteries gives electric planes a significant capex.

Electric motor inefficiencies: To create HDPM motors, extremely high currents are required. Alongside large amounts of copper, new expensive superconducting materials are needed to cope with these high currents. Advanced thermal insulation materials and thermal management systems are required as large amounts of waste heat will be generated throughout the motor.

Safety of new batteries: There are still safety concerns with battery technologies: lithium anodes have dendrite growth during cycling, there are problems using common electrolytes; and silicon anodes have significant volume expansion during cycling.

Potential solutions

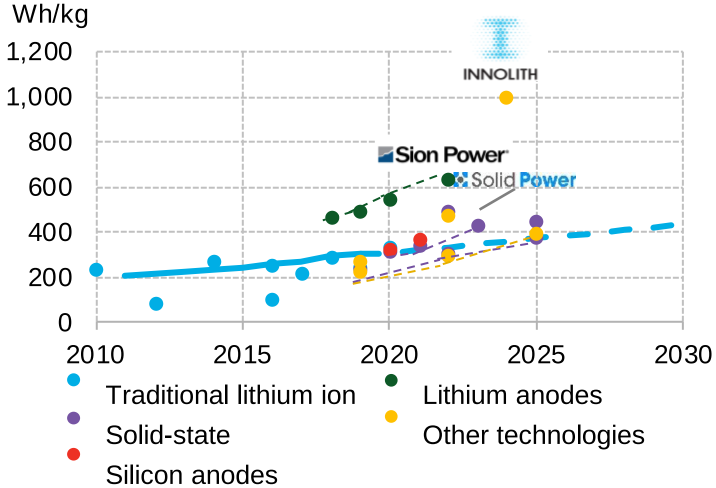
Use of electric aircraft for short haul: Proving the technology for higher value, short trips should help scale electric flight

Standardized plane re-design: The benefit of having to re-design planes is that there can be aerodynamic/efficiency improvements

Proving electric aircraft opex is low cost: As fuel prices rise, lower opex for electric flight could offset the high capex of electric aircraft.

New battery technology use in ground EVs: This will push investment into high energy density batteries increasing their safety, allowing quicker certification in aviation.

Battery cell gravimetric energy density



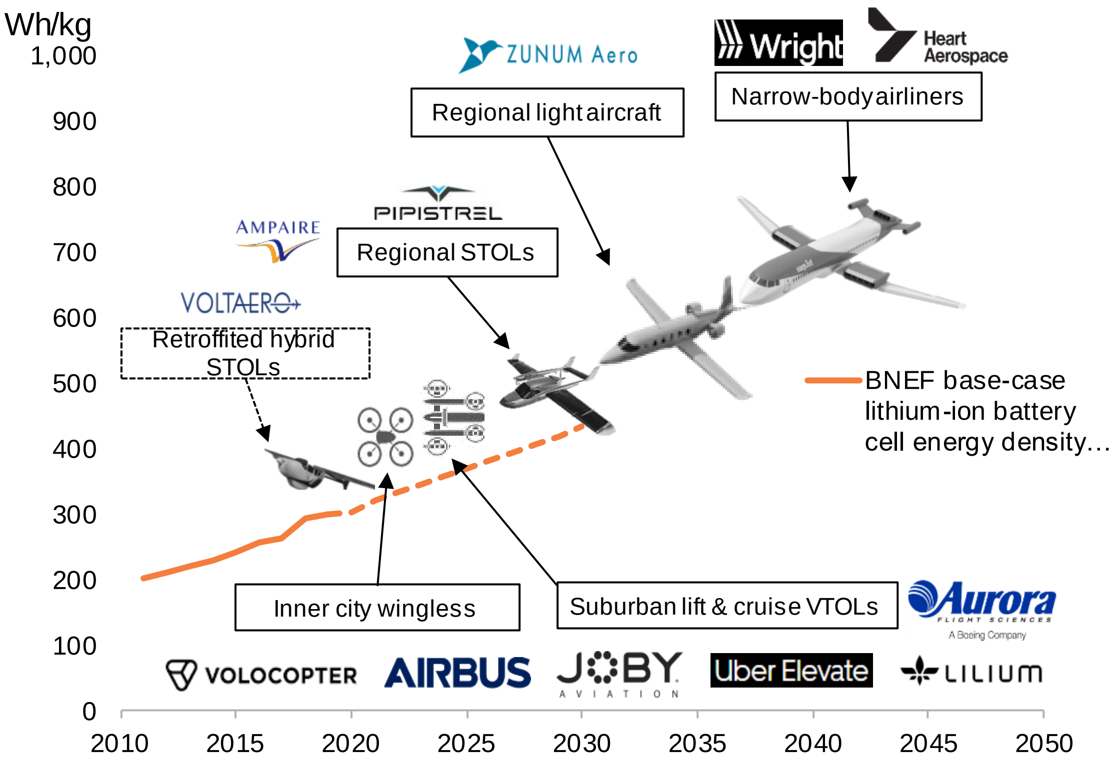
Source: BloombergNEF, public announcements, company interviews. Note: The blue line denotes observed battery cell energy density and forecasted likely energy density development for conventional lithium-ion.

Battery-electric propulsion

Electric aircraft manufacturers

	How does it work?	Maturity
Heart Aerospace	Heart Aerospace is an electric aircraft manufacturing company, aiming to build its electric ES-19 aircraft. As with most electric aircraft companies, its expertise is in assembling electric powertrains for aircraft, rather than innovation in any particular parts. For Heart Aerospace this is its e-drive system. The ES-19 will be a 19-passenger aircraft, have an operating range of 400km with today’s lithium batteries, and a power output of 4x400kW motors. It will be able to use runways of 750m, so can target cheaper regional airports.	Heart completed a Series A round in 2021, raising $35 million. Notable investors include United Airlines Ventures, Mesa Air Group and Breakthrough Energy Ventures. The ES-19 is scheduled to enter service in 2026. United Airlines and Mesa Airlines have made a provisional order for 200 ES-19 aircraft with an option to buy 100 more at a later date.
EVIATION	Eviation is an electric aircraft manufacturing company, aiming to build its electric Alice aircraft. Its expertise is in assembling all electric powertrains for aircraft. The Alice will carry 9 passengers, have an operating range of 815km using currently available batteries, and will use two MagniX 640kW electric motors. It will have a take-off distance of 800m and so can target cheaper regional airports.	Eviation was founded in 2015 and went public via IPO in 2017. It plans to conduct Alice’s first flight in 2022, expecting FAA certification in 2024. In 2019, it said it had a backlog of more than 150 orders from customers including Cape Air, though it has not commented on where its order book stands now.

Battery cell energy densities to enable different electric aircraft



Source: BloombergNEF, Roland Berger, companies. Note: Zunum Aero discontinued its operations in 2019

Battery-electric propulsion

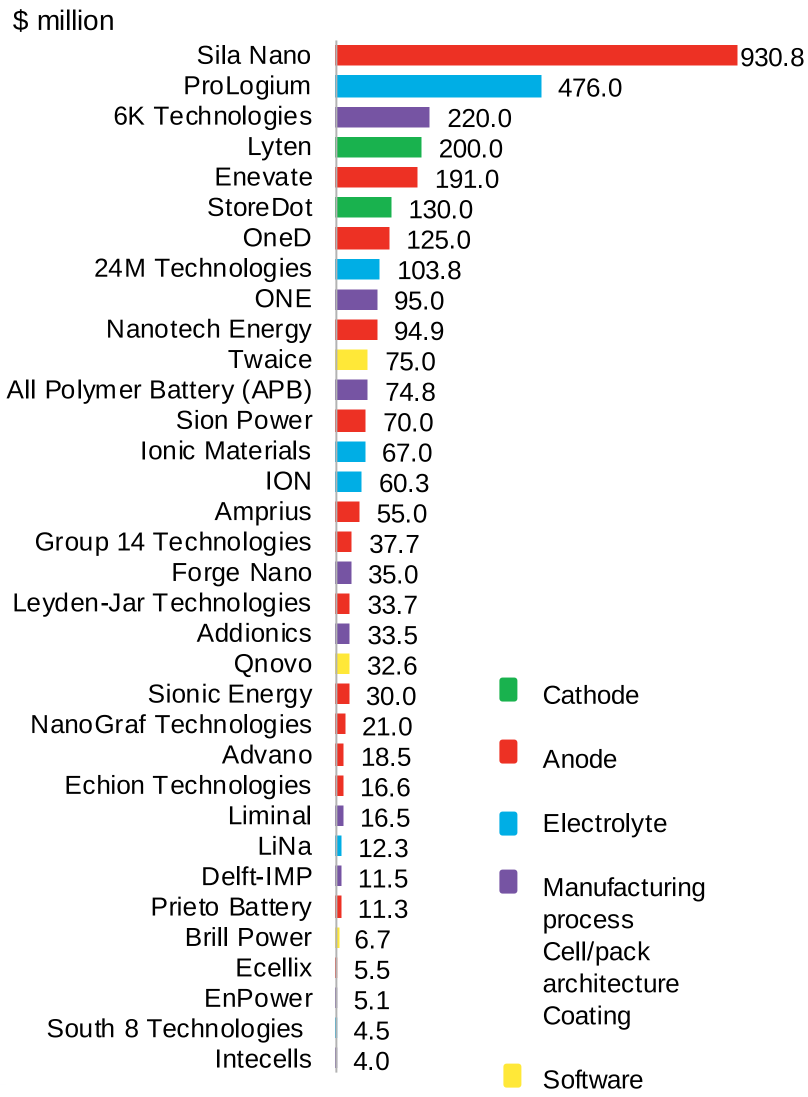
		How does it work?	Maturity
Electric motor manufacturers	magniX	MagniX is the largest electromagnetic motor manufacturer for aircraft, also developing whole electric propulsion systems for commercial aviation. It produces electric motor systems with 170kW, 350kW and 640kW max power outputs at around 4-5kW/kg electromagnetic motor power density – good for heavier electric motors. MagniX has multiple proven projects.	MagniX, founded in 2007, is one of the main frontrunners in electric aviation motors. It has notable partners and projects, such as the world's first all-electric commercially focused aircraft in Canada in 2019, a Cessna in 2020, and has been selected by NASA to help rapidly electrify aviation. The NASA grant was $74.3 million. It also has an upcoming project with Universal Hydrogen's 40-60 seater, 625-mile range, hydrogen aircraft.
Electric motor manufacturers	H3X	H3X claims to have developed an electric motor called the HDPM-250 that produces 13kW/kg, which would enable electrification of mid- to long-haul electric flight, according to ARPA-E. This is one of the highest power densities claimed for aviation electric motors. The increased performance is due to a 3D printed cooling jacket, new stator coils that offer a 40% increase in continuous maximum power density, and optimized electromagnetics system architecture. If its power density for its electric motor is proved it will be a large step toward electrifying heavier commercial aircraft.	H3X, founded in 2020, is still in its early stages. It raised $3.8 million in a 2021 seed round led by Metaplanet. It claims to have closed $105 million in LOIs in the first half of 2021. The seed round money will be used to expand and test the prototype and move into a headquarters facility.
Electric motor manufacturers	Wright	Wright Electric's key technology is the Wright Motor, which claims 2MW propulsive power per motor and a 10kW/kg power density, higher in general than standard aviation electric motors. It plans to retrofit older BAe 146 regional jets to make the Wright Spirit, a 100-passenger airliner for one-hour flights, using its megawatt-class propulsion system. Its electric motor system is claimed to be scalable from 500kW to 4MW for different applications. The aim is to one day scale to a 20MW aircraft, as powerful as an A320 Airbus, for its Wright 1.	Wright Electric was founded in 2016. It plans to have the fully electric Wright Spirit retrofitted regional jet enter in service in 2026 - planning to electrify only a portion of the engines in a retrofitted jet until this point.
Electric plasma jets	SYLPHAERO	Sylphaero is attempting development of a new technology for aviation − the electric plasma jet engine. Other electric aviation companies attempt to rotate a propeller using an electromagnetic motor, whereas Sylphaero attempts to create thrust by using electric current to create a plasma from the air. It claims that electromagnetic motors will be inefficient at the higher speeds and power densities necessary for heavier aircraft, whereas electric plasma jets could theoretically solve this problem. Electric plasma engines have a high potential but are still only a concept.	Sylphaero is still pre-proof of concept and as such is at a very early stage. No funding information is public.

It should be noted that there is an inverse relationship between an electromagnetic motor's weight, and its power density, thus having large powerful electromagnetic motors for planes with high power densities is a significant challenge, and a large part of the reason why small aircraft are being targeted by electrification first. Average power densities for smaller car electric motors are significantly higher than for heavy commercial transport.

Battery-electric propulsion

Batteries		How does it work?	Maturity
	Sion Power	Sion Power makes lithium metal anodes, allowing for significantly higher energy density than traditional graphite anodes. It is designing batteries to store 490 Wh/kg at cell level, with targets to eventually reach up to around 610 Wh/kg. It has mentioned both EVs and aviation as target areas. Its batteries are used in UAVs, and it is targeting eVTOL as well. While lithium dendrite formation (causing battery fires) is always a potential problem, lithium metal anodes have a much higher risk potential. Sion Power claims to have leading lithium-anode dendrite-resistant cells.	Sion Power was founded in 1989 as a spin-off from Brookhaven National Laboratory. It raised $50 million in 2011 from BASF. In 2021 it announced it would participate in a multi-year program to develop large-format lithium metal battery cells for use in Cummins battery packs. Other funding since 2011 has not been disclosed.
	ADDIONICS	Addionics has designed a manufacturing method for a 3D electrode structure (anode and cathode), made of metal, that is able to hold the active material throughout the structure. This produces a battery cell with many benefits over traditional 2D electrode cells – including better energy density, lifetime and cost, which fit well with aviation battery requirements. The 3D electrode is able to drop into the usual battery cell assembly line and is compatible with any existing chemistry (plus silicon and solid state). The company was started by founders originally researching the cause of hazardous explosions in batteries as part of academic research at the Imperial College London.	Addionics was founded in 2018, and has raised $33.5 million to date. It recently raised $27 million of this as part of a Series A led by Deep Insight, with other investors including Novelis and JX Nippon Mining and Metals. It is collaborating with Saint-Gobain to develop next generation solid-state lithium-ion batteries.

Total VC/PE and grant funding by battery start-ups, April 2022



Source: BloombergNEF, company statements, CB insights

Hybrid-electric propulsion

Hybrid-electric systems – that run on both electricity and liquid fuels – are a promising technology for decarbonizing aviation compared with other new low-emissions systems. They can allow for large emissions decreases, especially if the fuel used is SAF, while maintaining higher energy and power densities compared with more nascent battery-electric and hydrogen-electric systems. Hybrid systems can be in series or parallel architectures, each with their own benefits and shortcomings, the main of which is the complex systems management involved. Hybrid systems have a greater potential, at least in the short term, to be used in large aircraft, compared to battery-electric and hydrogen-electric.

New approaches and technologies

Series and parallel hybrid architecture: These are the two main architectures being researched for joint-propulsion hybrid planes. Series uses an ICE for additional electricity generation, whereas parallel has two independent drive systems, ICE and battery-electric, that can be coupled to the propeller.

Dual-use of SAFs and electric systems: This approach has aircraft with some standard jet engines, running on SAFs, and some replaced with electric engines. This decreases emissions while still maintaining better performance metrics than pure battery-electric systems.

Easier retrofit of current aircraft: Due to the increased power and energy density of hybrid-electric systems, compared with battery-electric and hydrogen-electric systems, retrofit is significantly easier, which also gives more potential to decarbonize longer-haul aircraft.

Limitations

Increased complexity of powertrain: This is compared with pure electric or jet fuel power systems, due to integration of two different power sources and hybrid systems control. Parallel architecture is more complicated than series.

Series architecture energy conversion: Jet fuel is converted to electricity in the series architecture, giving poor energy efficiency

Increased weight of parallel architecture: Due to the need for two fully separate drivetrains in parallel architecture, parallel systems have increased weight over series architecture systems - not ideal for aviation

Hybrid-electric systems still emit CO2 in flight: Because SAF is expensive and in limited supply, for now it is more likely that hybrid-electric planes will partially run on fossil fuels, making them lower emission but not zero emission.

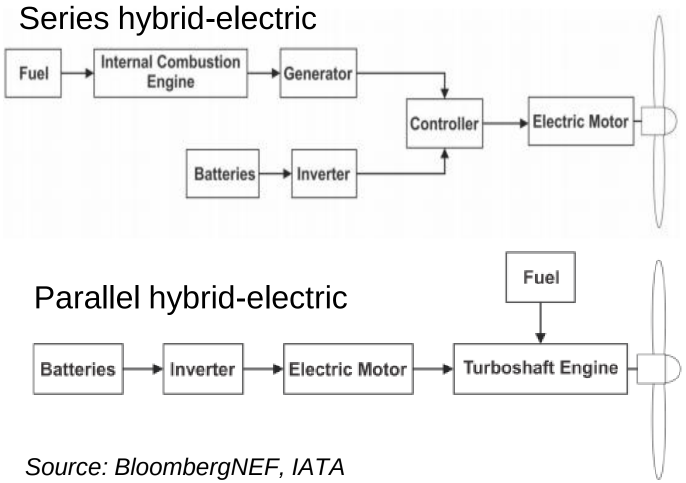
Potential solutions

Ground hybrid systems and management research: Significant ground hybrid power systems research can be applied to aviation, increasing rate of adoption and cost decreases

Hybrid-electric could pair well with SAFs: SAFs are 2.5-8x more expensive than conventional jet fuel, so fueling all jet planes with them is unlikely in the medium term. Using SAF in hybrid-electric flight could be a good way to help scale SAF use. Non-cruise parts of flights use around 30% of a flight's fuel (for flights <1,000km).

Fast hybrid adoption in short haul: Adoption of hybrid systems for short-haul flights may be faster than for pure electric or hydrogen planes. This may enable a route for hybrid systems to scale earlier in long-haul flight use.

Series and parallel architecture



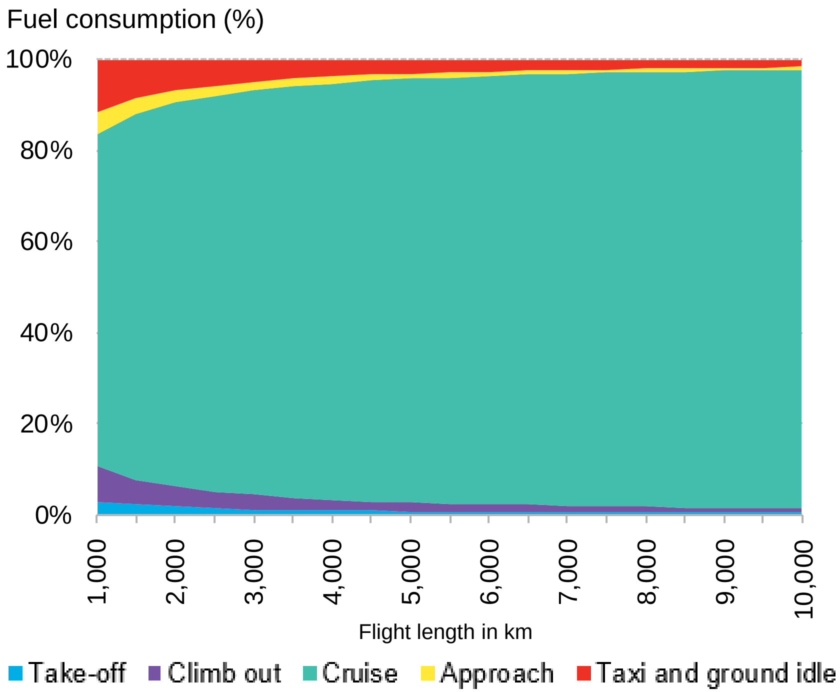
Source: BloombergNEF, IATA

Hybrid-electric propulsion

Hybrid-electric aircraft manufacturers

	How does it work?	Maturity
AMPAIRE	Ampaire is a hybrid-electric aircraft manufacturer. Its operational aircraft is the Electric EEL, a hybrid-electric retrofitted three passenger Cessna 337, with 640km range. Its Eco Otter SX is the next vehicle, also hybrid-electric. It then plans to create the Tailwind, a fully electric aircraft. From this it seems that hybrid-electric is being utilized to improve iterations of electric propulsion system design before fully implementing electric propulsion systems.	Ampaire was founded in 2016, and was acquired in early 2021 by Surf Air, a subscription-based airline with services in California, Texas and Europe. Its hybrid-electric aircraft, the electric EEL, made its first flight in 2019. It has received funding from NASA among other notable investors.
faradair	Faradair is creating an 18-seater hybrid electric plane, though aims to offer an all-electric variant of its bio-electric hybrid aircraft (BEHA). The BEHA will use a 1,600hp turboprop engine capable of both conventional jet fuel or biofuel use, and a 500kW electric motor to be used strategically to reduce fuel burn. This likely means use for non-cruise parts of flights.	Faradair was founded in 2014. Little public funding information is available. The maiden voyage of its BEHA hybrid-electric plane is planned for 2024, with the all-electric variant to come after.

Jet fuel consumption share by flight phase and by distance



As seen here, the shorter the flight the more significant the fuel consumption of the non-cruise parts of the journey. Electrifying non-cruise elements of flight provides more significant decarbonization for short-haul flights (around 30%) rather than for long-haul (around 15%), thus hybrid electrification targets short-haul first.

Source: ICAO, BloombergNEF. Note: Data for B787-9 with Trent 1000-AE3 engines were used. The analysis assumed 42 seconds for take-off, 132 seconds for climb out, 240 seconds for approach, and 1,560 seconds for taxi and ground idle. The actual fuel consumption by phase varies by flight, but its trend is similar to this chart.

Hybrid-electric propulsion

How does it work?

Maturity

Airships

Hybrid Air Vehicles (HAV) is planning to use hybrid-electric propulsion systems to propel its Airlander airship vehicles in the future. Its Airlander 10 will originally use four pure combustion engines in its base configuration, with electric motors in a hybrid-electric configuration to be implemented from 2025, and a 100% all-electric configuration in service from 2030. HAV claims the airships with hybrid-electric and all-electric propulsion systems will reduce emissions by 90% and 100% compared with other regional aircraft. The Airlander 10 will transport up to 100 passengers, with a range of 750km.

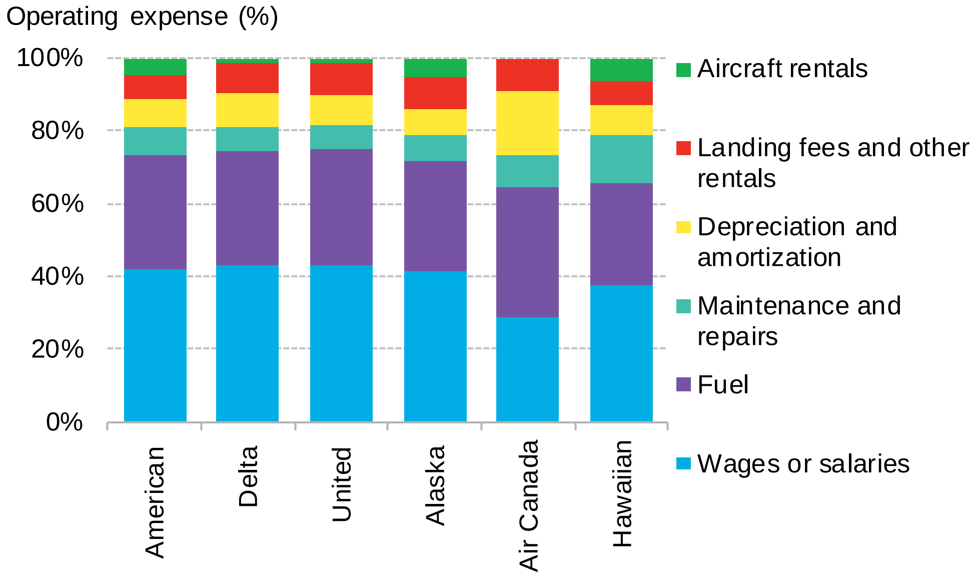
HAV was founded in 2007 and has raised almost $20 million to date. The majority of this funding came in 2015. In 2020, HAV received a $2 million grant from the UK government. It is in collaboration with Air Nostrum as a development partner of its Airlander 10.

Hybrid-electric drivetrain

Rolls Royce is trying to develop a hybrid-electric 2.5MW Power Generation System 1 (PGS1). The PGS1 started testing in around November 2021, and reached a milestone of 1MW output after a couple of weeks. The system is aimed at powering regional aircraft operations currently, however Rolls-Royce has stated that in the long term it believes it can be used to partially electrify larger aircraft propulsion systems to decrease emissions, as well as have ground applications. The PGS1 will provide a technology basis for future hybrid Rolls Royce aircraft.

Rolls-Royce is one of the largest industrial technology companies in the world, founded in 1884 and publicly traded. It operates in four segments, one of which is aerospace. The PGS1 is supported by the UK Aerospace Technology Institute's Megaflight project and the EU Clean Sky 2 program.

Operating expense breakdown for selected airlines in North America, 2019



Source: Bloomberg Intelligence, BloombergNEF

Fuel is 25-30% of airline costs, thus electrifying large energy-intensive portions of a flight (with electricity claimed to be cheaper than fuel for aircraft by some electric aircraft companies) can save operational costs.

Hydrogen-powered propulsion

Hydrogen propulsion can be either fuel-cell electric or hydrogen combustion powered by modified engines. The latter allows for easier adoption through current engine adaptation. Hydrogen has high gravimetric energy density, 60 times more than batteries pre-storage, but low volumetric energy density, so requires significant plane re-design. Hydrogen powertrains also have low power densities compared to battery-electric systems. Fuel cell innovations and new forms of hydrogen storage could negate this. Low-emission green hydrogen is also expensive – currently $5-8/kg. More established electrolyzer supply chains, and falling renewable energy prices, can decrease hydrogen costs. Localized hydrogen production can also avoid high hydrogen transport costs due to lack of hydrogen infrastructure.

New approaches and technologies

New aircraft configurations: These are essential for hydrogen aviation, as hydrogen has a high gravimetric energy density, 60 times more than batteries pre-storage, but has extremely low volumetric energy density.

Hydrogen systems' gravimetric power density: Fuel cell innovations can eventually increase system power density, up to 4kW/kg from 1kW/kg, by decreasing weight of the fuel cell by up to 60%, using turbo air-cooling.

New hydrogen storage methods: These will allow for increased volumetric density of hydrogen, such as metal-organic frameworks (MOFs) which could allow for a 4-5x increase.

Electrolyzer innovations: These could increase efficiency/decrease cost of green hydrogen, though they are far from scaled.

Hydrogen combustion engines: These can allow for quick hydrogen use using modified current jet engines running on hydrogen gas.

Limitations

Expensive custom designs/capex: While custom aircraft designs for hydrogen are also a big issue, other main limitations include use of extremely expensive platinum in hydrogen systems, along with more required system elements compared with full electric systems.

Volume of air-cooled fuel cells: While air-cooling decreases mass significantly compared with liquid systems, the cooling efficiency is much lower meaning that volume of the fuel cell is much larger. Significant energy is also required to pressurize air for air-cooled systems.

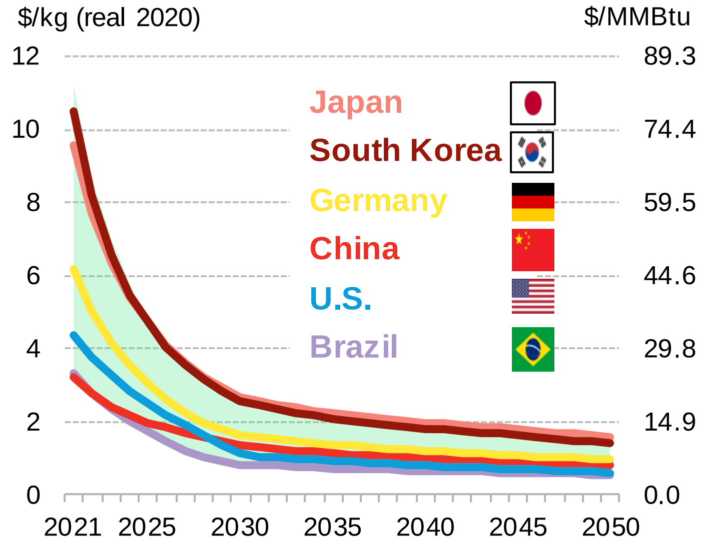
Untested MOFs: While MOFs hold great potential, many are still theoretical and their properties have been determined via simulation. Those that have been tested have a number of issues to fix, with research efforts going toward structure stability/pore collapse and complete solvent removal from the material.

Potential solutions

Research into non-precious metal catalysts: Replacement of platinum catalysts will bring hydrogen system costs down, with researchers looking into catalysts such as nitrogen-doped carbon-coated nickel anodes for use instead.

Scale-up and adoption of hydrogen: Use of hydrogen in other areas, e.g. ground transport, industrial, etc will create a more mature supply chain for electrolyzers, driving down costs. BNEF predicts rapid cost decreases until 2030, approaching cost-parity with natural gas per MMBtu around 2050 (See chart below).

Levelized cost of hydrogen production from renewable electricity, 2021-2050



Source: BloombergNEF. Assumes our optimistic alkaline electrolyzer cost scenario (Chinese in China, western elsewhere).

Hydrogen-powered propulsion

Hydrogen aircraft manufacturer

How does it work?

Maturity

ZeroAvia

ZeroAvia is developing hydrogen-electric powertrains to replace conventional engines, aiming to both retrofit and build new planes, as hydrogen aviation will likely require significant re-design in the future. Its timeline is to have a 10-20 seat plane, 300+ mile range, as its first commercial offering in 2024, building up to 40-80 seats and 1,000+ mile range in 2030. By 2050 it plans a 200+ seats and 5,000+ mile range plane. Its expertise lies in plane and powertrain design rather than innovation in a particular element of the system. It also plans to develop hydrogen refueling infrastructure at airports.

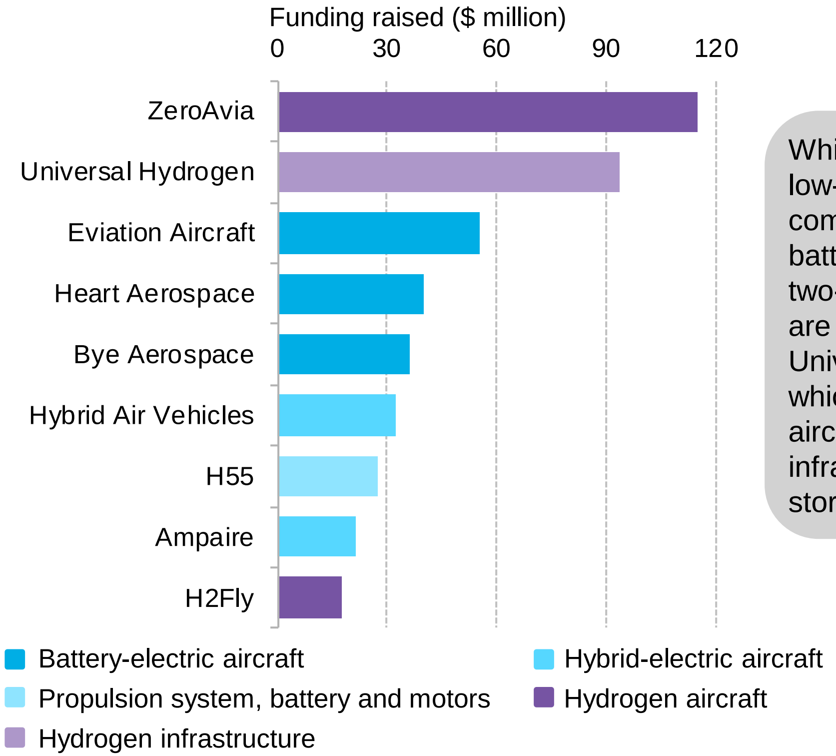
ZeroAvia was founded in 2018, and is one of the highest-funded zero-emission aviation companies to date. It flew the first-ever plane with a fuel-cell hydrogen-electric drivetrain in 2020, and has raised $114 million. Notable investors include Breakthrough Energy Ventures, Alaska Air Group and Shell Ventures.

APUS Zero Emission

APUS is a hydrogen aircraft manufacturer developing both a pure hydrogen-electric plane and a hybrid-electric plane. It will use engines fueled by SAF and hydrogen-fuel cell powered electric engines. The APUS i-2 pure hydrogen aircraft is powered by four 150kW electric motors with two 100kW hydrogen fuel cells with a three-passenger capacity and 900+ km range. The APUS i-5 hybrid does not mention technical specifics but will use two small SAF-powered engines with two hydrogen-powered electric engines.

APUS was founded in 2014. No public funding information is available. On May 1, 2022, APUS displayed a mockup of its APUS i-2 aircraft at Aero Friedrich-shafen.

Commercial long-range low-emissions aviation start-ups by funds raised, April 2022



Source: BloombergNEF, PitchBook, CB Insights.

While the majority of low-emissions aircraft companies are battery electric, the two-highest funded are ZeroAvia and Universal Hydrogen, which are hydrogen aircraft and hydrogen infrastructure (and storage) respectively.

Hydrogen-powered propulsion

How does it work? / Maturity

Hydrogen fuel cell producers

Hypoint

Hypoint is creating a new fuel-cell system designed for aviation, specifically a turbo air-cooled high temperature polymer electrolyte membrane (HTPEM) fuel-cell system. Compared to standard LTPEM (liquid cooled) fuel cell systems, it offers a 61% weight reduction and 1,000 times the CO impurity resistance (1% CO) in the hydrogen fuel. It states battery systems have 1.5 kW/kg currently, LTPEM has 1kW/kg, and Hypoint's HTPEM system can achieve 2kW/kg today, rising to 4kW/kg in the future.

Hypoint was founded in 2018. It has raised $2 million to date, and in 2020 won the NASA iTech Initiative. In 2021 it formed a partnership with Piasecki worth $6.5 million to develop its fuel cell systems for eVTOLs. ZeroAvia is a partner and is testing HyPoint fuel cells in its planes.

PowerCell

PowerCell is an established PEM fuel cell developer, developing fuel cells for numerous applications including marine, stationary, road and aviation. Its 35.5kW fuel cell reaches a power density of around 1kW/kg, which is one of its higher power density fuel cells. Its PEM fuel cells are commercially available.

PowerCell was founded in 2008 and raised $31 million before going public via IPO in 2014. It is now one of a few publicly traded, hydrogen-specific, companies. It has a number of deals across the various sectors its fuel cells cover. It originally worked with Volvo group, and now has a strategic partnership with Robert Bosch.

Hydrogen fuel cell systems generally have lower power density than electric aviation systems, which is a key component of electrifying heavier aircraft propulsion systems. Hydrogen systems have higher energy density storage though. Hypoint's fuel cell aims to achieve higher power densities with hydrogen's higher energy density.

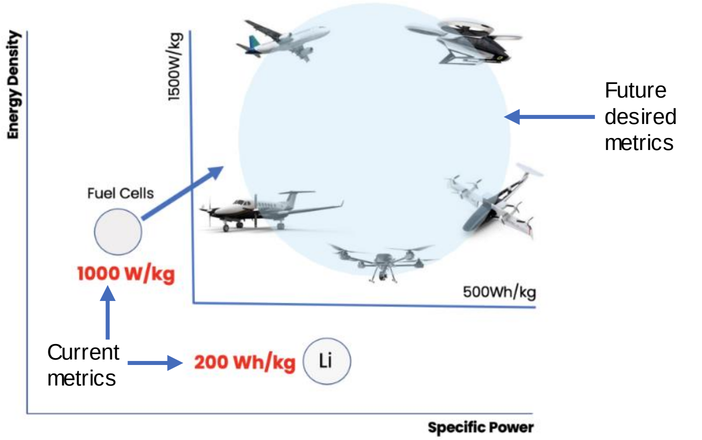
Hydrogen combustion

cfm + AIRBUS

Airbus and CFM International signed a partnership agreement in February 2022 to develop a hydrogen combustion engine demonstration. This will be an A380 aircraft aimed to take its maiden flight in the mid-2020s and to be entered into service in 2035. Airbus will define the specifications for the hydrogen combustion engine, and CFM International will design and modify the combustor, fuel delivery system and control system. A GE Passport turbofan will be used. The project will use liquid hydrogen fuel.

Airbus was founded in 1970 and is one of two major aircraft manufacturers dominating the market (the other being Boeing). It is publicly traded and has stated intentions to produce hydrogen planes for a number of years. CFM International was founded in 1974 and is a Safran and GE Aviation JV producing aircraft engines.

Hydrogen-electric and battery-electric metrics for aviation



Source: HyPoint

BloombergNEF

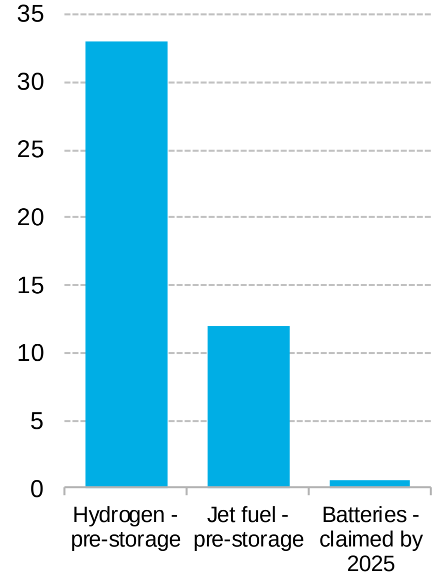
Hydrogen-powered propulsion

Hydrogen storage technologies

	How does it work?	Maturity
Universal Hydrogen	Universal Hydrogen is an end-to-end fuel logistics company for hydrogen-powered commercial flight. It transports hydrogen in modular capsules over the existing intermodal container freight network from production sites to airports. It is starting with carbon-fiber composite gaseous hydrogen storage but plans to move to liquid hydrogen storage tanks in future. The company is also developing a conversion kit to retrofit existing regional airplanes with a hydrogen-electric powertrain compatible with its modular capsule technology.	Universal Hydrogen was founded in 2020. It is currently valued at just under $200 million and had a recent raise of $62 million in October 2021, bringing its total to $82.5 million. In March 2022, it chose a 50-acre property in New Mexico to construct its hydrogen storage modules, assemble aircraft retrofit kits and perform hydrogen aircraft maintenance services.
GTL	Gloyer-Taylor Laboratories (GTL) is a technology company with a number of products directed at the aerospace industry. It has recently developed a cryogenic composite storage tank, called the BHL Cryotank, for liquid hydrogen. It claims the tank can store 10 times more hydrogen than state-of-the art liquid hydrogen tanks currently, at the same combined total weight of fuel and tank. This is achieved supposedly by its tanks being 75% lighter than any other cryogenic tank on the market.	GTL was founded in early 2004, and has only disclosed funding of a loan of $0.25 million to date. It claims to have worked on NASA lunar projects in the past, and has worked on ultra-lightweight cryogenic tanks since 2009. Recently it has announced its intention to use its tanks in aircraft powered by HyPoint fuel cells.
Kubagen	Kubagen is developing a metal-organic framework (MOF) structure that it claims will be able to store hydrogen at around five times the density of gaseous hydrogen at 700 bar. For reference, the storage densities of 700 bar gaseous hydrogen, liquid hydrogen, and Kubagen's claimed hydrogen sponge (KHS-1) material are 40, 71 and 197 kgH_2 m^{-3} respectively. Kubagen claims its KHS-1 MOF will store hydrogen at 100 bar at room temperature, using cheap base-metal compounds. This will result in 50+ cheaper energy storage in terms of kWh per kg than standard lithium-ion batteries. The company is still very early stage.	Kubagen has little to no funding information available and is extremely early stage with only 2 employees currently. It received a patent to allow commercial scaleup of its KHS-1 MOF in May 2019, though there has been little activity since then.

Gravimetric energy densities of fuels

kWh per kg



Source: BloombergNEF

It is important to note that for hydrogen and jet fuel these are pre-storage energy densities. Due to hydrogen having an extremely low density at room temperature and pressure, extremely heavy and large tanks are needed to store high pressure gaseous or cryogenically cooled liquid hydrogen, at around 5 to 10% of pre-storage energy density.

Sustainable aviation fuels

Sustainable aviation fuels

Sustainable aviation fuels (SAFs) hold the strongest short-term potential to decarbonize aviation. This is especially true for long-haul flights, the hardest segment, as they are drop-in replacements for fossil fuels. SAF technologies can use a diverse range of feedstock, including municipal and agricultural waste, and can potentially reduce lifecycle emissions by 80-90%. IATA states that SAF currently accounts for less than 0.1% of jet fuel demand. BNEF predicts a carbon price of $252/ton is necessary for SAFs to be cost-competitive, as they are currently between 2.5-8x the price of conventional jet fuel.

What is it?

SAFs are drop-in replacements that have significant lifecycle emissions savings over fossil fuels. There are three general levels of maturities for SAFs currently; biofuel refineries that are producing hundreds of millions of gallons of SAF a year through hydrotreatment; gasification and alcohol-to-jet (ATJ) (on the border of commercialization, with a small number of demonstration plants currently running); and power-to-liquids (PTL) that require only CO_2, water, and electricity as inputs, which are nascent. The feedstock for hydrotreatment is oils and fats. The gasification and alcohol-to-jet routes are attempting to use municipal solid waste (MSW), forestry residue, and agricultural residue as feedstock. Power-to-liquids' eventual aim is to use captured CO_2 to create e-fuels.

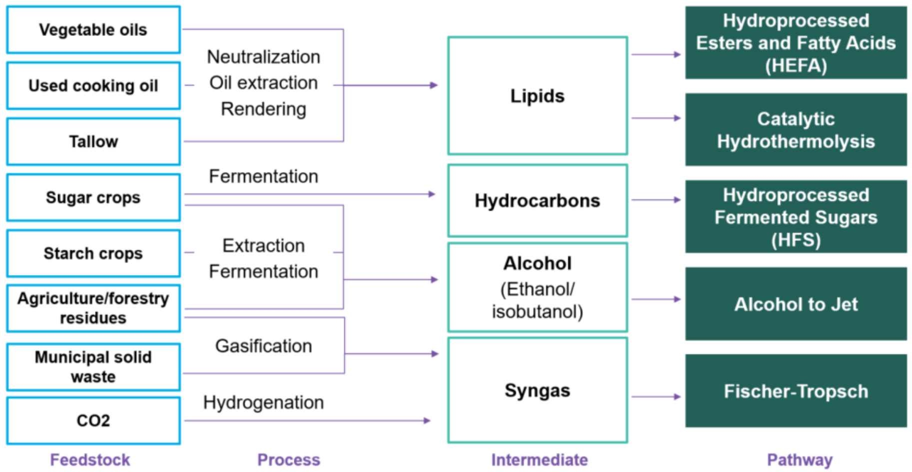
What should we tackle first?

The first goal should be to scale hydrotreated biofuel refinery capacity, as it is by far the best short-term route to SAFs. Any policies that promote biomass feedstock use (and availability) of waste oils and fats, such as used cooking oil (UCO) and animal fats, will be useful, as would regulation to set a minimum biofuel blend for oil refineries. Next, scale-up and build-out of gasification and ATJ plants should be achieved to increase the availability of SAFs. Investment in PTL should be done now to ensure scale-up and cost decreases of e-fuels long-term.

Why is it difficult to solve?

SAFs are currently 2.5-8x more expensive than conventional jet fuel. This makes it hard for airlines to buy large amounts of SAFs due to the slim profit margins for passenger aviation, and fuel already being 25-30% of an airline's costs. For biofuel refineries, feedstock choice is limited. Vegetable oil-based crops compete with food crops for space, and animal waste fats are used by other industries. For gasification to use MSW, significant sorting of metals, glass, non-toxic feedstock, etc. is required, and there is no commercial plant in the world making alcohol (for ATJ) using forestry or agricultural waste. PTL fuels are still nascent and have no real confirmed timeframe or cost comparison with conventional fuels.

SAF production pathways



Source: BloombergNEF

Refinery biofuels

Hydrotreated biofuels using oil refining methods are currently the most technologically feasible, commercially proven and cheapest way of making SAF. The two main methods are using new-build/re-purposed refineries to make 100% biofuels, or co-processing with crude oil in existing refineries. Initially using vegetable oils as feedstock, producers now have access to a wider range of non-food oils and fats, allowing for decreased lifecycle emissions, although this requires significant pre-treatment. Cost reduction limitations are due to high feedstock costs and a 4x increase in hydrogen requirements compared to crude-oil based fuels. Carbon credits/subsidy schemes and falling green hydrogen costs can start to offset higher biofuel costs. These hydrotreated biofuels are mostly produced by larger companies due to existing infrastructure.

New approaches and technologies

Stand-alone facilities: New facilities are being constructed specifically to produce renewable fuels, which, due to built-in pre-treatment plants, allow for a wider feedstock availability, decreasing lifecycle emissions. Re-purposed modified refineries can decrease project timeline from 3+ to 1-2 years.

Co-processing facilities: Existing fossil-fuel refineries can use bio-feedstock co-processed with crude oil to decrease lifecycle emissions, which allows for much faster decarbonization of fuels than new-build or re-purposed facilities and are often larger scale.

Waste feedstock sources: Waste feedstock, such as used cooking oil (UCO) and animal waste fats, can decrease lifecycle emissions by decreasing the land use for oil-based crops. UCO-based SAFs are already being trialed by airlines.

Limitations

Limited feedstock supply: Feedstock supply is a fundamental limitation for hydrotreated biofuels. Oil-based crops take up space used by, or are, food crops. There is competition from the cosmetic, biochemical and other industries for animal fats. UCO availability is highly distributed and limited. In 2019, aviation used around a trillion gallons of oil a year. For reference, UCO production globally is around 5.5 billion gallons, capable of producing around 4.5 billion gallons of SAF. Even if all of it is utilized for aviation, this would meet just under 5% of demand.

Hydrogen requirements: Biofuels production requires around four times more hydrogen than conventional oil refining processes, and depending on gray or green hydrogen use, will significantly increase either lifecycle emissions or price of production, respectively.

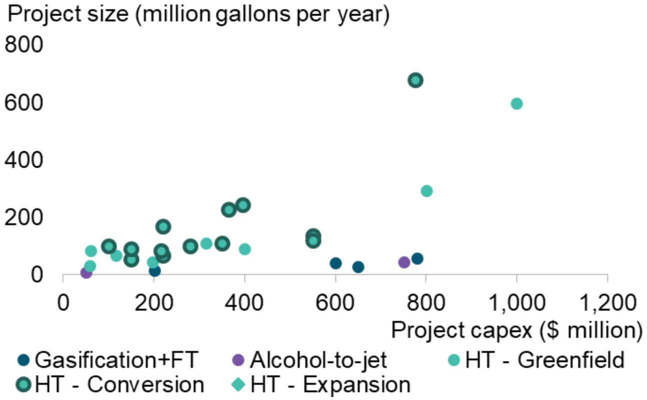
Potential solutions

Low-cost green hydrogen: Making SAFs via hydrotreatment requires around 40kg of H_2 per 1,000 liters of SAF. At today's green hydrogen prices, this means H_2 costs account for one-fifth of the cost of SAF production. By 2035, green H_2 should undercut gray H_2 in the majority of markets.

Supportive biofuel policies: Initiatives to mandate higher levels of co-blended fuels – such as California's LCFS – can help make pre-treatment facilities at co-processing plants worth the investment.

Alternative feedstocks: Algae or crops grown on fallow fields, such as camelina, could negate land-use and food competition issues. These show promise but are yet to be scaled up and used.

Sustainable aviation fuels projects by size and pathway, March 2021



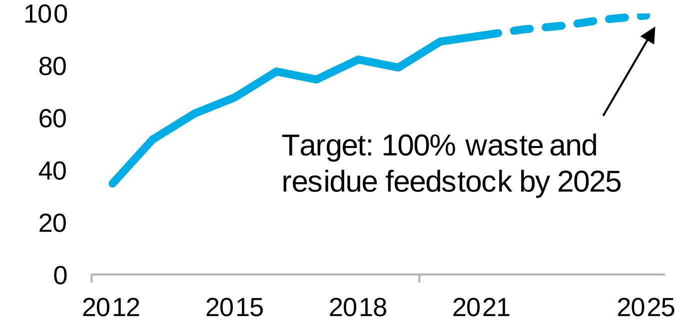
Source: BloombergNEF. Note: HT = hydrotreated

Refinery biofuels

Stand-alone facilities		How does it work?	Maturity
	NESTE	Neste is one of the world's largest producers of renewable fuels – particularly SAF – using stand-alone biorefineries in Finland, the Netherlands and Singapore. Its Neste MY SAF is made from wastes and residue oils such as UCO and animal waste fat. It produces around 1.1 billion gallons of renewable products per year currently, including both renewable diesel and SAF. Neste can retrofit old refineries or build new ones to hydrotreat fats and oils to convert to renewable fuels/SAF. It plans to use 100% waste residue by 2025 and use no conventional palm oil by the end of 2023.	Neste was founded in 1948 as an oil refining company. For biofuel refinery processes, refineries can be reprocessed to treat the fats and oils used as feedstock. As such, Neste was able to transition into renewable fuels easily. It has a market cap of $27.8 billion.
	world energy	World Energy has six biorefineries across the US and Canada, though only its Paramount facility in California currently produces SAF. It makes just over 100 million gallons of renewable products per year from a variety of feedstocks. It uses a ShockWave power reactor that increases energy efficiency and reduces catalyst utilization. It launched a JV with Biox in 2016 that claims to have a proprietary improved biofuels production process.	World Energy was founded in 1998 and operates throughout the US. It was founded as a biofuels production company specifically, and in 2018 acquired Biox, a small Canadian biofuels production company. World Energy is currently valued at $345 million. It has announced plans to expand its Southern California refinery (acquired through acquisition of AltAir Fuels in 2018) to become the world's biggest and most advanced SAF refinery.

Neste waste feedstock use, 2021-2025

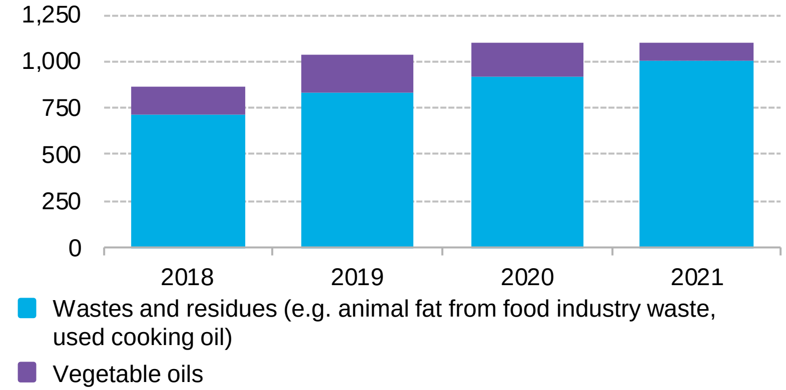
% share of waste and residues for Neste



Source: BloombergNEF, Neste

Neste renewable raw material inputs globally

Millions of gallons



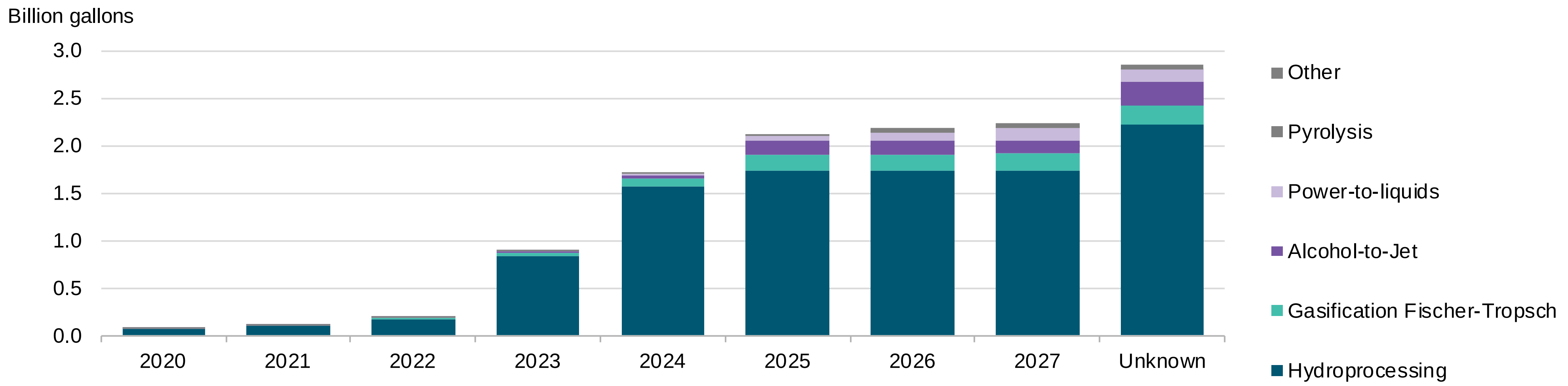
Neste in 2021 accounted for around 27% of global renewable drop-in fuels production. Global drop-in fuels production is around 90% renewable diesel, with the remaining 10% being renewable jet fuel, naphtha and other drop-ins.

Source: Neste

Refinery biofuels

Co-processing facilities	How does it work?	Maturity
TotalEnergies	Total is one of the largest oil producers in the world. While it has both stand-alone and co-processing facilities, its co-processing facilities provide the majority of its output capacity for biofuels, specifically SAFs. It is moving toward co-production using waste materials, which will require larger plants for cost-effective pre-treatment.	Total is increasing its focus on renewable fuels, and last year stated it planned to add 100 million gallons of renewable diesel capacity in Europe from co-processing at existing refineries. It aims to produce around 0.7-1 billion gallons of renewable diesel and SAF by 2025, and is converting its Paris facility to produce 130 million gallons per year of renewable products, 23 million gallons per year of which will be SAF.
bp	BP produces the majority of its cleaner fuels through co-processing. Like many oil majors, it is looking at stand-alone facilities to produce 100% biofuels. It was focused more on renewable diesel but is increasing its focus on SAFs.	BP has been investing in biofuels for many years. In 2018 it launched a renewable fuels co-processing facility at its Cherry Point refinery that supplies a significant portion of the Pacific Northwest US, and in 2021 stated it will invest $270 million to double its renewable diesel capacity there. In 2022, BP started to produce SAF from waste fats, oils and greases at its facility in Lingen, Germany. It also acquired a 30% stake in Green Biofuels Ltd. in February 2022.

Cumulative capacity of SAF produced by year per technology



Source: BloombergNEF

Gasification and alcohol-to-jet

Gasification Fischer-Tropsch, and alcohol-to-jet (ATJ), are two methods of SAF production on the verge of being commercialized. Both methods can use a wider range of feedstock than hydrotreatment as they do not need oil-based feedstock. Options include agricultural waste, forestry residue and municipal solid waste (MSW). Gasification produces syngas, and ATJ creates alcohols, which are each then converted to hydrocarbons. Both processes are currently more expensive and less developed than hydrotreatment, with no existing infrastructure and only a couple of small commercial-scale plants. While forestry and agricultural waste generally produce fuels with lower lifecycle emissions, plastics and hydrocarbon rich materials for gasification, and corn and sugar crops for ATJ, produce fuels at cheaper cost. High costs could be offset if carbon credit prices increase, avoided emissions from landfill are realized, and tipping fees are utilized.

New approaches and technologies

Gasification with Fischer-Tropsch (FT): Gasification processes heat up and break down biomass to produce syngas (CO and H_2), which is then converted to fuels using catalysts via FT.

Plasma gasification: This new method of gasification uses plasma torches to achieve extremely high temperatures to break down waste, allowing for less waste pre-treatment.

Alcohol-to-jet (ATJ): ATJ processes typically use fermentation of biomass, mostly corn or sugarcane, but could also use biomass waste, to produce ethanol or butanol. Hydrocarbons are produced through dehydration, oligomerization and hydrotreatment

Waste feedstock use: Gasification, with some technical tweaks, can utilize agricultural and municipal waste. For comparison, 2 billion tons of MSW per year is produced, compared with 16.5 million tons for UCO.

Limitations

MSW feedstock: While MSW is low cost, it can be costly to pre-treat as metals in it must be separated. Plastics/hydrocarbon-based materials have higher carbon intensities, along with a widely varying chemical composition.

Gasification temperatures: High temperatures (1,000^{0}C – standard, 3,000^{0}C – plasma) for gasification are necessary to utilize MSW, a relatively low calorific value feedstock, which causes significant wear on process equipment.

Making non-food based ATJ: To avoid food-based alcohol, the industry must scale complex and costly cellulosic alcohol production.

High production costs: Capex accounts for 60-90% of gasification-to-fuels costs, while for ATJ the low conversion yield of ethanol to jet (50% yield) accounts for 70% of ATJ costs. This means that even at commercial scale, production costs would be around $6-10/gallon.

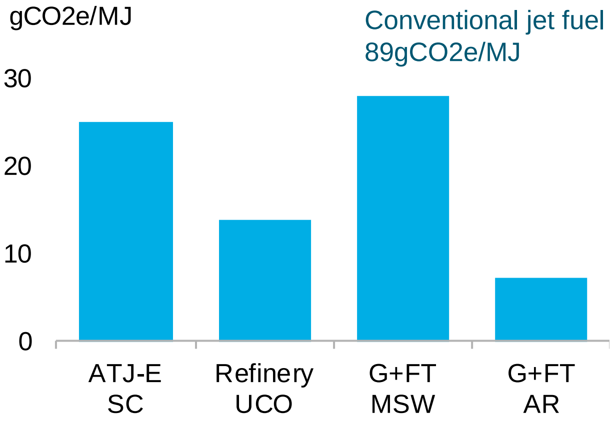
Potential solutions

Aggregated waste streams: Waste feedstock is highly distributed, making it expensive to use. Turning it into a centralized commodity would help.

Localized production: Smaller gasification facilities located where waste is produced might be an option. Transporting biomass/waste feedstock is costly. SAFs are drop-in fuels, thus easy to distribute.

Incentives to avoid incineration and landfill: Incentives such as tipping fees for companies to use waste to avoid landfill, and credits from avoided emissions produced by landfill, decrease costs of expensive biofuels from waste.

Net emissions for SAF production



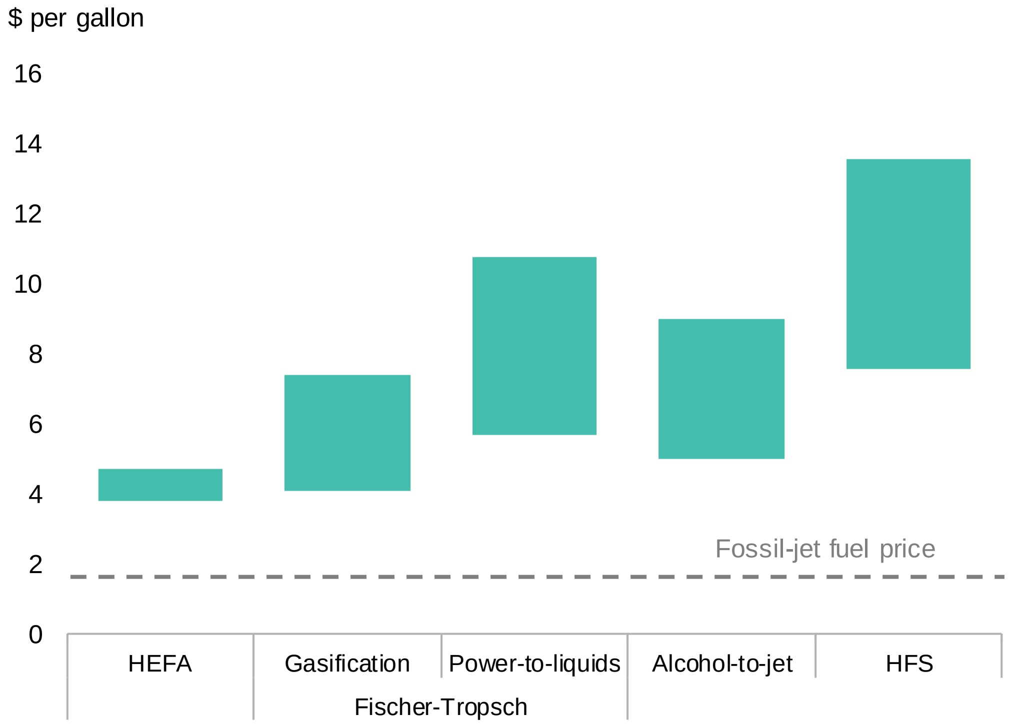
Source: BloombergNEF. Note: ATJ-E = alcohol-to-jet via ethanol, SC = sugarcane feedstock, UCO = used cooking oil, G+FT = Gasification + Fischer-Tropsch, AR = agricultural residue.

Gasification and alcohol-to-jet

Gasification with Fischer-Tropsch

	How does it work?	Maturity
Enerkem	Enerkem is one of the better-known renewable fuels production companies for gasification and FT. It has multiple projects in progress. Its focus is primarily on methanol, but it is moving toward SAF production.	Enerkem was founded in 2000, and has now raised over $800 million to date, with both a Series H and a Series I taking place in 2019. It raised a $255 million round led by Repsol in early 2022. A full-scale plant in Alberta, Canada, is currently producing biofuels. Another is being built in Quebec which will produce biofuels using primarily forest biomass. In June 2021 it announced changes to its proposed Rotterdam plant with partners Shell and Port of Rotterdam, to produce SAFs.
Fulcrum Bioenergy	Fulcrum Bioenergy uses gasification and FT. It claims to use the waste heat created by its process to generate electricity to use in its plants. It has multiple projects in progress and is designing its technology to be scalable. It is focused on SAF production.	Fulcrum Bioenergy was founded in 2007, and has now raised an estimated $520 million to date, with $50 million raised by undisclosed equity partners in December 2021. Both United Airlines and BP invested $30 million each into Fulcrum in 2015/2016. It is planning an $800 million production facility in North-West England to produce around 27 million gallons of SAF per year in 2025, partnering with Essar Oil to build the facility and blend the SAF fuels to serve UK airports.

SAF production cost per gallon, by technology route



Source: BloombergNEF. Note: Based on an average carbon intensity per pathway, HEFA = hydroprocessed esters and fatty acids (biorefinery SAFs), HFS = hydroprocessed fermented sugars.

Gasification and alcohol-to-jet

BNEF pioneers

Alcohol-to-jet

How does it work?

Maturity

LanzaTech

LanzaTech's ATJ process is different to standard processes, as the IP lies in the fermentation of waste gases to fuels. Others ferment the sugars in sugarcane or corn crops into alcohols. LanzaTech's microbe produces ethanol from a mixture of gases such as CO_2, CO and hydrogen, which then undergoes catalytic cracking and conversion to hydrocarbon fuels. It both produces its own ethanol, and buys ethanol from other sources, to convert directly into fuels.

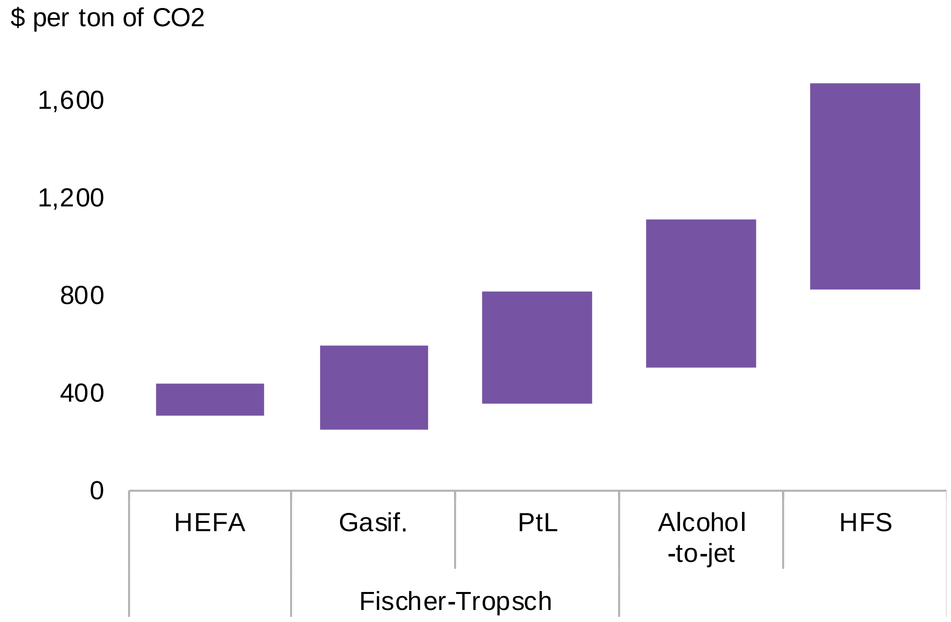
LanzaTech was founded in 2005 and has raised $415 million. In March 2022 it announced a planned reverse merger with SPAC AMCI Acquisition Corp II at a valuation of $2.2 billion. It has a commercial-scale plant in Georgia, US. In August 2021 its DRAGON project, aiming to produce almost 27 million gallons of SAF from ethanol by ATJ in Port Talbot, South Wales, was shortlisted for the UK's Green Skies competition. The fuel produced will be used by British Airways and Virgin Atlantic.

gevo FUELING THE FUTURE

Gevo uses the ATJ process to produce a number of different products, one of which is SAF. Unlike LanzaTech, Gevo uses a butanol pathway to produce fuels. Its Gevo integrated fermentation technology continuously removes butanol from the fermentation process. It then goes through standard dehydration, oligomerization and hydrotreatment to create SAF.

Gevo was founded in 2005 and is publicly traded. It went through an IPO in 2011, and has a market cap of $740 million currently. Gevo's ATJ process was certified for jet fuel as of March 2016. Gevo signed a letter of intent with Chevron in September 2021 to jointly invest in building new facilities to process inedible corn to produce SAFs. In March 2022, the Oneworld Alliance announced its plans to purchase up to 200 million gallons of SAF from Gevo, with SAF delivery expected to commence in 2027.

Implied carbon price needed to make SAF cost-competitive with jet fuel



Source: BloombergNEF. Note: Based on an average carbon intensity per pathway, HEFA = hydroprocessed esters and fatty acids (biorefinery SAFs), HFS = hydroprocessed fermented sugars.

Power-to-liquids fuels

Power-to-liquids (PTL) fuels use captured CO_2, H_2, and electricity as feedstock to produce synthetic hydrocarbon fuels (e-fuels). There are two routes for PTL: syngas (CO and H_2) production for FT conversion to fuels, or alcohol production for conversion to fuels. For the more common syngas and FT route, the innovation and distinction between PTL companies is mostly how the syngas is produced. The most common method is the reverse water gas shift reaction to produce CO and electrolysis to produce green H_2. However, there are more nascent methods such as electrolysis of CO_2 and water, and sunlight-to-fuels using a solar reactor. PTL fuels are currently up to 8x the price of fossil fuel equivalents, and the feedstock is not easy to procure. PTL processes are still very early stage and proof of their effectiveness is still to be established, and there are doubts they will reach the cost-competitiveness claimed by some companies. Innovations in direct air capture can decrease cost of CO_2 and make it available onsite. Co-location at electricity generation sites or airports can also decrease overall costs.

New approaches and technologies

CO_2 polymer electrolyte membrane (PEM) electrolyzer: This converts CO_2 and H_2O into syngas with O_2 as a byproduct using a retrofitted PEM electrolyzer with new catalysts.

Electrochemical alcohol production: Use of captured CO_2 and H_2O in an electrochemical cell, similar to an electrolyzer. This produces longer chain alcohols that are then combined via catalysts to produce fuels and water.

Reverse water gas shift (RWGS) and electrolysis: The most established method to produce syngas for PTL is CO from RWGS ($CO_2 + H_2 \rightarrow CO + H_2O$) and H_2 from green electrolysis.

Solar heat reactor: This passes CO_2 and H_2O over new catalysts at temperatures of $1{,}500^0$C, heated by concentrated solar, to produce syngas.

Limitations

Expensive compared to other SAFs: PTL fuels are up to 8x the price of standard fuels currently. The high price for clean e-fuels stems from the high price of DAC, electrolysis, and the energy required to break stable CO_2 bonds. Many of these processes also use their own new catalysts which will be expensive to manufacture, as there is no established supply chain and manufacturing process for them.

Feedstock competition: There is existing demand for green hydrogen, renewable electricity, and CO_2 in other industries, often at higher price premiums.

PTL is nascent: Many of these methods are still pre-commercial stage and unproven, and will require significant investment for scale-up.

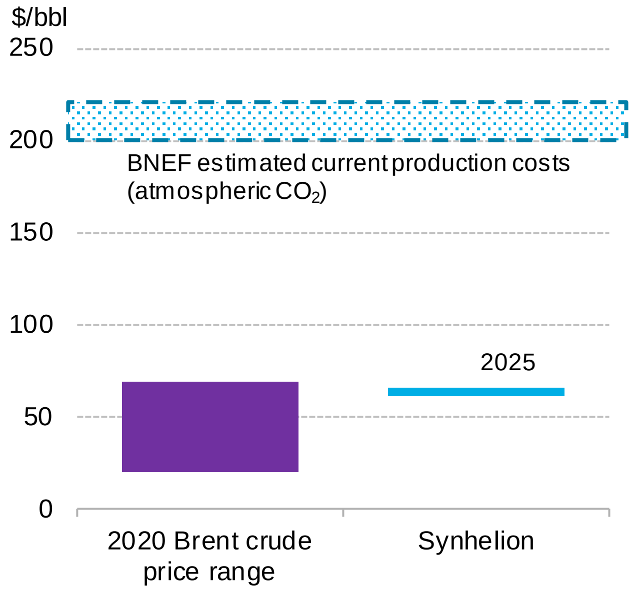
Potential solutions

Decreasing direct air capture (DAC) cost: Innovations in DAC are decreasing the cost of onsite atmospheric CO_2 availability

Localized production: Since PTL facilities are small they can be placed to produce onsite at airports or near DAC

Co-location with clean electricity: Production of these fuels next to electricity production would allow power that would normally be curtailed to be used.

Production costs comparison of synthetic fuels from CO_2



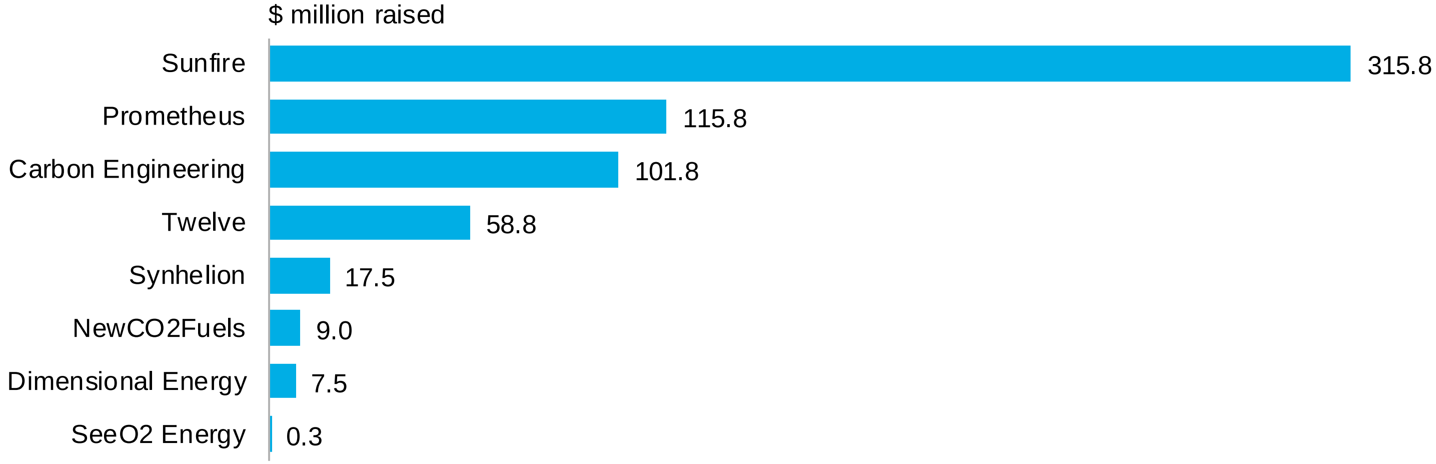
Source: BloombergNEF

Power-to-liquids fuels

BNEF pioneers

	How does it work?	Maturity
CO_2 electrolysis (twelve)	Twelve uses CO_2 from the air to produce feedstock for chemical processes, mainly CO. Other technologies can be used in conjunction with this to produce Twelve's e-Jet fuel. Twelve's IP lies in its CO_2 electrolyzer and proprietary catalyst that splits CO_2 and water into CO, O_2 and H_2. Rather than electrify the plane, which for long haul transport is tough due to low zero-emission fuel energy densities, it has decided to electrify the fuel process, which it claims reduces lifetime emissions by up to 90% compared with standard fossil fuels.	Twelve, founded in 2015, was formerly known as Opus 12. It is one of the highest-funded CO_2-to-fuels companies to date, and raised $57 million in a Series A in late 2021 from Breakout Ventures and Capricorn Investment Group. In summer 2021, the US Air Force tested and qualified Twelve's E-Jet fuel; it plans to scale production in future.
CO_2 to fuels via alcohols (PROMETHEUS)	Prometheus Fuels plans to create its electrofuels from air and renewable electricity. Unlike many CO_2-to-fuels companies it plans to produce all parts of the process in one modular unit, the Titan Fuel Forge, which has only the requirement of electricity to function. The Titan pulls air into it, and a strong waterfall captures CO_2 and water vapor from the air. Renewable electricity is then used to charge the CO_2 with H_2 in an electrochemical stack called the Faraday reactor to produce longer chain alcohols, which a catalyst then combines to create longer chain hydrocarbons. Each Titan will be roughly a 40-foot container size, claiming to make 100,000 gallons a year. This technology is still at the very early stages, with little to no third-party validation.	Prometheus fuels was founded in 2019. In March 2019 it was selected for investment by Y-Combinator. In mid-2020, it received investment of $12.5 million from BMW I Ventures. Its plan is a megafactory producing Titan Fuel Forges by 2025.

Amount raised by power-to-liquids companies, April 2022



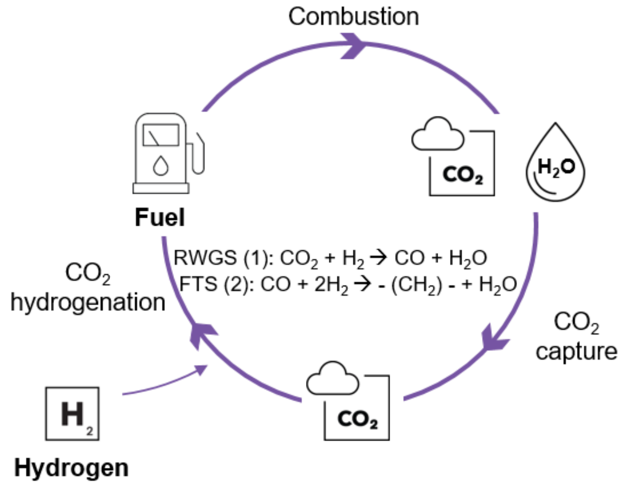
Source: BloombergNEF, CB Insights, PitchBook

PTL fuels are still very nascent and are an expensive technology in general. However, they may still play an important role in decarbonizing aviation. To do so will require significant investment now to be cost-competitive in the future. Many PTL startups do not focus on making SAFs, but focus instead on higher value chemicals. Sunfire makes hydrogen and green chemicals, while Twelve makes mostly plastic precursors.

Power-to-liquids fuels

		How does it work?	Maturity
RWGS and electrolysis	Arcadia eFuels	Arcadia eFuels makes renewable fuel by using hydrogen from green electrolysis and captured CO_2 to produce syngas, and then the Fischer-Tropsch process to convert syngas to sustainable aviation fuels. The Arcadia process uses reverse water gas shift.	Arcadia eFuels was founded in 2021. In early 2022 the intention of the P2X project was announced, which aims for around 18 million gallons of e-fuels production by 2025, though a site has not been picked.
Sunlight-to-fuels	Synhelion	Synhelion combines solar tower systems with greenhouse gases to produce syngas, which can then be reformed into SAFs via standard Fischer-Tropsch technologies. The CO_2 and water vapor put into the process can be obtained either from DAC or other CO_2 sources. Synhelion's thermochemical reactor traps sunlight and produces process heat at temperatures above 1,500ºC, which when combined with Synhelion's proprietary reactive materials (catalysts) inside the reactor produces syngas. Thermal energy storage allows for round-the-clock production of the sunlight-to-fuels products.	Synhelion was founded in 2016. It has raised $17.5 million, the majority of which came from a Series B in 2021. It originally spun out from ETH Zurich. It plans to begin production in 2023, and to ramp up production to 230 million gallons of solar fuel by 2030. Investors include CEMEX and AMAG.

Typical circular fuel production, direct CO_2 hydrogenation route



Source: BloombergNEF, adapted from Nature. Note: RWGS refers to reverse water gas shift, FTS refers to Fischer-Tropsch Synthesis

It is important to note that using RWGS requires external hydrogen input to create e-fuels, however companies such as Twelve, Synhelion, Prometheus and others are aiming to design processes that require only CO_2 and H_2O as input to make syngas, removing the need for external hydrogen to be added to the process to make syngas for FTS.

Optimizing operations and aircraft

Optimizing operations and aircraft

Optimizing current airport operations and aircraft design has short-term decarbonization potential, and will also help support the future of aviation (batteries, hydrogen, SAFs). Airport operations should be a focus for decarbonization, as regulations governing them are less stringent than for aircraft. Airports are also constrained environments with established infrastructure, so implementation of electric and autonomous ground vehicles can be quick. The aviation sector is behind many others in adopting digital technologies for optimization. New aircraft design and manufacturing techniques are hard to implement quickly due to regulations, but there have been steady improvements over the past decades. Composites for lighter frames will be useful for all aircraft, and jet engine improvements will be effective for decades, until battery/hydrogen-electric is commercialized.

What is it?

Optimizing current aircraft design and airport operations will result in less decarbonization impact than fuel decarbonization, however it does provide short-term gains, and will also apply to all future aircraft. Airport operations can be electrified, ground vehicles automated, flight route efficiency improved by AI and digital fuel management used to replace paper forms. Optimizing current aircraft will provide an increase in fuel efficiency, and an emissions decrease, for both today's aircraft and future aircraft using low-emission fuels. This can entail making aircraft lighter using higher strength composites. instead of metal and optimizing manufacturing processes using 3D printing to decrease wasted material. Current jet engines and their efficiencies can be improved in multiple ways. One example is by using open rotor architecture, which can decrease emissions by 20%+. Aircraft engines have improved in efficiency by around 1% per year from 1970 to today. Relaxation of regulations surrounding airport slots could also reduce empty flights flown by airlines as required by airports.

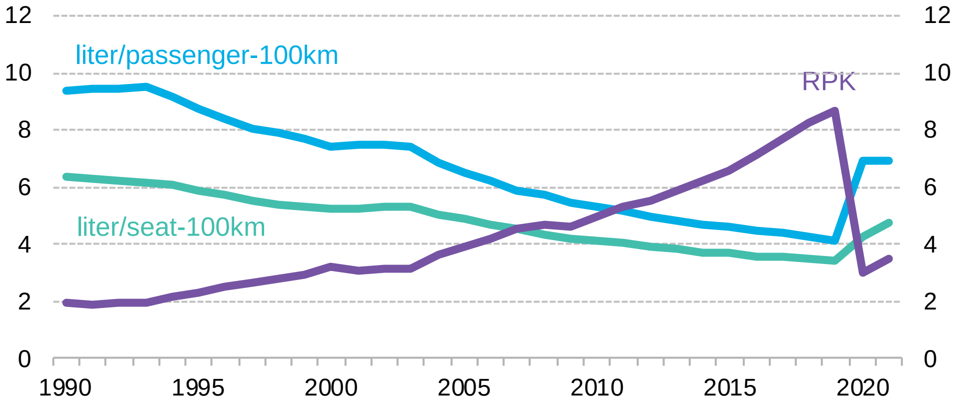
What should we tackle first?

First airport-side operations should be decarbonized/electrified, as regulations are less stringent than for aircraft. Airports are constrained environments, providing the easiest deployment case for autonomous electric vehicles. Digital fuel management allows for accurate tracking of fuel consumption, helping airlines quantify their fuel use, and optimize it. Aircraft design optimizations should be researched now, as they will take time to be certified, before being implemented in low-emissions planes.

Why is it difficult to solve?

For many airport operations and aircraft design improvements, it is not always easy to justify the upfront cost of investment, in terms of environmental/economic benefits. For example, switching over from the current fueling system to digital saves only up to $116 per flight and 1% fuel savings, while re-designing manufacturing lines is expensive once a reliable factory process has been established. New aircraft designs hold promise, but composites are brittle and shatter easily compared with metals. Open rotor architectures are significantly louder than current jet engines, increasing noise pollution.

Aircraft fuel efficiency trends, 1990-2021



Source: IATA, ICAO, Bloomberg Terminal, BloombergNEF. Note: RPK = revenue passenger kilometers.

Airport and operations

Airport and ground operations decarbonization is much easier and quicker to tackle than aircraft decarbonization but doesn't hold as much emissions savings potential. Numerous operations technologies together, though, can have a significant effect on the aviation industry's emissions. Improvements such as digital fuel supply chain management, autonomous electric ground vehicles, and AI for route/passenger load efficiency can help quantify and reduce emissions. Digital fuel supply chain management, for example, can reduces emissions per flight by around 1%. Another example is airport slots that airlines must fill, often by flying empty planes, increasing unnecessary emissions. Solutions include regulations requiring accurate understanding of aircraft emissions, increase in autonomous vehicle research, human use of AI suggestions to increase trust and reliability of the route changes, and a decrease in requirements for airlines having to fill a certain percentage of airport slots to retain use of them.

New approaches and technologies

Digital fuel supply chain management: Aviation fuel supply chains are still mostly paper forms. Digital optimization can prevent operational costs, up to around $116 per flight, decrease over-fueling, cut emissions by 1% and quantify fuel use.

Autonomous EV ground vehicles: Autonomous electrification of airport vehicles decreases emissions through optimization of routes, hence fewer vehicles are needed.

Flight route optimization: AI for flight planning and prediction decreases emissions by increasing efficiency of flight routes.

AI to increase load/passenger efficiency: Increasing flight capacities to full load can cause significant savings, with AI predicting flight destination bookings at certain times of the year to predict where planes should be.

Limitations

Competition for airport slots: Highly valued slots at airports for airlines cause ghost flights with no passengers on board to be flown to fill the slots. Lufthansa alone ran 21,000 empty flights over 2021-2022 winter, equivalent in emissions to 280,000 cars.

Autonomous vehicle integration: The capex of implementing autonomous airport vehicles will be high and using autonomous airport vehicles alongside standard vehicles would be difficult.

Integration of separate AI systems: Different companies with different AI programs for flight planning optimization could clash in their planning, creating confusion and inefficient route planning.

Potential solutions

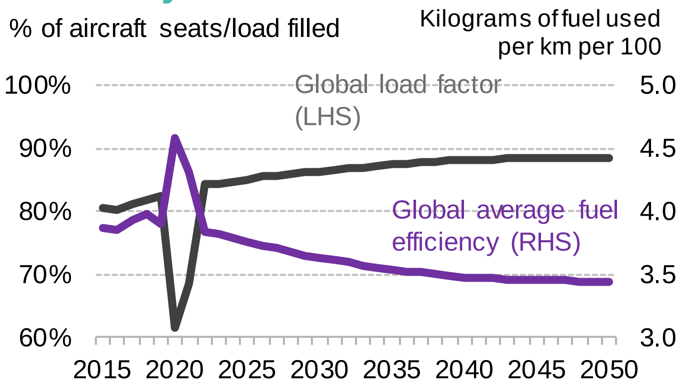
Decrease usage percentage for airport slots: Decreasing the percentage of flight slots that must be used by an airline to keep their assigned slots would decrease the number of ghost flights.

Fuel tracking regulations: Regulations requiring more accurate tracking of fuel use and emissions could drive adoption of digital systems.

Autonomous vehicle commercialization: As proof of autonomous vehicle efficacy in constrained environments is established, adoption by airports might increase.

Human - AI interface: Suggested alterations can be made by AI that operators can then confirm, retaining a human trust element, to prevent system clashes between AI programs.

Passenger load factor and fuel efficiency



Source: ICAO, BloombergNEF

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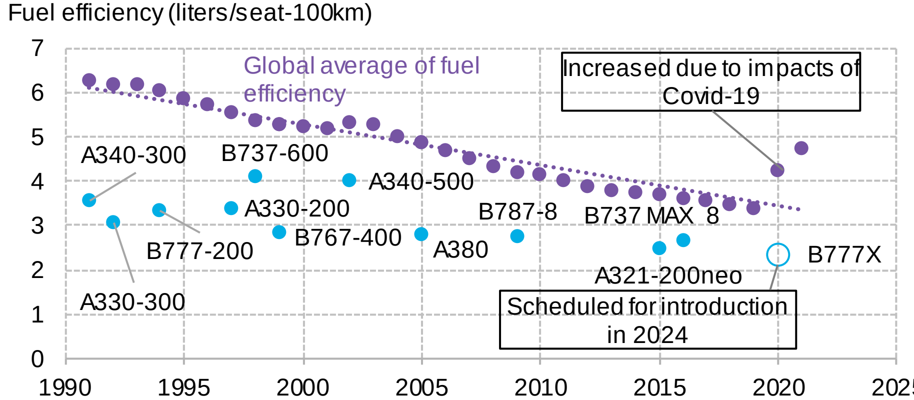
Airport and operations

		How does it work?	Maturity
Digital fuel management	i6 GROUP	i6 Group provides digital products to manage fuel movement for airlines, airports and fuel suppliers. Its cloud software replaces paper-based operations and is shown to result in fuel and emission savings and broader operational efficiencies. It claims 65kg of fuel and 201kg of CO_2e are saved per flight, which works out at around 1% savings per flight. It greatly improves airlines' abilities to track fuel usage and efficiently refuel.	i6 group was founded in 2013 and has running contracts with British Airways, Virgin Atlantic at San Francisco and Boston Logan airports, and KLM at Amsterdam Schiphol, among others. Its technology is deployed at over 150 airports, and it raised an undisclosed Series A in 2020.
Autonomous vehicles	Moonware	Moonware is trying to automate and optimize airside operations by using fully autonomous vehicles and a cloud management software stack, aimed at larger airports. By electrifying and optimizing ground transport, emissions are reduced by decreasing aircraft taxiing and ICE ground vehicle use at airports. Autonomous vehicles also are best suited to constrained ordered environments, such as airports, with few random elements.	Moonware announced its launch as an independent company in 2020 after a year-long collaboration with Uber Elevate. Its team contains ex-Google, Uber and Amazon employees. The company plans to first enter the general aviation market in 2023.
Flight route optimization	AIRSPACE INTELLIGENCE	Airspace Intelligence provides an AI software platform, Flyways AI. The platform helps pilots select optimal flight routes based on analysis of a complex set of information such as air traffic volume and weather conditions. Its platform uses cloud-based software to take into account current air operations, giving airline operators and personnel across the platform recommendations on what to do.	Airspace Intelligence was founded in 2017. It raised a $22 million Series A in early-2021. In mid-2021 it announced its first customer, a multi-year contract with Alaska Airlines. The Flyways platform claims it found opportunities to reduce miles and fuel use for 64% of mainline flights, and in six months saved 0.5 million gallons of fuel and avoided 4,600 tons of CO_2e.

Aircraft fuel efficiency



The aircraft in blue are on the more fuel-efficient end of aircraft. Many more less-efficient aircraft are also operating, giving a poorer global average of fuel efficiency. Also, the aircraft in blue are for first flight year, so will be particularly fuel efficient for their year, where older aircraft from 20 years ago, for example, are still flying.

Source: IATA, ICAO, Bloomberg Terminal, BloombergNEF. Note: The estimates of the fuel efficiency for selected aircraft variants assumed flight range of 920km.

Aircraft design and manufacturing

New aircraft designs, materials, coatings and engine innovations can decrease drag and increase fuel efficiency, thus decreasing emissions. Optimizing manufacturing processes and smart manufacturing of aircraft parts can decrease material waste, improving lifecycle emissions of aircraft chassis and decrease the weight of aircraft. While these technologies hold potential, they can be expensive to implement, with some unproven so far. For example, analyzing and altering an established factory manufacturing process would be expensive for potentially small operational benefits. Large-scale adoption, proof of emissions reduction, and certification are key to effective implementation in aircraft.

New approaches and technologies

Aircraft streamlining: New aircraft designs can optimize the trade-off between practical robust planes and aerodynamics. New wing shapes, longer wings, new body designs and aircraft coatings can decrease drag. These can be optimized extremely quickly using specialist software.

Manufacturing optimization: AI analysis can be used to see where excess materials and energy are being used, and thus can be eliminated. Smart manufacturing allows for customized composite parts to be specifically made rather than cut from larger pieces, limiting waste material.

Composites: Composites significantly decrease aircraft weight (they are 75% lighter than steel) and give higher impact resistance and thermal stability than metals

Jet engine innovations: Innovations such as open-rotor architectures can decrease emissions by 20% or more.

Limitations

Implementation restrictions: New designs must be rigorously tested to be certified, and also must be practical. For example, wider wings on aircraft may cause operational issues in an airport due to aircraft width.

Expensive new manufacturing processes: Once an established assembly line has been created, the cost of optimization may not justify the financial benefit. Many 3D additive printers are unproven long term, with many moving parts allowing for high risk of failure.

Composite shortcomings: Unlike metals, composites will not warp or bend, but will break because they are brittle. Composites also are extremely hard to process and recycle compared with their metal counterparts.

Open-rotor constraints: Compared with current closed-rotor (turbofan) engine architectures, open-rotor (propfan) engine architectures significantly increase noise.

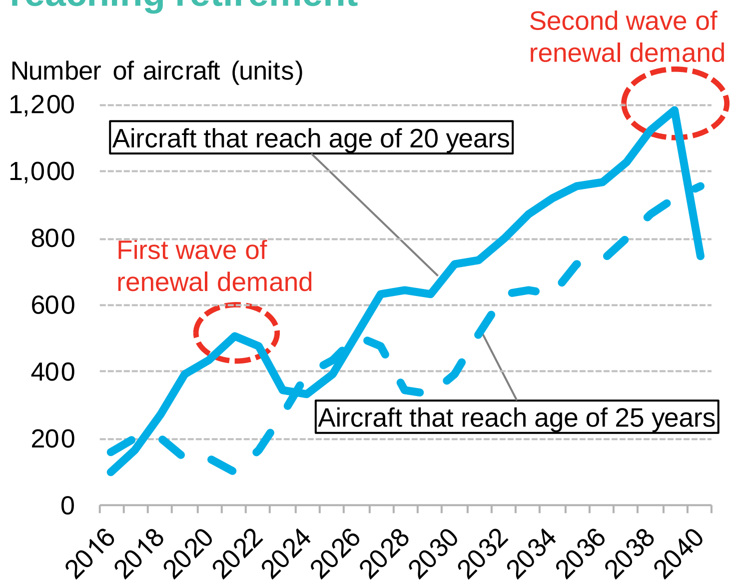
Potential solutions

New aircraft efficiency: New designs can be proven to decrease drag, and emissions, in simulations. This can warrant investment.

Large-scale adoption of smart manufacturing: Mainstream adoption of smart manufacturing will decrease cost through mature supply chains and increased reliability. 76% of manufacturers already have smart factory initiatives in place or in development.

Composite blending: Hybrid metal-composite structures can be made, decreasing weight of aircraft while gaining increased thermal/impact resistance properties compared with metals.

Number of narrowbody aircraft reaching retirement



Source: ch-aviation, BloombergNEF

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Aircraft design and manufacturing

		How does it work?	Maturity
Aircraft streamlining	BASF We create chemistry + Lufthansa	AeroSHARK is a new innovation by BASF and Lufthansa that lowers frictional air resistance and thus fuel consumption. The surface structure consists of ribs around 50 micrometers high and is based on the properties of shark skin. For Lufthansa's Boeing 777F freighters, this could lead to a 1% decrease in frictional resistance. This is predicted to correlate to an annual savings of around 1.2 million gallons of jet fuel for Lufthansa's 10 aircraft fleet, or 11,700 tons of CO_2 emissions.	The AeroSHARK has been developed recently and is planned to roll out across Lufthansa Cargo's 10 aircraft freighters in 2022. If proven effective during trial, it can be rolled out across many other airlines and aircraft allowing for emissions savings.
Open-rotor architecture	cfm	CFM RISE is a project from CFM International, a 50/50 JV between GE Aviation and Safran, to develop an engine to operate the same as current aircraft engines but able to produce 20+% fewer emissions. The main innovation allowing this is a propfan design, or open-rotor architecture, rather than a turbofan. Propfan engine rotors are outside the engine duct, whereas rotors are within the engine duct in turbofans.	CFM RISE is a specific project within CFM International launched in mid 2021. CFM International develops, produces and sells new advanced aircraft technologies. It has been a JV of Safran and GE since 1974.
Manufacturing optimization	Productive Machines	Productive Machines is an AI company that specializes in maximizing the sustainability of manufacturing processes using machines. Using its software, it provides analysis to decrease engineering costs and waste. It can also improve the energy efficiency of the process. It can also optimize design of the machines for the manufacturing process itself.	Productive Machines was founded in 2019. It does not publicly disclose funding, however it received around $130,000 from the ATI Boeing accelerator, which picked 10 companies to invest in. Sponsors of the program include Boeing, GKN Aerospace and Rolls-Royce.

Average fuel burn of new commercial jet aircraft

Manufacturer	Next-generation engine	Target service entry year	Fuel efficiency improvement
Pratt & Whitney	Geared turbofan (GTF) Advantage	2024	17%
Rolls Royce	UltraFan	2025	25%
GE, cfm	Revolutionary Innovation for Sustainable Engine (RISE)	by 2035	20%+

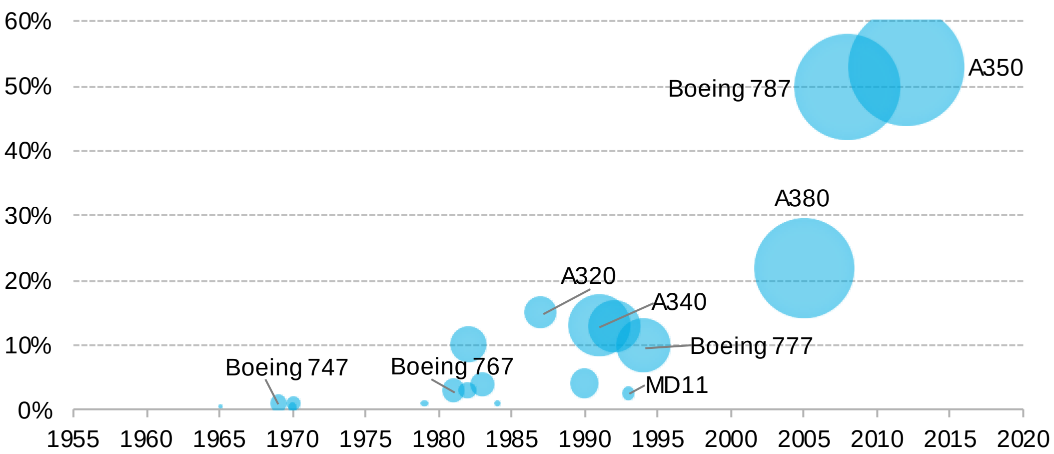
Source: Engine manufacturer websites, BloombergNEF

Aircraft design and manufacturing

3D composite manufacturing

	How does it work?	Maturity	
9T LABS	9T Labs produces 3D printers to print composite materials that are stronger and lighter than regular materials, with a particular use in the aerospace industry. 9T Labs automates and digitizes the production process, providing a self-built software-as-a-service suite that allows customers to come up with highly optimized specialist solutions for their needs. The ultimate aim is to allow serial manufacturing of complicated composite parts.	9T Labs was founded in 2018 and has raised almost $29 million. It raised $17 million in Series A funding in February 2022, counting Stratasys, ACE & Company and Solvay Ventures as investors.	Emissions reductions predicted from using carbon composites for planes vary, but are estimated at between 15% to 20% once aircraft are designed around composite architecture.
iCOMAT	iCOMAT has developed a patented process for manufacturing carbon-fiber composites that are supposedly lighter and stronger than standard composites. Its rapid tow shearing (RTS) process is supposedly the world's first automated process that can place carbon fiber tapes along curved paths without generating defects in material strength.	iCOMAT was founded in 2019, and has raised just over $2.7 million to date. No current customer deals could be found.	

Evolution of overall composite structural weight in commercial aircraft



Source: Aviation English Academy, BloombergNEF, aircraft manufacturer specifications.
Note: Bubble size represents composite content by weight in kg.

Materials strengths and weaknesses

	Composites (FRPs)	Metals	Plastics	Ceramics
Strength	Good	Good - Fair	Fair - Poor	Good
Brittleness	Fair - Poor	Good	Good	Poor
Thermal conductivity	Varies	Good	Poor	Poor
High temp performance	Fair	Good	Fair - Poor	Good
Electrical conductivity	Varies	Good	Poor	Poor
Weight	Good	Varies	Good	Poor
Cost	Fair - Poor	Varies	Good - Fair	Good – Fair
Processability	Poor	Fair	Good	Fair
Recyclability	Poor	Good	Fair	Fair

Source: BloombergNEF

Relevant research content

Research note	Links
2022 Aviation Fuel Outlook	web | terminal
Low-Carbon Aviation Technology Startup Investment Trends	web | terminal
Is Electric Aviation Ready for Takeoff?	web | terminal
Commuter Electric Aircraft Open a Path to Decarbonization	web | terminal
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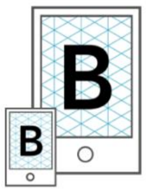

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