

# TEN CRITICAL INSIGHTS ON THE PATH TO A NET-ZERO AVIATION SECTOR



AVIATION INITIATIVE / OCTOBER 2021



**MISSION  
POSSIBLE  
PARTNERSHIP**



**Clean Skies  
for Tomorrow**

An initiative of the World Economic Forum

Supported by  
Energy  
Transitions  
Commission

**McKinsey  
& Company**

Aviation, shipping and trucking are the backbone of our global transport sector. Together with concrete, steel, aluminium, and chemicals, these seven sectors are jointly responsible for 30% of greenhouse gas emissions and, without action, this share is expected to grow. The mission is clear. Humanity needs to cut emissions by 50% in this decade to limit the rise in global temperatures to 1.5°C and reach net-zero emissions by 2050 at the latest. By 2030, we must see entire value chains committing to and transitioning towards net-zero emissions, and systems in place to reliably track those commitments. The next wave of low-carbon technologies must be brought to market and deployed on a scale that will unlock cost reductions. Simultaneously, industries need to stop investing in and begin retiring carbon-intensive assets.

Catalysing these changes is the goal of the Mission Possible Partnership (MPP), an alliance of climate leaders focused on supercharging efforts to decarbonize these industries. Led by the Energy Transitions Commission, RMI, the We Mean Business Coalition, and the World Economic Forum, our objective is to propel a committed community of CEOs from carbon-intensive industries, together with their financiers, customers, and suppliers, to agree – and more importantly, to act – on the essential decisions required for decarbonizing industry and transport. MPP will orchestrate high-ambition disruption through net-zero industry platforms for seven of the world's most carbon-intensive sectors: aviation, shipping, trucking, concrete, steel, aluminium, and chemicals.

The aviation sector has initiated ambitious efforts. The International Air Transport Association (IATA) committed to achieve net-zero carbon emissions by 2050, and the Air Transport Action Group (ATAG) provides corresponding technology projections up to 2050.<sup>1</sup> The European Union's "Fit for 55" package includes a proposed blending mandate for sustainable aviation fuels (SAFs) through the ReFuel EU Aviation initiative. Similarly, the US administration aims to increase the production of SAFs to at least 3 billion gallons/year by 2030. And the proposed US Sustainable Skies Act aims to cut aviation's carbon emissions through tax credits for SAFs that demonstrate a reduction in greenhouse gas emissions of at least 50%. An increasing number of individual airlines and airline associations have also made commitments to reduce emissions, with more than 30 pledging to achieve carbon neutrality by 2050. Also partnerships between the private and public sector are emerging, like the UK's Jet Zero Council.<sup>2</sup>

The Clean Skies for Tomorrow Coalition (CST) provides a crucial global mechanism for top executives and public leaders, across and beyond the aviation value chain, to align on a transition to SAFs as part of a meaningful and proactive pathway for the industry to achieve carbon-neutral flying. The Clean Skies for Tomorrow Coalition is led by the World Economic Forum in collaboration with RMI and the Energy Transitions Commission.

The MPP, together with the CST, has developed a sector transition strategy that outlines how the aviation sector can phase out fossil fuels by 2050. It has the aim to inform decision-makers from the public and private sector about the nature, timing, cost and scale of actions necessary to deliver net-zero within the sector. Through this work, we hope to inspire and inform an accelerated transition to net-zero for the aviation sector and expedite innovation, investments, and policies to support the transition.

The following 10 critical insights are a preview of this sector transition strategy. Two sectoral pathways have been modelled to 2050: the aviation's current business-as-usual (BAU) pathway and a climate ambition pathway.

- In the BAU pathway, the aviation industry seeks the lowest total cost of ownership (TCO) for aircraft, implementing new technologies only if they offer an economic advantage or are mandated by government regulations.
- The climate ambition pathway assumes progressive technology assumptions (regarding costs, fuel production efficiencies, and for hydrogen and battery-electric aircraft also their market entry and potential range) and the sector's willingness to pay a premium of up to 20%-50% for emissions-reducing technologies.

Underlying assumptions for both pathways are provided at the end of this document. Additional pathways, including a midpoint between the two pathways shown, will be modelled as part of a future full report.



## ACKNOWLEDGEMENTS

This report was codeveloped with members of the Clean Skies for Tomorrow community and the Target True Zero initiative. Although not all parties necessarily agree with each statement, the signatories below have formally endorsed the general thrust of the viewpoints expressed in this report. These companies agree on the importance of reaching net-zero emissions from the energy and industrial systems by mid-century and share a broad vision of how the transition can be achieved.

The fact that this agreement is possible between those industry leaders should give decision makers across the world confidence that it is possible to simultaneously meet the surging demand for aviation and reduce emissions from the sector to net-zero emissions by 2050. It also demonstrates that the critical actions required in the 2020s to set the sector on the right path are clear and can be pursued without delay, and that the industry is ready to collaborate with its value chain to achieve those goals.

Airbus Group  
Ampaire  
bp  
Copenhagen Airport  
Delta Air Lines  
Deutsche Post DHL Group  
EmbraerX  
Eve Air Mobility  
Heathrow Airport  
Joby Aviation  
KLM Royal Dutch Airlines  
Loganair  
London Luton Airport  
Luxaviation Group  
MagniX  
McKinsey & Company  
Neste  
Norsk e-Fuel  
Punjab Renewable Energy System Pvt. Ltd  
San Francisco International Airport  
Royal Schiphol Group  
SkyNRG  
Sounds Air  
Surf Air Mobility  
United Airlines  
Universal Hydrogen  
Virgin Atlantic Airways  
VoltAero  
Wright Electric  
ZeroAvia

This report was prepared by the Mission Possible Partnership modelling and analytics team. The team was led by Faustine Delasalle (Energy Transitions Commission, ETC), Timothy Reuter (World Economic Forum), Robin Riedel (McKinsey), Eveline Speelman (ETC) and Lauren Uppink Calderwood (World Economic Forum). The analysis was coordinated by Elena Gerasimova (McKinsey) and undertaken by Carlos Agnes (ETC), Andrea Bath (ETC), Charlotte Bricheux (McKinsey), Axel Esque (McKinsey), Maximilian Held (ETC), Jason Martins (ETC), Adam Mitchell (McKinsey), Daniel Riefer (McKinsey), Austin Welch (McKinsey) and Maaïke Witteveen (ETC), with input and guidance from the World Economic Forum's Laia Barbarà, David Hyde and Kevin Soubly, as well as RMI and the ETC. McKinsey & Company is a knowledge partner for the Mission Possible Partnership and provided fact-based analysis for this report.

We would like to thank the Clean Skies for Tomorrow Coalition and the Target True Zero Initiative, as well as other industry participants and experts, for their input.







### Mission Possible Partnership (MPP)

Led by the ETC, RMI, the We Mean Business Coalition, and the World Economic Forum, the Mission Possible Partnership (MPP) is an alliance of climate leaders focused on supercharging the decarbonisation of seven global industries representing 30 percent of emissions – aluminium, concrete, chemicals, steel, aviation, shipping, and trucking. Without immediate action, these sectors alone are projected to exceed the world's remaining 1.5°C carbon budget by 2030. MPP brings together the world's most influential leaders across finance, policy, industry and business. MPP is focused on activating the entire ecosystem of stakeholders across the entire value chain required to move global industries to net-zero. Learn more at [www.missionpossiblepartnership.org](http://www.missionpossiblepartnership.org).



### Clean Skies for Tomorrow Coalition

The Clean Skies for Tomorrow 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 Clean Skies for Tomorrow Coalition is led by the World Economic Forum in collaboration with the RMI and the Energy Transitions Commission. Learn more at [www.weforum.org/projects/clean-skies-for-tomorrow-coalition](http://www.weforum.org/projects/clean-skies-for-tomorrow-coalition).



### Energy Transitions Commission

#### Energy Transitions Commission (ETC)

ETC is a global coalition of leaders from across the energy landscape committed to achieving net-zero emissions by mid-century, in line with the Paris climate objective of limiting global warming to well below 2°C and ideally to 1.5°C. Our Commissioners come from a range of organisations – energy producers, energy-intensive industries, technology providers, finance players and environmental NGOs – which operate across developed and developing countries and play different roles in the energy transition. This diversity of viewpoints informs our work: our analyses are developed with a systems perspective through extensive exchanges with experts and practitioners. Learn more at [www.energy-transitions.org](http://www.energy-transitions.org).

### The World Economic Forum

The World Economic Forum is the International Organization for Public-Private Cooperation. The Forum engages the foremost political, business, cultural and other leaders of society to shape global, regional and industry agendas. Learn more at [www.weforum.org](http://www.weforum.org).

### McKinsey & Company

#### McKinsey & Company

McKinsey & Company is a global management consulting firm committed to helping organizations create Change that Matters. In more than 130 cities and 65 countries, their teams help clients across the private, public and social sectors shape bold strategies and transform the way they work, embed technology where it unlocks value, and build capabilities to sustain the change. Not just any change, but Change that Matters – for their organizations, their people, and in turn society at large. Learn more at [www.mckinsey.com](http://www.mckinsey.com).







# 1 The goal of net-zero aviation by 2050 is possible.

The BAU pathway does not achieve net-zero by 2050 and generates almost 40 Gt CO<sub>2</sub>e of cumulative emissions between 2022 and 2050. This means that aviation would use up 10% of the remaining global carbon budget, a significant mismatch to the industry's current contribution of approximately 2.5% of CO<sub>2</sub> emissions.<sup>i</sup> In the climate ambition pathway, approximately 25 Gt CO<sub>2</sub>e of emissions between 2022 and 2050 are eliminated, phasing out fossil jet fuel entirely by 2050.<sup>ii</sup> To achieve these goals, it is critical that governments around the world continue to invest in SAF production for today's fleets as well as incentivize zero-emissions technological solutions such as electric and hydrogen.

<sup>i</sup> Global carbon budget of 400 Gt CO<sub>2</sub> to stay on a 1.5°C pathway with a 67% probability taken from "Climate Change 2021: The Physical Science Basis," IPCC Sixth Assessment Report, 2021. Current greenhouse gas emission share of global aviation taken from Hannah Ritchie, "Climate change and flying: what share of global CO<sub>2</sub> emissions come from aviation?," 2020. Including the total climate impact of non-CO<sub>2</sub> climate forcers like NO<sub>x</sub>, contrails, and cirrus clouds would increase the climate impact of aviation substantially, as they amount to 66% of the total effective radiative forcing, see Lee et al., "The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018," Atmospheric Environment, vol. 244 (117834), 2021. These non-CO<sub>2</sub> climate forcers are not included in this analysis due to the high uncertainty ranges.

<sup>ii</sup> Even in this case, residual upstream emissions of ~0.15 Gt CO<sub>2</sub>e will remain in 2050, see insight #8.



Exhibit 1: In a climate ambition pathway, fossil fuels are entirely phased out by 2050

The aviation sector’s final energy demand by technology to 2050 in a BAU pathway (left) and a climate ambition pathway (right). On the current path (left), SAF allocation stems from the planned use of SAFs in the United States and the European Union. HEFA refers to hydroprocessed esters and fatty acids.

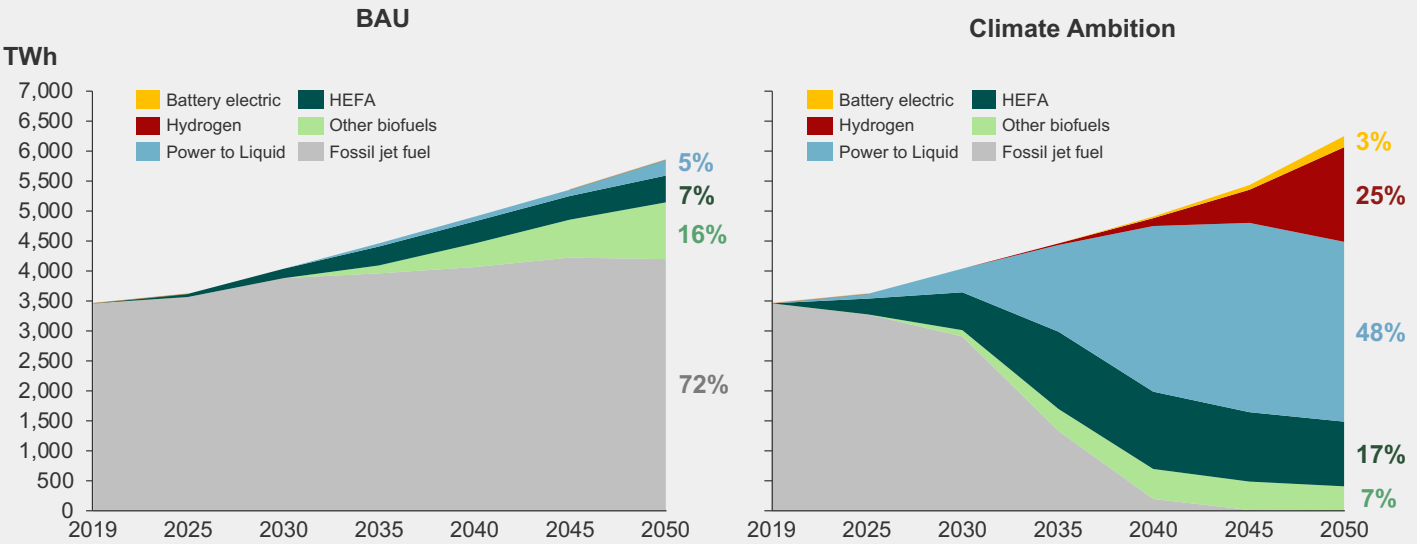
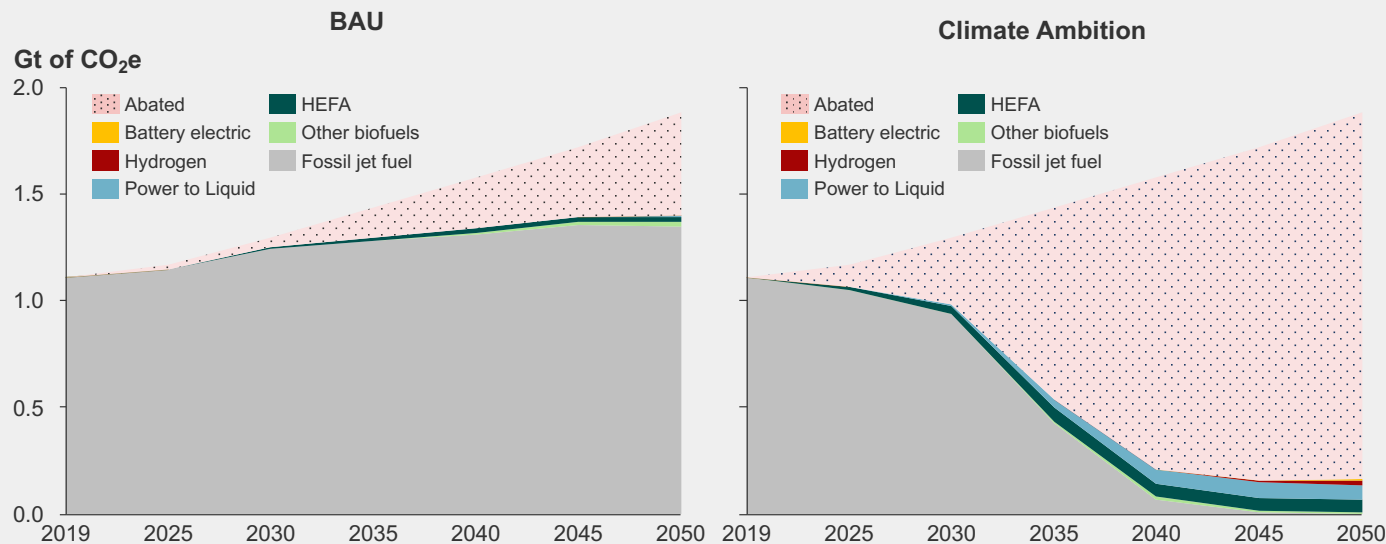


Exhibit 2: Climate ambition pathway would cut cumulative emissions by >60% compared with BAU

Aviation sector emissions by technology until 2050 in a BAU pathway (left) and a climate ambition pathway (right). Abated area shows emissions abated due to the use of renewable energy carriers compared to the use of fossil jet fuel. Remaining area represents CO<sub>2</sub>e emissions from fossil jet fuel and residual lifecycle emissions of renewable energy carriers. In the BAU path, “abated” emissions stem from the planned use of SAFs in the United States and the European Union.



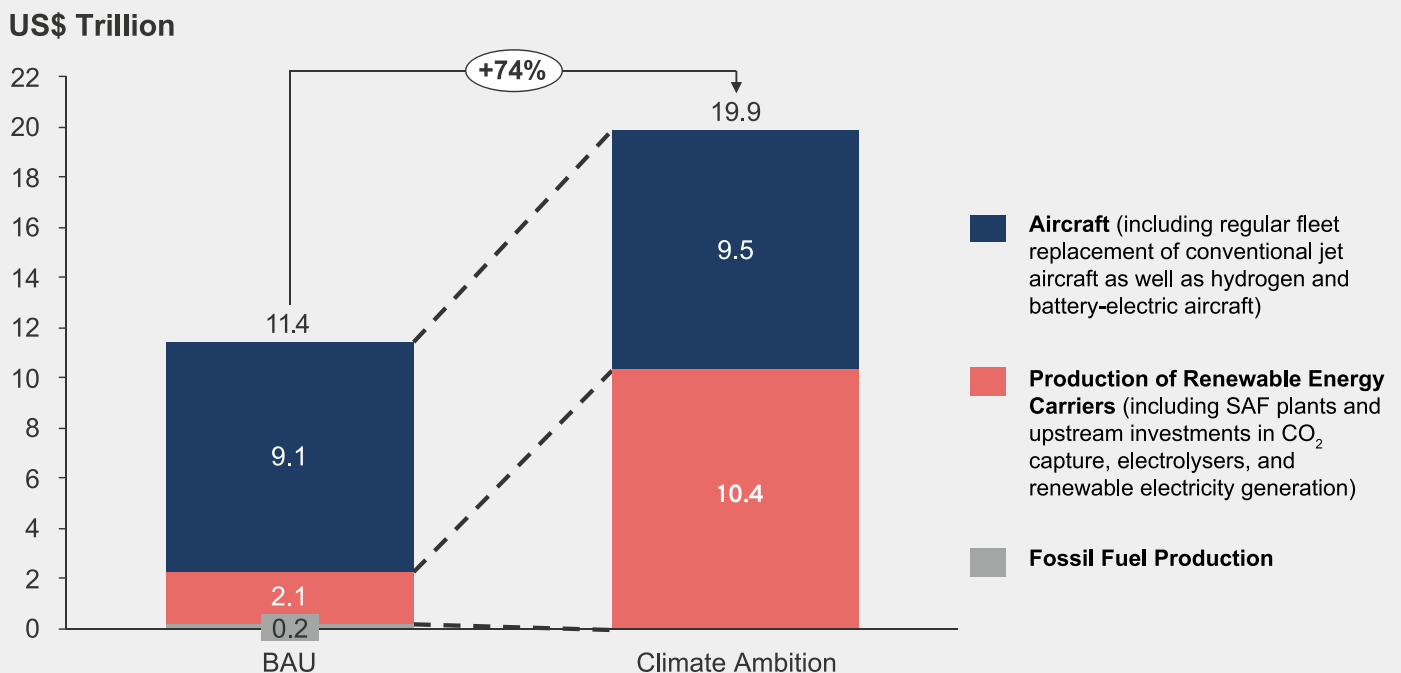
## 2 Phasing out fossil jet fuel by 2050 is likely to require additional annual investments of about US\$300 billion compared with the BAU path.

Large-scale investments will be required across the full aviation value chain. In the aggregate, phasing out fossil fuels by 2050 in the climate ambition pathway will require an additional average investment of approximately US\$300 billion each year in excess of BAU between 2022 and 2050. That includes the cost of developing and implementing disruptive technologies in aircraft, estimated at about US\$15 billion per year above

the BAU pathway. Most of the additional investments (on average US\$285 billion per year) will be required to finance the production of renewable energy carriers.<sup>iii</sup> This includes SAF production and upstream investments like CO<sub>2</sub> capture, electrolyzers, and dedicated new renewable electricity generation capacity, but excludes refuelling and recharging infrastructure at airports.

### Exhibit 3: Majority of investments needed to phase out fossil fuels will finance renewable energy carrier production

Cumulative investments (between 2022 and 2050) required for the BAU and the climate ambition pathway. Renewable energy carrier production includes fuel production facilities for biofuels and e-fuels (e.g., Fischer-Tropsch synthesis), as well as upstream investments for electrolyzers, CO<sub>2</sub> capture plants, and renewable electricity generation capacity.<sup>iv</sup>



<sup>iii</sup> Renewable energy carriers include sustainable aviation fuels (SAFs), hydrogen, and electricity for direct use in battery-electric aircraft. SAFs include biofuels (e.g., hydroprocessed esters and fatty acids [HEFA]) and power-to-liquids (PtL).

<sup>iv</sup> In the climate ambition pathway, investment costs for PtL are derived from a progressive assumption of low electricity costs and lower-cost solid oxide electrolysis.





### **3 Immediate action can unlock a reduction of ~1.5 Gt CO<sub>2</sub>e by 2030 and lay the foundation for large-scale adoption of renewable energy carriers in the longer term.**

Immediate action in the 2020s is necessary to enable the large-scale adoption of renewable energy carriers and can reduce cumulative emissions between 2022 and 2030 by ~1.5 Gt CO<sub>2</sub>e compared with the BAU path. Concentrated R&D and investment in fuel production plants are necessary to support the market entry and scale-up of SAFs immediately and that of other technologies in the midterm.

Early action is necessary to catalyse learning curves and reduce initially high fuel costs. In addition, the industry should keep investing in fuel efficiency gains for conventional engines, along with improved airframe design, ground operations, air traffic management, and route planning. These measures are expected to improve efficiency by 2% each year in both pathways and should remain a priority for the industry, in conjunction with the development of novel technologies.

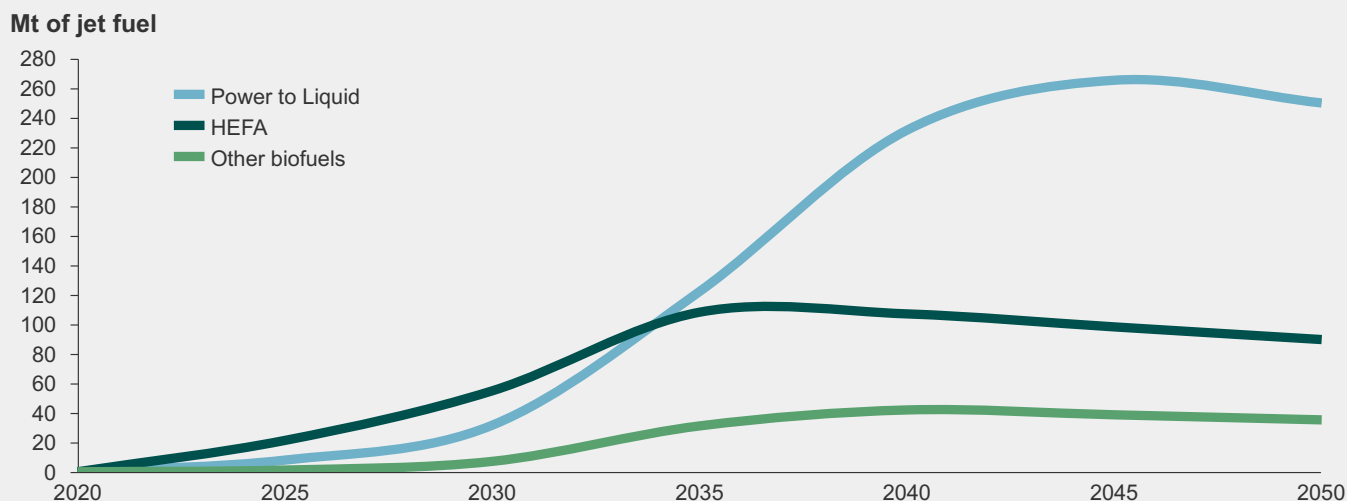
## 4 SAFs are the most viable short-term option for reducing CO<sub>2</sub>e emissions, and the industry should ramp up production and adoption.

In the short term, SAFs are the only viable option to decrease emissions in the aviation sector, as they are compatible with current aircraft engines and airport fuelling infrastructure and they can power flights without any limits of distance.<sup>v</sup> In the climate ambition pathway, 25%–30% of the sector's energy demand in 2030 could be met by SAFs if required investments into production and infrastructure ramp up were made.

Potential constraints on SAF feedstocks, along with a relatively immature supply chain, result in SAF costs that are ~3x higher than fossil jet fuel prices today.<sup>vi</sup> By 2050, SAF production costs could decrease by ~20%–50%, without considering carbon pricing for fossil jet fuel. Power to liquids (PtL) are expected to play a crucial role in the future, as their feedstock is theoretically unlimited and they can offer CO<sub>2</sub>e emissions reductions (on a life-cycle accounting basis) up to 100% compared with fossil jet fuel.<sup>vii</sup>

### Exhibit 4: In the climate ambition pathway, power to liquids are projected to dominate SAF production after 2035

Ramp-up of aviation sector SAF production until 2050 in a climate ambition pathway. The decline in SAFs from 2045 to 2050 is due to an increasing share of hydrogen.



<sup>v</sup> Currently, most certified SAFs have an upper blending limit of 50%, but this is expected to be lifted before a system-wide SAF blending rate of 50% is actually reached.

<sup>vi</sup> Average of a range of SAF costs against fossil jet fuel at ~US\$650/t in 2019.

<sup>vii</sup> With a fully decarbonized supply chain. [Sustainable Aviation Fuels as a Pathway to Net-Zero Aviation, Clean Skies for Tomorrow, 2020.](#)





## 5 Hydrogen-powered aircraft could cover up to ~25 % of the total energy demand in 2050.

Hydrogen propulsion technologies, including fuel-cell and combustion-powered aircraft, will be crucial for reducing CO<sub>2</sub>e emissions for mid-to-long-haul flights. In a progressive projection, hydrogen fuel cell aircraft could power flights up to ~2,000 km already in 2030, and hydrogen combustion aircraft could power flights over all distances starting in 2035.<sup>viii</sup> In this case, hydrogen could cover up to ~25% of the total energy demand in 2050, and potentially replace a large share of SAF beyond 2050 due to costs lower than SAFs starting in the 2040s. Together, both types of hydrogen-powered aviation could reduce cumulative CO<sub>2</sub>e emissions between 2022 and 2050 by up to ~2.5 Gt compared with the BAU path.

## 6 Battery-electric aircraft could become a viable option to reduce CO<sub>2</sub>e emissions on shorter flights starting in 2030.

One of the industry's most disruptive technologies to reduce aviation's total climate impact, battery-electric propulsion, is forecast to enter the market starting in 2025 under ambitious projections.<sup>ix</sup> Considering future breakthroughs in battery technology, battery-electric aircraft might be able to power flights up to ~2,000km.

In the climate ambition pathway, battery-electric aircraft could represent ~3 % of the sector's energy demand in 2050 and reduce cumulative CO<sub>2</sub>e emissions by ~0.5 Gt between 2022 and 2050 compared with using fossil jet fuel. Hybrid solutions, combining different propulsion technologies, will be crucial for enabling broader adoption and can combine novel propulsion and SAF in the future as a solution. To supply the future electricity demand, investing in charging infrastructure and renewable microgrids at the airport level could help alleviate pressure from the overall grid. Battery-electric regional aircraft for short-range flights and electric vertical take-off and landing (eVTOL) vehicles could create new markets.

<sup>viii</sup> Technology commercially available but not widespread in the fleet. Assumptions on hydrogen technology represent a progressive case and are based on consultations with a broad group of stakeholders including incumbent OEMs, engine manufacturers, airlines, airports, academic institutions, investors, and startups.

<sup>ix</sup> Technology projected to be commercially available but not widespread in the fleet.





## 7 Decarbonising aviation could require an additional 10,000 TWh of renewable electricity.

Decarbonising air transport has massive implications on the global energy system. If PtL and hydrogen are to dominate the energy mix in 2050, up to 10,000 TWh in additional renewable electricity production capacity would be required, comprising about 10% of the expected global electricity production in 2050.<sup>3</sup> This surge in demand for renewable electricity will likely coincide with the electrification of other sectors like road transport, an increased demand for hydrogen or hydrogen-derived fuels e.g. in the steel sector or for maritime shipping, and the overall transition of the power sector from fossils to renewables. In the face of competing demand, ramping up sufficient renewable electricity generation capacity—along with cross-sector collaboration—will be critical to decarbonise aviation and our global economy.



## 8 Negative emissions solutions can support the transition to net-zero but are not a replacement for an ambitious decarbonization pathway.

The climate ambition pathway projects wide adoption of renewable energy carriers by 2050, but it does not reduce emissions fully. The industry would still face residual emissions from fuel production of ~0.15Gt Co<sub>2</sub>e by 2050, which need to be mitigated by carbon dioxide removal solutions (either natural or technological). This would require an additional investment of about US\$15 billion from natural climate solutions (NCS); bioenergy, carbon capture, and storage (BECCS); and direct air carbon capture and storage (DACCS) in 2050 alone.<sup>x</sup> NCS, such as conservation, restoration, and improved land management provide a ready-to-market option for carbon removal. But finding truly sustainable and measurable options can be challenging particularly given that NCS will be in high demand across other industries.<sup>4</sup>

Technology-led solutions will likely be necessary, such as DACCS, which can remove CO<sub>2</sub> directly from the air. Yet, DACCS is years away from market readiness at scale, requires large volumes of clean power, and is expected to stay two to three times more costly than NCS.<sup>5</sup> Thus, the transition to net-zero can be aided by a portfolio of negative emissions solutions. They should not be used as a tool for compensating the continued use of fossil fuel. However, they can be used in the near-term in case renewable energy carriers are not introduced to the market quickly enough.

<sup>x</sup> Based on a mix of NCS, BECCS, and DACCS with an average carbon dioxide removal cost of US\$100/tonne of CO<sub>2</sub> taken from [Reaching Climate Objectives: the Role of Carbon Dioxide Removals, ETC, 2021](#). Note that the additional investments for NCS, BECCS, and DACCS are not included in the investment figures provided in insight #2.



## 9 Market forces alone will not be sufficient to close the cost gap between fossil jet fuel and renewable energy carriers—governments need to support the transition through policies that explicitly incentivize sustainable aviation.

A tailored and robust set of policies—underpinned by recognized sustainability standards—will be needed to overcome the technological and economic factors that have been preventing renewable energy carriers from scaling. For example, the proposed SAF blending mandate in the European Union, or the proposed Sustainable Skies Act in the United States, are key steps to making SAFs commercially viable. Policymakers should aim to ensure feedstock sustainability, support R&D for new pathways to market, de-risk private investments for

infrastructure, and stimulate demand through fiscal incentives and market mechanisms that appropriately price in the cost of jet fuels' CO<sub>2</sub>e emissions.<sup>xii</sup>

Stringent emissions reduction targets can enable long-term planning horizons that can help de-risk investments into renewable energy carriers. Additional tailored policies can promote a global level-playing field and forge collaboration across the value chain for specific solutions through national and international consortiums.



## 10 All stakeholders across the value chain can benefit from moving early towards renewable energy carriers.

Aside from policy interventions, accelerating the transition to net-zero will only be possible with a focus on the full value chain. Proactive collaboration among all stakeholders can resolve chicken-and-egg-problems of supply and demand, de-risk transition technology projects, and fairly distribute incremental costs. In fact, all stakeholders can benefit from this full-value-chain approach.

Early-mover airlines can establish a reputation as climate leaders in their sector, while airports can benefit from lower noise and pollutant emissions from landing and take-off. Fuel producers can benefit from government R&D grants for novel technologies, and can achieve economies of scale by aggregating demand for electricity, hydrogen, and biomass from different sectors. Finally, policymakers may be able to encourage greater local production, decrease dependence on conventional fuel, and improve energy security.

<sup>xii</sup> An upcoming dedicated SAF policy toolkit report by the CST will provide more detail and nuance on potential policy measures (to create a SAF market at scale).

## KEY MODELLING ASSUMPTIONS

### Model overview

The model estimates in five-year time steps between 2019 and 2050 how demand is met by supply. Within a fleet turnover model, existing aircraft are retired when they reach a certain age and new aircraft enter the fleet to make up the retired aircraft

and any demand increase. For new aircraft, the model selects its propulsion technology and energy carrier. For new and existing aircraft, it updates the blending rate of SAFs in every five-year step (assuming the maximum blending rates will reach 100% in the future). The two modelled pathways, their scope, and the model constraints are detailed below.

### Pathways

	Business-as-Usual (BAU) Pathway	Climate Ambition Pathway
Selection criterion for renewable energy carrier	Lowest total cost of ownership (TCO)	Lowest CO <sub>2</sub> e emissions within defined willingness to pay
Willingness to pay a premium <sup>xiii</sup>	No	Yes (20%–50%) Commercial segments: 20%–30% General aviation and public sector segments: 40%–50%
Availability of hydrogen and battery-electric propulsion systems	Conservative (First availability in: 2030 for battery electric and hydrogen fuel cell and 2040 for hydrogen combustion)	Progressive (First availability in: 2025 for battery electric and hydrogen fuel cell and 2035 for hydrogen combustion)
Levelized cost of renewable electricity (LCOE)	Conservative: based on offshore wind power	Progressive: based on solar PV power
Green hydrogen costs	Conservative: produced from offshore wind electricity and PEM (polymer electrolyte membrane) electrolysis	Progressive: produced from solar electricity and PEM electrolysis
Power-to-liquids technology costs	PEM electrolysis, point source capture of CO <sub>2</sub> in 2019, being fully replaced by direct air capture of CO <sub>2</sub> towards 2050.	Solid oxide electrolysis, point source capture of CO <sub>2</sub> in 2019, being fully replaced by direct air capture of CO <sub>2</sub> towards 2050.
Fossil fuel production investments	Investments in fossil fuel production include upstream and downstream investments in oil resulting from the increasing fossil jet fuel demand in this pathway. These have been estimated by calculating an incremental cost associated with increasing fossil jet fuel demand and the historical share of jet fuel investment per barrel of crude oil.	No additional investments in fossil fuel production are estimated. It is assumed all existing upstream, downstream, and refining capacities are able to meet the decreasing demand for fossil jet fuel in the coming decades.

<sup>xiii</sup> The Willingness-to-Pay more than the cheapest propulsion technology and energy carrier is defined on a total cost of ownership basis with a 20-year investment horizon.





## Scope of transition strategy

	Topic	Assumptions
General	Operations included	Commercial (passenger + cargo), general aviation and public sector
	Boundary of aviation emissions <sup>xiv</sup>	Scope 1 and Scope 3 category 3 emissions (well-to-wake, WTW)
	Aviation demand growth (2019–2050) <sup>xv</sup>	3.8% p.a. (impact of COVID not modelled, 2019 as reference year)
Decarbonization levers	Assumed annual efficiency gains from conventional propulsion technologies	2% p.a.
	Renewable energy carriers considered	<ul style="list-style-type: none"> <li>Sustainable aviation fuels, hydrogen fuel-cell, hydrogen combustion, and battery electric</li> <li>Hybrid technologies can play an important role beyond fully electric and pure hydrogen aircraft, but are not explicitly modelled</li> </ul>
	Range of SAFs modelled	<p>Biofuels:</p> <ul style="list-style-type: none"> <li>Hydroprocessed esters and fatty acid (HEFA)</li> <li>Other biofuels produced via gasification Fischer-Tropsch (G-FT), alcohol to jet (AtJ), pyrolysis, etc.</li> </ul> <p>E-fuels:</p> <ul style="list-style-type: none"> <li>Power to Liquid (PtL)</li> </ul>
	Investments considered	<ul style="list-style-type: none"> <li>Aircraft</li> <li>Renewable energy carriers: <ul style="list-style-type: none"> <li>Production of HEFA, other biofuels, and PtL</li> <li>CO<sub>2</sub> capture as feedstock for SAF production</li> <li>Green hydrogen to power hydrogen aircraft and as feedstock for SAF production</li> <li>Renewable electricity to power battery-electric and hydrogen aircraft and SAF production</li> </ul> </li> <li>Airport infrastructure investments are required for hydrogen and battery electric aircraft, but are not modelled in this iteration due to a lack of data granularity</li> </ul>

<sup>xiv</sup> In line with [Science-based target setting for the aviation sector, v1.0, SBTi, 2021](#).

<sup>xv</sup> Directionally in line with estimates of 4% from [Commercial Market Outlook 2021-2040, Boeing, 2021](#) and of 3% from [Waypoint 2050, ATAG, 2020](#).

<sup>xvi</sup> In line with Science-based target setting for the aviation sector, v1.0, SBTi, 2021 and with ICAO's aspirational goal until 2050, see [“Environmental Trends in Aviation to 2050,” Aviation and Environmental Outlook, ICAO, 2019](#).



## Scope of emissions

- The model accounts for emissions from scope 1 (jet fuel combustion, “tank-to-wake”) and scope 3 category 3 (production and transport of jet fuel, “well-to-tank”).<sup>xvii</sup>
- The emissions of fossil jet fuel are based on CORSIA’s lifecycle assessment (LCA) methodology at 89g CO<sub>2</sub>e/MJ, or 3.83t CO<sub>2</sub>e per ton of jet fuel consumed.
- New technologies have different abatement potentials compared with fossil jet fuel: HEFA (84%), other biofuels (75%–93%), PtL (93%), hydrogen (93%), and battery electric (95%).<sup>6</sup> These emission reduction factors are representing ambitious figures and could be smaller in their early market ramp-up.
- All emissions calculations account for the carbon dioxide equivalent (CO<sub>2</sub>e) emissions of CO<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub>O from well-to-tank activities (scope 3) and CO<sub>2</sub> emissions from tank-to-wake activities (scope 1). Following ICAO’s CORSIA methodology, CO<sub>2</sub>e emissions of CH<sub>4</sub>, N<sub>2</sub>O, and H<sub>2</sub>O from combustion are excluded.<sup>7</sup>
- The abatement potential of SAFs includes the impact of indirect land use change (ILUC) as estimated by ICAO. However, the reduction potential is limited to 100% versus emissions of the fossil jet baseline, following SBTi guidance.<sup>8</sup>
- The model does not account for the effective radiative forcing (ERF) of non-CO<sub>2</sub> pollutants like NO<sub>x</sub>, contrails, and cirrus clouds. They are, however, estimated to have significant impact: taking those effects into account, aviation could have a share of about 3.5% of the “net anthropogenic ERF.”<sup>9</sup> Recent insights point towards a considerable reduction of aviation-induced cloudiness through the use of SAFs.<sup>10</sup> This is not the case for a continued use of fossil jet fuel offset by DACCS.

## Model constraints<sup>xviii</sup>

- Technology constraints are based on the availability of hydrogen and battery-electric propulsion at certain points in time, and for specific flight ranges.
- Feedstock availability is constrained for biofuels, based on regional availability of crops, woody biomass, and waste feedstocks.
- Announced blending mandates in the European Union and SAF production goals in the United States are reflected in all calculations.<sup>xix</sup>

- New technologies entering the market are limited by initial ramp-up constraints per origin-destination flow (values for five-year step): 5% blending share of the total for each SAF type and 15% of the total energy demand for hydrogen and batteryelectric aircraft.
- Afterwards, all technologies are limited by a maximum threefold capacity addition in each five-year step. For SAFs, this capacity addition is defined in the form of a blending rate of the total final energy demand.

## Endnotes

<sup>1</sup> Net-Zero Carbon Emissions by 2050, IATA, 2021, <https://www.iata.org/en/pressroom/2021-releases/2021-10-04-03/>; and Waypoint 2050, ATAG, 2021, <https://aviationbenefits.org/environmental-efficiency/climate-action/waypoint-2050/>

<sup>2</sup> UK Department for Transport, 2021, <https://www.gov.uk/government/groups/jet-zero-council>

<sup>3</sup> Making Mission Possible, Energy Transitions Commission, 2020, <https://www.energy-transitions.org/publications/making-mission-possible/>.

<sup>4</sup> Reaching Climate Objectives: the Role of Carbon Dioxide Removals, ETC, 2021, <https://www.energy-transitions.org/wp-content/uploads/2021/05/ETC-NegEmiss-White-paper-v4-Final.pdf>.

<sup>5</sup> The Case for Negative Emissions, Coalition for Negative Emissions, 2021, <https://coalitionfornegativeemissions.org/wp-content/uploads/2021/06/The-Case-for-Negative-Emissions-Coalition-for-Negative-Emissions-report-FINAL-2021-06-30.pdf>; and Reaching climate objectives: the role of carbon dioxide removals, ETC, 2021, <https://www.energy-transitions.org/wp-content/uploads/2021/05/ETC-NegEmiss-White-paper-v4-Final.pdf>.

<sup>6</sup> ICCT: CO<sub>2</sub>-Based Synthetic Fuel: Assessment of Potential European Capacity and Environmental Performance, ICCT, 2017, <https://theicct.org/publications/co2-based-synthetic-fuel-assessment-EU>; Marta Yugo and Alba Soler, “A look into the role of e-fuels in the transport system in Europe (2030–2050),” Concawe, 2019, <https://www.concawe.eu/publication/a-look-into-the-role-of-e-fuels-in-the-transport-system-in-europe-2030-2050-literature-review/>; CORSIA Default Life Cycle Emissions Values for CORSIA Eligible Fuels, International Civil Aviation Organization, 2021, <https://www.icao.int/environmental-protection/CORSIA/Documents/ICA0%20document%2006%20-%20Default%20Life%20Cycle%20Emissions%20-%20March%202021.pdf>.

<sup>xvii</sup> In line with [Science-based target setting for the aviation sector, v1.0, SBTi, 2021](#).

<sup>xviii</sup> Detailed constraints and methodology to be shared along with the full report.

<sup>xix</sup> Even if, for example, European blending mandate has not been put in law yet.



<sup>7</sup> CORSIA Eligible Fuels – Life Cycle Assessment Methodology, International Civil Aviation Organization, 2019, [https://www.icao.int/environmental-protection/CORSIA/Documents/CORSIA%20Supporting%20Document\\_CORSIA%20Eligible%20Fuels\\_LCA%20Methodology.pdf](https://www.icao.int/environmental-protection/CORSIA/Documents/CORSIA%20Supporting%20Document_CORSIA%20Eligible%20Fuels_LCA%20Methodology.pdf).

<sup>8</sup> Dan Rutherford et.al., Science-based target setting for the aviation sector, v1.0, Science Based Targets Initiative, 2021, [https://sciencebasedtargets.org/resources/files/SBTi\\_AviationGuidanceAug2021.pdf](https://sciencebasedtargets.org/resources/files/SBTi_AviationGuidanceAug2021.pdf).

<sup>9</sup> Lee et al., “The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018,” Atmospheric Environment, vol. 244 (117834), 2021, <https://www.sciencedirect.com/science/article/pii/S1352231020305689?via%3Dihub>.

<sup>10</sup> Voigt et al., “Cleaner burning aviation fuels can reduce contrail cloudiness,” Communications Earth & Environment 2 (114), 2021, <https://www.nature.com/articles/s43247-021-00174-y>.

