MAKING NET-ZERO AVIATION POSSIBLE

An industry-backed, 1.5°C-aligned transition strategy

AVIATION TRANSITION STRATEGY / JULY 2022

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At current emissions levels, staying within the global carbon budget for 1.5°C might slip out of reach in this decade. Yet efforts to slow climate change by reducing greenhouse gas (GHG) emissions run into a central challenge: some of the biggest emitters of greenhouse gases into the atmosphere — transportation sectors like aviation, shipping and trucking, and heavy industries like steel, aluminium, cement/concrete, and chemicals manufacturing — are the hardest to abate. Transitioning these industries to climate-neutral energy sources requires complex, costly, and sometimes immature technologies, as well as direct collaboration across the whole value chain, including companies, suppliers, customers, banks, institutional investors, and governments.

Catalysing these changes is the goal of the Mission Possible Partnership (MPP), an alliance of climate leaders focused on supercharging efforts to decarbonise these industries. 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 decarbonising heavy industry and transport. Led by the Energy Transitions Commission, the Rocky Mountain Institute, the We Mean Business Coalition, and the World Economic Forum, MPP will orchestrate high-ambition disruption through net-zero industry platforms for seven of the world's most hard-to-abate sectors: aviation, shipping, trucking, steel, aluminium, cement/concrete, and chemicals.

The foundation of MPP's approach: 7 Sector Transition Strategies

Transitioning heavy industry and transport to net-zero GHG emissions by 2050 — while complying with a target of limiting global warming to 1.5°C from preindustrial levels — will require significant changes in how those sectors operate. MPP facilitates this process by developing **Sector Transition Strategies** for all seven hard-to-abate sectors.

A Sector Transition Strategy

is a suite of user-friendly tools (including a report, an online explorer, and an open-source model) aiming to inform decision makers from the public and private sectors about the nature, timing, cost, and scale of actions necessary to deliver net zero within the sector by 2050 and to comply with a 1.5°C target.

In line with industry-specific replacement cycles of existing assets (like steel plants or aircraft) and the projected increase in demand, the market penetration of viable decarbonisation measures each sector can draw on is modelled.

The objectives of the MPP Sector Transition Strategies are:

1. **To demonstrate industry-backed, 1.5°C-compliant pathways to net zero,** focusing on in-sector decarbonisation and galvanising industry buy-in across the value chain.

2. **To be action-oriented with clear 2030 milestones:** By quantifying critical milestones for each sector in terms of its required final energy demand, upstream feedstock resources, and capital investments, MPP wants to lay the foundation for tangible, quantitative recommendations of ways to reach these milestones through collaboration among industry, policymakers, investors, and customers.

3. **To be transparent and open:** MPP's long-term goal is to fully lay open the internal machinery of the Sector Transition Strategies, that is, to make its Python models open source and all data inputs open access. In addition, MPP is developing online explorers that bring the Sector Transition Strategy reports to life: individual users will be able to explore the results of the reports and to customize model input assumptions, study the impact of individual levers, and dive deeper into regional insights.

4. **To break free from siloed thinking:** The transition of a sector to net zero cannot be planned in isolation since it involves interactions with the broader energy system, for instance, via competing demands for resources from multiple sectors. All MPP Sector Transition Strategies are based on similar assumptions about the availability and costs of technologies and resources like electricity, hydrogen, or sustainable biomass. By providing a harmonized, cross-sectoral perspective, we intend to inform decision makers with a fair, comparable assessment of transition strategies for all seven sectors.

On the basis of its Sector Transition Strategies, MPP intends to develop practical resources and toolkits to help operationalize industry commitments in line with a 1.5°C target. Among others, the quantitative results of the Sector Transition Strategies will inform the creation of standards, investment principles, policy recommendations, industry collaboration blueprints, and the monitoring of commitments. These will be developed to expedite innovation, investments, and policies to support the transition.

Goals of the MPP Aviation Transition Strategy

This publication builds on the work of other aviation organizations that have announced initiatives to reduce emissions. In particular, we acknowledge and appreciate the following important building blocks to shape the aviation sector's decarbonisation path:

- *Waypoint 2050* by the Air Transport Action Group (ATAG) and its accompanying ICF report, *Fueling Net Zero*"[1]
- *Report on the Feasibility of a Long-Term Aspirational Goal (LTAG) for International Civil Aviation CO_2 Emission Reductions* by the International Civil Aviation Organization (ICAO)[2]
- *Decarbonising Air Transport* by the International Transport Forum (ITF) and the Organisation for Economic Co-operation and Development (OECD)[3]
- *Horizon 2050: A Flight Plan for the Future of Sustainable Aviation* by the Aerospace Industries Association (AIA) and Accenture[4]
- *Destination 2050* by European aviation industry associations[5]
- *2021 Aviation Climate Action Plan* by the US Federal Aviation Administration[6]
- *PtL Roadmap* by the government of Germany[7]
- *Decarbonisation Road-Map* by Sustainable Aviation for the United Kingdom[8]
- *Roadmap to Climate Neutral Aviation in Europe* by Transport & Environment [9]

Through the support of industry stakeholders from the Clean Skies for Tomorrow (CST) and Target True Zero (TTZ) initiatives,[i] MPP has considered the different perspectives of the roadmaps above and has developed **an industry-backed Sector Transition Strategy** that outlines how the global aviation sector can reach net-zero GHG emissions by 2050 while also complying with a 1.5°C target. Beyond that, **it takes the next step from strategic thinking to near-term milestones and provides recommendations for action for industry, policymakers, and financial institutions on ways to unlock the transition in this decade.**

i The Clean Skies for Tomorrow (CST) and the Target True Zero (TTZ) initiatives of the World Economic Forum convene top executives and public leaders, across and beyond the aviation value chain, to accelerate the uptake of Sustainable Aviation Fuels and novel propulsion aircraft.

Industry support for MPP's Aviation Transition Strategy

This report constitutes a collective view of participating organizations in the Aviation Transition Strategy, foremost the CST and TTZ community. Participants have validated the model inputs and architecture, and endorse the general thrust of the arguments made in this report, but their endorsement should not be taken as agreeing with every finding or recommendation. These companies agree on the importance of limiting global warming to 1.5°C and the importance of reaching net-zero GHG emissions in heavy industry and transport by mid-century, and they share a broad vision of how the transition can be achieved. The fact that this agreement is possible among the industry leaders listed below should give decision makers across the world confidence that it is possible to meet simultaneously rising air travel demand, reduce emissions from the sector to net zero by 2050, and comply with a 1.5°C target. It should also provide assurance 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.

1. ACI
2. Aena
3. AeroMéxico
4. Aeroporto di Roma
5. Air France–KLM Group
6. Air France
7. Air New Zealand
8. Airbus
9. Alaska Airlines
10. Amelia International
11. American Airlines
12. American Express Global Business Travel
13. ASL Aviation
14. Boeing
15. Boom Supersonic
16. bp
17. Brisbane Airport Corporation
18. Caphenia
19. Carbon Engineering
20. Cargolux
21. Cathay Pacific
22. Chooose
23. Dubai Airports
24. EasyJet
25. EDL Anlagenbau Gesellschaft mbH
26. Embraer Commercial Aviation
27. Eve Air Mobility
28. Faradair Aerospace Limited
29. Fly Victor
30. Fraport
31. GenZero
32. Gol Linhas Aéreas
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48. Novo Nordisk
49. Occidental Petroleum
50. Oneworld Alliance
51. Praj
52. Prometheus
53. Qatar Airways
54. Repsol
55. SAF+ Consortium
56. Schiphol
57. Shell
58. SkyNRG
59. Sounds Air
60. Sunfire
61. SYSTEMIQ
62. Twelve
63. Vancouver Airport Authority
64. Varo Energy
65. Velocys
66. Virgin Atlantic
67. VoltAero
68. Widerøe Zero
69. Wright Electric

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PREPARED BY

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% of emissions: aviation, shipping, trucking, steel, aluminium, cement/concrete, and chemicals. Without immediate action, these sectors alone are projected to exceed the world's remaining 1.5°C carbon budget by 2030 in a Business-as-Usual scenario. 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. **www.missionpossiblepartnership.org**

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 organizations — 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. **www.energy-transitions.org**

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 we 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. McKinsey & Company is a knowledge partner for the Mission Possible Partnership and provided fact-based analysis for this report. Learn more at **www.mckinsey.com**.

Clean Skies for Tomorrow (CST)

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

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**.

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Target True Zero Coalition

The Target True Zero Coalition, led by the World Economic Forum, brings together leaders from across the aviation sector to understand the role that new technologies such as electric and hydrogen aircraft can play in delivering flying with a true zero climate impact. The coalition works to establish consensus on the key issues that will be required to realize the benefits of alternative propulsion in aviation and identify unlocks to accelerate the development and deployment of technologies with reduced climate impact. Learn more at **www.weforum.org/agenda/2021/07/targeting-true-net-zero-aviation/**.

CONTENTS

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

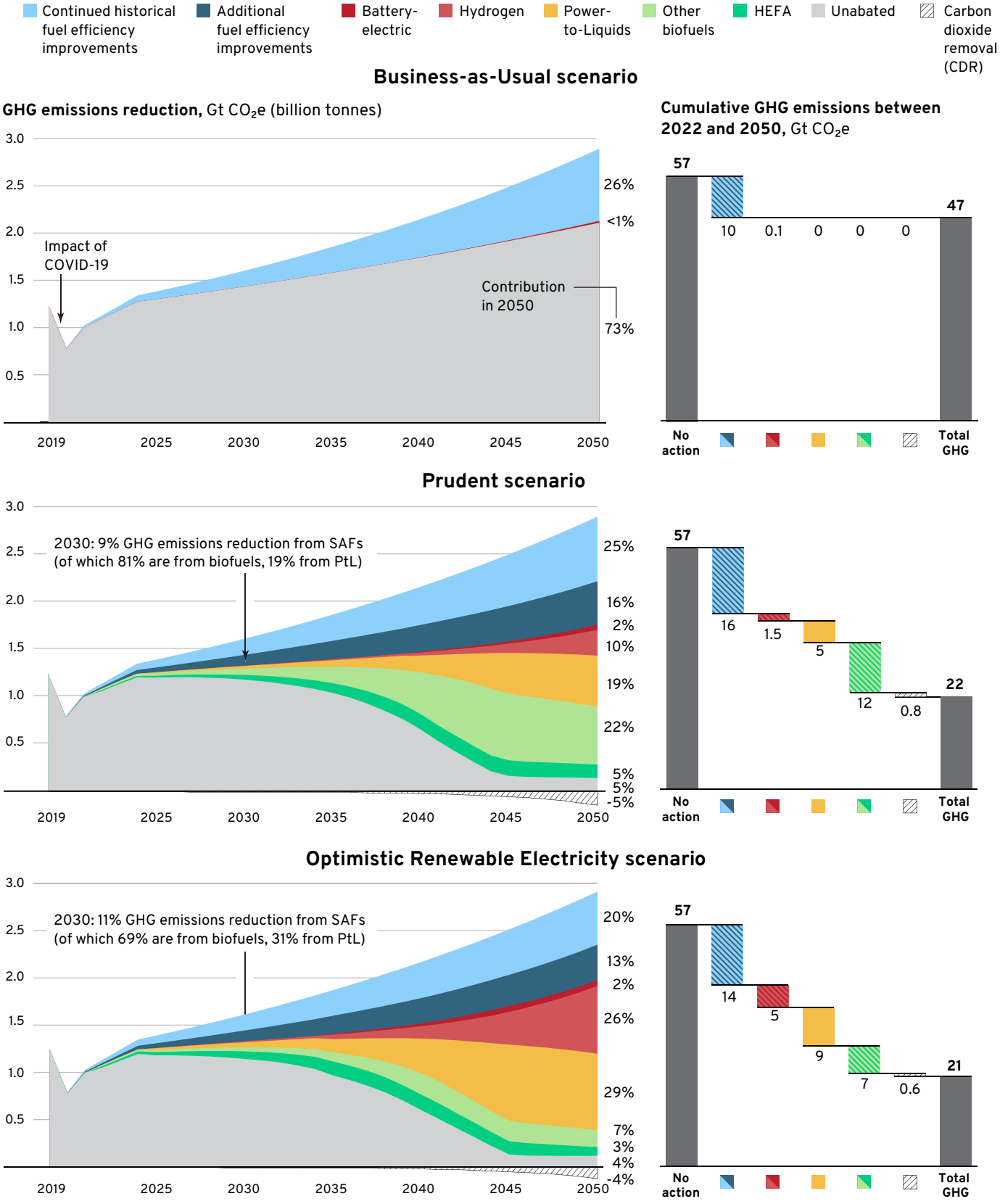
1. Bringing aviation on a path to net-zero emissions by 2050 requires a doubling of historical fuel efficiency gains of aircraft, a rapid roll-out of Sustainable Aviation Fuels (SAFs), and the market entry of novel propulsion aircraft in the mid-2030s.

In 2019, global aviation was responsible for GHG emissions of 1.2 Gt CO_2e[ii] — about 2% of global anthropogenic GHG emissions and 3.5% of the anthropogenic climate impact (measured in net effective radiative forcing). In contrast to a Business-as-Usual (BAU) scenario, two net-zero scenarios combine a different set of decarbonisation measures to reach net zero by 2050 (Exhibit A). The main difference between the Prudent (PRU) scenario and the Optimistic Renewable Electricity (ORE) scenario is that the latter assumes a faster cost decline of renewable electricity and hence, more favorable economic conditions for electricity-based technologies. As a result, SAFs produced from electricity (Power-to-Liquids, PtL) as well as hydrogen and battery-electric aircraft enter the market earlier and at a larger scale — in contrast to the PRU scenario in which biofuels prevail.

ii Global aviation includes commercial passenger, commercial cargo, public sector, and general aviation. In 2019, the total emissions of global aviation of 1.24 gigatonnes (Gt) CO_2-equivalent (CO_2e) consisted of 1.02 Gt CO_2 tank-to-wake and 0.22 Gt CO_2e upstream (well-to-tank) emissions.

EXHIBIT A

A combination of GHG reduction levers can make net-zero aviation a reality



Note: Sums in contributions to 2050 GHG emissions may not total 100 due to rounding. Source: MPP analysis

For both net-zero scenarios, fuel efficiency improvements of aircraft and SAFs play the largest role in reducing emissions. Doubling the annual fuel efficiency gains compared with historical developments could avoid about 14–16 Gt CO_2e between 2022 and 2050 compared with a future without any climate action. SAFs can further reduce emissions by 16–17 Gt CO_2e.

Common ground between two net-zero scenarios

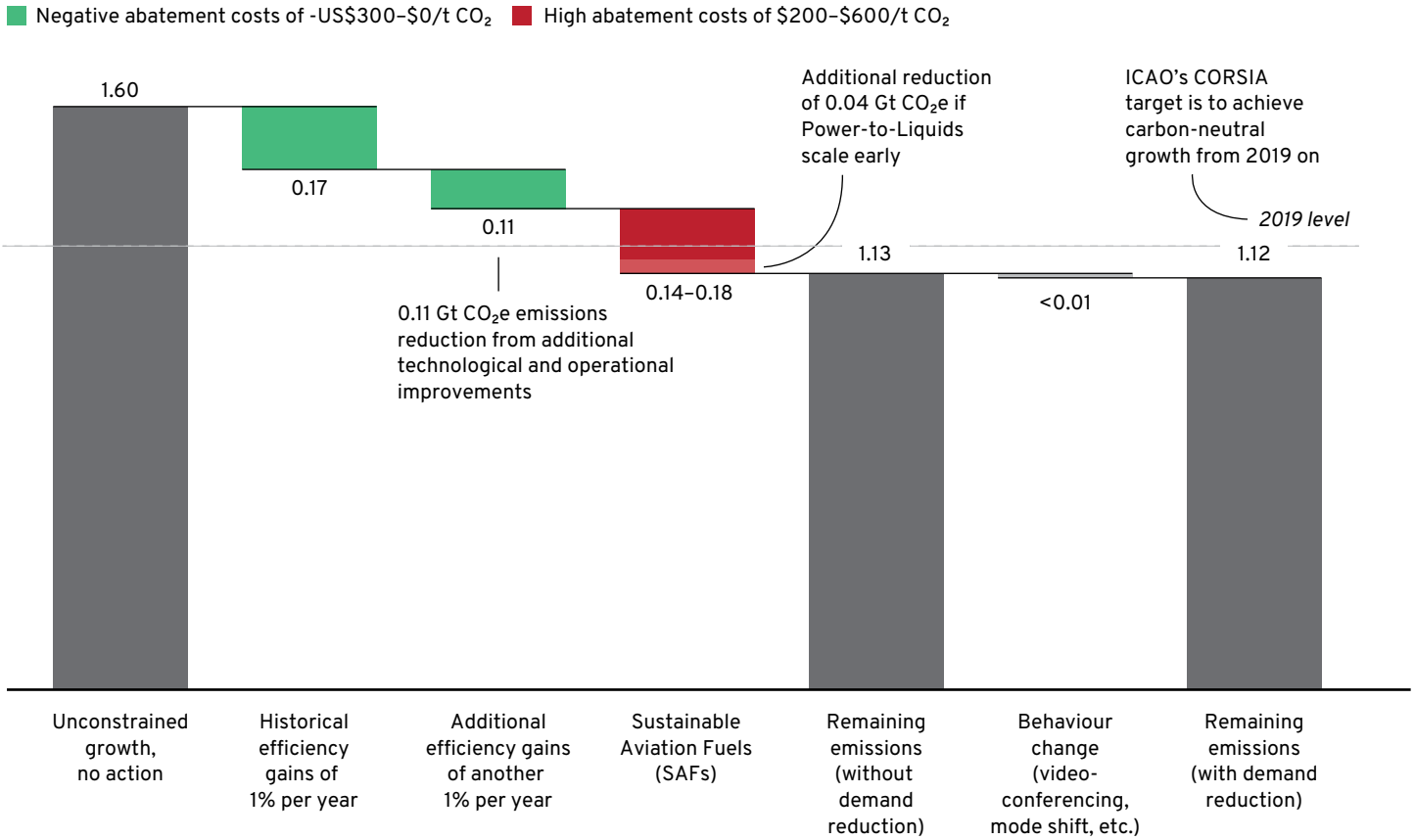
Carbon-neutral growth until 2030 is feasible (Exhibit B) if yearly fuel efficiency gains can be doubled compared with historical gains and if the production capacity of Sustainable Aviation Fuels (SAF) can be ramped up by a factor of 5–6 compared with existing and planned plants. Demand reduction triggered by a shift of short-haul flights to high-speed rail and behaviour changes (e.g., reduced business travel due to videoconferencing) could save an additional 5 megatonnes (Mt) CO_2e in 2030 if the required high-speed rail network were available.

Net-zero emissions by 2050 are feasible (Exhibit C) if yearly fuel efficiency gains can be doubled compared with average historical gains; SAF production capacity can be scaled up by a factor of 35–45 compared with existing or planned plants; hydrogen, battery-electric, and hybrid-electric aircraft enter the market in the mid-2030s; and carbon dioxide removals (CDR) counterbalance the residual emissions of renewable fuels by 2050, which can reduce GHG emissions compared with fossil jet fuel by about 75%–95% but not 100%. Demand reduction could cut the amount of SAF needed in 2050 by about 10%–15%.

EXHIBIT B

How carbon-neutral growth until 2030 could be achieved

GHG emissions in 2030, Gt CO_2e



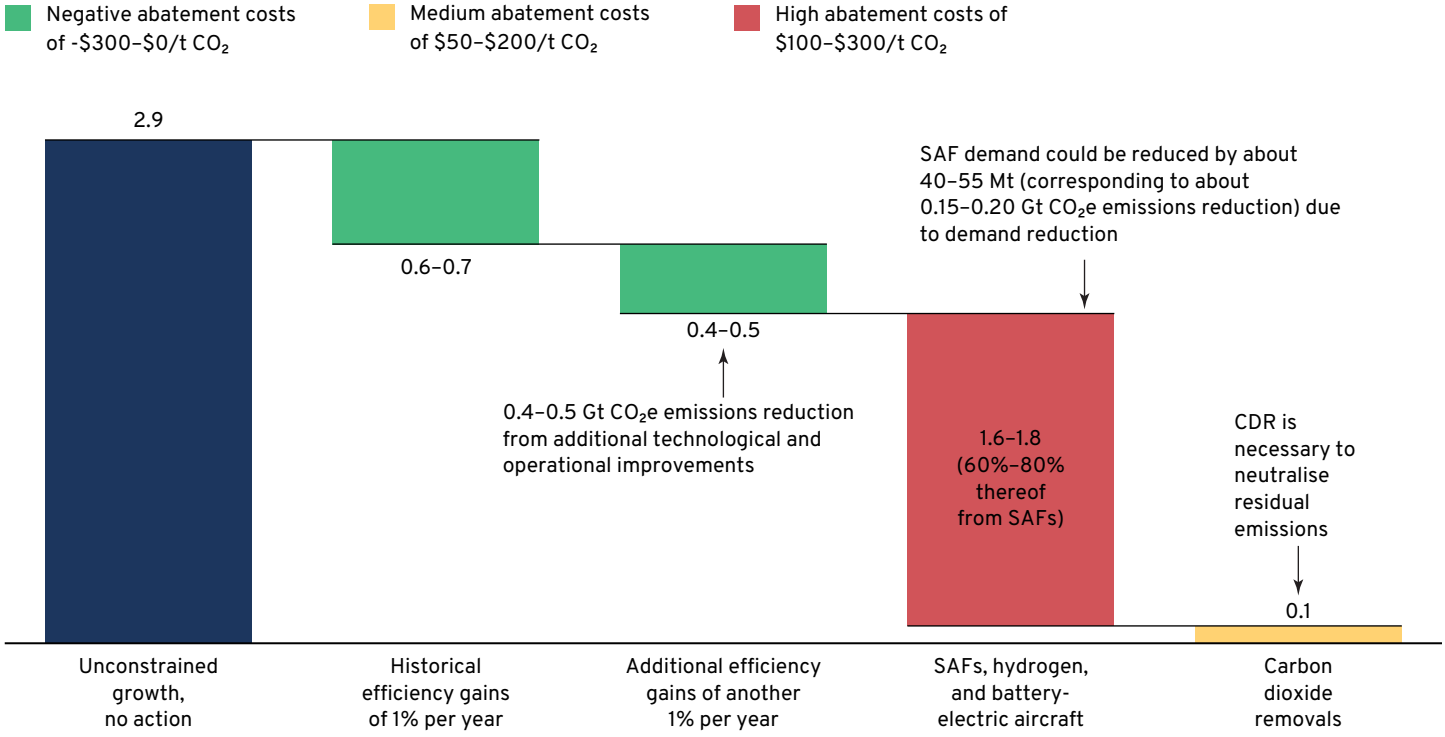
Note: Totals may not equal sums due to rounding.

Source: MPP analysis

EXHIBIT C

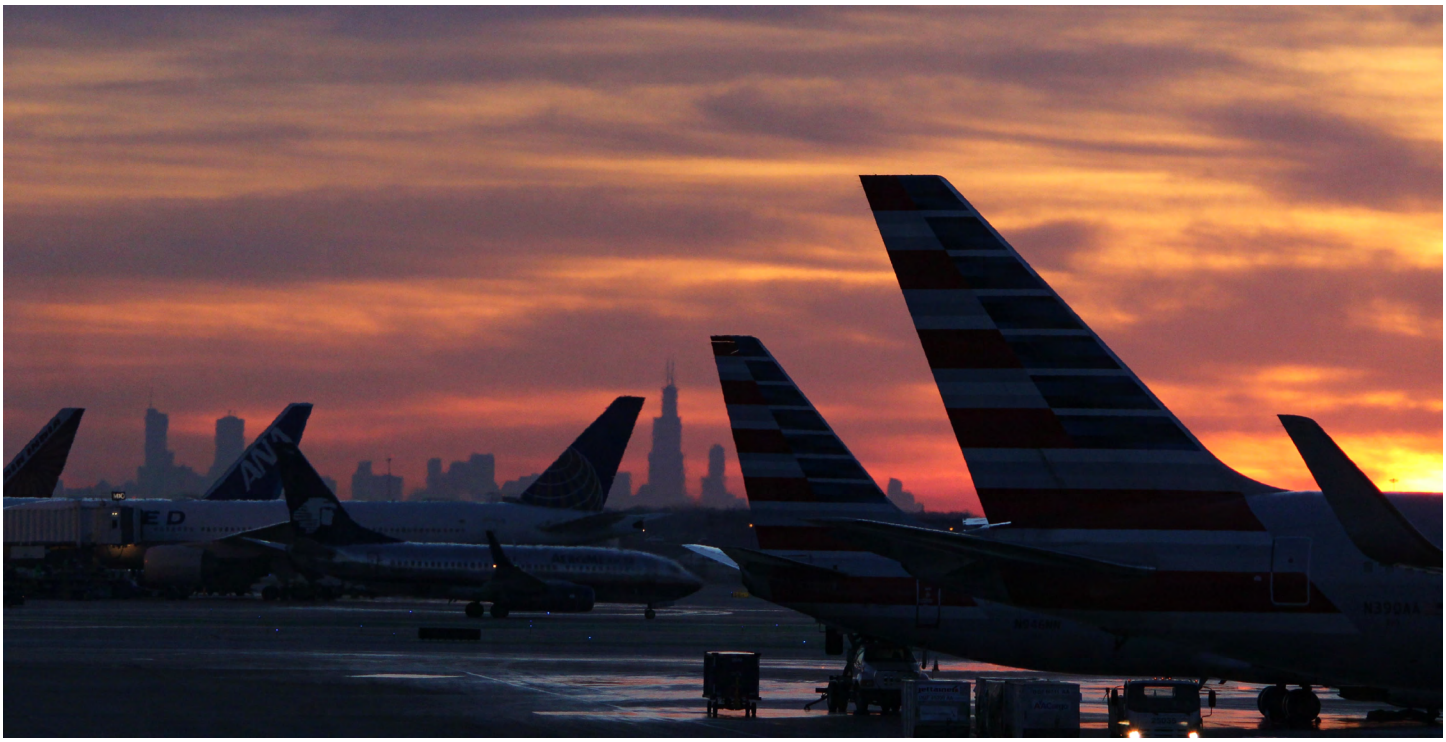
How net zero by 2050 could be achieved

GHG emissions in 2050, Gt CO_2e (billion tonnes)



Note: Totals may not equal sums due to rounding.

Source: MPP analysis

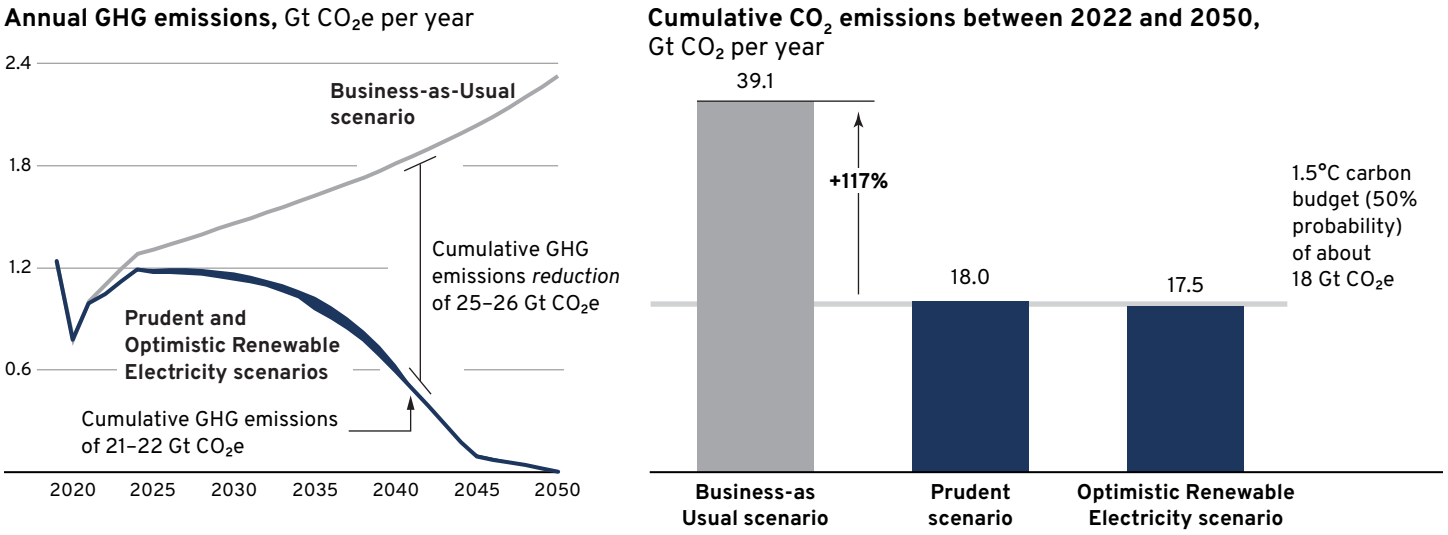


2. Aviation can comply with a sectoral 1.5°C carbon budget if all levers are pulled. Achieving net zero by mid-century avoids cumulative GHG emissions of 25–26 Gt CO_2e.

In a BAU scenario, cumulative GHG emissions between 2022 and 2050 sum to 47 Gt CO_2e, of which roughly 39 Gt are from in-flight CO_2 emissions (Exhibit D) — an overshoot of more than 100% against a 1.5°C carbon budget for global aviation of about 18 Gt CO_2.[iii] In contrast, the two net-zero scenarios are roughly in line with a 1.5°C carbon budget, being responsible for cumulative GHG emissions of only 21–22 Gt CO_2e, of which about 18 Gt CO_2 are in-flight CO_2 emissions and life-cycle CO_2 emissions of renewable fuels.

Both net-zero scenarios halve the cumulative GHG emissions of the BAU scenario

EXHIBIT D



Note: For the carbon budget comparison, only CO_2 emissions are compared (not GHG emissions) since the 1.5°C carbon budget is defined for CO_2 only, while it assumes a similar emissions reduction trajectory for non-CO_2 emissions. Similarly, we assume here that non-CO_2 emissions from aviation are reduced in a similar trajectory as CO_2 emissions. For the cumulative emissions, we have accounted for tank-to-wake CO_2 emissions of fossil jet fuel and life-cycle CO_2 emissions (incl. Scope 1 and Scope 3) for renewable fuels. Based on industry expertise and Chipindula et al. (2018), we have assumed that 95% of the assumed life-cycle GHG emissions are CO_2, the rest from non-CO_2 species. Only for waste-based fuels (e.g., used in G/FT or AtJ processes), we have assumed that 90% of the life-cycle GHG emissions are CO_2. The cumulative emission figures include emissions reductions from CDR.

Source: MPP analysis; Jesuina Chipindula et al., "Life Cycle Environmental Impact of Onshore and Offshore Wind Farms in Texas", *Sustainability* 10, no. 6 (June 2018)

iii The sectoral 1.5°C carbon budget is calculated as of the beginning of 2022 at a 50% probability of achieving a 1.5°C target. It has been broken down from a global carbon budget from the IPCC to individual sectors following an average of the sectoral allocations of BNEF NEO and IEA NZE reports. The methodology is documented in Box 1 (main text) and the *Technical Appendix*. See IPCC, "Summary for Policymakers", in *Global Warming of 1.5°C: An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty*, eds. Valérie Masson-Delmotte et al. (2018); BloombergNEF, *New Energy Outlook 2021 Executive Summary*, July 2021; and IEA, *Net Zero by 2050: A Roadmap for the Global Energy Sector*, May 2021. NZE refers to the "Net Zero Emissions by 2050 Scenario" of the IEA.

3. Average annual investments between 2022 and 2050 to get global aviation to net zero are estimated at about US$175 billion, about 95% of which would be required for fuel production and upstream assets.

Achieving carbon-neutral growth till 2030 (that is, maintaining the same levels of emissions as in 2019) would need average annual investments of about $40 billion to $50 billion in this decade. Until mid-century, a total annual capital investment of about $175 billion would be required (Exhibit E). This compares with aviation's yearly contribution to global GDP of roughly $2 trillion.

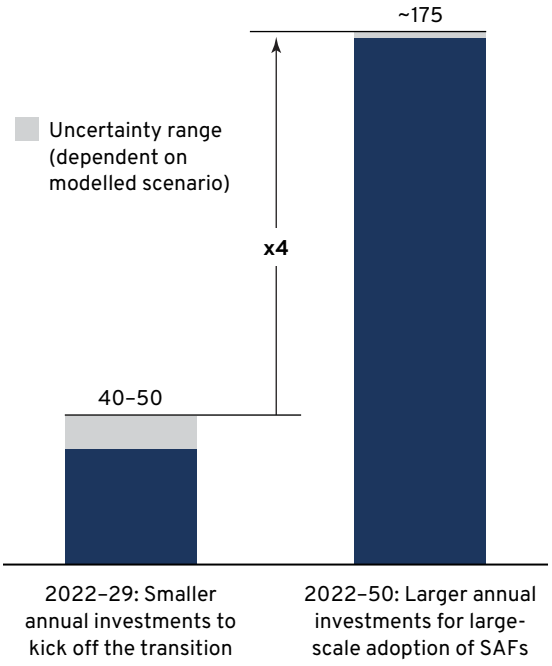
Of these investments, 92%–96% are required for the production of renewable fuels — including not only the final fuel production but also all upstream assets: about 30%–50% of that capital is required for new SAF production plants, about 35%–50% for new renewable electricity generation capacity, and the rest for CO_2 capture plants and electrolysers.

The remaining 4%–8% of the total investment requirement flows into the development of battery-electric, hybrid-electric, and hydrogen aircraft. The total annual capital investments do not include the capital cost of new conventional jet aircraft that would also be required for a regular fleet substitution/expansion without decarbonising. Since SAFs can simply be blended to fossil jet fuel as drop-in fuels, their impact on aircraft capital costs is negligible compared with investments required in the fuel production chain.

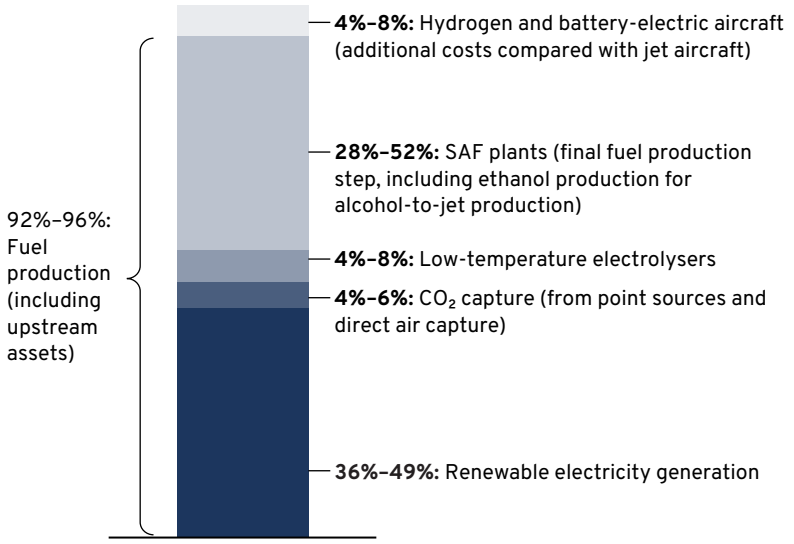
Investments to bring global aviation to net zero

EXHIBIT E

Annual investments across the whole value chain, billion $ per year, required for net zero by 2050



Breakdown of capital requirements across value chain, Percentage ranges dependent on modelled scenario



Source: MPP analysis

4. Current project pipelines for SAF production are insufficient and need to be scaled up by a factor of 5–6 until 2030.

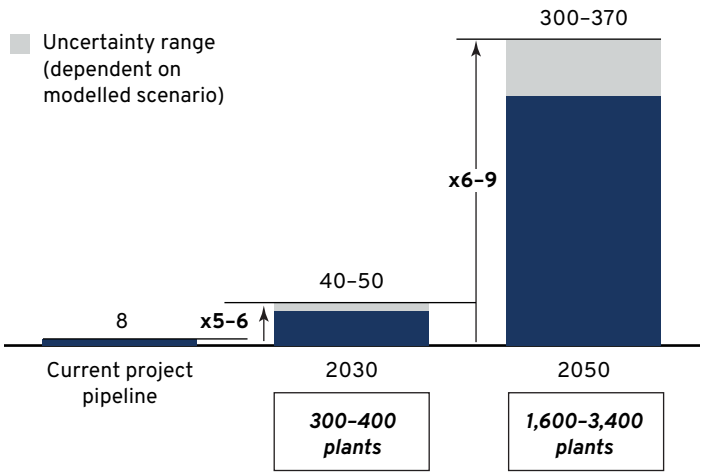
Sustainable bio-jet fuel and electricity-based (PtL) fuels need to be brought to market by 2030 to enable the massive scale-up in the 2030s that will be required to achieve net zero by 2050. To achieve SAF production levels of 40–50 Mt by 2030, investments into about 300–400 new fuel production plants and associated upstream infrastructure need to be made (Exhibit F). In particular, this 2030 target will be a challenge considering that it takes at least five years to build a new SAF plant and get it to full operation. With eight years left until 2030, new SAF plants need to be planned within the next two to three years if they are meant to meet 2030 targets.

Since the availability of sustainable biomass resources is limited, policies should incentivise priority use of biomass for sectors like aviation that have few other alternatives to decarbonise. To accelerate the scale-up of bio-jet fuel production, ethanol production volumes currently supplying the road transport sector could be redirected to the aviation sector. The electrification of cars will most likely free up certain ethanol volumes that can be transformed into bio-jet fuel via the alcohol-to-jet process. In addition, HEFA (hydroprocessed esters and fatty acids) plants could decrease their diesel outputs in favour of jet fuel. Both measures combined could unlock additional SAF supply of 14–22 Mt by 2030, about 25%–50% of the SAF demand in that year.

EXHIBIT F

How SAF project pipeline needs to be scaled

SAF production volumes in net-zero scenarios, Mt



Assumed plant sizes: SAF output capacities of 0.3 Mt/y for PtL and HEFA, 0.065 Mt SAF/y for other biofuels.

Source: MPP analysis

5. The faster the cost decline in renewable electricity generation, the higher the expected market share of PtL. In contrast, if electricity costs do not drop as rapidly, biofuels are likely to dominate the market.

To decarbonise aviation, a combination of different renewable fuels will be required, foremost biofuels, PtL, and hydrogen. In particular, there is a trade-off between the use of sustainable biomass on one hand and renewable electricity and green hydrogen on the other. While biofuels are the only SAF option today, PtL is projected to enter the market on a large scale in the late 2020s and become cheaper in the mid-2030s. The PtL market share by 2050 depends on how fast the levelised cost of electricity will fall in the next 15 years. Low electricity costs will lead to low green hydrogen production costs and finally low PtL costs that outcompete biofuels. Such a situation is reflected in our ORE scenario, in which PtL constitutes the main SAF type from around 2040 onwards. However, if the cost decline of renewable electricity generation is slower, biofuels are expected to dominate the market in 2050 if (and only if) sufficient volumes of sustainable biomass — which is subject to global resource constraints — can be directed to the aviation sector. This is reflected in the PRU scenario. Although the future might lie between those two scenarios, the high demand volumes of SAF will in any case require both fuel production pathways to deliver SAF.

6. Hydrogen and battery-electric aircraft can make global aviation more efficient starting in the late 2030s and supply up to a third of the final energy demand in 2050.

Hydrogen aircraft could enter the market in the 2030s and scale up through 2050 to reach as much as roughly a third of aviation's final energy demand by then (Exhibit G). With current aircraft designs, hydrogen aircraft could be range limited to about 2,500 km because storing hydrogen compared with jet fuel currently requires at least five times more volume to carry the same amount of energy. A redesign of airframes and storage technology innovation could, however, unlock longer ranges without reducing the number of available seats. If hydrogen aircraft were to enter the market around 2035 and achieve high ranges, they could gain a market share of about 32% by 2050 in terms of aviation's final energy demand. If they enter the market only at around 2040 and achieve lower ranges, their impact will be lower and rank at about 13% of the final energy demand by 2050.

Assuming breakthroughs in battery chemistries, battery-electric aircraft could potentially power regional aircraft on flights up to about 1,000 km by mid-century. Although they could replace more than 15% of the global jet aircraft fleet through 2050, they would contribute to only about 2% GHG emissions reduction because of their range limitation.

"Green corridors" could kick off the introduction of hydrogen and battery-electric aircraft, providing the necessary refuelling/recharging infrastructure at two dedicated airports with regular operations between them.

The technological potential of renewable fuels

EXHIBIT G

Best Medium Worst

	Battery-electric	Hydrogen	SAFs	
Efficiency of fuel production and propulsion system	~60%	~25%	~15%	Hydrogen and battery-electric aircraft are more efficient than jet fuel-powered aircraft, but can only perform short- to mid-haul flights.
Maximum range in 2050	Few 100s km up to 1,000 km	2,500 km up to no limitation	No limitation	
Expected large-scale market entry	Around 2035–40		<2030	
Share of cumulative GHG emissions reduction from renewable fuels (2022–50)	2%–3%	8%–22%	75%–91%	SAFs enter the market earlier and therefore have a larger impact on GHG emissions reduction.
Share of final energy demand in 2050	~2%	13%–32%	65%–85%	

Note: The GHG reduction potential of renewable fuels (SAFs and hydrogen and battery-electric aircraft) is defined by a trade-off between maximum aircraft range, expected market entry, and well-to-wake efficiency.

Source: MPP analysis

7. By 2050, net-zero aviation could require an additional 5,850 terawatt-hours (TWh) of renewable electricity (5% of the expected global demand), 95 million tonnes of hydrogen (10%–20% of the expected global demand), and 12 exajoules (EJ) of sustainable biomass (10%–25% of the expected global sustainable biomass availability) per year in the PRU scenario — or about double the electricity and hydrogen but only one-third of the biomass in the ORE scenario.

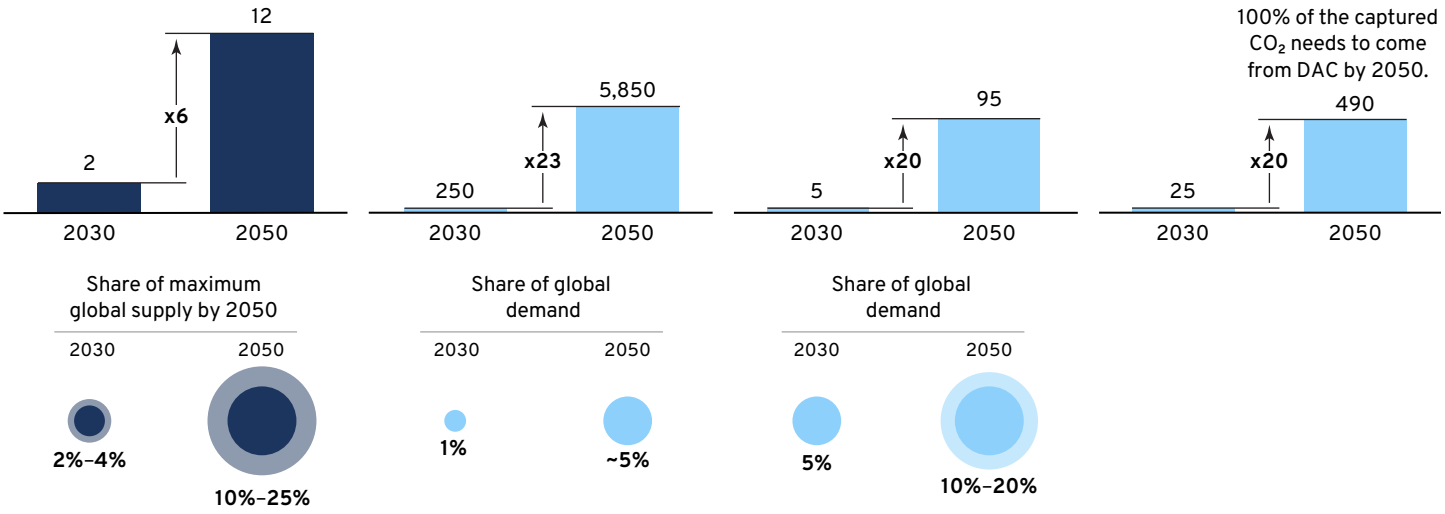
Decarbonising air transport has massive implications for global energy system resources (Exhibit H) — in particular for sustainable biomass (for biofuel production) as well as renewable electricity and green hydrogen (for PtL production and the direct use of hydrogen in hydrogen aircraft). One tonne of jet fuel can be produced by (1) about 1.1–1.2 tonnes of used cooking oil, (2) about 5–8 tonnes of municipal solid waste (MSW), agricultural/forestry residues, or nonfood energy crops, or (3) about 24–31 megawatt-hours (MWh) of renewable electricity (to yield about 0.5 tonne of hydrogen and to capture about 3.3 tonnes of CO_2). CO_2 can be sourced from point source capture (PSC) in the near term to scale up PtL production, but needs to come from direct air capture (DAC) in the long term.

Resource demand of global aviation in 2030 and 2050

EXHIBIT H

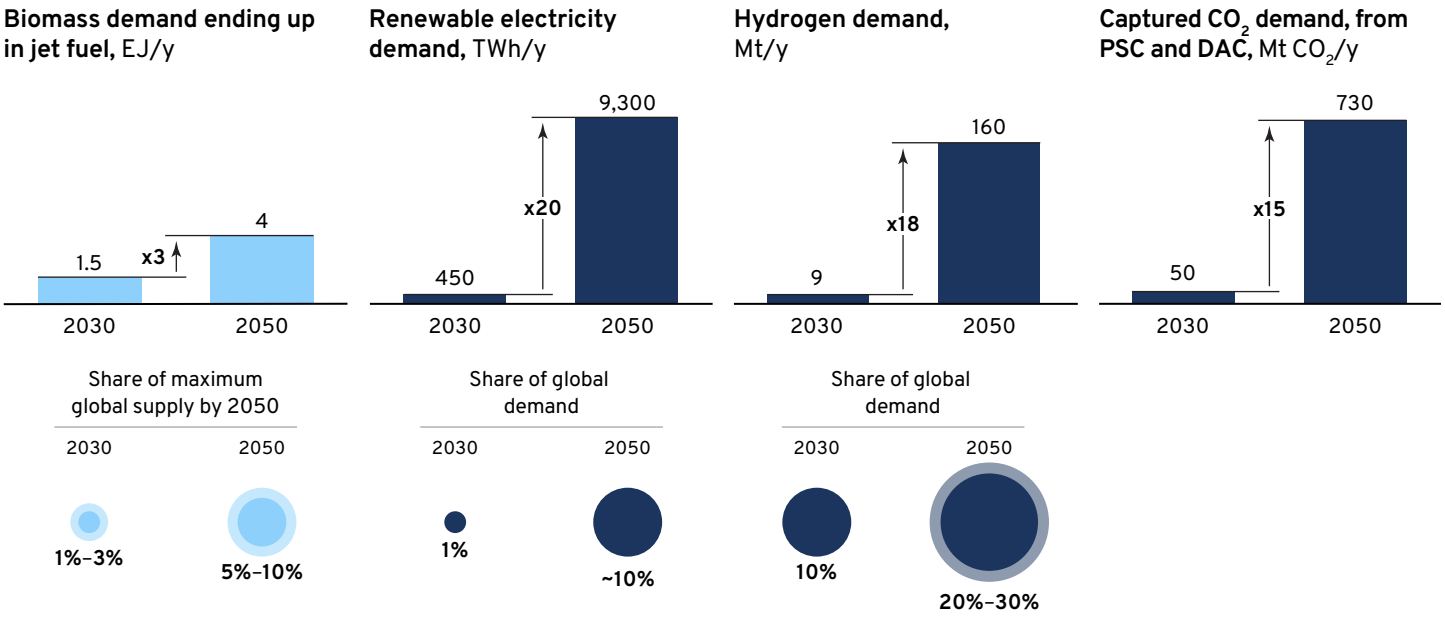
PRUDENT SCENARIO

A key challenge of a biofuel-dominated scenario is the sufficient supply of sustainable biomass, in light of the competition for this limited resource from other sectors. However, such a scenario will require only about half the electricity, H_2, and captured CO_2 of a PtL-dominated one by 2050.



OPTIMISTIC RENEWABLE ELECTRICITY SCENARIO

A key challenge of a PtL-dominated scenario will be the sufficient supply of renewable electricity, H_2, and captured CO_2, in light of growing global demand also from other sectors. However, such a scenario will require only one-third of the sustainable biomass of a biofuel-dominated one by 2050.



Source: MPP analysis

In 2030, aviation could demand 5 million–9 million tonnes of hydrogen, suggesting a share of 5%–10% of indicative global demand projections of the Energy Transitions Commission of 90 Mt. It could require 250–450 TWh of additional renewable electricity, suggesting a share of about 1% of indicative global demand projections of the Energy Transitions Commission of 35,000 TWh, depending on how fast PtL enters the market.

In a scenario where PtL and hydrogen dominate the energy mix in 2050 (ORE), up to 9,300 TWh in additional renewable electricity production capacity would be required. Supplied by up to 4 TW of renewable electricity generation capacity, aviation could thereby demand up to 10% (9,300 TWh) of the indicative expected global electricity production of 90,000–130,000 TWh in 2050, suggested by the Energy Transitions Commission. In addition, the production of about 160 Mt hydrogen would require an installed electrolyser capacity of up to about 2 TW.

In a scenario more reliant on biofuels (PRU), 12 EJ of biomass could be required for the aviation sector, demanding 10%–25% of the indicative global availability of sustainable biomass by 2050. The conversion of 12 EJ sustainable biomass to biofuels will simultaneously entail the production of by-products like diesel/gasoline or naphtha, which will demand an additional 8 EJ.[iv] Therefore, 20%–40% of the indicative globally available sustainable biomass would be used in biofuel production facilities, to primarily serve the aviation sector.

In the face of competing demand for these resources, also from other sectors, ramping up sufficient capacity will be critical in order to decarbonise aviation and our global economy. Sustainable biomass should be redirected from current sectoral use cases where alternative decarbonisation solutions exist (e.g., in road transport or shipping) to the aviation sector.

iv These by-products can decarbonise other sectors, wherefore the additional 8 EJ should not be attributed to aviation per se.

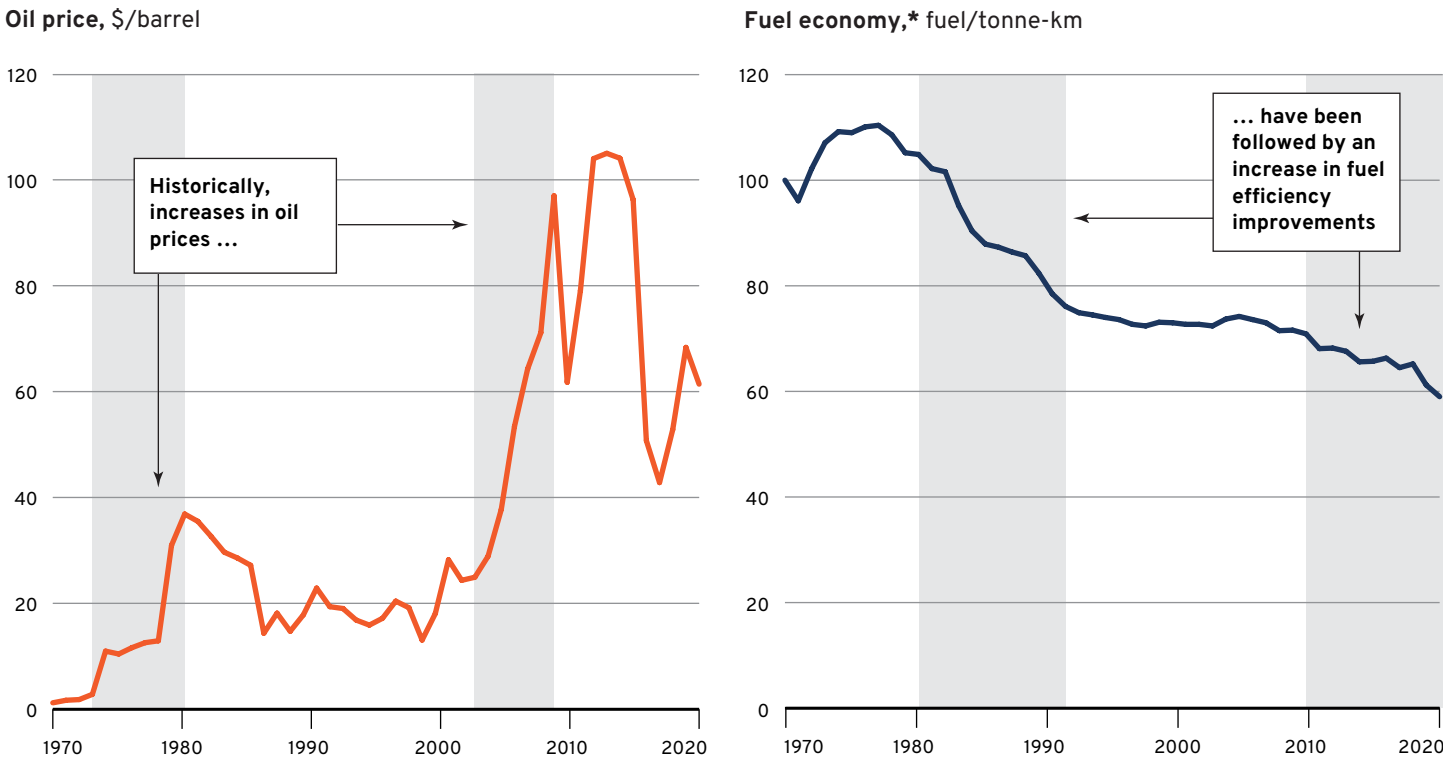
8. Aircraft fuel efficiency gains and operational measures could avoid over 15 Gt CO_2e of cumulative GHG emissions at zero or even negative abatement costs.

Sustainable biofuels and PtL will most likely enter the market at large scales only around 2030, and hydrogen and battery-electric aircraft even later in the 2030s. However, other measures can reduce emissions more quickly. 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 could improve fuel efficiency by 2% per year (see *Technical Appendix* for more detail), or about 40% by 2050 compared with 2019. Replacing the current commercial aircraft fleet with the most fuel-efficient aircraft that are in service today would already reduce fuel consumption by about 20%. Cumulatively between 2022 and 2050, efficiency measures could abate about 15 Gt CO_2e at far lower costs than other measures — often even at negative marginal abatement costs compared with current abatement costs of more than $200 per tonne of CO_2e for SAFs.

Historically, average efficiency gains of 1% per year have been recorded. However, in two periods in the 1980s and the 2010s, surging aviation fuel costs led to increased fuel efficiency measures of 1.5%–2.8% per year to save on fuel costs (Exhibit I). The prospect of future fuel cost increases due to the switch to SAFs could again be a key driver for increased fuel efficiency efforts.

Historically, aircraft fuel efficiency gains followed high oil prices

EXHIBIT I



* Relative to 1970 (1970 = 100%)

Source: MPP analysis, based on World Bank and ICCT

9. Although average fuel costs are increasing in the net-zero scenarios, the cost of flying could remain stable, being counterbalanced by efficiency gains.

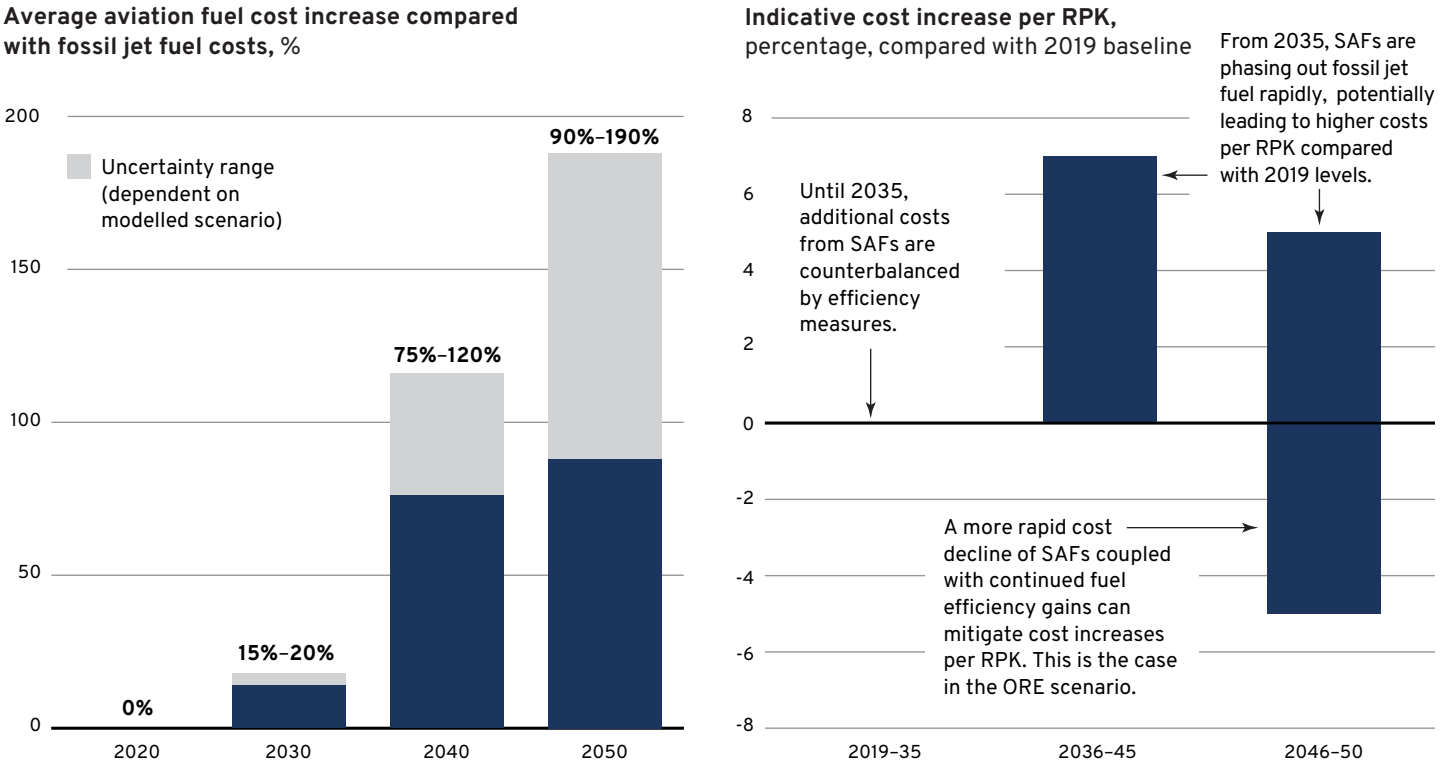
SAFs are currently 2–5 times more expensive than fossil jet fuel, and even in the long run, SAFs are likely to come at a premium, even though high oil prices could reduce this premium considerably.

The average energy cost for global aviation will depend on (1) the market share of renewable fuels, which will increase over time, (2) their production costs, which will decline over time (because of technology innovation, economies of scale, and/or carbon pricing schemes), and (3) the fuel efficiency of aircraft, which will increase over time. As a result of (1) and (2), a share of 13%–15% of SAFs by 2030 could increase the average cost of fuel by about 15%–20%. However, considering fuel efficiency gains of aircraft, the average cost increase per revenue passenger kilometre (RPK) could be negligible.

By 2050, average fuel costs for a fully decarbonised aviation sector could increase by about 90%–190% compared with projected fossil jet fuel costs (before considering any carbon pricing on top of fossil jet fuel costs). Average costs per RPK could, however, rise by only about 5%. Further technology improvements, economies of scale, and the introduction of more efficient hydrogen and battery-electric aircraft could even lead to a decrease of about 5% (Exhibit J) in the costs per RPK. Although these values are only indicative and it is unclear how individual segments of the value chain will react to increased fuel costs, efficiency gains could enable airlines to compensate for large parts of the economic impact of increased fuel costs.

EXHIBIT J

Increasing fuel costs could be balanced with fuel efficiency gains



Source: MPP analysis

10. Carbon dioxide removal (CDR) solutions are needed to remove residual emissions from renewable fuels but are not a replacement for deep and rapid in-sector decarbonisation.

CDR solutions are necessary in addition to, and not instead of, deep and rapid in-sector decarbonisation.

Renewable fuels reduce GHG emissions by about 75%–95% compared with fossil jet fuel. The GHG emissions reduction of biofuels can vary considerably depending on the biomass feedstock. For PtL, hydrogen, and battery-electric aircraft, the GHG emissions reduction potential depends on the embedded emissions in renewable electricity generation assets and is therefore expected to increase in parallel to the decarbonisation of the manufacturing industry.

Still, renewable fuels rarely reduce GHG emissions by 100%, and unabated residual emissions of about 120–140 Mt CO_2e will remain in 2050. Those will need to be mitigated by CDR solutions, including, for example: natural climate solutions (NCS); hybrid solutions like biochar or bioenergy with carbon capture and storage (BECCS); and engineered solutions like direct air carbon capture and storage (DACCS). Counterbalancing the residual emissions would cost an additional $15 billion–$18 billion in 2050 alone at an average abatement cost of $125 per tonne of CO_2. Investments in CDR should start immediately to be able to sequester 120–140 Mt CO_2e by 2050.

11. Policymakers must create a level playing field between fossil jet fuel and SAFs. Industry collaboration across the value chain can ramp up SAF demand and supply, as well as trigger technological innovation. Financial institutions must direct capital to SAF plants.

A tailored and robust set of policies will be needed to overcome the technological and economic challenges that have been preventing SAFs from scaling (Exhibit K).[v] In this decade, policymakers should (1) de-risk private investments for new SAF production pathways, (2) bridge their cost differential compared with fossil jet fuel, and (3) direct sustainable feedstock to the aviation sector. Simultaneously, the way for hydrogen/battery-electric aircraft can be paved by supporting R&D and ensuring future accessibility to renewable electricity and green hydrogen at scale.

EXHIBIT K

Key policy milestones in this decade

Global milestones

- Create demand for decarbonisation measures: ICAO commits to net zero by 2050 and adopts a long-term global aspirational goal (LTAG), e.g., in form of GHG emissions intensity reduction targets in line with this report.
- Create enabling conditions: A functional, global book-and-claim system is established by 2025.

National/regional supply incentives

- Change incentive schemes for renewable fuel production to redirect biomass use from road transport (biodiesel) to aviation (bio-jet fuel).
- Support R&D of new SAF pathways and hydrogen/battery-electric aircraft.
- De-risk projects, e.g., via blended finance, capital grants, concessional/low-interest loans, or long-term guarantees.

National/regional demand incentives

- Impose 5%–7% blending mandates for SAFs by 2025 and 10%–15% by 2030, and reduce the cost differential between SAFs and fossil jet fuel, e.g., by direct or indirect subsidies (like a blender's tax credit).
- Use green public procurement to supply 20% of public-sector air travel with SAF by 2030.
- Tighten emissions trading schemes.

Note: List is not mutually exclusive, nor collectively exhaustive; national policy packages should be tailored to the specific country and region.

Source: MPP analysis

v See overview of policy options to support the market entry and scaling of SAFs developed by the Clean Skies for Tomorrow Initiative, the Mission Possible Partnership, and the Energy Transitions Commission, *Clean Skies for Tomorrow: Sustainable Aviation Fuel Policy Toolkit*, November 2021, **www.energy-transitions.org/wp-content/uploads/2021/11/Clean_Skies_for_Tomorrow_Sustainable_Aviation_Fuel_Policy_Toolkit_2021.pdf.**

From an industry perspective, the market entry and scale-up of SAFs require radical collaboration across the value chain in this critical decade to overcome the chicken-and-egg problem between demand and supply of SAFs and to bridge their initially high cost differential compared with fossil jet fuel (Exhibit L).

Banks, institutional investors, and public-sector banks can collectively make commitments to invest in SAF plants and upstream energy infrastructure to unlock the annual capital requirements of $40 billion–$50 billion in this decade. Financial institutions should signal capital flow commitments early on to de-risk projects (Exhibit M). Besides SAF plants, novel propulsion aircraft should also receive investment support to increase their technology readiness level (TRL).

EXHIBIT L

Key industry milestones in this decade

Demand creation via offtake agreements

Current offtake agreement volumes — a cumulative 21 Mt SAF for varying offtake durations of 0.5–20 years — between SAF producers and customers (airlines, corporations, governments, etc.) are doubled by 2025 and increased by a factor of 5 until 2030 to overcome the chicken-and-egg problem between demand and supply.

Offtake agreements focus on this decade to scale up near-term supply of SAFs and meet the yearly demand for about 40–50 Mt SAFs by 2030. Advanced market commitments and initiatives like the First Movers Coalition provide similar powerful demand signals.

Supply changes in reaction to policy revisions

Triggered by revised biofuel policies, existing HEFA plants reduce their diesel output in favour of jet fuel: doubling the jet fuel share to 36% unlocks additional 7 Mt jet fuel by 2030. Increasing the jet fuel share to a maximum of 55% would unlock an additional 8 Mt.

Triggered by revised biofuel policies, 10% of global bioethanol supply (9 Mt) is redirected from road transport to aviation to produce 6–7 Mt of SAF by 2030.

Industry consortia

Cross-value chain consortia have de-risked currently low-TRL PtL production pathways and brought first-of-a-kind (FOAK) PtL plants to the market by 2025 and larger-scale second-of-a-kind (SOAK) PtL plants by 2030.

Cross-value chain consortia have de-risked the development of hydrogen and battery-electric aircraft, which enter the real-world test phase by 2030.

Note: List is not mutually exclusive, nor collectively exhaustive; industry action should be tailored to the national policy environment and region.

Source: MPP analysis

EXHIBIT M

Key finance milestones in this decade

Climate-aligned investment principles

By 2030, banks, institutional investors, and public-sector banks commit 100% of their investments to infrastructure assets and companies that comply with 1.5°C targets (similar to Poseidon Principles in shipping).

In collaboration with the financial sector, investment principles are established until 2023 to define sustainability criteria for infrastructure assets, companies' and financial institutions' aviation- and fuel-related portfolios. Investment principles should:

Encourage an engagement of investors and industry corporations

- To incentivise and facilitate 1.5°C-aligned target-setting;
- To develop best practices of new financing instruments tailored to make projects related to SAFs, efficiency measures, and novel propulsion aircraft investable, and
- To develop quantitative analyses on ways to de-risk such projects for financial institutions.

Mandate beneficiaries of any form of climate-aligned finance to disclose annual metrics to track their progress on decarbonisation targets.

Include exclusion criteria to trigger divestments from non-1.5°C-aligned assets and companies, e.g., banks do not provide loans to aviation companies that do not meet minimum 1.5°C-aligned criteria by 2030.

Include inclusion criteria (e.g., existing target to reduce GHG intensity per RPK by 20%–25% until 2030 for airlines, or a commitment to use 10%–15% SAF by 2030 for airlines and corporate customers, or the target of min. 85% GHG reduction compared with fossil jet fuel for a new SAF plant) to trigger new investments in 1.5°C-aligned assets and companies.

Public–private partnerships can de-risk technology projects of low maturity

Consortium of capital providers to share risk.

Public-sector banks to de-risk projects, e.g., via blended finance, concessional loans, capital grants, or long-term guarantees.

Note: List is not mutually exclusive, nor collectively exhaustive; finance action should be tailored to type of financial institution, their portfolios, the size of the companies that require capital for low-carbon technologies, and the technologies' maturity.

Source: MPP analysis

CONCLUSION

Bringing global aviation on a 1.5°C-aligned path to net zero is possible. It will require substantial annual investments in the order of $175 billion, of which about 95% would be in renewable fuel production, and entail large-scale implications for the energy system. Aviation demand could represent up to 10% of the expected global electricity demand and up to 30% of the expected global green hydrogen demand by 2050.

Policymakers, financial institutions, and industry leaders need to collaborate to set the course towards 1.5°C and net zero. Early action in this decade is required to unlock technological innovation and economies of scale and to enable large-scale GHG emissions reductions in the 2030s and 2040s.

In a joint effort by actors across the value chain, we can make this mission possible.

MAIN REPORT

MAKING NET-ZERO AVIATION POSSIBLE

An industry-backed, 1.5°C-aligned transition strategy

PART I

DECARBONISING AVIATION: CHALLENGES AND SOLUTIONS

1.1 Global aviation and its decarbonisation challenge

Before the COVID-19 pandemic, global aviation was responsible for about 1 Gt of CO_2 emissions per year, 12% of global transport emissions, and 2.8% of total global, anthropogenic CO_2 emissions.[10] Aviation emissions rose by over a third between 2010 and 2019 alone, from 760 Mt CO_2 to 1,020 Mt.[11] If aviation were unmitigated, it could be responsible for 22% of global emissions by 2050.[12]

Within the scope of this project, we include upstream GHG emissions and in-flight CO_2 emissions, which are responsible for about one-third of the total climate impact of aviation. In-flight nitrogen oxide (NO_x) emissions and the formation of contrails and cirrus clouds — subsumed under the term aviation-induced cloudiness — could be responsible for the other two-thirds of the climate impact (Exhibit 1.1), but are beyond the scope of this study because scientific uncertainties around the actual magnitude of these climate impacts are high. The formation and mitigation of contrails and cirrus clouds are discussed in more detail in the *Technical Appendix*.

EXHIBIT 1.1

Climate impact of global aviation, based on the current state of science

IN-FLIGHT CO_2 EMISSIONS

2.8%

of global CO_2 emissions

(based on direct tank-to-wake emissions of 1.02 Gt CO_2 out of roughly 36.7 Gt CO_2 globally in 2019)

+ Upstream GHG emissions

UPSTREAM GHG AND IN-FLIGHT CO_2 EMISSIONS

2.5%

of global GHG emissions

(based on well-to-wake GHG emissions of 1.24 Gt CO_2 out of roughly 50 Gt CO_2 globally in 2019)

+ Short-lived climate forcers in-flight

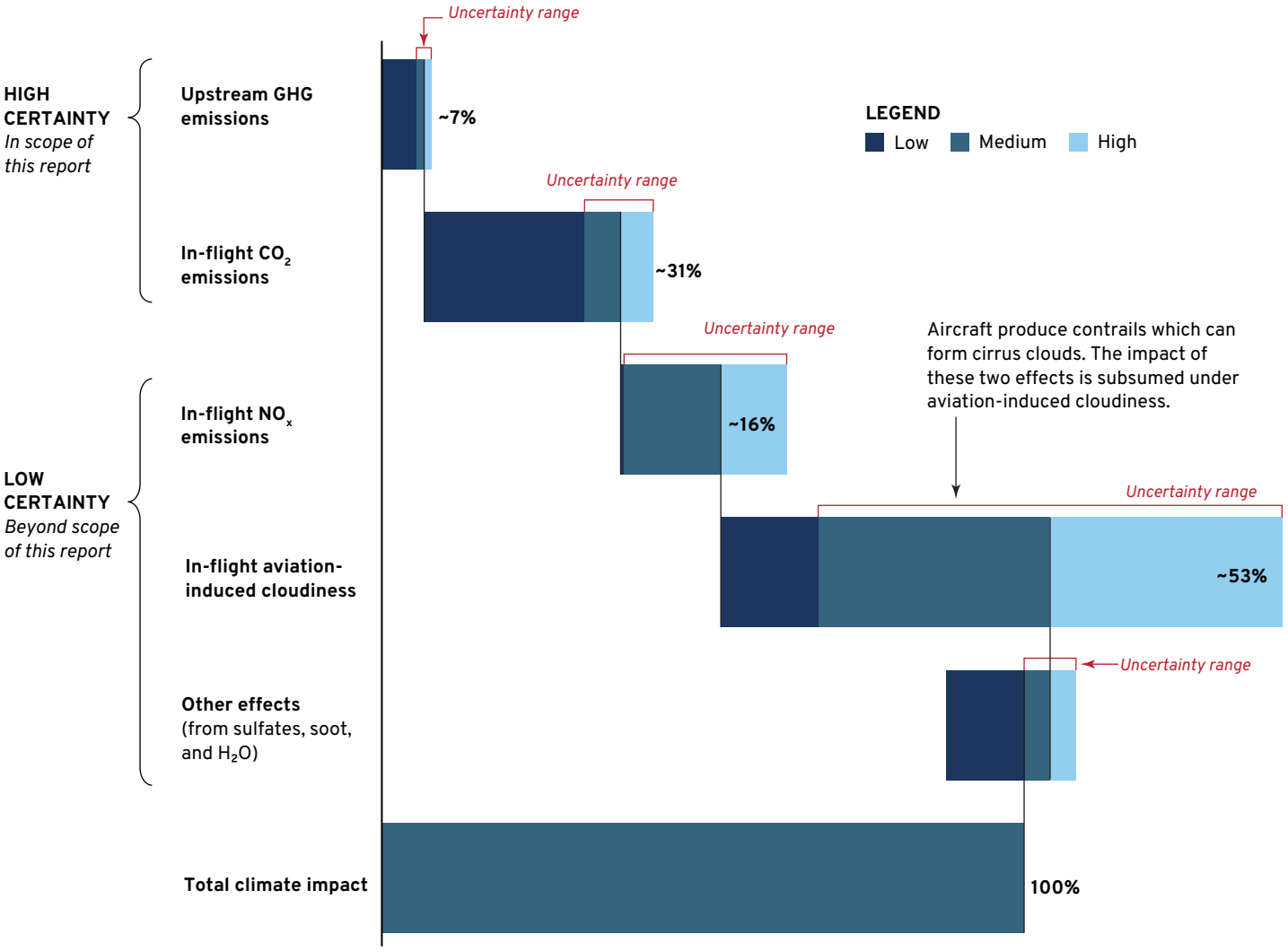
TOTAL CLIMATE IMPACT

3.5%–4%

of global warming impact

(based on net anthropogenic effective radiative forcing of 80.4 mWm/m² from in-flight emissions, out of 2,290 mW/m² globally in 2011)

Breakdown of the total climate impact, measured in effective radiative forcing, 2018 data



Note: mW/m² = milliwatts per square metre

The climate impact of upstream GHG emissions has been calculated using a multiplier of 1.2 on top of in-flight CO_2 emissions (3.16 tank-to-wake vs. 3.84 t CO_2e/t jet fuel well-to-wake). More research is needed to narrow the large uncertainty bandwidths for the non-CO_2 impact of flights. However, even the lower end of the uncertainty ranges suggests a significant impact of these so-called short-lived climate forcers (in particular NO_x and aviation-induced cloudiness).

Source: MPP illustration, based on Lee et al.; Our World in Data[13]

The climate impact of aviation stands in contrast to its benefits:[14]

- The aviation sector supports 11.3 million in-sector jobs worldwide and 18.1 million jobs in the aviation industry supply chain.
- Aviation's economic contribution amounted to $961.3 billion in the sector and an additional $816.4 billion in the supply chain.
- In 2019, 4.5 billion passengers were carried by air, for leisure and business purposes, connecting people around the world.

To serve the industry, airlines spent $188 billion on fuel in 2019, and aerospace companies are spending $15 billion each year on research for aircraft technology efficiency.[15]

Why is aviation hard to abate?

- **Limited decarbonisation options:** Compared with ground transport, aircraft rely on **energy-dense liquid fuels,** and most transport activity (measured in passenger-kilometres) takes place on **long distances**: flights longer than 1,000 nautical miles (1,852 km) are responsible for two-thirds of emissions in the aviation sector while representing only about 25% of all departures.[16] The more an energy carrier weighs and/or the more volume it needs, the lower the range of the aircraft will be. This trade-off limits the applicability of direct electrification of aircraft, which is a major decarbonisation lever for ground transport but not a large-scale solution for aviation.
- **High costs:** There are **few renewable alternatives** to fossil jet fuel, and all of them come at a **high additional cost.** The **only market-ready technology** to propel close-to-zero-emissions flights in this decade are **SAFs,** which are currently **2–5 times as expensive** as fossil jet fuel (before considering any policy incentives).
- **High demand growth**: Although COVID-19 has delayed the growth of air traffic by a few years, demand is expected to rebound to pre-pandemic levels by around 2024.[17] After this normalization, aviation will be back on a strong growth path with **growth rates of about 3.0% per year**. In 2018, 62% of the CO_2 emissions from global commercial passenger aviation were emitted from flights departing from high-income countries representing only 16% of the global population.[18] On average, humans spend about the same time per day in transit (approximately 1–1.5 hours per person per day), irrespective of their wealth (measured in GDP per capita of the country they live in).[19] However, with rising GDP, travellers switch to faster modes of transport. With a direct correlation between GDP and demand for air travel, the GDP growth in developing countries will unlock a huge additional demand for air travel.[20] And since the aviation industry reinforces GDP growth, decarbonising aviation becomes even more challenging and at the same time even more important.
- **Short-lived climate forcers:** According to the current scientific knowledge, **about two-thirds of aviation's climate impact could stem from non-CO_2 effects, primarily contrails and cirrus clouds.**[21] The good news: reducing CO_2 emissions always needs to be priority number one (because CO_2 accumulates in the atmosphere whereas short-lived climate forcers don't) and many CO_2 reduction technologies also reduce non-CO_2 effects. Recent insights point towards a considerable reduction of aviation-induced cloudiness through the use of certain Sustainable Aviation Fuel (SAF) types, so-called synthetic paraffinic kerosenes (SPKs), or hydrogen (see *Technical Appendix*).

Why is it particularly a challenge to kick off the transition to net zero in this decade?

- **Low TRLs:** Many SAF production pathways still have an **insufficient technology readiness level** (TRLs of 5–8[vi]) to ramp up immediately. Hydrogen and battery-electric aircraft rank at even lower TRLs of 1–5.
- **Taking action takes time: Building new SAF production plants** (and associated resource supply chains, such as for biomass delivery) usually **takes about five to six years** until they go fully operational. We have eight years until 2030. **New SAF plants** and the associated upstream infrastructure (renewable electricity generation, hydrogen production, CO_2 capture, supply of sustainable biomass) **need to be planned within the next two or three years** if they are meant to meet 2030 targets.
- **International nature of aviation:** 60% of the emissions from passenger aviation stem from international flights. Therefore, it is hard to get national model projects off the ground for international flights because they are at risk of certain market distortion effects and carbon leakage, meaning that, for example, stopover flights could be rerouted from intermediate airports in countries with carbon pricing schemes to countries that don't have such regulations. This could put the national aviation industry at a certain economic disadvantage compared with other markets that do not have any cost-adding sustainability measures in place.[22] However, such competitive market distortion effects could be alleviated by countermeasures from policymakers (as discussed for example in the European Commission's ReFuelEU Aviation policy proposal).
- **Competitive market:** Airlines operate on tight profit margins and under high capital expenditures. Additionally, competition is high, in particular from and among low-cost carriers. This weakens incentives for long-term sustainable investments from airlines.

vi TRL 1–3 represents the research stage, TRL 4–6 the development phase, and TRL 7–9 the deployment phase. TRL 9 means a technology has been proven in its expected operational environment.

1.2 Decarbonisation solution portfolio

This section provides a high-level overview of the available decarbonisation levers to get to net-zero GHG emissions by 2050, while complying with a 1.5°C carbon budget, based on the following definitions of a "1.5°C carbon budget" and "net zero".

BOX 1

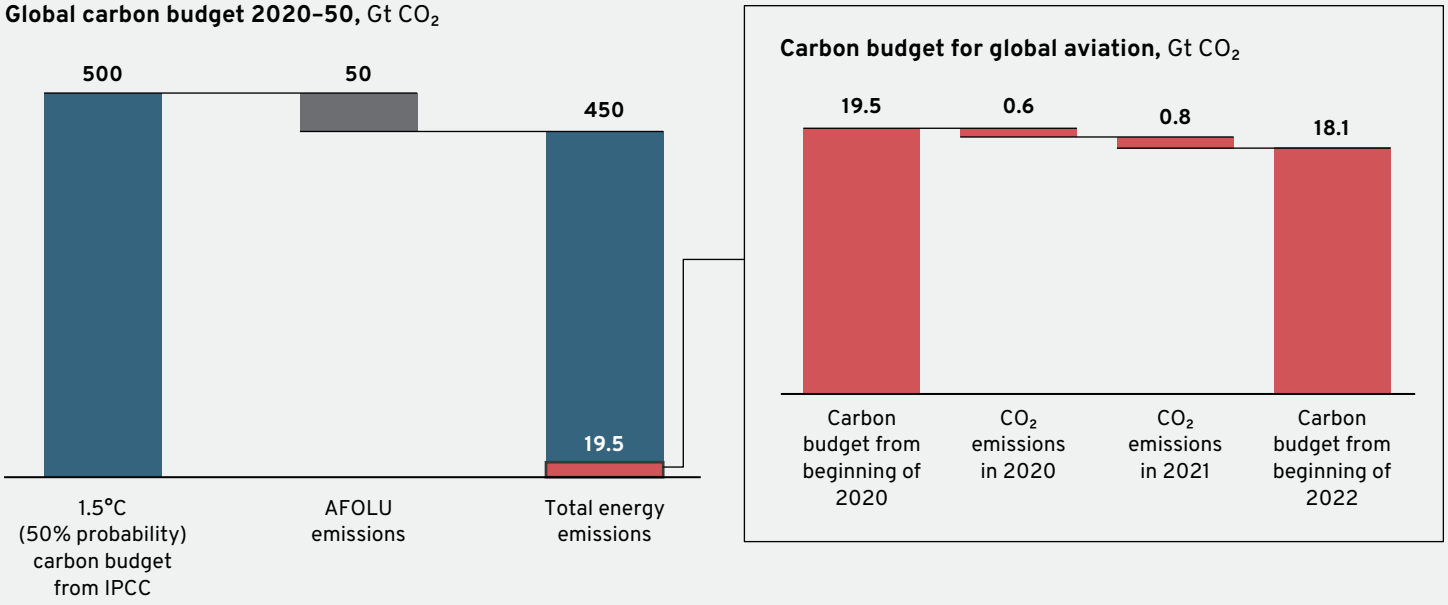
What is the 1.5°C carbon budget for aviation?

The Intergovernmental Panel on Climate Change (IPCC) estimates the global carbon budget to limit global warming to 1.5°C above preindustrial levels with a probability of 50% to about 500 Gt CO_2 from the beginning of 2020.

From that, about 50 Gt CO_2 of net anthropogenic emissions from agriculture, forestry, and other land use (AFOLU) are subtracted. That leaves roughly 450 Gt CO_2 for all energy sectors, which needs to be allocated to individual sectors according to their decarbonisation complexity. Hard-to-abate sectors are limited in their decarbonisation speed, whereas other sectors like the power or automotive sector could switch to low-carbon technologies more quickly.

In a preliminary assessment by MPP, roughly 50% of the 450 Gt CO_2 has been allocated to the seven MPP sectors (aluminium, chemicals such as ammonia and petrochemicals, concrete/cement, steel, aviation, shipping, and trucking). The sectoral allocation is based on the cumulative sectoral emissions from the IEA's *Net Zero by 2050* report and the BloombergNEF *New Energy Outlook 2021* report (and for some sectors the One Earth Climate Model) between 2020 and 2050, which serve as a proxy of how hard to abate each individual sector is.

Following this methodology, global aviation has a 1.5°C carbon budget of about 20 Gt CO_2 from the beginning of 2020. Subtracting the emissions from global aviation in 2020 and 2021 leaves a carbon budget of about 18 Gt CO_2 for global aviation from 2022 onwards. Given the variety of other potential sectoral allocation methods, this value should not be taken as the absolute truth but rather as an indicative figure for a 1.5°C carbon budget for global aviation.



Note: Detailed assumptions are documented in the Technical Appendix.

Source: MPP analysis, based on IPCC, IEA, and BloombergNEF[23]

BOX 2

What is "net zero"?

The world needs to get to net-zero GHG emissions by 2050 to avoid the most harmful effects of climate change. Thereby, "net zero" means priority in-sector decarbonisation, complemented by carbon dioxide removals (CDR).

- About 90%–95% of current emissions in each sector need to be reduced by in-sector measures. This is in line with the Science Based Targets initiative, which prescribes "long-term deep decarbonization of 90%–95% across all scopes before 2050" as the single most important target for a net-zero world.
- The remaining 5%–10% of residual emissions that cannot be reduced by in-sector decarbonisation need to be neutralised by CDR, the potential of which is described in a recent report from the Energy Transitions Commission.

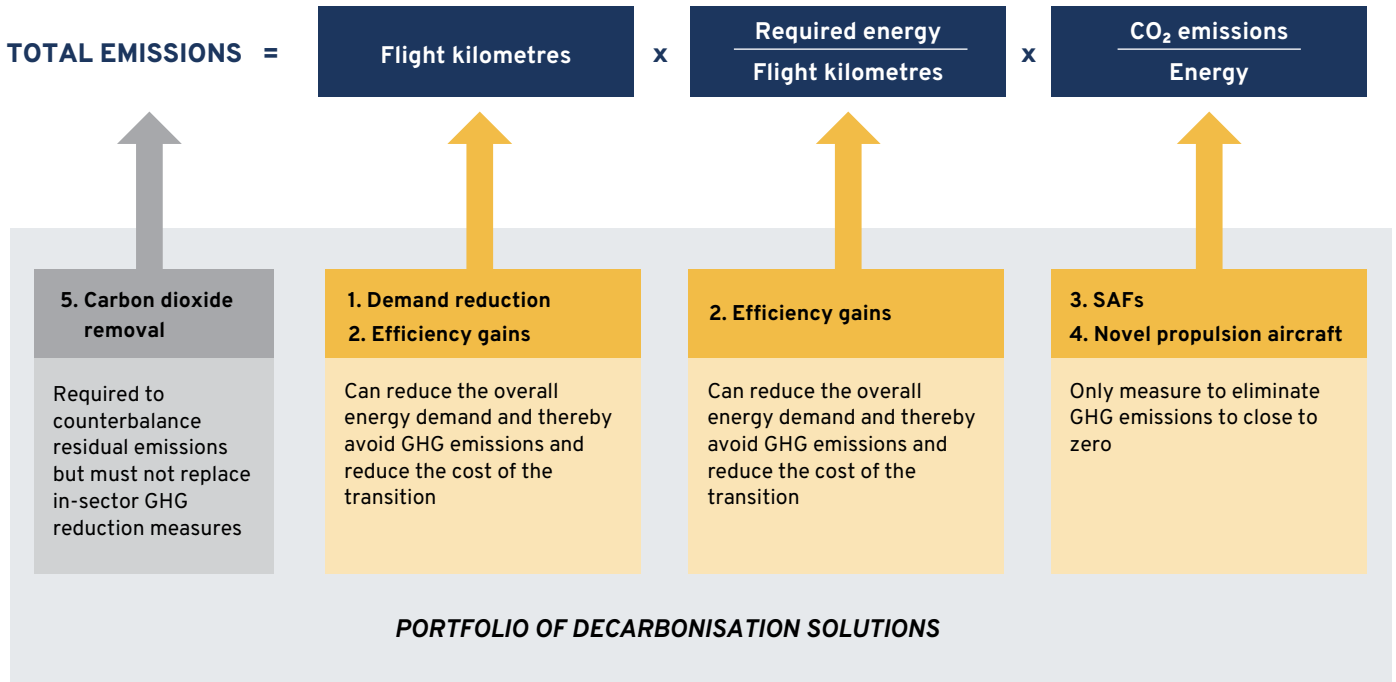
Note: Details on CDR can be found in *Mind the Gap: How Carbon Dioxide Removals Must Complement Deep Decarbonisation to Keep 1.5°C Alive*, a recent report of the Energy Transitions Commission, https://www.energy-transitions.org/wp-content/uploads/2022/03/ETC-CDR-Report-Mind-the-Gap.pdf

The aviation industry has five major levers that can propel it toward net-zero emissions: (1) reduction in air travel demand, (2) efficiency improvements, (3) SAFs, (4) novel propulsion (hydrogen, battery-electric and hybrid) aircraft, and (5) CDR solutions.

Exhibit 1.2 shows a breakdown of the causes of emissions from aviation and how each decarbonisation solution can contribute to reducing individual parts of the equation.

EXHIBIT 1.2

Decomposition of the roots of aviation's emissions and corresponding decarbonisation levers



Note: The numbers in the exhibit correspond to the following sections (on pp. 35–38) on each decarbonisation lever.

Source: MPP schematic

What is the contribution of each lever to decarbonise aviation?

- Although **efficiency improvements and reduction** in air travel demand often come at zero or even negative costs, they cannot bring down emissions to zero. Increasing the annual fuel efficiency gains to 2% can reduce the global final energy demand of aviation in 2050 by around 40%.

- **SAFs and novel propulsion aircraft** are the only levers to bring GHG emissions down to close to zero, but they come at high fuel production or aircraft development costs.[vii]

    - Different energy carriers and their propulsion systems face a trade-off between production efficiency (i.e., energy demand for producing the energy carrier), on-board energy conversion efficiency (i.e., energy demand to create thrust during flight), the resource availability (electricity, hydrogen, biomass, captured CO_2), energy costs, the GHG emissions reduction and the aircraft's maximum ranges (see overview in Exhibit 1.3).

    - SAFs (renewable jet fuel, e.g., produced from biomass or renewable electricity) have the broadest use case because they can replace fossil jet fuel one-to-one as drop-in fuels and can cover all flight distances. Without factoring in the value of the environmental benefit of SAFs, they are currently 2–5 times as expensive as the historical average fossil jet fuel price over the past two decades. However, strong cost reductions can be expected as the result of technology innovation, economies of scale, and policy incentives. Additionally, this cost differential narrows in times of high fossil fuel prices.

    - Hydrogen and battery-electric aircraft potentially offer lower costs and a greater reduction of aviation's climate impact. However, they are not expected to enter the market on large scales until the late 2030s or 2040s, and likely for short- and medium-haul flights only. In the long run (towards and after mid-century), however, particularly hydrogen aircraft could have an increasing market share.[viii]

- Lastly, **CDR solutions** do not reduce emissions within the sector. However, they are required in order to permanently neutralise residual emissions from SAFs and hydrogen or battery-electric aircraft, which reduce GHG emissions only by about 75%–95%.

Exhibits 1.3–1.5 show a high-level comparison of the five main decarbonisation levers.

vii SAFs, green hydrogen, and renewable electricity are subsumed under "renewable fuels/energy carriers".

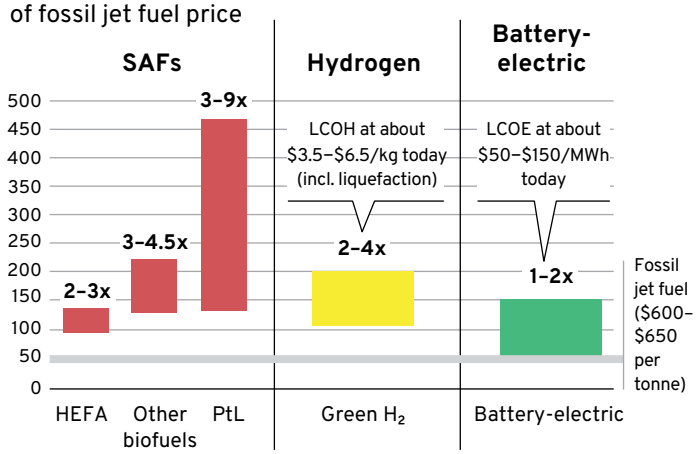
viii Retrofitting existing regional turboprops with hydrogen fuel cell propulsion systems could bring their market entry forward to as early as 2025.

EXHIBIT 1.3

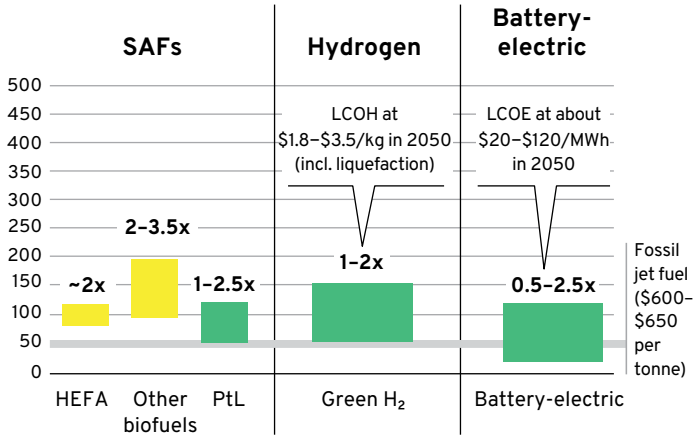
Comparison of SAFs and hydrogen and battery-electric aircraft

Indicative energy cost in 2020 …

$/MWh and as multiple of historical average of fossil jet fuel price

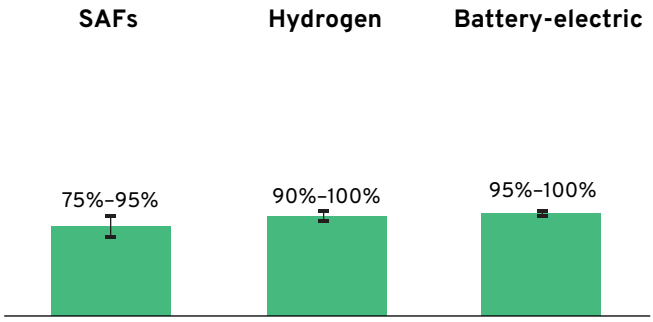


… and in 2050



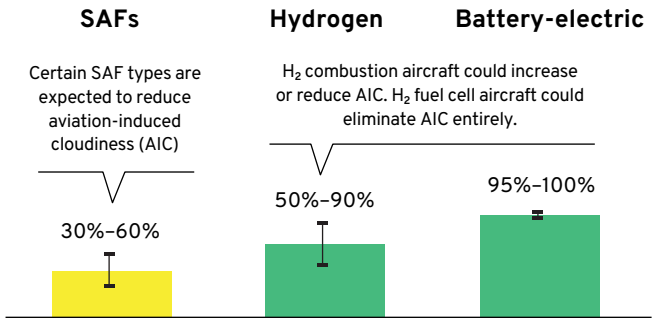
GHG abatement potential …

Upstream GHG + in-flight CO_2 emissions only; compared with fossil jet fuel

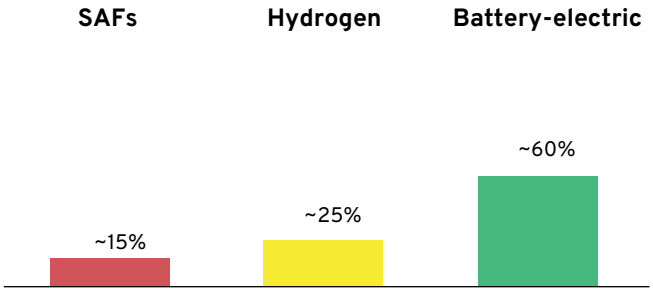


… and total climate impact abatement potential

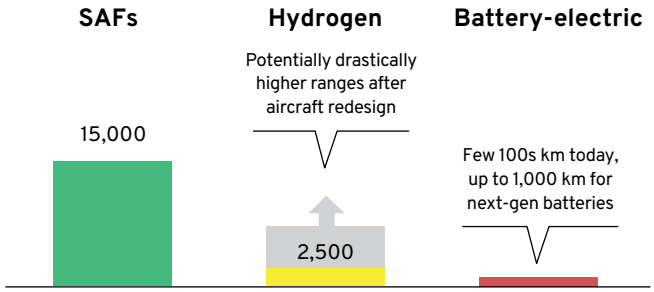
In addition to the GHG abatement potential, this includes non-CO_2 in-flight effects; compared with fossil jet fuel



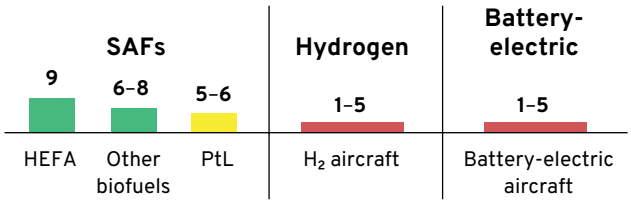
Well-to-wake efficiency …



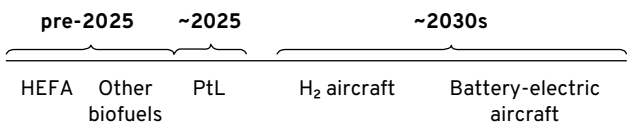
… and maximum range, km



Technology readiness level (TRL) …



… and large-scale market entry

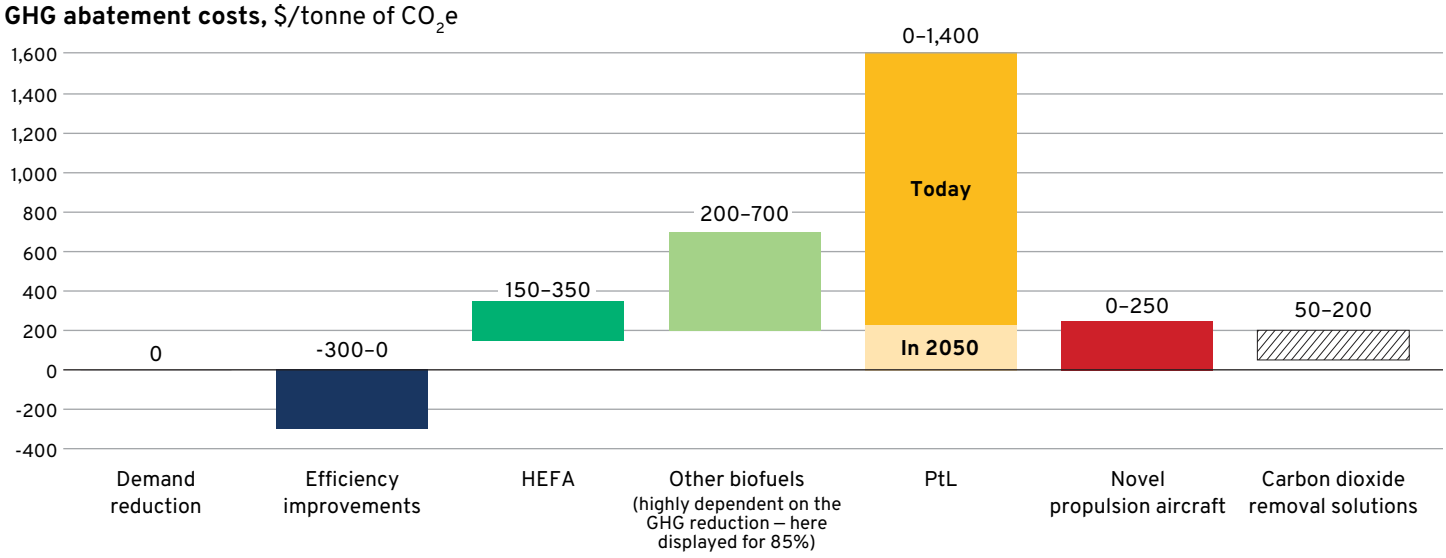


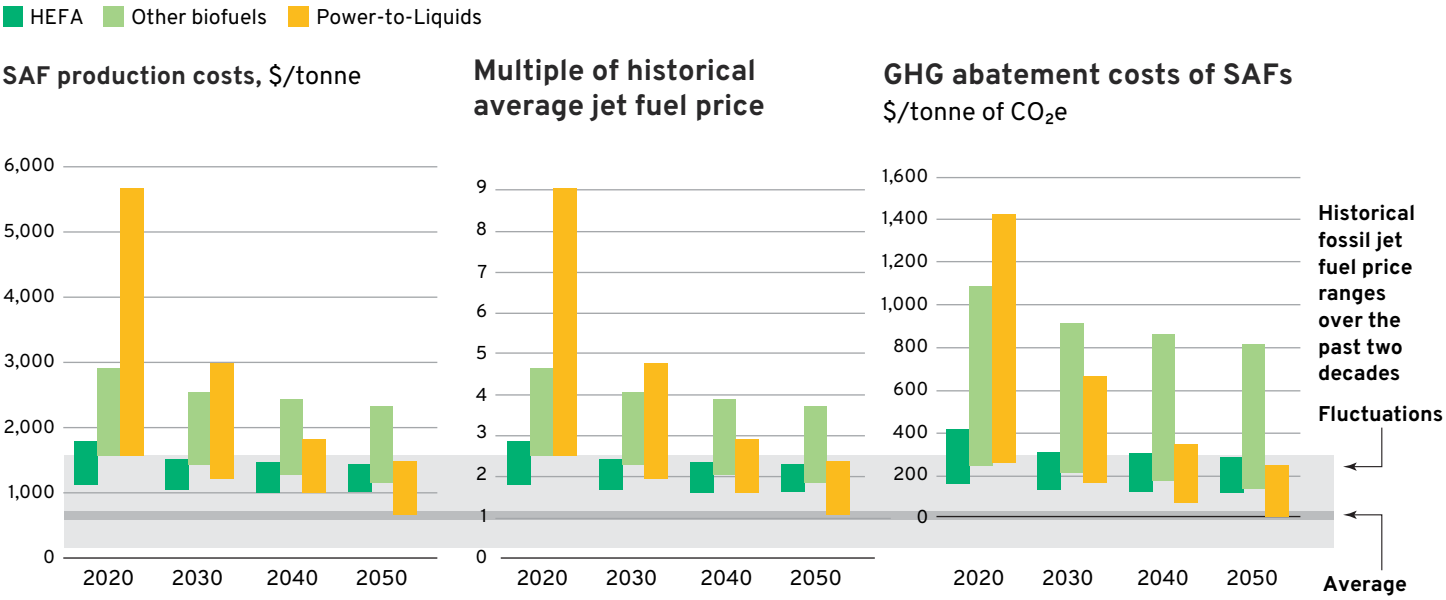
Note: The cost of fossil jet fuel is taken as the average market price of the past 20 years. It has, however, fluctuated substantially during that period, ranging from $135 to $1,590 per tonne. LCOE = levelised cost of electricity; LCOH = levelised cost of hydrogen.

Source: MPP analysis, based on European Commission; ICAO; McKinsey, Clean Sky 2 JU, and FCH 2 JU; Stolz et al.; industry expertise from CST community[24]

EXHIBIT 1.4

Indicative GHG abatement costs of all decarbonisation measures for aviation





Note: The cost of fossil jet fuel is taken as the average market price of the past 20 years. It has, however, fluctuated substantially during that period, from $135 to $1,590 per tonne. GHG abatement costs are based on the historical average fossil jet fuel price of $600–$650/tonne; however, high oil prices could reduce the GHG abatement costs of renewable fuels substantially and bring them earlier to market. This report's SAF cost assessment is built on insights into more than 30 feedstock types. However, given the broad variety of existing feedstocks and SAF production processes, the cost ranges do not necessarily reflect the full range of potential future SAF costs – in particular given regional differences and recent impacts of global supply chain disruptions. The GHG abatement costs are based on a higher GHG reduction of up to 95% for PtL, and a large range of 55%–100% for biofuels based on the ICAO CORSIA Eligible Fuels methodology.

Source: MPP analysis, based on CST; ICAO; Schäfer et al. (2016); McKinsey[25]

EXHIBIT 1.5

Comparison of decarbonisation solution portfolio for aviation

		Applicability at scale (i.e., potential impact)	Technology readiness level (TRL)	Market availability at scale	Main barriers
1) Air travel demand reduction • Modal shift of short-haul flights to high-speed rail • Behaviour change (e.g., reduced business travel caused by videoconferencing) • Elasticity on increased ticket prices		Strong dependence on future behaviour, regional market developments, and elasticity towards increased ticket prices	-	-	High demand growth, low development of high-speed rail network, trade-off with co-benefits of flying (connecting people and cultures)
2) Efficiency improvements • Turbine efficiency • Aircraft aerodynamics • Air traffic management • Flight operations efficiency • Ground operations efficiency		High impact from a maximum 2%/y efficiency improvement	**8–9** (more advanced efficiency measures rank lower)	**High**	**Aircraft efficiency:** upfront development costs **Operational efficiency:** international coordination
3) Sustainable Aviation Fuels (SAFs)	HEFA	High limitation of sustainable biomass feedstock to supply about 50 Mt SAF/y	**9**	**High**	Feedstock constraints
	Other biofuels	Limitation of sustainable feedstock to supply about 250 Mt SAF/y	**6–8**	**Medium**	Market entry at scale and currently considerably higher cost than fossil jet fuel (2–5x historical fossil jet fuel prices)
	PtL	Theoretically unlimited feedstock (but potential supply constraints of renewable electricity, hydrogen, and captured CO_2)	**5–6**	**Low**	
4) Novel propulsion technologies	Hybrid aircraft	Applicable to almost all flight ranges	**1–5**	**Not yet at market**	Up-front technology development costs and certification
	Hydrogen aircraft	Applicable to short- and mid-haul (+ maybe long-haul) flights			
	Battery-electric aircraft	Applicable to short-haul flights			
5) Carbon dioxide removal (CDR) solutions • Natural climate solutions (NCS): restoration of natural ecosystems (e.g., forests, peatlands) and better management of current use of land • Hybrid solutions (biochar and bio-energy with carbon capture and storage [BECCS]) • Engineered solutions: direct air carbon capture and storage (DACCS)		Only supporting measure, not replacing switch to renewable fuels	**3–9** (NCS: 8–9; DAC: 3–6; BECCS: 6–9)	**Medium**	Monitoring and measurement of long-term carbon sequestration, ramp-up limits, large investment requirements, in particular for hybrid and engineered solutions

Source: MPP, based on European Commission; Prussi et al.; ETC[26]

1.2.1 Demand-side measures

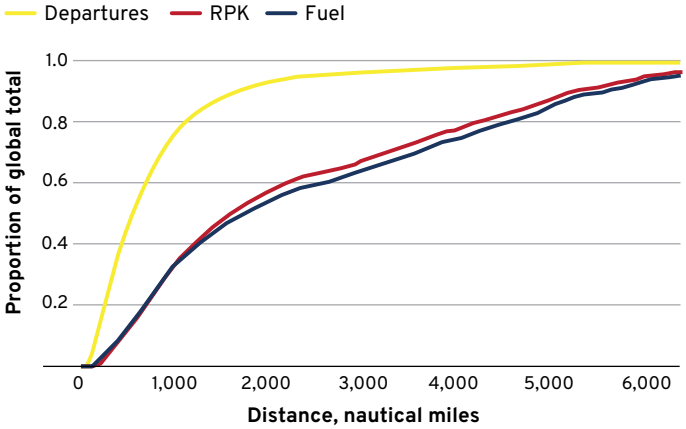
Although IATA expects a rebound to pre-pandemic air travel demand by 2024,[27] there are signs that future demand could be reduced by certain effects:

- **Videoconferencing:** In business, video calls have proven to be excellent substitutes for in-person encounters while cutting corporate travel expenses.
- **Modal shift:** Short-haul flights could be shifted to high-speed rail, which can reduce CO_2 emissions by up to 90% compared with today's aircraft.[28] Flights shorter than 650 nautical miles (1,200 km), which would be roughly equal to a four-hour train ride, are responsible for 18% of emissions of commercial aviation, while representing about 57% of all departures (Exhibit 1.6). Therefore, mode shift could at maximum reduce the CO_2 emissions of global commercial aviation by 15%. This maximum potential is reduced by the availability of high-speed rail infrastructure. The IEA estimates that future high-speed rail lines could absorb around 17% of all regional flights.[29] That would yield a maximum CO_2 reduction potential of 2% of all emissions from commercial aviation. To achieve this, substantial expansions in high-speed rail infrastructure (e.g., to enable the envisioned tripling of high-speed rail traffic in the EU by 2050[30]) would be required.[31]
- **Shifting consumer choice:** Transparent information on the impact of travel could lead to more sustainable travel choices by consumers. Google Flights, for instance, lets its users sort their flights not only by price or duration, but also by CO_2 emissions.[32]
- **Response to increasing costs per passenger kilometre:** Increasing costs per passenger kilometre due to the use of expensive SAFs could result in a demand reduction. The elasticity of demand is about 1; that is, an increase in ticket prices of 5% could result in a demand reduction of 5%.[33]

EXHIBIT 1.6

Flights longer than 1,800 km are responsible for two-thirds of GHG emissions from commercial passenger aviation

Cumulative share of departures, revenue passenger kilometres (RPK), and fuel burn dependent on flight distance, 1 nautical mile = 1.852 km



Source: Schäfer et al. (2019)[34]

1.2.2 Efficiency improvements

Over the past decades, the aviation industry has made huge progress in making its aircraft and flight procedures more efficient. Within normal fleet turnover cycles, the replacement of retired aircraft with new, more efficient aircraft leads to regular efficiency improvements at negative CO_2 abatement costs of $70–$250 per tonne of CO_2.[35] That means per every abated tonne of CO_2, $70–$250 can be saved. Other aircraft technology improvements — like reducing cabin weight, retrofitting aircraft with blended winglets, or switching to electric

taxiing — have similar negative abatement costs. Individual operational strategies from airlines and air traffic management (ATM) improvements can have similar effects — at negative CO_2 abatement costs of $250–$300 per tonne of CO_2.[36]

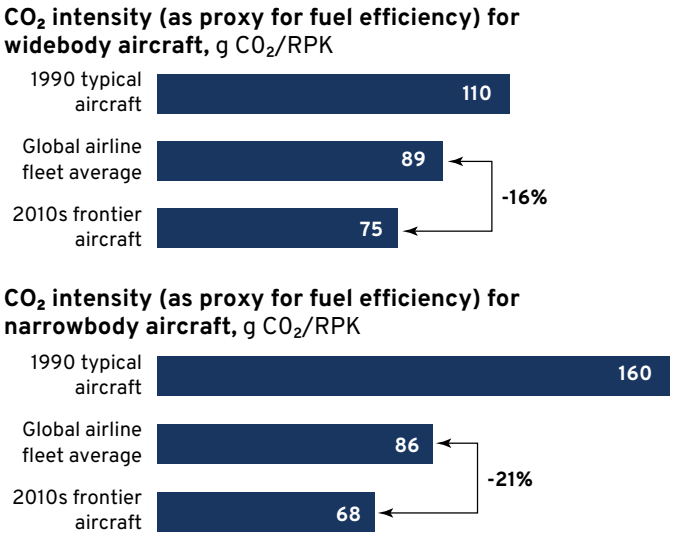
Increasing the efficiency of flying reduces fuel costs. As a result, the industry achieved average yearly efficiency improvements of 1.0% between 1970 and 2019, and it reached 1.5%/y between 2010 and 2019.[37] Beyond those continued historical trends, we assume that overall efficiency improvements could be increased to 2.0%/y by 2030 through additional efficiency gains from:

- Operational improvements and ATM[38] (e.g., optimized approach/departure procedures, vertical speed inefficiency reductions during cruise from improved aerodynamics, improved congestion management, single-engine taxiing, engine washes)
- Other efforts like retrofits or new engine and aircraft designs[39]

If these efficiency targets are achieved, the global aircraft fleet could be about 40% more fuel efficient in 2050 than in 2019. Replacing the average aircraft with the most efficient aircraft currently in service would save about 16%–21% of fuel (Exhibit 1.7), without introducing any new technologies to the market. Further efficiency improvements can be achieved through novel turbine technologies (like open rotor engines) or airframe or operational improvements, such as those recently outlined in a study from the Aerospace Industries Association and Accenture[40] and in Europe's decarbonisation roadmap for aviation, *Destination 2050*.[41]

EXHIBIT 1.7

The most efficient aircraft in service are 15%–20% more efficient than the global fleet average



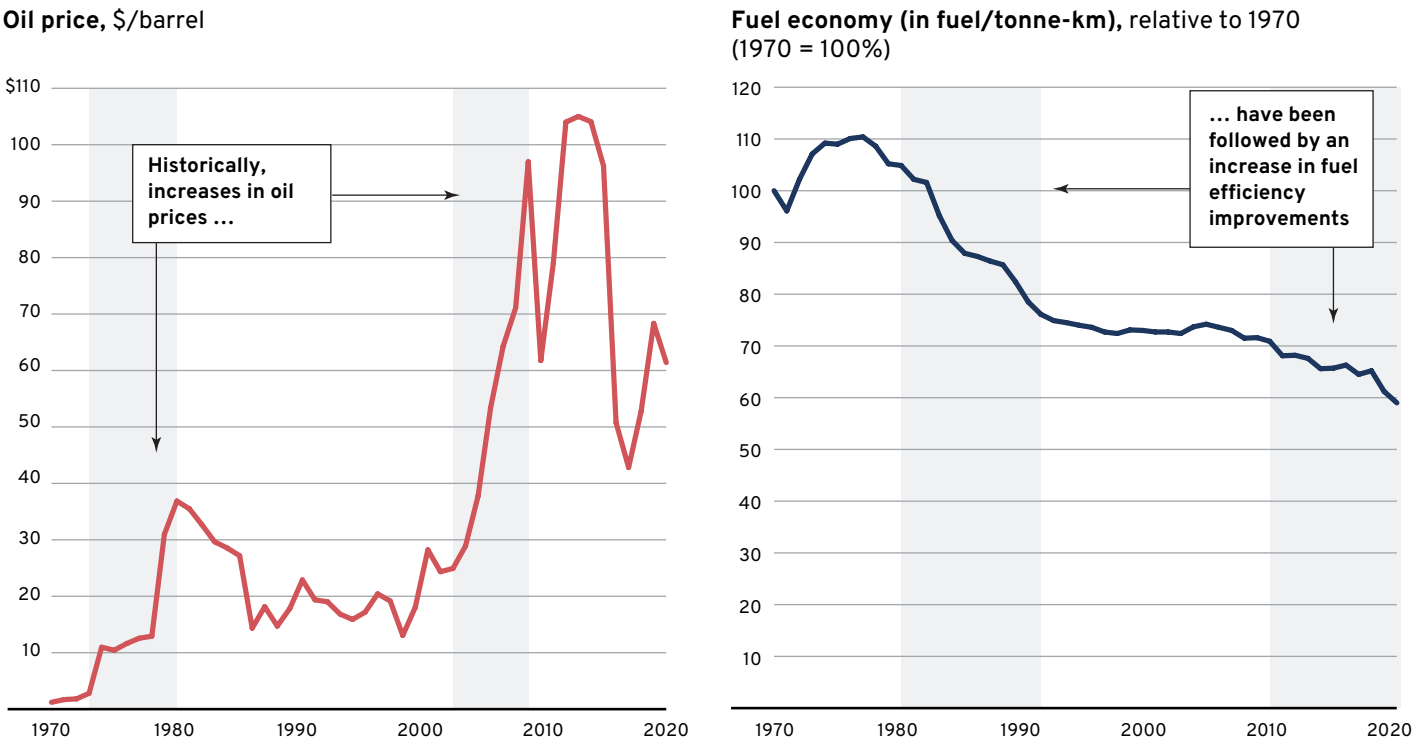
Note: Average fuel economy for wide- and narrowbody aircraft (which are responsible for about 80% of the CO_2 emissions of commercial aviation) in 2019 and indicative values for the older aircraft and the newest aircraft in the fleet.

Source: MPP analysis, based on International Council on Clean Transportation (ICCT)[42]

Policy incentives are needed to support bridging the gap between the historical 1%–1.5%/y efficiency gains and the aspired 2%/y, which will require massive research, development, and demonstration (RD&D) efforts from original equipment manufacturers (OEMs) and engine/parts suppliers. There is evidence from historical data that times of high oil prices have been followed by a stronger focus on fuel efficiency gains (Exhibit 1.8). Similarly, the prospect of future fuel price increases will serve as a key driver for increased fuel efficiency measures. Therefore, policies need to create certainty about the switch from fossil jet fuel to SAFs in the future (through blending mandates, carbon pricing, emissions trading schemes, etc.) and corresponding increases in average fuel costs.

EXHIBIT 1.8

Historically, high oil prices have been followed by increased fuel efficiency improvements



Source: MPP analysis, based on World Bank and ICCT[43]

1.2.3 Sustainable Aviation Fuels (SAFs)

SAFs are the most important lever to decarbonise aviation. Until hydrogen and battery-electric aircraft enter the market in the 2030s, SAFs will be the only viable option to decrease emissions to close to zero, and they will remain the only lever for long-haul flights in the future. They are chemically almost identical to conventional jet fuel, and therefore compatible with current airport infrastructure and aircraft engines. Currently, most certified SAFs can be blended with conventional fossil jet fuel up to 50 vol%,[44] but OEMs and engine manufacturers have announced plans to target certification of 100% unblended SAF by 2023–30.[45] In this report, SAFs from sustainable biomass (HEFA and other biofuels like gasification/Fischer-Tropsch and alcohol-to-jet) and electricity (Power-to-Liquids) are modelled:

- **HEFA:** SAFs made from waste and residue fats, oils, and greases that are produced through so-called hydroprocessing of esters and fatty acids are known as HEFA, which is the only biofuel that is commercially available today. Its production costs are in the range of 2–3x the cost of the average historical fossil jet fuel price (average over the past two decades). Its scale-up is limited by the availability of sustainable biomass feedstock. Additionally, HEFA feedstock (like used cooking oil) is also in demand from other sectors, and only minor cost reductions are expected from scale effects: by 2050, HEFA is still expected to cost around 2x the cost of the historical fossil jet fuel price.

- **Other biofuels:** Agricultural and forestry residues, municipal solid waste (MSW), as well as cellulosic (non-food) energy crops can be converted to jet fuel via gasification and a subsequent Fischer-Tropsch synthesis (G/FT) or to alcohols and then to jet fuel via an alcohol-to-jet synthesis (AtJ). Feedstock for these biofuels is significantly less limited than HEFA feedstock, but many sectors are competing for

sustainable biomass. Such biofuels currently cost about 3.0–4.5x the historical average jet fuel price, but as these technologies mature, this cost surplus is expected to drop to 2.5–4.0x by 2030 and to 2.0–3.5x through 2050.

- **PtL:** Water and captured CO_2 (from point sources or from air[ix]) can be converted into liquid fuels using renewable electricity, electrolysers, and a Fischer-Tropsch synthesis. This process is known as Power-to-Liquids (PtL), which currently has the lowest TRL (5–6) among all SAFs. There are theoretically no feedstock constraints for PtL. Supply potentials for global renewable electricity generation exceed projected demand, and CO_2 can be captured from ambient air basically without limitation.[x] The production cost of PtL currently ranks at 3–9x the average historical jet fuel price but is expected to drop massively to 2.0–4.5x by 2030 and 1.0–2.5x by 2050. Currently, 85% of the cost of PtL production stems from hydrogen production and the related renewable electricity generation.[46] The expected cost decline of renewable electricity and hydrogen also drives a rapid reduction of PtL costs, whereas biofuels have a smaller cost reduction potential due to capital-intensive plant equipment or biomass feedstock prices that show a smaller cost decline. Because of these expected cost reductions, PtL could reach close-to-cost parity with the average historical jet fuel price by 2050, if it is produced at locations with extremely low levelised costs of renewable electricity.

A variety of other SAF production pathways could potentially match the characteristics of the highlighted SAF pathways (HEFA, G/FT, AtJ, PtL) in terms of sustainability, GHG reduction potential, costs, and other factors. Pyrolysis and catalytic hydrothermolysis could for example be subsumed under "other biofuels", and recycled carbon fuels based on carbon monoxide off-gases from steel or ferroalloy plants would be subsumed under PtL, given that they are based on non-biomass feedstocks. Because of the high uncertainties about future technology and cost developments of new SAF production pathways, they are implicitly included in this analysis: under the prerequisite that they match the sustainability, costs, and GHG emission reduction impact of G/FT, AtJ, or PtL, they would be included in those categories. An extended list of existing SAF production pathways is provided in the *Technical Appendix*.

1.2.4 Novel propulsion aircraft

Hydrogen, battery-electric, and hybrid-electric aircraft can reduce CO_2 emissions by about 95%. They could potentially also reduce aviation-induced cloudiness and improve local air quality. However, three major barriers limit their contribution to achieving net zero by 2050:

- **Range limitation:** Hydrogen aircraft are limited to ranges up to 2,500 km, battery-electric aircraft to a few hundred km. Redesigns of conventional airframes could potentially unlock much larger distances for hydrogen aircraft — and new battery chemistries could potentially enable flights up to 1,000 km for battery-electric aircraft, should they be able to quadruple current battery pack energy densities of 200 Wh/kg. However, even then, their energy density would still be 10x lower compared with jet fuel. Hybrid aircraft can serve as bridging technologies until full-electric aircraft reach commercial readiness.

- **Technology development risk:** Historically, the development of new aircraft has required large investments from OEMs and has been a high-risk endeavour in a more or less duopoly market between Airbus and Boeing. Not until 2020 did Airbus announce its plans for hydrogen aircraft,[47] with Embraer following the year after with its announcements of electric and hydrogen aircraft concepts, and only over the past few years have smaller companies or startups entered the race to bring hydrogen, battery-electric, and hybrid-electric aircraft to the market.[48] Currently, novel propulsion aircraft have TRLs of 1–5.

- **Market introduction lead time:** Airworthiness certifications for new aircraft can take about 5–9 years.[49] Also on the ground, new transportation, logistics, and refuelling infrastructure will be required — however, the feasibility of hydrogen infrastructure at airports has already been demonstrated in Heathrow, Berlin, and Los Angeles.[50]

Hybrid-electric aircraft offer the potential for earlier carbon reductions by enabling efficient electric aircraft configurations to be combined with SAF.

1.2.5 Carbon dioxide removal (CDR) solutions

CDR solutions are needed *in addition to, not instead of,* deep and rapid in-sector decarbonisation, in line with the Science Based Targets initiative.[51] For aviation, CDR solutions are necessary in order to neutralise the residual emissions from SAFs, hydrogen, and electricity as these renewable fuels typically do not reduce GHG emissions by 100% but by only about 75%–95%. CDR solutions are also needed to neutralise the residual warming effect of aviation-induced cloudiness that cannot be mitigated

ix CO_2 can be sourced from point source capture in the near term to scale up PtL production, but needs to come from direct air capture in the long term. Double-counting of the emissions reduction credit between the emitting industry that captures the CO_2 and the PtL producer using the CO_2 in fuel production needs to be avoided at all times.

x The abundant availability of these two resources will be critical in order to avoid any harmful side effects (like delayed phase-out of coal because scarce renewable electricity is used for PtL production rather than for replacing coal power). There could be a risk of near-term supply constraints because aviation competes with other sectors for renewable electricity and green hydrogen, and supply might lag behind demand. However, supply pipelines for both green electricity and hydrogen are accumulating rapidly.

by renewable fuels. Net zero can be achieved only through a combination of renewable fuels and CDR.

CDR solutions include (1) natural climate solutions like land use management, (2) hybrid solutions like biochar or bioenergy with carbon capture and storage (BECCS), and (3) engineered solutions like direct air carbon capture and storage (DACCS).[52]

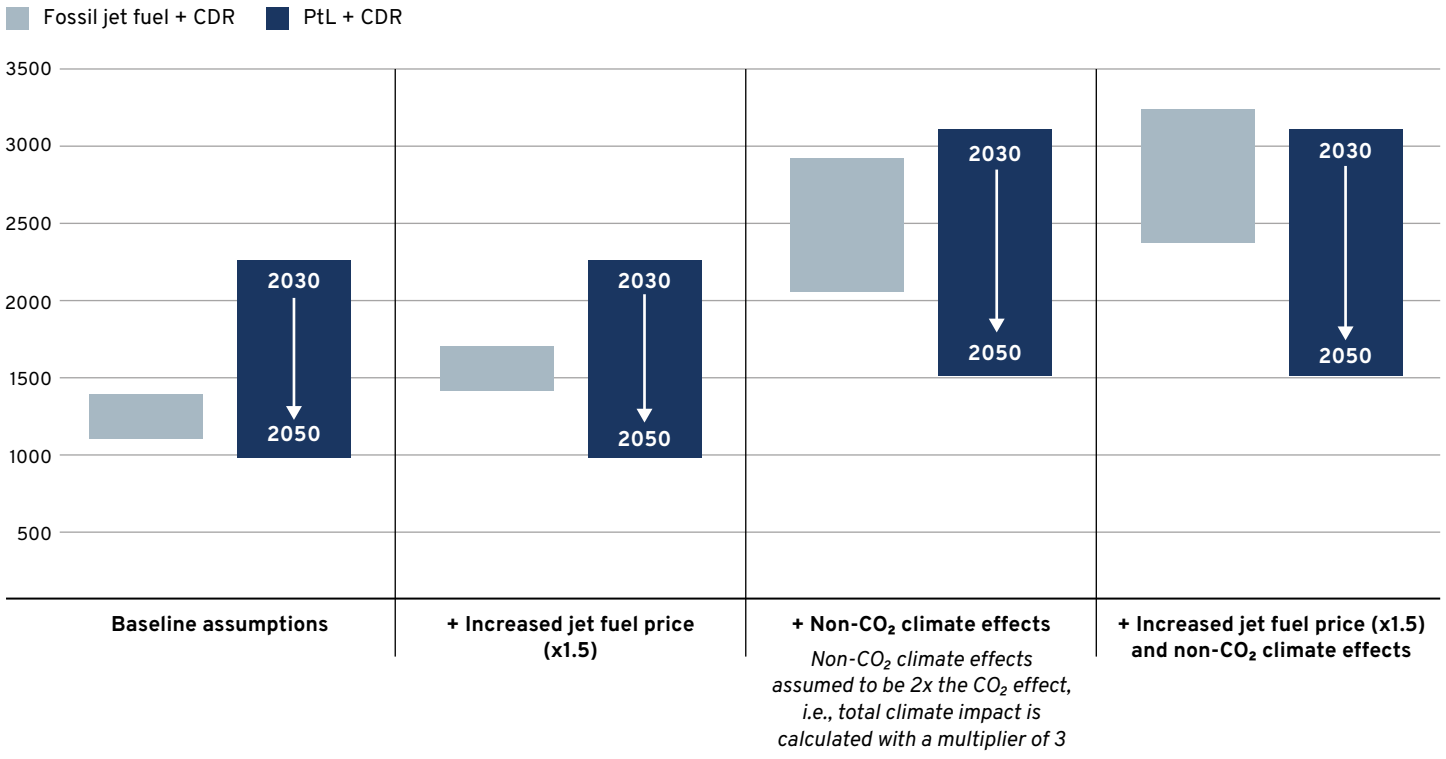
Natural climate solutions come at a cost of \$0–\$100/t CO_2. Meanwhile, hybrid and engineered solutions cost between \$300 and \$600/t CO_2 today but with more cumulative deployed capacity could reach a cost level of \$100–\$300/t CO_2 by 2050.[53] Background information on the role of CDR solutions, based on a recent in-depth analysis from the Energy Transitions Commission on the role of CDR to complement deep decarbonisation,[54] can be found in the *Technical Appendix*. The ETC's CDR report provides further details on quality criteria for CDR (like the permanence of CO_2 removal), the potential CDR volumes per specific measures, and the required investments over the next decade to scale CDR solutions.

The continued use of fossil jet fuel combined with CDR neither represents an in-sector decarbonisation measure nor is economically preferrable if oil prices are high. Capturing CO_2 and converting it into PtL jet fuel is likely going to be a cost-competitive alternative to using fossil jet fuel and neutralising all associated emissions via CDR. Factoring in aviation-induced cloudiness, the non-CO_2 climate impact of aviation, creates cost parity between fossil jet fuel/DACCS and e-jet fuel produced via PtL with CO_2 from DAC (Exhibit 1.9). In the long run, PtL is most likely going to outcompete fossil jet fuel/DACCS in terms of fuel costs, if PtL proves to significantly reduce non-CO_2 climate forcing (which is currently estimated to be the case but subject to high uncertainties).[55] Therefore, the continued use of fossil jet fuel combined with CDR is not considered in this report.

EXHIBIT 1.9

The use of PtL could be more cost competitive compared with the use of fossil jet fuel when factoring in non-CO_2 climate effects

Jet fuel costs, \$/t



Note: Fossil jet fuel price at \$600–\$650/t. Emissions of 3.84 tonnes CO_2e/tonne of fossil jet fuel. Lower bound of fossil jet fuel: CDR via mix of NCS, BECCS, and DACCS at \$125/t CO_2. Upper bound of fossil jet fuel: CDR via DACCS at \$200/t CO_2. PtL is assumed to reduce CO_2e emissions by 90% and the total climate impact (incl. aviation-induced cloudiness) by 60%. Lower bound of PtL: Estimated fuel production cost in 2050 is 1.5x fossil jet fuel price, residual emissions neutralised by CDR assuming a mix of NCS, BECCS, and DACCS at \$125/t CO_2. Upper bound of PtL: Estimated fuel production cost in 2030 is 3.5x fossil fuel price, residual emissions neutralised by CDR assuming DACCS at \$200/t CO_2. Residual climate impacts (CO_2/non-CO_2 effects) of fossil jet fuel and PtL are neutralised by CDR. Comparison is similar for other SAF types and would be different for different fossil jet fuel cost assumptions. In general, a higher oil price will make the case for PtL more compelling.

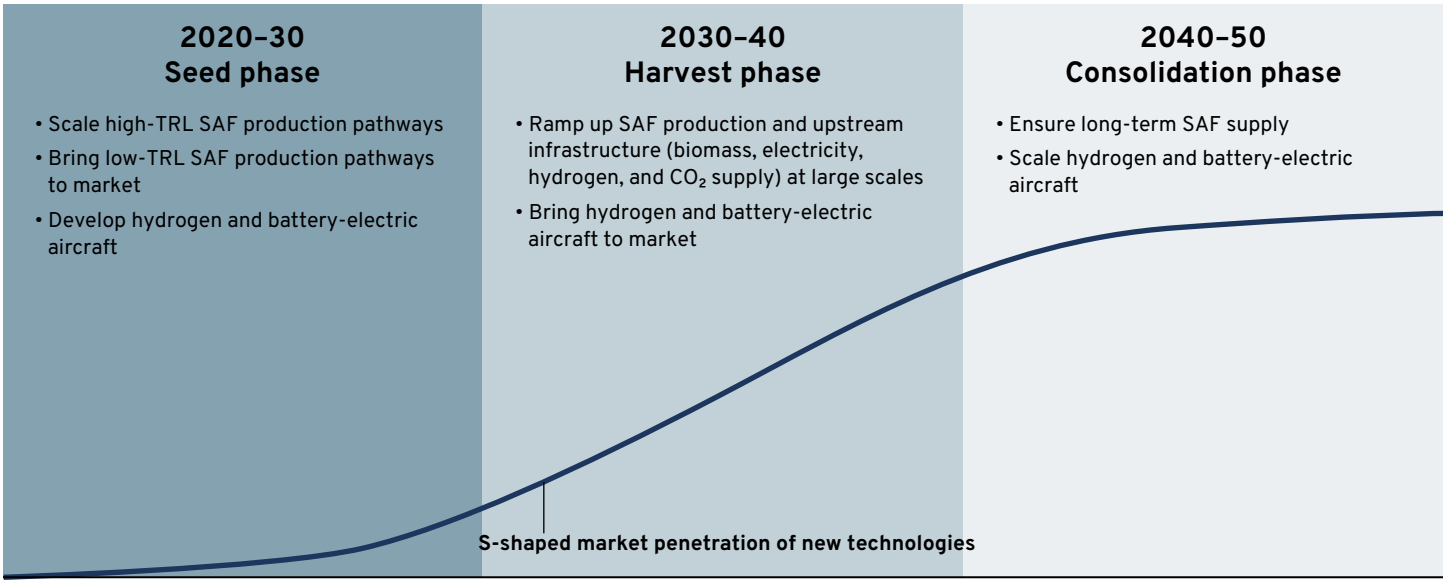
Source: MPP analysis based on ETC CDR report[56]

1.2.6 Summary

Considering the current state of all decarbonisation measures above, **the role of action in this decade** is not to achieve large emission reductions by 2030 compared with 2019 levels, but **to unlock the massive scale-up** of decarbonisation technologies **in the 2030s** (see Exhibit 1.10).

EXHIBIT 1.10

The role of each decade to achieve carbon-neutral growth until 2030, halve emissions by 2040, and get to net zero by mid-century



Source: MPP schematic

Early progress is already under way (see overview in Exhibit 1.11). Around 0.05–0.10 Mt SAF are currently produced annually,[57] all from HEFA plants that make not only jet fuel, but also diesel/gasoline and light ends like naphtha. However, HEFA plants have a total product output capacity of 9 Mt and could produce more jet fuel (up to 55% instead of the current 18%), but existing regulations disincentivise the production of jet fuel in favour of road transport fuels. Because of increasing political and industrial pushes to use significant volumes of SAF in the future, fuel producers are meanwhile investing in new SAF production plants. The current project pipeline of planned SAF plants would ramp up SAF production to 8.4 Mt by 2030. About 90% of these announced volumes are coming from HEFA.

EXHIBIT 1.11

Early progress towards net-zero aviation

Targets from international bodies

Industry-wide goal of net zero by 2050

IATA/ATAG have committed to achieve **net-zero carbon emissions by 2050**

ICAO: Carbon-neutral growth

ICAO member states have committed to **CORSIA**, the carbon offsetting and reduction scheme for international aviation, i.e., to achieve **carbon-neutral growth from 2019 on**

Targets from (supra-)national policy

5% SAF by 2030

Blending mandate within the **European Union**

10%–15% SAF by 2030

SAF use target of 9 million tonnes by 2030 for the commercial aviation fuel market in the **United States** (range of 10%–15% dependent on demand projection)

Industry action

>35 airlines: Carbon neutral by 2050

>35 airlines have announced plans to target **carbon neutrality by 2050** or earlier

First Movers Coalition

Committed to using **cutting-edge SAFs and propulsion technologies** for air travel by 2030

100 companies: 10% SAF by 2030

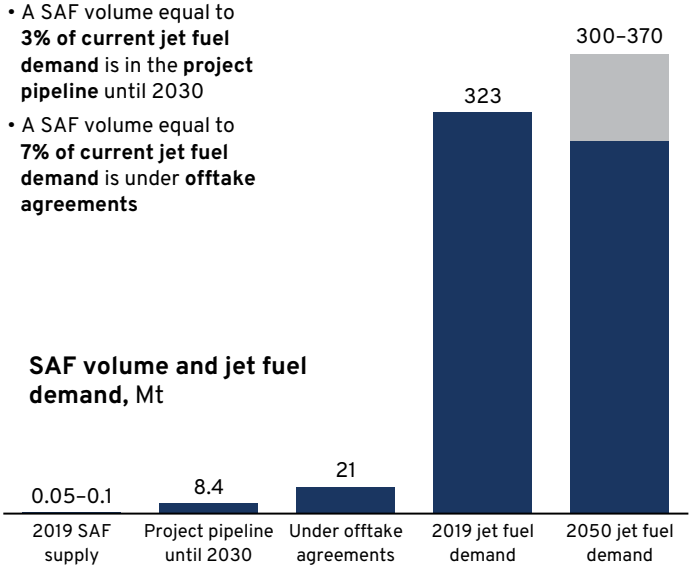
100 companies have signed CST's ambition statement to use **10% SAF by 2030**, orchestrated by the World Economic Forum and supported by MPP

80+ industry leaders

80+ aviation companies across the whole value chain engaged in the **Mission Possible Partnership**

SAF supply starting to take off

- A SAF volume equal to **3% of current jet fuel demand** is in the **project pipeline** until 2030
- A SAF volume equal to **7% of current jet fuel demand** is under **offtake agreements**



Source: MPP overview, based on IATA; ICAO; ATAG; European Commission; the White House; First Movers Coalition; McKinsey analysis; CST[58]

PART 2

ACHIEVING NET ZERO: POSSIBLE TRAJECTORIES

There is a range of possible scenarios how to achieve net-zero GHG emissions in aviation. Different combinations of the whole portfolio of decarbonisation measures can lead to the same target. By modelling two potential trajectories to net zero by 2050, we aim to illustrate the potential pace of change under different circumstances and highlight the prerequisites for both scenarios in terms of required investments, resource demand, and 2030 milestones to kick off the transition.

The two scenarios paint two pictures of how the transition to net zero can be mastered by mid-century; the reality might lie in between. However, these two scenarios will allow for a discussion of no-regret moves — that is, action that needs to be taken no matter which set of decarbonisation measures is used — and key trade-offs between certain types of decarbonisation measures, e.g., the demand for sustainable biomass for biofuel production versus the demand for renewable electricity for PtL production. We also identify the key drivers for these trade-offs and conclude under which circumstances certain technologies would have more or less market penetration.

2.1 Scenario definition

The two net-zero scenarios aim to minimize the total costs of ownership for the aviation sector within a given set of constraints, including (A) technology market entry and ramp-up constraints, (B) biomass feedstock constraints, (C) aircraft range constraints, and (D) regulations that incentivize the use of SAFs.

To gauge real-world impacts, the two net-zero scenarios are compared with a business-as-usual scenario (Exhibit 2.1).

- **Business as Usual (BAU):** In the BAU scenario, the aviation industry seeks the lowest total cost of ownership for aircraft, implementing new technologies only if they offer an economic advantage.
- **Prudent (PRU):** The PRU scenario describes a trajectory to net-zero GHG emissions by 2050 that relies on technologies that either are already available or will enter the market over the coming decades, according to industry consensus. Based on prudent technology improvement assumptions, this scenario posits the deployment of a diversified mix of technologies.
- **Optimistic Renewable Electricity (ORE):** The ORE scenario describes a trajectory to net-zero GHG emissions by 2050 in which abundant and cheap clean electricity spurs rapid R&D and faster than anticipated cost declines for electricity-based technologies. As a result, PtL and hydrogen aircraft enter the market earlier and at a larger scale.

All three scenarios include a compound annual growth rate (CAGR) of the global air travel demand of 3.0%/y between 2024 and 2050, while demand is projected to recover to pre-pandemic levels by 2024. Between 2019 and 2050, that yields an overall demand growth rate of roughly 2.5%/y. This is a crucial assumption. Demand needs to be kept below or at this global average demand growth rate, while at the same time considering a just transition with regionally differing growth rates, in particular allowing for higher growth rates in developing countries. If demand for air travel were to rise at a faster pace, reaching net zero would require larger volumes of renewable fuels than highlighted in the PRU and ORE scenario in the next section.

The BAU scenario assumes a continuation of historical annual fuel efficiency improvements of 1%/y, while PRU and ORE assume annual efficiency gains of 1.5% in 2019, linearly increasing to 2% until 2030 and constant at 2% afterwards through 2050.

For PRU and ORE, we also model the EU's proposed SAF blending mandate covered in the ReFuelEU Aviation policy proposal.[59] For the United States, we implement its *SAF Grand Challenge* to supply at least 3 billion gallons of SAF a year by 2030 (about 15% of pre-pandemic US jet fuel demand from airlines[60]) and to meet 100% of the projected aviation fuel demand with SAFs by 2050.[61]

In both PRU and ORE, the aviation industry is modelled to accept a certain green premium on top of BAU in order to get to net zero. The maximum accepted green premium is measured as the difference in airlines' total costs of ownership when using SAFs, hydrogen, or battery-electric aircraft compared with using fossil jet fuel. This concept of a green premium does not suggest that it will be paid by a single entity; it can be shared across the value chain. For PRU and ORE, the model selects the technology with the lowest GHG abatement costs within all solutions that are in reach within a certain green premium on top of the total costs of ownership.

Scenario overview

EXHIBIT 2.1

	Business-as-Usual scenario (BAU)	Prudent scenario (PRU)	Optimistic Renewable Energy scenario (ORE)
Fuel efficiency improvements	**Moderate:** 1%/y	**High:** 1.5%/y in 2019, ramping up to 2%/y in 2030, then constant at 2% until 2050	
Renewable electricity costs	**Moderate:** $50–$200/MWh today, $50–$120/MWh by 2050		**Low:** $30–$150/MWh today, $20–$80/MWh by 2050
Power-to-Liquids technology	**Medium cost:** Driven by medium hydrogen cost reductions ($3.5–$6.5/kg H_2 today, $2.25–$3.75/kg H_2 by 2050)		**Low cost:** Driven by high hydrogen cost reductions ($2–$4/kg H_2 today, $0.7–$1.3/kg H_2 by 2050)
Sustainable biomass availability	**High:** Up to about 14 EJ of sustainable biomass feedstock available for aviation		**Medium:** Up to about 6 EJ of sustainable biomass feedstock available for aviation
Market entry of hydrogen and battery-electric aircraft	**Late:** Around 2040		**Early:** Around 2035
Maximum range of hydrogen fuel cell and battery-electric aircraft	Max. 1,000 km for battery-electric and 2000–2,500 km for hydrogen fuel cell aircraft (100–200 km in the near term)		
Maximum range of hydrogen combustion aircraft	**Moderate:** ~2,500 km for hydrogen combustion aircraft in the long term		**High:** No range limitation for hydrogen combustion aircraft in the long term
Maximum green premium before efficiency gains*	**0%**	**37.5%**	**25%**
Model logic	Selects **technology with lowest GHG abatement costs** among the options that lie **within the maximum green premium range**, considering a set of constraints		

*The maximum accepted green premium is measured as the difference in airlines' total costs of ownership when using SAFs, hydrogen, or battery-electric aircraft compared with using fossil jet fuel on individual routes. This concept of a green premium does not suggest that it will be paid by a single entity; it can be shared across the value chain.

Source: MPP modelling; see more details on modelling assumptions in the *Technical Appendix*.

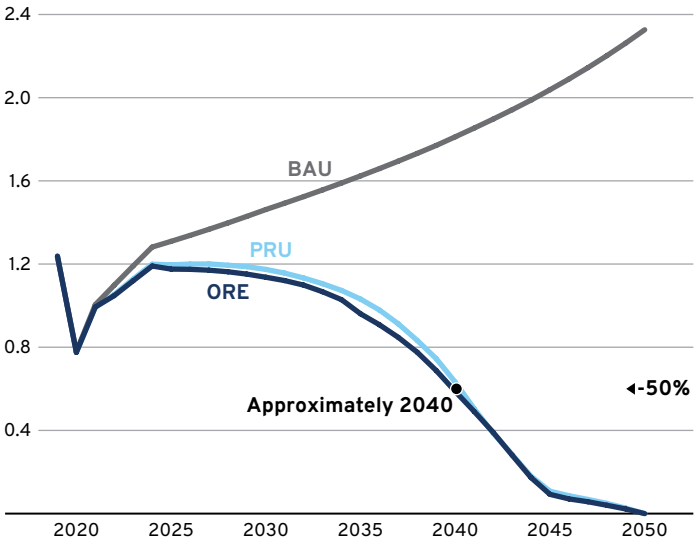
2.2 What it will take to achieve net-zero aviation

2.2.1 CO_2-neutral growth until 2030, halving emissions by 2040, net zero by 2050

EXHIBIT 2.2

Both net-zero scenarios halve emissions by around 2040 and get to net zero by 2050

Annual emissions, Gt CO_2e



Source: MPP analysis

- **Until 2030, achieving carbon-neutral growth** based on 2019 levels — and thereby complying with ICAO's CORSIA goal[xi] — is critical (Exhibit 2.2). This alone will require the industry to bring new SAF production pathways to market and scale them up rapidly. The net-zero scenarios manage to stay below 2019 emission levels at all times, and the share of SAFs on total jet fuel consumption by 2030 amounts to 13% for the Prudent scenario and 15% for the Optimistic Renewable Electricity scenario. In both cases, half of the SAF volumes are from HEFA, the other half from other biofuels and PtL. Because of a more ambitious cost reduction path for PtL, the ORE scenario already has a PtL share of 30% on total SAF volumes by 2030.

- **By 2040,** a critical milestone will be to **halve 2019 emission levels.** In both net-zero scenarios, renewable energy carriers (i.e., SAFs, hydrogen, and electricity) reach 50% market share of the final energy demand shortly before 2040.

- **By 2050,** the aviation sector could **reduce its GHG emissions by about 95%** through in-sector decarbonisation measures compared with 2019 emissions levels, despite high demand growth rates. Both net-zero scenarios halve the cumulative GHG emissions between 2022 and 2050 compared with the BAU scenario. In both net-zero scenarios, residual value chain emissions of 0.12–0.14 Gt CO_2e (mainly from biofuels and PtL) need to be counterbalanced by CDR to reach net zero. The CDR solutions must be ramped up well before 2050 to attain the required volumes towards mid-century and beyond, starting with investments in this decade.[xii]

2.2.2 Compatibility with 1.5°C carbon budget

Both net-zero scenarios comply with the 1.5°C carbon budget.

The carbon budget of about 18 Gt CO_2 (defined in **Box 1**) compares with cumulative emissions of about 18 Gt CO_2 in the two net-zero scenarios (Exhibit 2.3). Hereby, the Prudent scenario shows slightly higher CO_2 emissions than the Optimistic Renewable Electricity scenario. However, both net-zero scenarios are 1.5°C-compliant.

By contrast, in the Business-as-Usual scenario, the 1.5°C carbon budget for aviation is exceeded by 117%. Emitting 39 Gt CO_2 between 2022 and 2050, aviation would emit 10% of the global carbon budget still available from the beginning of 2022 (roughly 380 Gt CO_2), compared with an emissions share of only about 3% today.

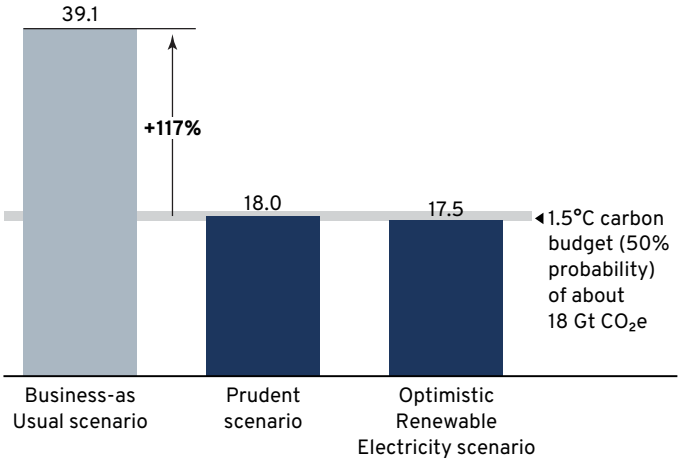
xi ICAO's Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) aspires carbon-neutral growth of international aviation from 2019, that is, keeping global CO_2 emissions of international aviation below/at 2019 levels.

xii In this report, a constant growth rate of 20%–25% is assumed for CDR to reach the required levels in 2050 to counterbalance residual emissions from renewable fuels, starting with a CO_2 removal capacity of 1 Mt/y in 2025.

EXHIBIT 2.3

Both net-zero scenarios are 1.5°C-compliant, halving cumulative emissions of a BAU scenario

Cumulative CO_2 emissions between 2022 and 2050, Gt CO_2

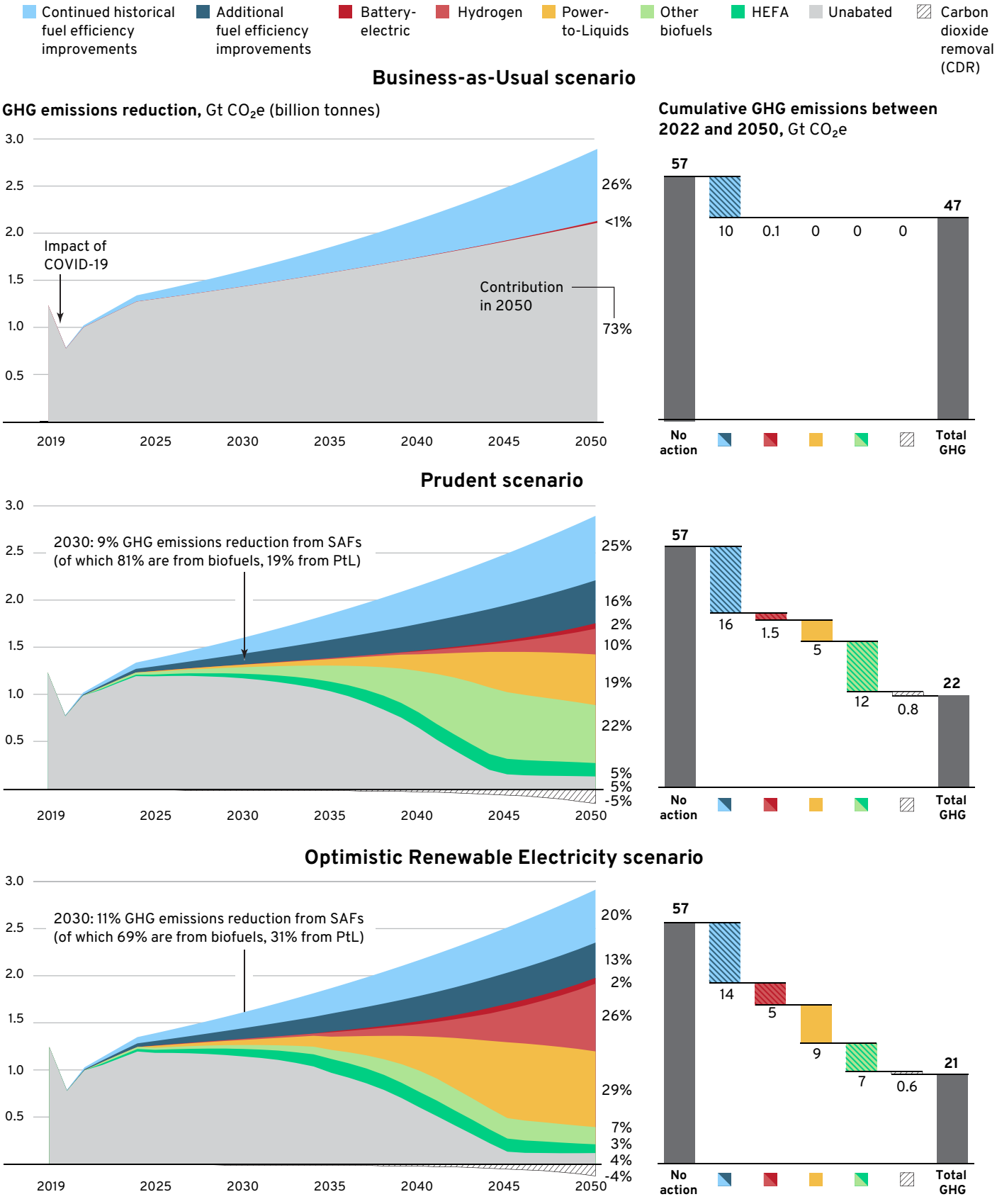


Note: For cumulative emissions, we have accounted for tank-to-wake CO_2 emissions of fossil jet fuel and life-cycle CO_2 emissions (incl. Scope 1 and Scope 3) for renewable fuels. Based on industry expertise and Chipindula et al. (2018), we have assumed that 95% of the assumed life-cycle GHG emissions are CO_2, the rest from non-CO_2 species. Only for waste-based fuels (e.g., used in G/FT or AtJ processes), we have assumed that 90% of the life-cycle GHG emissions are CO_2. The cumulative emission figures include emissions reductions from CDR.

Source: MPP analysis

EXHIBIT 2.4

A combination of GHG reduction levers can make net-zero aviation a reality



Note: Sums in contributions to 2050 GHG emissions may not total 100 due to rounding. Source: MPP analysis

2.2.3 The role of SAFs and fuel efficiency measures

The two **main GHG emissions reduction levers** in the two net-zero scenarios **are fuel efficiency improvements and the use of SAFs (Exhibit 2.4):**

- **PRU:** 95% of the cumulative GHG emissions reduction from in-sector decarbonisation measures between 2022 and 2050 stems in equal parts from the use of SAFs (of which 30% is from PtL, 70% from biofuels) and fuel efficiency gains.
- **ORE:** 85% of the cumulative GHG emissions reduction between 2022 and 2050 stems in equal parts from the use of SAFs (of which 60% is from PtL, 40% from biofuels) and fuel efficiency gains.

The **main difference between PRU and ORE** is the underlying assumption around the **development of PtL and hydrogen aircraft.** Two prerequisites are decisive for a large-scale market penetration of those two:

- **Low-cost and abundant renewable electricity and hydrogen production:** The major cost driver for PtL is the cost of electricity and hydrogen.
- **Rapid technological advancements:** If PtL can be introduced to the market at significant scale by 2030, economies of scale could unlock higher cost reductions in the 2030s and 2040s compared with biofuels. Technological advancements in the energy density of hydrogen storage systems could unlock longer ranges for hydrogen aircraft. Coupled with an early market entry, they could take a significant market share by 2050.

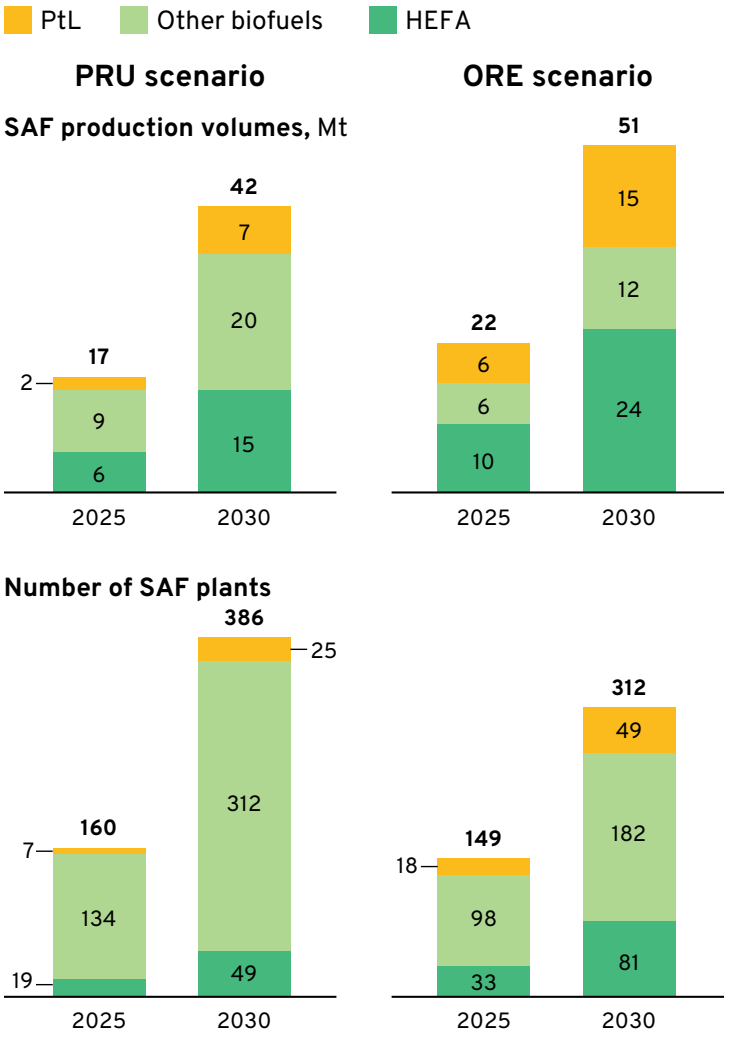
The ORE scenario incorporates those prerequisites. Although market introduction for PtL is modelled to be 2025 for both net-zero scenarios, only in the ORE scenario does PtL scale early as a result of high cost reductions and technology innovation. As a consequence, PtL dominates the SAF market and makes up 50% of the final energy demand of global aviation by 2050. Similarly, hydrogen aircraft benefit from ambitious range assumptions and low-cost green hydrogen. They could be responsible for up to roughly a third of the final energy demand by 2050.

In contrast, the PRU scenario relies on more biofuel volumes since PtL becomes competitive only in the 2040s.

Beyond 2050, hydrogen aircraft could replace a certain share of SAFs. Future total costs of ownership, technology innovation to increase the maximum aircraft range (in particular lightweight liquefied hydrogen tanks and novel airframes), and increasing certainty around the total climate impact reduction (GHG emissions and aviation-induced cloudiness) of hydrogen aircraft against SAFs will be three important factors that determine whether hydrogen aircraft could replace a certain share of SAFs beyond 2050.

EXHIBIT 2.5

300–400 SAF plants could be needed to produce 40–50 Mt SAF by 2030



Note: Assumed plant sizes: SAF output capacities of 0.3 Mt/y for PtL and HEFA, 0.065 Mt SAF/y for other biofuels.

Source: MPP analysis

2.2.4 2020s milestones to kick off the transition to net zero in aviation

By 2030, about 42–51 Mt of SAFs — 13%–15% of total jet fuel demand — are required to achieve credible 1.5°C pathways in the Prudent and Optimistic Renewable Electricity scenarios. SAF production needs to increase by a factor of

5–6 from currently planned SAF projects by then. If new SAF projects receive appropriate kickoff support, **their production cost could drop by about 10%–20% within this decade**, thanks to economies of scale. The ORE scenario relies on larger (and therefore fewer) PtL plants, and the PRU scenario requires the construction of smaller (and therefore more) non-HEFA biofuel plants.

Given project lead times of about five to six years, project planning for the 310–390 SAF plants required to supply the 2030 SAF demand levels (Exhibit 2.5) is feasible but needs to start now. The initial scale-up to a 13%–15% SAF share by 2030 can be accomplished if the following levers are pulled simultaneously: bringing PtL to the market and accelerating the scale-up of bio-jet fuel production. Three low-hanging fruits that can help to achieve this target are (Exhibit 2.6):

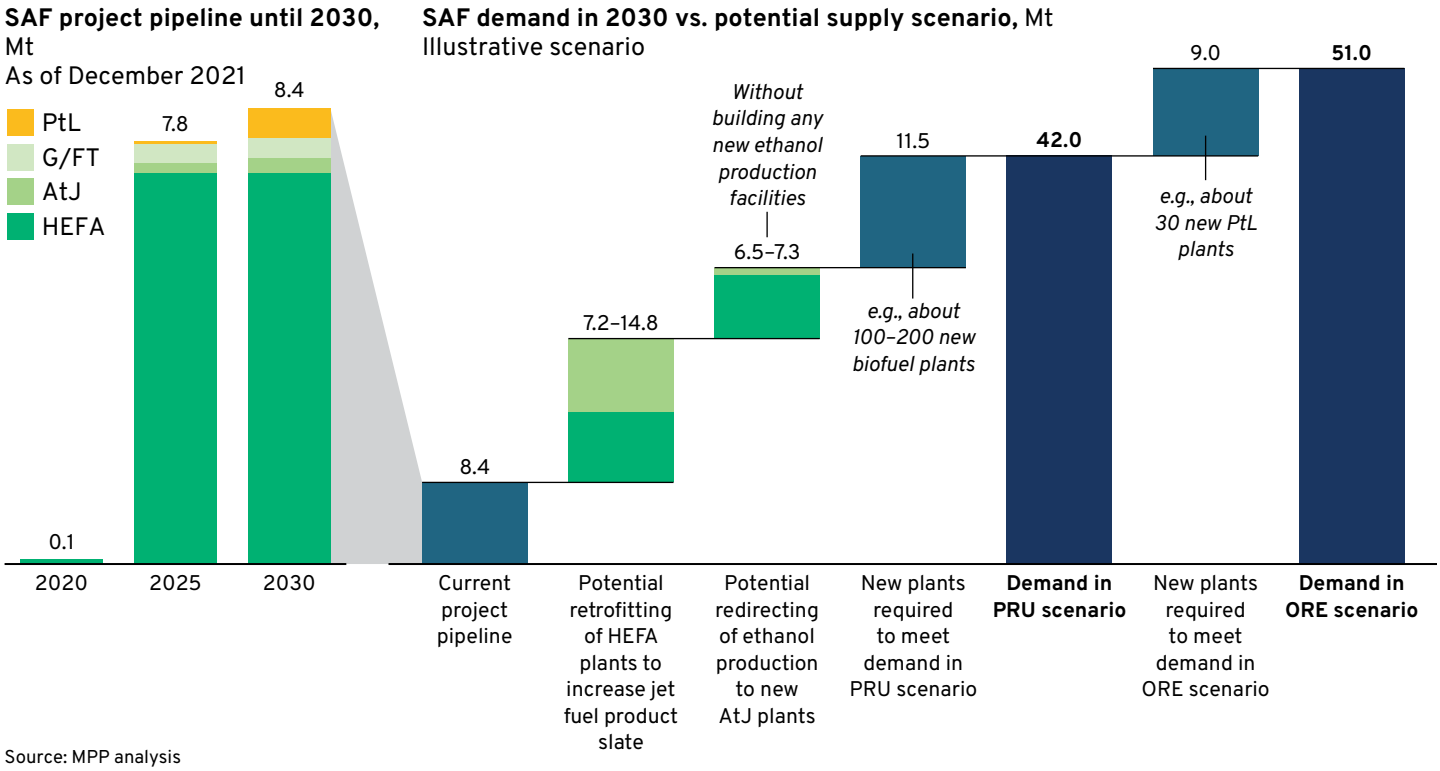
1. Today, **HEFA plants** produce only about 18% jet fuel because certain policies incentivise the production of other fuel types like diesel.[62] New HEFA plants can be optimized to achieve a 55 weight% jet fuel share on the total product output.[63] Similarly, retrofitting HEFA plants could unlock an increase in biojet volume "at a moderate investment cost".[64] A doubling of the average jet fuel share from 18% to 36% could make an additional 7.2 Mt of jet fuel available by 2030. Increasing the jet fuel share to the maximum 55% would unlock 14.8 Mt in total.

2. **Ethanol production facilities,** currently used to supply the road transport sector, could be repurposed to serve the aviation sector.[65] The electrification of cars could accelerate that process as large ethanol volumes could be freed up because of declining demand for conventional vehicles. In 2019, 115 billion litres (91 Mt) of bio-ethanol were produced globally.[66] If the replacement of conventional vehicles by battery-electric vehicles freed up 10% of that demand by 2030, an additional 6.5 Mt of jet fuel could be produced.[xiii]

3. **Bringing PtL to the market** and accelerating the scale-up of new bio-jet fuel production from non-HEFA routes can tap new SAF supply. The supply of low-cost green hydrogen, produced from renewable electricity, and captured CO_2 (from PSC or DAC) will be key enablers for a near-term PtL market entry.

EXHIBIT 2.6

Indicative SAF supply scenario for 2030



Source: MPP analysis

xiii A conversion efficiency from ethanol to jet fuel of around 90% and a jet fuel selectivity on the total product output of 77% is assumed. In Brazil, the ethanol demand could be reduced by up to 40% by 2035 because of the electrification of cars. The 10% ethanol demand reduction is estimated as a more moderate global average decrease in demand. In the long term, the 91 Mt of bio-ethanol could cover about 20% of the global jet fuel demand in 2050. See Clean Skies for Tomorrow Initiative (CST), World Economic Forum, and McKinsey & Company, *Clean Skies for Tomorrow: Sustainable Aviation Fuels as a Pathway to Net-Zero Aviation*, November 2020, www3.weforum.org/docs/WEF_Clean_Skies_Tomorrow_SAF_Analytics_2020.pdf; Guolin Yao et al., "Stochastic Techno-Economic Analysis of Alcohol-to-Jet Fuel Production", *Biotechnology for Biofuels* 10, no. 18 (2017); and Fabiana Batista, Leonardo Lara, and Isis Almeida, "Get Ready for a Flood of Sugar as Brazilians Buy Electric Cars", Bloomberg, June 15, 2021, www.bloomberg.com/news/articles/2021-06-15/get-ready-for-a-flood-of-sugar-as-brazilians-buy-electric-cars.

Although the required SAF production volumes for 2030 represent only about 10%–15% of the demand in 2050, they are key to bringing the technologies to market and unlocking the ramp-up to about 300–370 Mt SAF by 2050 (Exhibit 2.7).

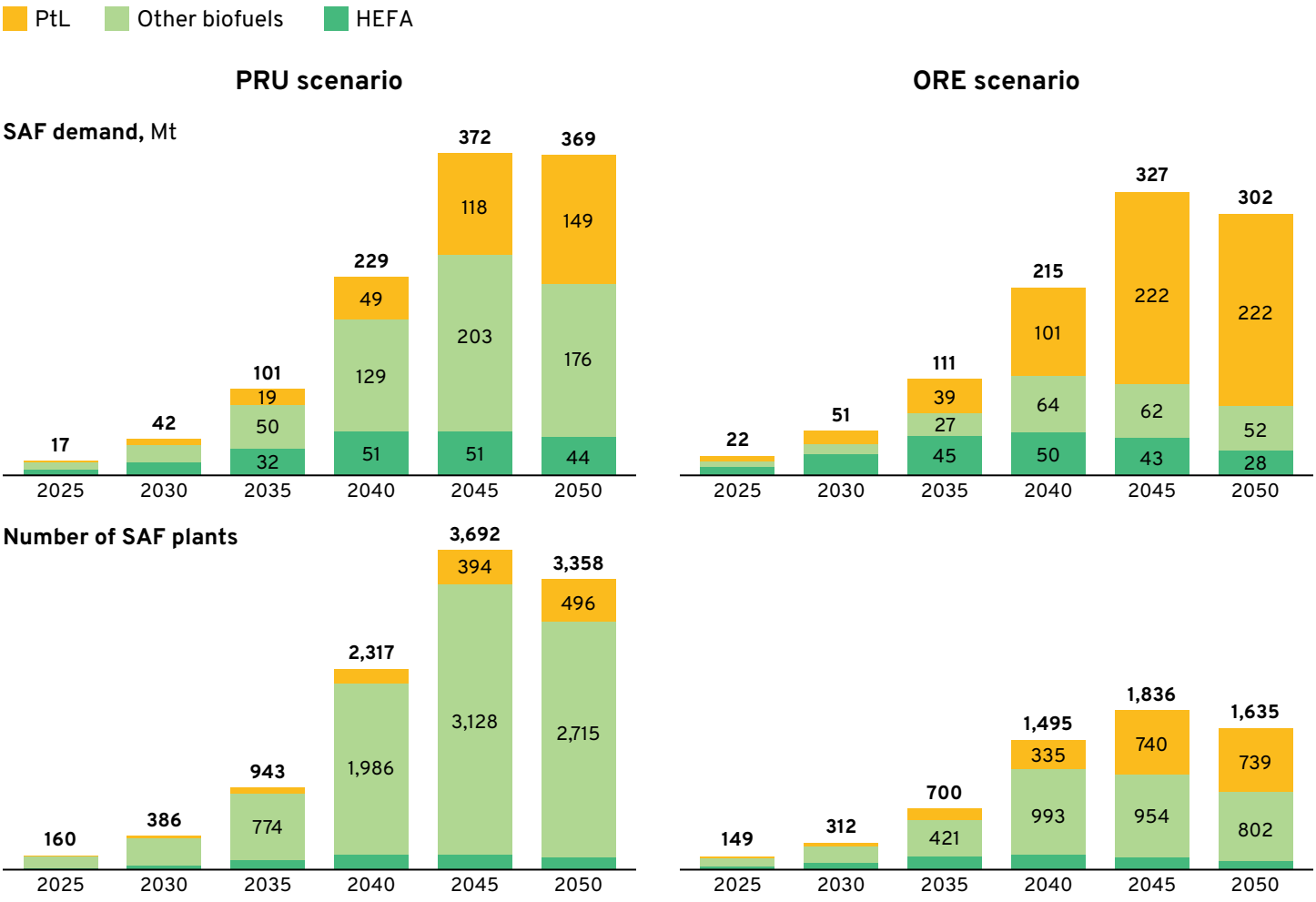
New SAF plant projects are expected to be subject to drastically lower risk from 2030 onwards. By deploying first- and second-of-a-kind commercial plants by 2030 and thereby gaining experience in these maturing technologies, the TRL of novel SAF production technologies can be brought to a higher level, inducing a reduction of investment risks. The deployment of an increasing number of SAF production facilities after 2030 will then unlock cost declines from economies of scale.

This learning-by-doing, that is, the cost decline per doubling of cumulative installed capacity, is based on (1) **technology-related learnings** like the standardisation of processes, increased operational efficiencies, greater specialisation in manufacturing, and lower prices due to the purchase of larger quantities of resources.[67] Additionally, it can be based on (2) **financial learnings**: the technological learnings "can lower the risk perceptions held by project developers and financial institutions ensuring more favourable financing conditions",[68] state investment banks can "build investor confidence in new technologies",[69] and a growing group of investors can create competition that drives down the financing cost of new projects.

For some components like electrolysers, learning rates are expected to be 13%–18%[70] with the potential to increase to rates similar to that of solar photovoltaic (PV),[71] which has experienced learning rates of about 30%, that is, a cost decline of 30% per doubling of cumulative installed capacity.[72]

EXHIBIT 2.7

1,600–3,400 SAF plants could be necessary to produce 300–370 Mt SAF by 2050



Note: Assumed plant sizes: SAF output capacities of 0.3 Mt/y for PtL and HEFA, 0.065 Mt/y SAF for other biofuels. Totals may not equal sums due to rounding.

Source: MPP analysis

2.2.5 Cost of the switch to low-carbon solutions

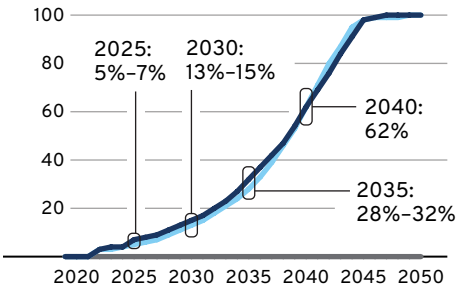
Replacing fossil jet fuel with low-carbon alternatives comes at an additional cost. As the share of those alternatives increases, economies of scale will reduce their cost. Currently, GHG abatement costs for SAFs show a high range of $200–$1,400 per tonne of CO_2e. In the Prudent scenario, the average GHG abatement cost for all renewable fuels (weighted by the volume of each fuel type) decreases to about $200 per tonne of CO_2e by 2050, and in the Optimistic Renewable Electricity scenario the cost drops even more to about $100 per tonne of CO_2e because of more ambitious assumptions about future reductions of PtL production costs. This difference of $100 per tonne of CO_2e exemplifies the value of higher technology learning rates.

EXHIBIT 2.8

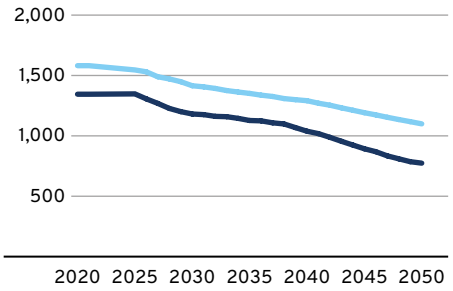
The aviation industry could avoid an increase of the cost of flying through counterbalancing increasing fuel costs with fuel efficiency gains

PRU ORE Fossil jet fuel only

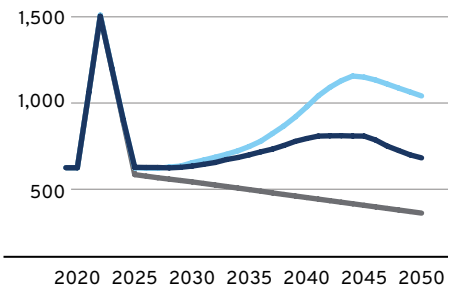
1 SAF blending rate, % of final jet fuel demand



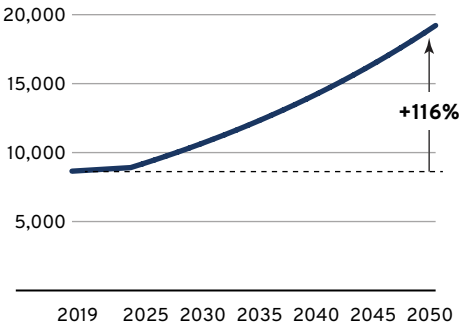
2 SAF cost, $/tonne of SAF (weighted by SAF volumes of each SAF type)



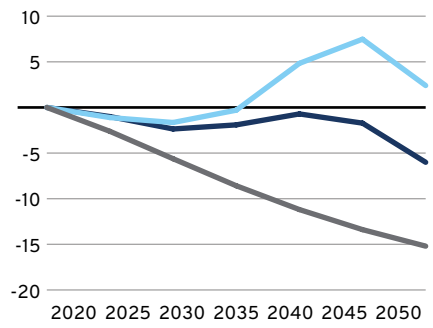
3 Average fuel cost, $/tonne jet fuel equivalent (weighted average of all energy carriers)



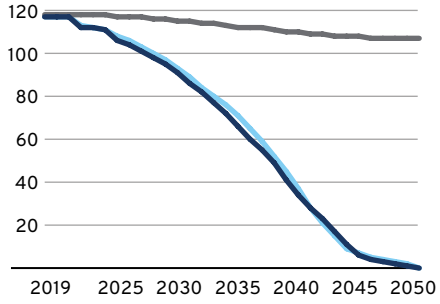
4 Billion RPK, for commercial passenger aviation (without impact of COVID-19)



5 Cost increase or decrease per RPK, % (compared with 2019 baseline)



6 GHG emissions per revenue passenger kilometre, g CO_2e/RPK for commercial passenger aviation



1 + 2 + 3 + 4 + Additional assumptions = 5

Additional assumptions

- **Fuel costs are 25%** of total airline costs in 2019
- Non-fuel-related costs stay constant at 2019 levels
- Fuel **efficiency gains of 2%/y** from 2030 onwards (linearly increased from 1.5%/y in 2019)

Note: SAF costs, SAF blending rate, and the resulting average aviation fuel costs for commercial passenger aviation — and an indication of how that impacts the average costs per revenue passenger kilometre (RPK). The average fuel cost and the cost increase per RPK in the net-zero scenarios do not include the additional cost to neutralise residual emissions. Including these would raise the cost increase per RPK by 1–2 percentage points in 2050. The cost of the transition to net zero (5th graph) is juxtaposed with its benefit in terms of GHG emissions per RPK (6th graph).

Source: MPP analysis; share of fuel costs on ticket prices based on Wassermann et al.[73]

The transition towards SAFs could be cost-neutral (on a cost-per-RPK basis) if renewable electricity and green hydrogen costs decline rapidly and fuel efficiency gains of 2%/y are achieved (Exhibit 2.8).

Projected fossil jet fuel costs (before considering any carbon pricing schemes) are modelled to be declining towards mid-century in line with the IEA's *Net Zero by 2050* report,[74] assuming an oversupply of oil in a decarbonising global economy. Compared with these *projected* fossil jet fuel costs, the average fuel cost in the net-zero scenarios increases by 90%–190% by 2050. Compared with the *historical average* fossil jet fuel costs of $600–$650/tonne, however, the increase in average fuel costs is only about 70% in the PRU scenario and 10% in the ORE scenario. These cost increases are counterbalanced by fuel efficiency improvements, leading to an increase of costs per RPK of only about 5% in the PRU scenario by 2050. In the ORE scenario, costs per RPK could even decrease by up to 5% because of the assumed rapid cost decline of renewable electricity and green hydrogen.

Where airlines purchased aviation fuel for $188 billion in 2019,[75] these expenses will rise to about $250 billion to $400 billion in 2050 while increasing air travel (in RPK) by more than a factor of 2.

Crucially, costs per RPK could stay constant until 2035 despite the ramp-up of SAFs if:

- The assumed annual efficiency improvements of 2% are achieved (if only the historical efficiency gains of 1%/y were to be continued, costs per RPK could increase by 10%–15%)
- Suitable policy measures are introduced to overcome market entry barriers, in particular for SAFs
- Sufficient investments are made now in new technologies with low TRLs

At the same time, global commercial air travel could reduce its GHG intensity per RPK by about 40% by 2035.

2.2.6 Investment needs for the transition to net zero

Bringing global aviation to net zero by 2050 will require an additional investment of about $175 billion in upfront capital annually over the next three decades.[xiv] Of these investments:

- 28%–52% will be required from fuel producers for SAF production plants (including reverse-water-gas-shift reactors to produce syngas, and Fischer-Tropsch synthesis units for PtL, ethanol production and AtJ plants, G/FT, and HEFA plants).
- 44%–64% will be required from energy providers for assets further upstream. These upstream assets include renewable electricity generation (e.g., wind power plants or solar PV parks), low-temperature electrolysers (for hydrogen production), and CO_2 capture plants for SAF-, hydrogen- and electricity-powered aircraft.
- 4%–8% will be required from airlines for hydrogen and battery-electric aircraft (additional capital costs for new engines and airframes entering the market, compared with optimised conventional jet engines and airframes).[xv]

Overall, $5.1 trillion of capital investments could be required between 2022 and 2050 to bring global aviation to net zero. However, for the same capital investments, the Optimistic Renewable Electricity scenario offers larger fuel cost reductions and a cost-neutral transition (in $/RPK) compared with the Prudent scenario (as highlighted in the previous section), mainly driven by more progressive underlying assumptions for renewable electricity costs. This highlights the economic opportunity of investing in renewable electricity generation assets and green hydrogen production (thereby making them cheaper and/or more efficient).

The $175 billion would not be distributed equally across the decades to come. In the 2020s, 6%–8% of the cumulative investments required between 2022 and 2050 need to happen. This $38 billion–$49 billion of average annual investments would be sufficient to kick off the transition (Exhibit 2.9) and compares with the spending of aerospace companies for research in aircraft technology efficiency on the order of $15 billion per year.[76]

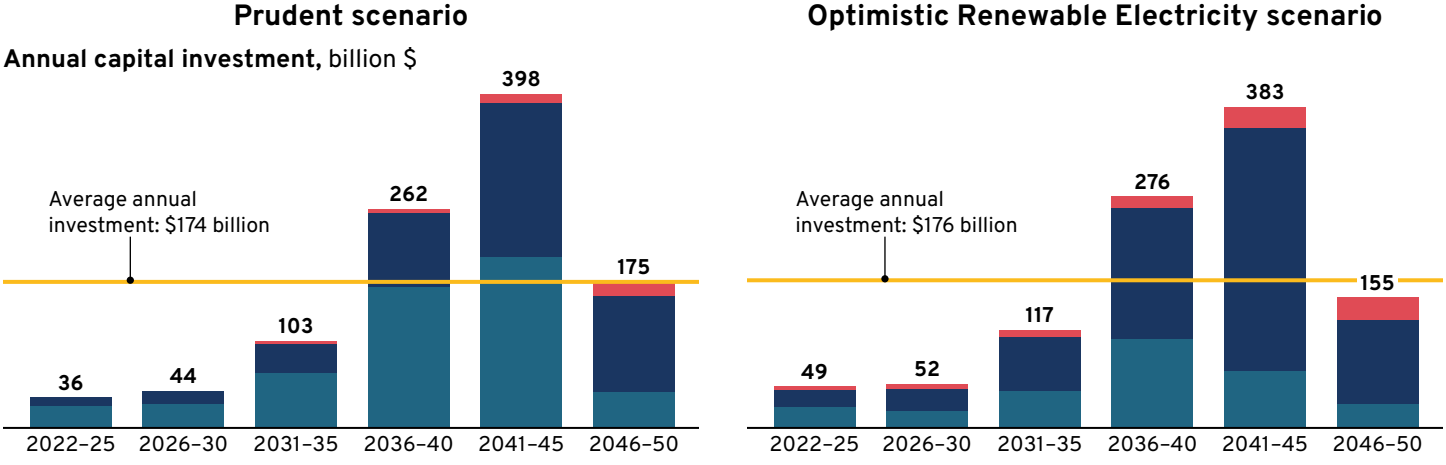
xiv All investment numbers are in real 2019 US dollars of capital required in the specific years and do not represent a net present value.

xv The capital investments in new conventional jet aircraft are excluded in these investment requirements because they would also be required for a regular fleet substitution/expansion without decarbonisation. Since SAFs are drop-in fuels, their impact on aircraft capital costs is negligible compared with investments required in the fuel production chain.

EXHIBIT 2.9

Average annual investments to get global aviation to net zero are estimated at about $175 billion

- Hydrogen and battery-electric aircraft (additional costs compared with jet aircraft)
- Upstream inputs to fuel production (renewable electricity, hydrogen, CO_2 capture)
- Fuel production (final fuel production step, e.g., reverse-water-gas-shift reactors + Fischer-Tropsch plants for PtL, and AtJ plants incl. ethanol production)



Note: Annual investments are on top of a BAU scenario and do not include the investments in regular fleet replacements. Investments for CDR are not included here since they could come from different sources (NCS, BECCS, DACCS, etc.).

Source: MPP analysis

In the **PRU scenario** (Exhibit 2.10), an average $174 billion/y ($5.1 trillion cumulatively between 2022 and 2050) would be required for the production of renewable fuels (52%), corresponding upstream investments (44%), and novel propulsion aircraft (4%). Fifty per cent of all investments flow into biofuels, 41% into PtL, and 9% into hydrogen and battery-electric aircraft (and their fuel). While the capital for biofuels is largely allocated to the final fuel production plant, about 84% of PtL costs are required for upstream assets (67% for renewable electricity generation, 17% for electrolysers and CO_2 capture plants).

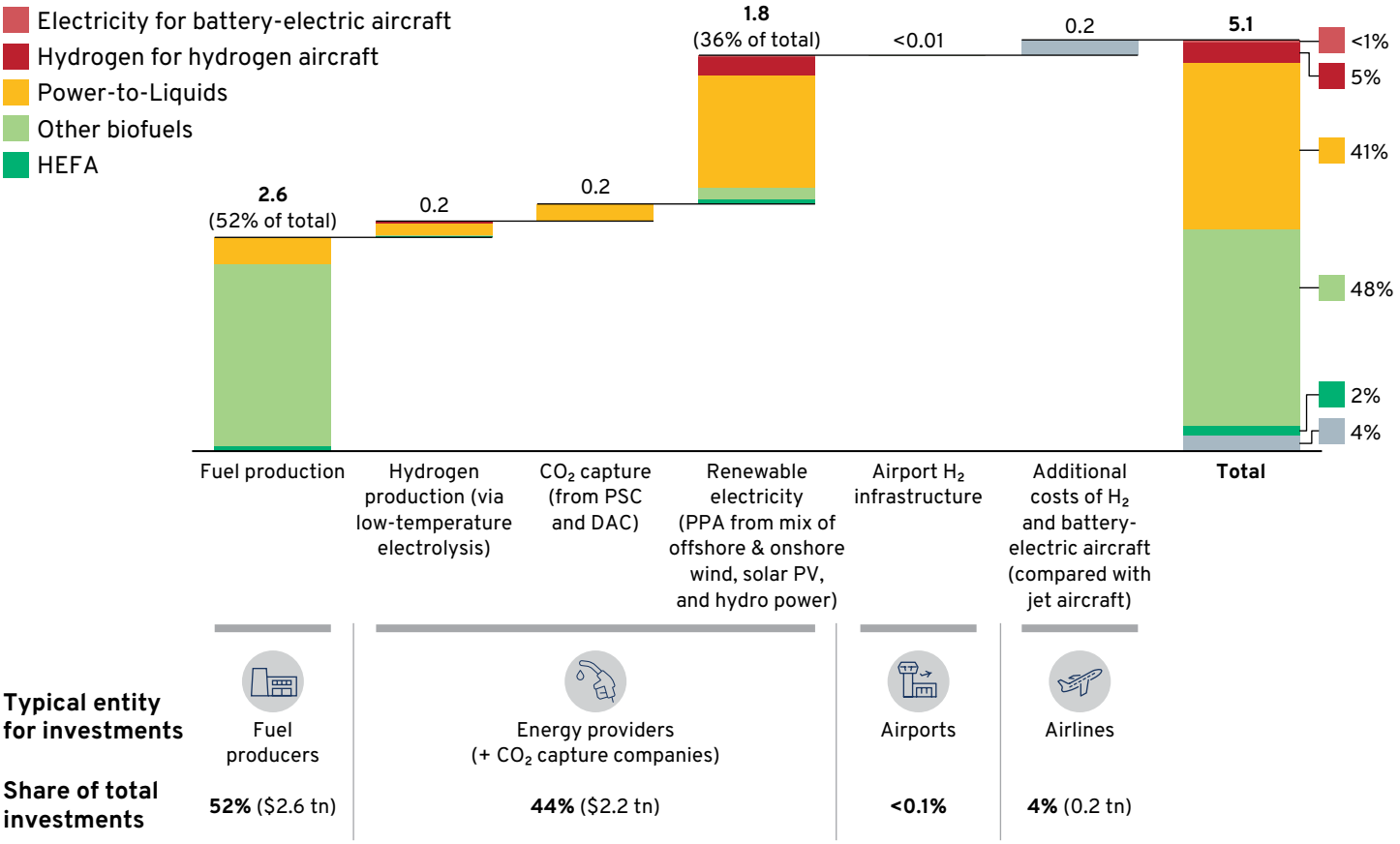
In the **ORE scenario** (Exhibit 2.11), an average $176 billion/y ($5.1 trillion cumulatively between 2022 and 2050) would be required for the production of renewable fuels (28%), corresponding upstream investments (64%), and novel propulsion aircraft (8%). Nineteen per cent of all investments flow into biofuels, 59% into PtL, and 22% into hydrogen and battery-electric aircraft (and their fuel). Since about half of the final energy mix in 2050 is supplied by PtL in this scenario, it is also responsible for the largest share of investments.

Behavioural change could reduce the total SAF demand by about 40–55 Mt by 2050, assuming (1) a modal shift of short-haul flights to high-speed rail in line with the IEA's *Net Zero by 2050* report[77] and (2) an additional overall reduction of air travel demand of 10% (e.g., triggered by reduced business travel). This could reduce investments in the whole value chain (SAF plants and upstream infrastructure like renewable electricity generation) by $500 billion–$700 billion, cumulatively, between 2022 and 2050.

EXHIBIT 2.10

In the Prudent scenario, 52% of capital investments are required for fuel production, 36% upstream for renewable electricity generation

Breakdown of capital investment requirements in the PRU scenario, cumulatively between 2022 and 2050, trillion $



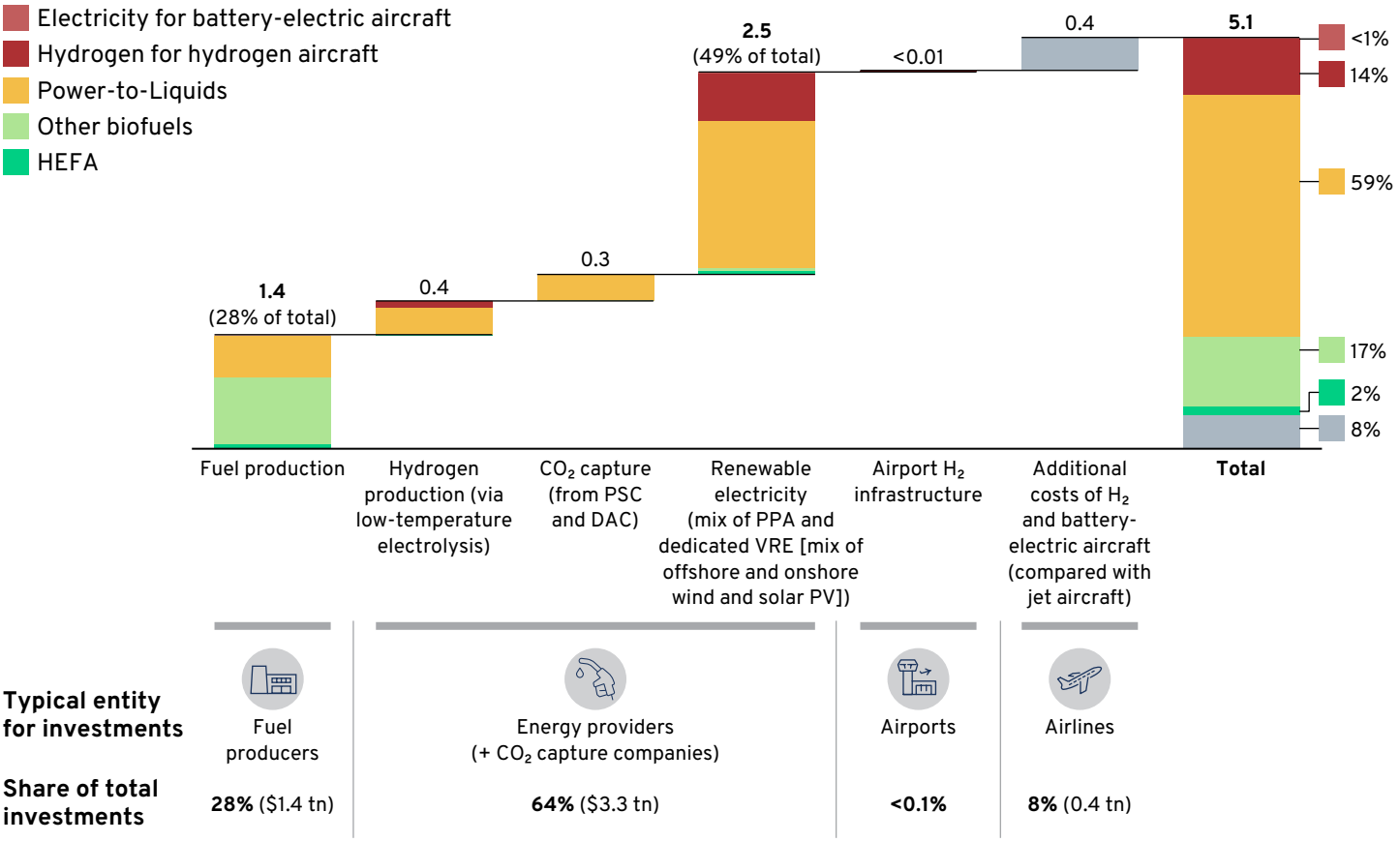
Note: Annual investments are on top of a BAU scenario and do not include the investments in regular fleet replacements. Investments for CDR are not included here since they could come from different sources (NCS, BECCS, DACCS, etc.). PPA = power purchase agreements. Totals may not equal sums due to rounding.

Source: MPP analysis

EXHIBIT 2.11

In the Optimistic Renewable Electricity scenario, 28% of capital investments are required for fuel production, 49% upstream for renewable electricity generation

Breakdown of capital investment requirements in the ORE scenario, cumulatively between 2022 and 2050, trillion $



Note: Annual investments are on top of a BAU scenario and do not include the investments in regular fleet replacements. Investments for CDR are not included here since they could come from different sources (NCS, BECCS, DACCS, etc.). Totals may not equal sums due to rounding. PPA = Power Purchase Agreement.

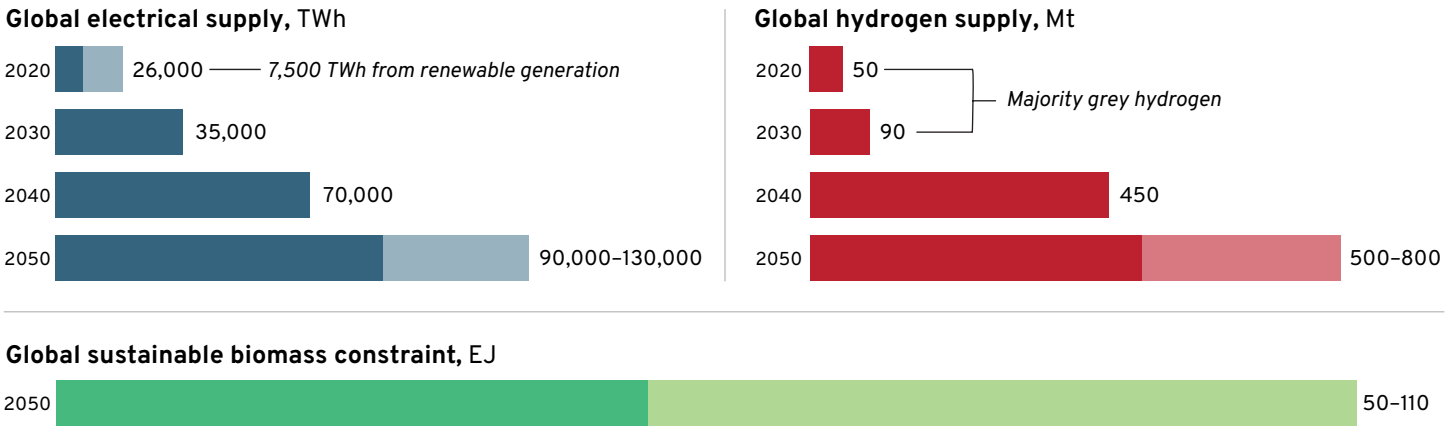
Source: MPP analysis

2.2.7 Energy prerequisites and requirements

To limit global warming to 1.5°C, the entire energy sector needs to transition to net-zero GHG emissions in less than three decades. Renewable electricity, green hydrogen (based on electrolysis powered by renewable electricity), and sustainable biomass are three key resources that can enable this transition (Exhibit 2.12).

EXHIBIT 2.12

Indicative global demand/supply of electricity and hydrogen, and availability of sustainable biomass



Note: Projected indicative global demand/supply of electricity and the current share of renewable electricity. Projected indicative global hydrogen demand (including grey hydrogen to be replaced with clean sources) and global sustainable biomass availability.

Source: ETC; Our World in Data[78]

From a global energy systems perspective, the **supply of renewable electricity needs to increase by a factor of 15 by 2050.** Besides the replacement of fossil fuel power plants by clean electricity, the electrification of road transport, shipping, steel, aviation, and other sectors poses an additional demand on top of current levels — either via the direct use of electricity or via hydrogen or hydrogen-derived fuels. The projected indicative demand for renewable electricity in 2050 (90,000–130,000 TWh) is well below the estimated theoretical maximum potential for solar and wind electricity alone, which ranks at 200,000–1,000,000 TWh, depending on how much land is made available for electricity generation.[79] The corresponding global installed capacity from wind and solar PV ranks at 40–50 TW required to fulfil global demands.[80]

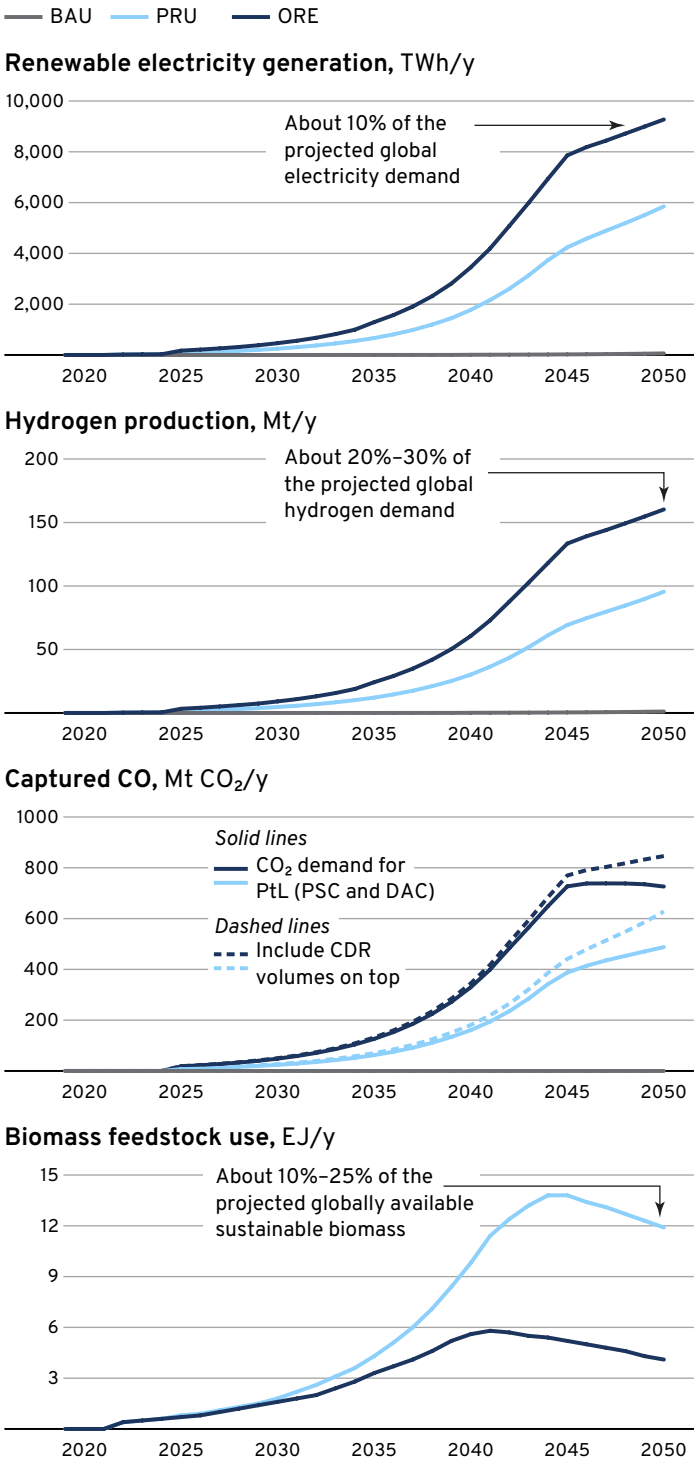
Although global installed capacities of solar PV and wind power ranked at just above 0.7 TW each at the end of 2020, the annual capacity additions gain in momentum: within the past decade (2011–20), the installed capacity of solar PV increased by almost a factor of 10.[81] This equals a CAGR of 26%, about double the pace that is needed to achieve the 2050 targets.[82] In the same period, wind energy increased by a factor of more than 3.[83] This equals a CAGR of 13%, about the pace needed to achieve 2050 targets.[84] Continuing this trend, the global installed capacity of solar PV is set to double every two to three years, wind energy every five or six. The supply of sufficient renewable electricity generation is a key enabler for the energy transition of many sectors, and short-term supply constraints must be avoided through orchestrated action from energy providers, investors, and policymakers. However, its supply is theoretically not constrained.

Similar to renewable electricity, current **hydrogen production needs to scale by a factor of 10–15** by 2050 and to switch from grey to clean hydrogen production pathways. First signs of a scale-up of electrolyser capacity are emerging. A total electrolyser capacity of 150 GW has been announced to get online through 2030,[85] and the announced project pipeline is increasing massively in a short time: the pipeline for all electrolyser capacity to go online prior to 2040 went up 36% between April and November 2021 alone.[86] Policymakers need to support the sufficient production of clean hydrogen in the short term to avoid supply constraints. In particular, the initially high cost of producing hydrogen via electrolysis needs to be overcome in this decade, but as with renewable electricity, there is no theoretical upper limit that would constrain the use of hydrogen.

In contrast, the **maximum amount of globally available sustainable biomass is constrained.** The exact limits are debated — a "cautious" scenario estimates a global constraint of about 50 EJ of sustainable biomass (primary energy); the maximum potential could be about 110 EJ but is tied to very ambitious assumptions about unlocking additional sustainable biomass compared with the cautious scenario (see detailed discussion in the *Technical Appendix*).[87] Many sectors will demand sustainable biomass in the future — from traditional use cases in pulp and paper or wood products to new demands, such as from the production of chemicals. Although many sectors, like automotive, have alternative technology options, others, like aviation, do not, particularly in the near term. Therefore, the use of sustainable biomass should be prioritized for such sectors.

EXHIBIT 2.13

By 2050, aviation could demand up to 25% of globally available sustainable biomass



Note: All resources displayed here are only the volumes that end up in jet fuel. However, SAF plants will produce unavoidable by-products (Exhibit 2.15); therefore the overall resource inputs to SAF plants will be higher.

Source: MPP analysis

Fulfilling the energy demand of aviation needs to be planned in the context of all sectors' energy and resource demand. Aviation will be a major competitor for renewable electricity, green hydrogen, and sustainable biomass (Exhibit 2.13). The more biomass the aviation sector can access, the less renewable electricity and hydrogen production capacity it will require, and vice versa. However, in both net-zero scenarios (PRU and ORE), no single feedstock will be sufficient to supply the total energy demand of the aviation sector in 2050. It will need a combination of all.

A. **Renewable electricity: 5%–10% of the global demand for renewable electricity, i.e., 5,850–9,300 TWh, could be required to decarbonise aviation.** The PtL- and H_2-dominated ORE scenario thereby ranks on the upper end of the demand, whereas the PRU scenario has a lower electricity but higher biomass demand. Aviation's demand for renewable electricity would require an additional installed capacity of about 2.5–4.0 TW of solar PV, onshore, and/or offshore wind power — about 5%–10% of the projected global installed capacity of solar and wind power.

B. **Hydrogen: Aviation will become one of the largest hydrogen-demanding sectors.** The PRU scenario will demand 95 Mt of hydrogen by 2050 — a 10%–20% share of global demand — and the ORE scenario has a higher demand of about 160 Mt of hydrogen, or a 20%–30% share of global demand, to supply hydrogen- and PtL-powered aircraft. This demand translates to a required installed electrolyser capacity of about 1.5–2.0 TW.

C. **Biomass: Aviation should be given priority to use sustainable biomass feedstocks.** Given the few technological alternatives to decarbonise aviation and the comparatively higher cost of abatement compared with other industries, aviation should be treated as a priority sector for biomass consumption. In the PRU scenario, about 12 EJ primary biomass energy would be required in 2050 for the production of 220 Mt bio-jet fuel (20 EJ in total when accounting for by-products). In the ORE scenario, 4 EJ primary biomass energy would be required to produce about 80 Mt bio-jet fuel (7 EJ in total when accounting for by-products).

In the PRU scenario, 10%–25% of the global sustainable biomass feedstock could supply up to 50% of the aviation sector's final energy demand in 2050, with the rest being supplied by PtL, hydrogen, or electricity. Decarbonising aviation without the use of biofuels is hardly imaginable. In any scenario, biofuels will dominate the decarbonisation story of aviation in this decade, and policymakers should redirect sustainable biomass flows to the sectors most in need. Giving aviation priority over the road transport sector could be an important first step.

Finally, the use of waste materials as biomass feedstocks can have positive side effects. For instance, using municipal solid waste as a biofuel feedstock could improve local air quality.

D. **Aviation will become one of the largest applications for direct air capture of CO_2.** The more the aviation sector relies on PtL, the more CO_2 capture technologies will be required — up to a capacity of 490–730 Mt/y by 2050 (for jet fuel only — for all product outputs of PtL plants, 800–1,200 Mt CO_2 need to be captured by then). A rapid ramp-up of CO_2 supply for PtL production will require a cross-border CO_2 transport network and/or a marketplace for long-term CO_2 offtake agreements that can decouple CO_2 capture plants from PtL plants.

The required CO_2 volumes could stem from direct air capture (DAC) or point source capture (PSC) of CO_2 from natural gas processing, cement, steel, coal power plants, and others.[88] PSC will be required as a bridging technology to kick off PtL production in the next few years, before DAC is available at large scales to power PtL production in the future. However, in the long run, only DAC is an acceptable solution to supply CO_2 for PtL production.

PtL based on PSC should be counted as in-sector decarbonisation only if the CO_2 reduction credit can be claimed 100% by the aviation sector and if no double-claiming (from the fuel producer *and* the CO_2-emitting industry) occurs. CO_2 reduction credits can be claimed by only one party, not both, which has caused reluctance from policymakers to allow PtL from PSC-CO_2 in the future as a potential SAF production pathway. In addition, PSC relies on excessive emissions from industrial sources that will reduce their emissions over time in a decarbonising global economy. Therefore, PSC investments should be made in sectors where CO_2 emissions will be unavoidable, as in the cement sector, where CO_2 is formed not from the combustion of fossil fuels but from the manufacture of cement. In these cases, the PSC appliances will not become "stranded assets" if the aviation sector moves 100% to DAC because they will still be needed in the respective sector to get to net zero there.

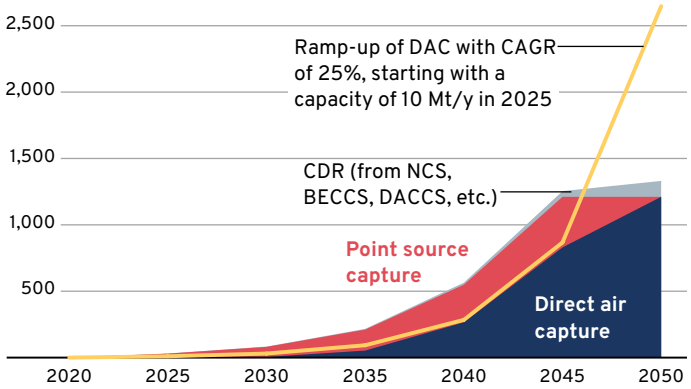
Capturing CO_2 from air is projected to be about three times more expensive in the long run (and even more in the near term), with $100–$300 per tonne of DAC-CO_2 compared with $50–$100 per tonne of PSC-CO_2.[89]

Exhibit 2.14 shows the CO_2 supply mix (DAC versus PSC) in the PtL-dominated ORE scenario. To cater to the CO_2 demand for PtL production within aviation, DAC technologies need to be ramped up at a CAGR of roughly 25% to meet the full demand by 2050. In the near term, lower-cost PSC can kick-start the market entry of PtL. Because of these early investments in PSC facilities, they remain in the CO_2 supply mix until 2050 but will be replaced by 2050 at the latest to get to real net zero within the aviation sector. If DAC scales faster, it could phase out PSC already in the 2040s.

EXHIBIT 2.14

A fast ramp-up of DAC is required to cater to the CO_2 demand of PtL

Captured CO_2 in ORE scenario (including for by-products of PtL production), Mt CO_2



Note: Indicative PSC/DAC mix of CO_2 supply for PtL production plants in the ORE scenario. CO_2 volumes contain the total CO_2 demand, including for by-products, not only what ends up in jet fuel. If the large-scale market entry, and significant cost decline, of DAC can be achieved earlier than expected, it could take larger shares of the total CO_2 supply in this decade and the next.

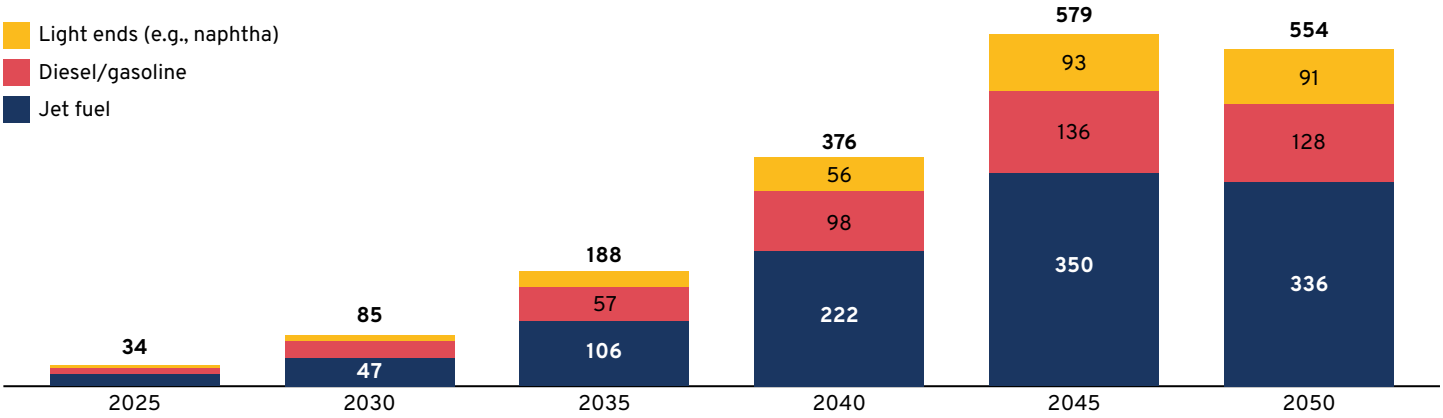
Source: MPP analysis, based on Hanna et al.[90]

E. **By-products of SAF production plants can be used to decarbonise other sectors.** New SAF production facilities should maximize the product slate of jet fuel, that is, the share of jet fuel being produced in contrast to other by-products, such as diesel/gasoline or light ends (liquefied petroleum gas, naphtha). By-products will not always be completely avoidable, but they can help decarbonise other sectors (Exhibit 2.15). Off-takers for diesel/gasoline could include trucking. Off-takers for light ends could include the chemical industry — to produce olefins, which are the precursor monomers for plastics.

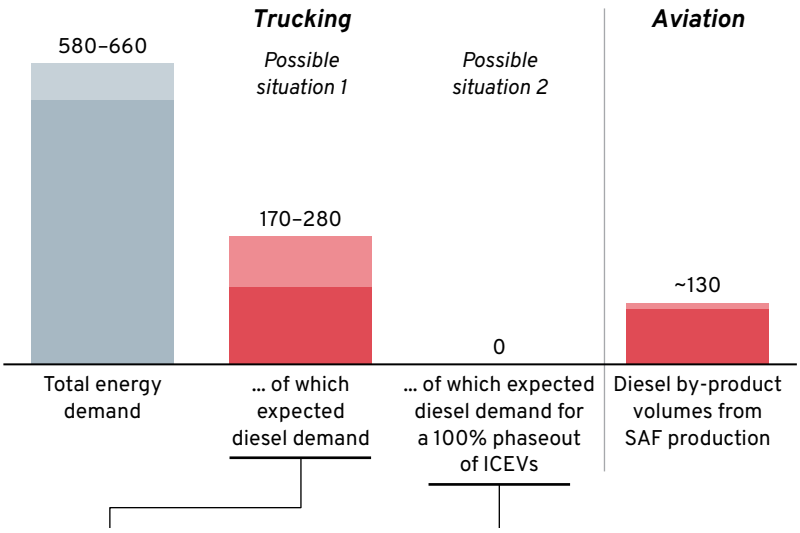
EXHIBIT 2.15

By-products of SAF production could find potential off-takers in the trucking and chemicals sectors

By-products of SAF plants, Mt of yearly production volumes (average of PRU and ORE scenarios)



Projected energy demand in trucking vs. diesel by-product volumes from SAF production in 2050, Mt diesel-equivalent



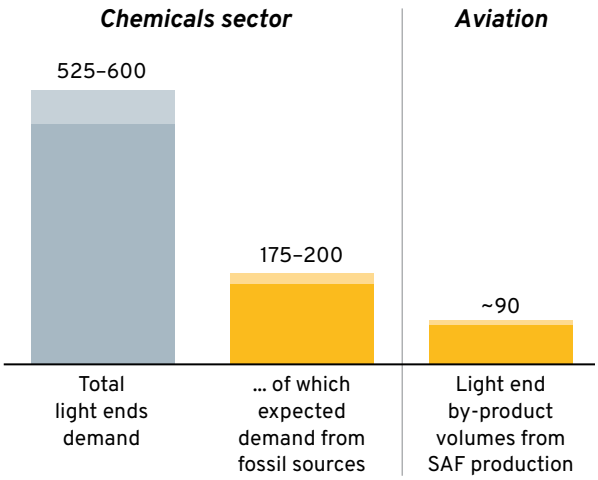
Possible situation 1

By 2050, the **diesel by-product volumes from SAF production** could fulfill **45%–75% of the expected diesel demand** from trucking. In such a scenario, diesel would still be used in mining vehicles and long-distance, heavy-duty trucks by 2050.

Possible situation 2

In a scenario where the whole trucking sector switches to electricity/hydrogen, the **diesel by-product from SAF production would have no demand**. SAF producers could, however, tailor their fuel synthesis processes to avoid diesel as by-products. In this scenario, a higher specificity of fuel production processes towards jet fuel as product would be beneficial.

Projected demand of light ends in the chemicals sector vs. by-product volumes from SAF production in 2050, Mt naphtha-eq.



By 2050, the chemicals sector could have a demand for light ends (naphtha, propane [LPG], and ethane) of up to 600 Mt.

Thereof, about **175–200 Mt could still be derived from fossil fuels.**

By-products from SAF production could decarbonise roughly 45%–50% of this demand.

Note: ICEV = internal combustion engine vehicle. Totals may not equal sums due to rounding.

Source: MPP analysis, based on IEA; MPP Trucking Transition Strategy; SYSTEMIQ analysis[91]

F. CDR solutions are necessary to neutralise residual emissions. In both net-zero scenarios, residual emissions from SAFs, hydrogen, and battery-electric aircraft (75%–95% GHG reduction potential compared with fossil jet fuel use) of about 0.12–0.14 Gt CO_2e will remain by 2050. Annual removals of these residual emissions even beyond 2050 will be required to achieve net zero. At an average cost of about \$125/t CO_2,[92] CDR solutions will incur additional annual costs of about \$15 billion–\$18 billion in 2050 and after. To achieve these required CDR volumes and the project price points by 2050, increased investments into high-quality CDR solutions are needed already in this decade.

xvii The additional capital investments for CDR are not included in the investment figures shown in this report.

CONCLUSION: FROM STRATEGIC THINKING TO ACTION IN THIS DECADE

In the Glasgow Climate Pact, agreed in 2021, the parties to the United Nations Framework Convention on Climate Change (UNFCCC) recognize "that limiting global warming to 1.5°C requires rapid, deep and sustained reductions in global greenhouse gas emissions, including reducing global carbon dioxide emissions by 45 per cent by 2030 relative to the 2010 level".[93] They add that this will require accelerated action this decade, on the basis of the best available scientific knowledge.

Although the aviation sector is not expected to contribute to this goal as much as easier-to-abate sectors, the aviation value chain, policymakers, and financial institutions should start on the path towards a net-zero aviation sector now. The following two sections highlight (1) key milestones that should be achieved until 2030, and (2) what key policy, industry, and finance actions can bring about these milestones.

3.1 Key milestones until 2030

The commercialisation of SAFs until 2030 is *the* decisive task to achieve carbon-neutral growth by 2030 and to lay the foundation for net-zero aviation by 2050 (Exhibit 3.1). SAF production volumes need to be increased by a factor of 5–6 compared with the current project pipeline until 2030. Given this lead time, decisions need to be made now.

In this decade, $40 billion–$50 billion of annual investments (foremost in SAF production plants and corresponding upstream infrastructure) would be sufficient to meet the estimated demand of about 40–50 Mt by 2030. Of these investments, $20 billion–$25 billion would be required for SAF plants, and $10–$20 billion upstream for renewable electricity generation, hydrogen production, and CO_2 capture. Even if the demand for hydrogen and PtL will accelerate to scale only after 2030, policymakers need to set ambitious renewable expansion targets now to meet the future clean electricity demand in the 2030s and '40s. Investments into SAFs and hydrogen, hybrid, or battery-electric aircraft should be accompanied by infrastructure investments at airports and in the upstream supply chain and need to be planned within the next few years.

EXHIBIT 3.1

Key milestones for 2025 and 2030: Kicking off the transition to net zero within this decade is crucial

	Key milestones by 2025	Key milestones by 2030
SAF ramp-up	17–22 Mt SAF production volumes (EU blending mandate: ~2 Mt)	42–51 Mt SAF production volumes (EU blending mandate and US SAF Grand Challenge: ~14 Mt)
	150–160 SAF plants or repurposing of existing HEFA/ethanol plants	310–390 SAF plants, or repurposing of existing HEFA/ethanol plants
	$35 billion–$50 billion of annual investments in SAF plants and upstream assets	$45 billion–$50 billion of annual investments in SAF plants and upstream assets
Upstream energy infrastructure	20–40 GW of dedicated electrolyser capacity	50–100 GW of dedicated electrolyser capacity
	35–75 GW of dedicated installed capacity for renewable electricity generation	100–200 GW of dedicated installed capacity for renewable electricity generation
	0.7–0.8 EJ/y of sustainable biomass directed to the aviation sector	1.6–1.8 EJ/y of sustainable biomass directed to the aviation sector
	10–20 Mt of annual CO_2 capture capacity for PtL production	25–50 Mt of annual CO_2 capture capacity for PtL production
TRLs	First commercial scale PtL plant online	Battery-electric and hydrogen aircraft enter test phase
	Novel SAF production pathways certified	

Source: MPP analysis

3.2 Policy, industry, and finance action to achieve 2030 milestones

Policymakers, industry leaders, and financial institutions can make the transition of global aviation to net zero a success story by addressing **three major challenges in this decade:**[xviii]

1. A lack of demand for SAFs due to their high cost differential compared with fossil jet fuel
2. The first-mover risk of investing into first- and second-of-a-kind (FOAK and SOAK) SAF production plants because of their low TRL
3. The sufficient availability of sustainable resources to produce SAFs

To overcome these challenges, policymakers, industry leaders, financial institutions, and customers need to act hand in glove (see high-level overview in Exhibit 3.2).

xviii This section focuses primarily on SAFs since they are responsible for about 75%–90% of cumulative GHG emission reductions from all renewable fuels between 2022 and 2050. However, similar challenges as well as policy, industry, and finance actions are required to spur innovation and the market entry for novel propulsion aircraft. Additionally, fuel efficiency improvements, demand reduction measures, and the promotion of CDR solutions are essential in order to complement the portfolio of decarbonisation solutions. All levers need to be pulled to master the transition of global aviation to net zero.

EXHIBIT 3.2

The three key challenges that need to be overcome to kick off the transition to net zero: Lack of demand for SAFs, high investment risk, and availability of sustainable feedstock

Problem statement	High-potential solutions	Policy	Industry	Finance	Customers	Examples
DEMAND						
High cost differential between SAFs and fossil jet fuel	Make SAFs cheaper (subsidies to support R&D and scale-up)	✓				• SAF blender's tax credits by United States • Public–private partnership "Clean Aviation" to promote energy efficiency (initiated by European Commission)
	Make fossil jet fuel more expensive (carbon price)	✓				
	Promote efficiency measures to reduce energy demand	✓	✓			
Lack of demand for SAFs	Create voluntary demand signals via offtake agreements		✓		✓	• Offtake agreements among airlines, large corporations, and SAF producers • First Movers Coalition (led by United States) • Proposed SAF blending mandate by European Commission (ReFuelEU Aviation policy proposal)
	Mandate blending rates for SAFs or GHG intensity reduction pathway via legal emission limits (in GHG/RPK)	✓				
	Establish green public procurement	✓				
SUPPLY						
Low TRL, high uncertainty, little experience	Support R&D	✓				• PtL FOAK plant funding in Germany • PtL development via SAF+ consortium
	Create industry consortia to share risk		✓			
High investment risk for FOAK and SOAK SAF plants	Encourage climate-aligned investments			✓		• Capital grants for FOAK SAF plants in United States • Climate-aligned investment principles similar to Poseidon Principles for shipping
	De-risk FOAK projects via public–private partnerships	✓	✓	✓		
	De-risk SAF plants via cross-sectoral diversification (e.g., joint production of jet fuel, diesel, and naphtha for aviation, trucking, and chemicals sectors in SAF plants)		✓	✓		
FEEDSTOCK AVAILABILITY						
Limited availability of sustainable biomass	Prioritise feedstock for aviation (e.g., via triggering shift of biodiesel production for road transport to bio-jet fuel production)	✓	✓			• Plans within UK's Decarbonisation Road-Map for aviation
High demand for renewable electricity, hydrogen, and carbon capture	Bring down costs of renewable electricity, hydrogen, and captured CO_2 (foremost DAC)	✓	✓	✓		• "Hydrogen Shot" by U.S. Department of Energy (to reduce H_2 costs to $1/kg by 2030) • Partnership between ArcelorMittal and LanzaTech (CO captured at steel plants used for SAF production)
	Enable cross-value chain partnerships (e.g., via power purchase agreements)		✓			

Note: Lists of potential solutions and examples are non-exhaustive.

Source: MPP schematic, based on Sustainable Aviation; European Commission; First Movers Coalition; 117th US Congress; Clean Aviation Joint Undertaking; Federal Ministry for Digital and Transport of Germany (BMVI); Brandt et al.; Poseidon Principles; US Department of Energy; ArcelorMittal[94]

Additional costs from this transition should always be measured against the value they create — in terms of climate change mitigation, local air quality improvements, noise reduction, national/regional energy security, and job creation.

3.2.1 Key policy actions in this decade

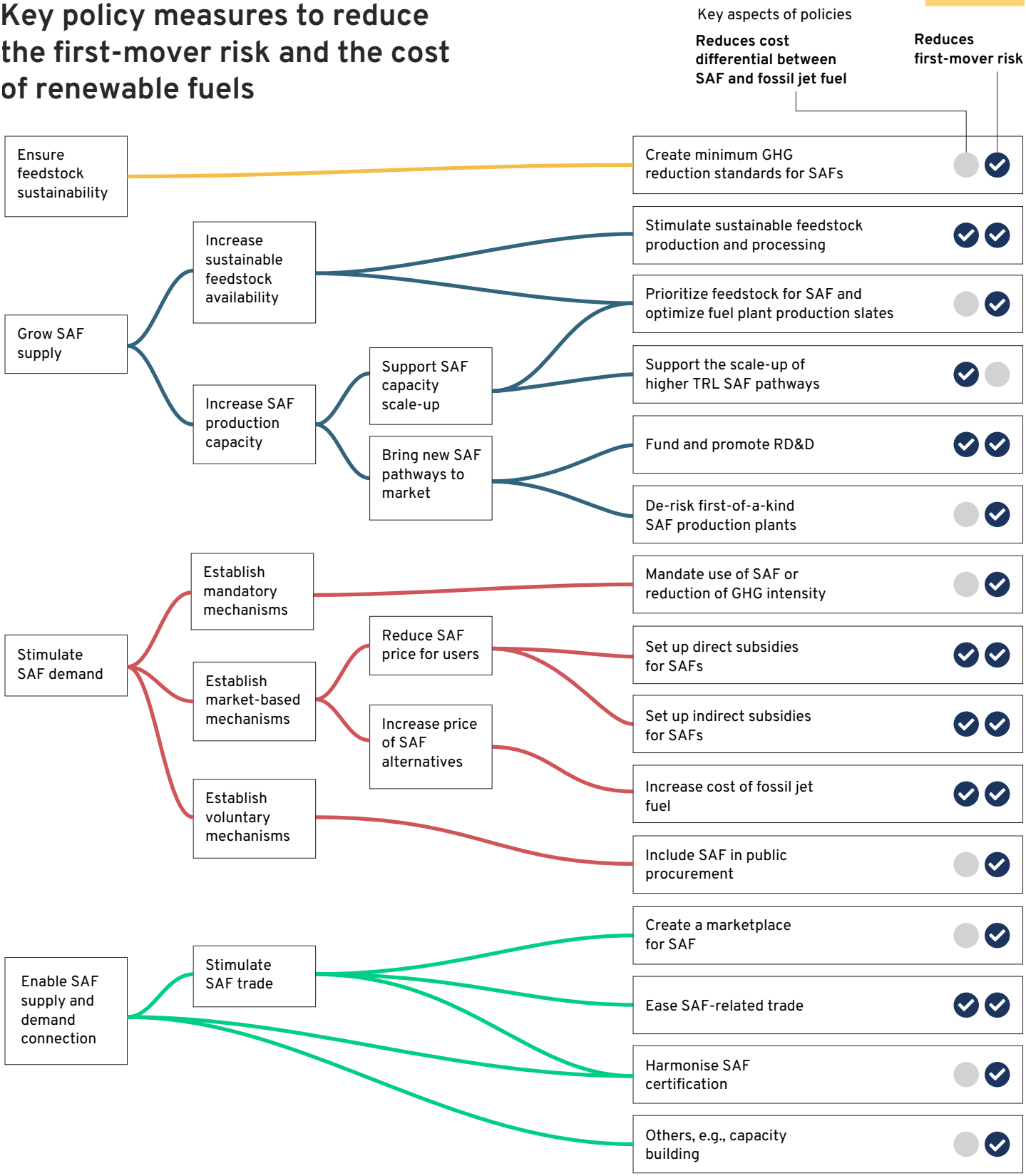
Decisive policy action will be needed to create a level playing field between fossil jet fuel and SAFs, ideally on a global level to avoid regional market distortions. Fossil jet fuel has been tax exempt since 1944, triggered by Article 24 of the ICAO's Chicago Convention.[95,xix] For decades, this created unfavourable conditions for the introduction of low-carbon technologies.

SAFs can currently only be produced at 2–5x the cost of the average historical fossil jet fuel price, but policymakers could trigger a reduction of this cost by about 10%–20% in this decade through a combination of supply and demand measures as well as by ensuring feedstock sustainability and through other enabling measures. A tailored and robust set of policies will be required to support the market entry of SAFs (Exhibit 3.3).

xix Per se, the Chicago Convention does not allow the taxation of "fuel [...] on board an aircraft [...] on arrival in the territory of a contracting State" — it does not prohibit countries from taxing jet fuel sold to aircraft operators in a country.

EXHIBIT 3.3

Key policy measures to reduce the first-mover risk and the cost of renewable fuels



Note: Policy measures to reduce the cost differential of SAFs against fossil jet fuel and the first-mover risk of financial institutions investing in and airlines purchasing SAFs. Most policy measures are also applicable to hydrogen and battery-electric aircraft.

Source: Detailed policy overview of CST/ETC, *Clean Skies for Tomorrow*[96]

Based on the generic overview of potential SAF-related policies in Exhibit 3.3, a few key milestones in this decade are derived in more detail:

A. The ICAO should set global CO_2 standards.

The ICAO has already demonstrated the feasibility of a long-term aspirational goal (LTAG) to reduce emissions in international aviation.[97] Governments should now act upon this assessment and adopt an LTAG, e.g., in the form of a GHG intensity reduction pathway (like the GHG-per-RPK pathway shown in Exhibit 2.8) or SAF usage targets. The adoption of an LTAG could strengthen CORSIA and provide the long-term planning security that is currently lacking for hesitant investors.

B. Policymakers should reduce the first-mover risk by:

- Stimulating demand via blending mandates (like that proposed by the European Commission[98,xx]) — ideally with at least 5%–7% SAF share on aviation's final energy demand by 2025, 10%–15% by 2030, about 30% by 2035, 60%–65% by 2040, and 95%–100% from 2045 on. Such blending mandate levels could cover the full required SAF supply indicated in the two net-zero scenarios of this report. In general, SAF blending mandates can be based on SAF volumes or carbon intensity reductions for uplifted fuel.

- Stimulating demand via direct or indirect subsidies for SAFs, e.g., tax incentives for SAF offtakers, producers, or blenders.

- Stimulating demand via green public procurement (such as the US government using its scale to achieve certain climate targets, e.g., 100% clean road transport for its own fleet in advance of nationwide timelines[99]).

- De-risking private investments to scale SAF production through public–private partnerships (like the Jet Zero Council, convened by the UK government to scale sustainable aviation solutions[100]) and blended finance (like the Catalyst Program by Breakthrough Energy[101]).

- Supporting RD&D and providing long-term planning security for new SAF production pathways for at least 10 years to enter the market (like the German PtL funding for 10 years[102]) and for novel propulsion technologies (like the FlyZero program by the Aerospace Technology Institute[103]).

- Redirecting existing SAF supply capacities from road transport to the aviation sector by revising policies that favour the production of ground transportation fuels like biodiesel, and unlocking additional sustainable biomass volumes for the production of SAF.

- Ensuring the recognition of SAFs under regional and global GHG reduction schemes (e.g., EU ETS, CORSIA) while ensuring that double counting is avoided.

C. Policymakers can bridge the cost differential of SAFs and fossil jet fuel by:

- Establishing market mechanisms that appropriately price in the cost of GHG emissions from the use of fossil jet fuel at about \$100–\$200 per tonne of CO_2e (e.g., by taxing fossil jet fuel, as discussed by the European Commission in its ReFuelEU Aviation policy proposal,[104] while avoiding competitive market distortions)

- Reinvesting the revenues from carbon pricing mechanisms into SAF projects

- Providing direct subsidies for FOAK and SOAK SAF plants, e.g., via fiscal incentives (like tax credits in the United States[105]) or capital grants,[106] while ensuring technology neutrality

xx Individual EU countries like Sweden and Finland are discussing even higher targets (30% SAF by 2030) than proposed in the ReFuelEU Aviation proposal. See Airlines for Europe (A4E), Civil Air Navigation Services Organisation (CANSO), European Regions Airline Association (ERA), Airports Council International-Europe (ACI), and Aerospace & Defence Industries Association of Europe (ASD), *Destination 2050: A Route to Net Zero European Aviation*, February 2021.

3.2.2 Key industry actions in this decade

To achieve a fast scale-up of SAFs, initiatives of individual value chain actors need to be actioned in concert. Therefore, industry leaders should combine demand and supply measures.

A. Demand for SAFs can be spurred by offtake agreements between:

- Airlines and large corporations (e.g., among Microsoft, KLM, and Delta Air Lines[107])
- Fuel suppliers and large corporations (e.g., the Board Now program by SkyNRG[108]).
- Fuel suppliers and airlines (see list by Commercial Aviation Alternative Fuels Initiative[109])
- Aircraft manufacturers and corporations (like offtake agreements between DHL and Eviation or UPS, Amazon, and Beta Technologies for battery-electric aircraft[110])

Twenty-one Mt of SAF are currently under offtake agreements, spanning durations between six months and 20 years.[111] From that volume, almost 40% (9 Mt) were announced in 2021 and 30% (6 Mt) in the first half of 2022 — showing the momentum of this kind of demand–supply cooperation — and initiatives like the First Movers Coalition are pooling voluntary demand for decarbonisation solutions across multiple sectors.[112]

Furthermore, CST is developing an industry-backed SAF certificate system to accelerate the scale-up of SAF and enable a book-and-claim system for global SAF trade. In November 2021, the Roundtable on Sustainable Biomaterials (RSB) launched a book-and-claim pilot with Air bp, United Airlines, and Microsoft.[113] A separate CST report on that topic will be published later this year. A global book-and-claim system would need to be coordinated with national regulations, e.g., if different participating countries have different taxation schemes. National book-and-claim systems could kick off this kind of system and provide important insights into how a global book-and-claim system could work.

B. Supply of SAFs can be increased via a variety of actions

Sustainable biomass should be redirected to the aviation sector.

- Triggered by revised biofuel policies, existing HEFA plants could reduce their diesel output in favour of jet fuel. A doubling of their jet fuel share to 36% of the total product output could unlock an additional 7 Mt of jet fuel by 2030. Increasing the jet fuel fraction to the technical maximum of 55% would unlock about 15 Mt in total by 2030.

- Additionally, the electrification of cars could free up 10% of global bioethanol supply (9 Mt). If it were redirected from road transport to aviation, an additional 7 Mt of SAF could be produced by 2030.

Industry consortia can expedite the supply of SAFs.

- Industry stakeholders including airlines, airports, manufacturers, fuel producers, and other entities can share the risk of the supply ramp-up of technologies that are not yet proven at scale. Such industry collaboration can benefit from standardisation, pooling of expertise, and economies of scale in order to de-risk sustainable aviation projects. The SAF+ Consortium, for instance, consisting of an OEM, an airline, an airport, a chemical company, academic institutions, and others, aims to bring PtL to the North American market by 2026.[114] Similar initiatives could de-risk other low-TRL technologies.
- Collaboration between certification authorities and SAF producers could expedite the certification time of new fuel types, which has historically been about four years.[115]

3.2.3 Key finance actions in this decade

The enormous market opportunities of SAFs, with a global volume of up to $400 billion by 2050, have started to raise attention from capital providers. A variety of interventions by financial institutions can accelerate the capital flow to SAF production at the scale needed to achieve the 2030 milestones (Exhibit 3.1) — of which two essential actions are highlighted ahead.

A. Climate-aligned investment principles are required to unlock the race to the top.

Capital providers (banks, institutional investors, public-sector banks) should invest only in the 50% most ambitious companies and infrastructure projects. Climate-aligned investment principles similar to the Poseidon Principles in the shipping sector[116] can create clarity and transparency on what companies and projects are investable and what are not in line with net-zero and 1.5°C targets (Exhibit 3.4).

EXHIBIT 3.4

Essential elements of climate-aligned investment principles

100% 1.5°C-alignment until 2030

By 2030, banks, institutional investors, and public-sector banks commit 100% of their investments to infrastructure assets and companies that comply with 1.5°C targets (similar to Poseidon Principles in shipping).

Investment principle requirements

In collaboration with the financial sector, investment principles are established until 2023 to define sustainability (and in particular decarbonisation) criteria for infrastructure assets, companies, and financial institutions' aviation- and fuel-related portfolios.

Encourage an engagement of investors and industry corporations

- To incentivize and facilitate 1.5°C-aligned target-setting
- To develop best practices of new financing instruments tailored to make projects related to SAFs, efficiency measures, and novel propulsion aircraft investable
- To develop quantitative analyses on ways to de-risk such projects for financial institutions.

Mandate beneficiaries of any form of climate-aligned finance to disclose annual metrics to track their progress on decarbonisation targets.

Include exclusion criteria to trigger divestments from non-1.5°C-aligned assets and companies, e.g., banks do not provide loans to aviation companies that do not meet minimum 1.5°C-aligned criteria by 2030.

Include inclusion criteria (e.g., existing target to reduce GHG intensity per RPK by 20%–25% until 2030 for airlines, or a commitment to use 10%–15% SAF by 2030 for airlines and corporate customers, or the target of min. 85% GHG reduction compared with fossil jet fuel for a new SAF plant) to trigger new investments in 1.5°C-aligned assets and companies.

Source: MPP analysis

B. Novel technologies need to be de-risked via public–private partnerships.

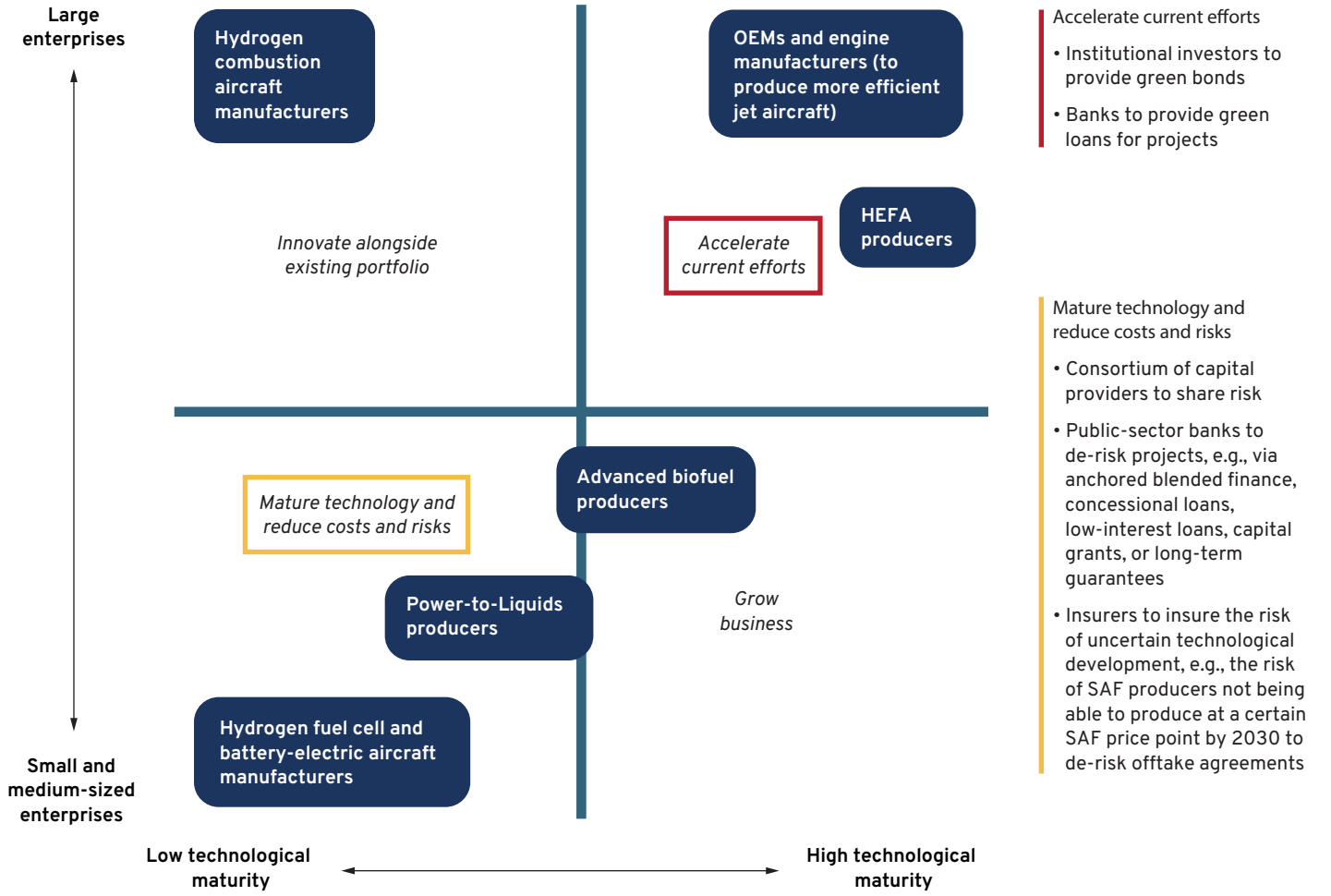
Depending on the maturity of the technology and the size of a company, different sources of capital and different financing instruments are best suited to enable new investments into low-carbon technologies like FOAK and SOAK SAF plants (Exhibit 3.5).

Two examples of public–private partnerships to scale SAFs and novel propulsion aircraft are:

- Breakthrough Energy has identified SAFs as one of four focus areas of its Catalyst Program.[117] More initiatives like that are required in order to de-risk investments and guarantee the capital flows needed for more than 300 new SAF production plants by 2030.
- In the same manner, a partnership between the European Commission and industry intends to spur innovation for hydrogen and hybrid-electric aircraft as well as efficient propulsion systems via supporting R&D with €4.1 billion over the next decade (€1.7 billion covered by Horizon Europe, €2.4 billion by industry).[118]

Financing mechanisms for low-carbon technologies differ for individual decarbonisation levers

EXHIBIT 3.5



Note: Ideal financing mechanisms depend on technology maturity and company size. Over time, growing corporations deploying maturing technologies will demand different financing instruments.

Source: MPP analysis

THE WAY FORWARD

The aviation industry has laid out its ambition to get to net zero by 2050, and has buy-in from a broad range of stakeholders. Now, the onus is on decision makers to navigate the green transition in the context of their own circumstances. The global scenarios presented in this report need to be broken down by region. Transition strategies need to be drafted and brought to action, tailored to regional resource availabilities, local technological innovation, and national policy options. Securing a just transition and an equitable distribution of the green premium of sustainable flights will be key. Public–private partnerships are one of many solutions to ensure an economically, ecologically, and socially viable, just, and successful transition to climate neutrality by 2050. CST and MPP can drive the transition through their convening power across the whole aviation value chain and including policymakers and financial institutions. Building upon the 2030 milestones in the last section of this report, CST and MPP will connect the dots among industry, policy, and finance via workshops, quantitative analyses, and other formats.

The first-mover risk needs to be transformed to a first-mover advantage so that success stories can empower hesitant actors to follow pioneers. De-risking investments in clean technologies and providing real-world proof points that their initially high costs can be reduced rapidly in only a few years will be critical ingredients of a successful takeoff of this transition to make climate-neutral aviation the new normal. By working hand in glove with their broad stakeholder community, CST, MPP, and their partners aim to develop quantitative tools (1) to reduce uncertainties around the capital requirements for FOAK and SOAK SAF plants, and (2) to better understand how to kick off real-world projects, for instance by identifying mismatches between the perceived and real risk for investors, and by quantifying the impact of individual policies and investment decisions on the cost differential of low-carbon technologies vis-à-vis fossil jet fuel. Furthermore, CST is already developing a book-and-claim system and a SAF registry to enable the large-scale coupling of SAF supply and demand in the future.

The MPP Aviation Transition Strategy demonstrates that SAF costs are likely to decline rapidly if the right incentives are put in place now. Together with efficiency gains and the deployment of new propulsion technologies, the cost of flying could remain at 2019 levels and not increase. New technologies will additionally offer new market opportunities: for example, regional battery-electric aircraft can unlock new routes and enable higher connectivity between cities. By working together, the aviation industry can master this transition. Already, it brings together people from around the globe, connects families, and enables the sharing of cultures, perspectives, and ideas. Flight is arguably one of the great technological achievements of humankind, and the industry has the creative and technical resources to reinvent itself. To get there, it needs decisive leadership from companies, governments, and financial institutions, and dedication to delivering a sustainable future for the industry and the planet.

GLOSSARY

AFOLU	Agriculture, forestry, and other land use
AIC	Aviation-induced cloudiness
ASTM	American Society for Testing and Materials
ATAG	Air Transport Action Group
AtJ	Alcohol-to-Jet
ATM	Air traffic management
ATS	Aviation Transition Strategy
BAU	Business as Usual
BECCS	Bioenergy with carbon capture and storage
CAGR	Compound annual growth rate
CCUS	Carbon capture, utilisation, and storage
CDR	Carbon dioxide removals
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
CST	Clean Skies for Tomorrow initiative
DAC	Direct air capture
DACCS	Direct air carbon capture and storage
EJ	Exajoule
ETC	Energy Transitions Commission
eVTOL	Electric vertical takeoff and landing
FOGs	Fats, oils, and greases
FOAK	First of a kind
GDP	Gross domestic product
G/FT	Gasification/Fischer-Tropsch
GHG	Greenhouse gas, expressed in CO_2e (carbon dioxide equivalent)
Gt	Gigatonne
HEFA	Hydroprocessed esters and fatty acids
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
ICEV	Internal combustion engine vehicle
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
ICCT	International Council on Clean Transportation
LCOE	Levelised cost of renewable electricity
LPG	Liquefied petroleum gas
LTAG	Long-term aspirational goal
LTO	Landing and takeoff
MPP	Mission Possible Partnership
MSW	Municipal solid waste
Mt	Megatonne
MWh	Megawatt-hour
mW/m^2	Milliwatts per square metre
NCS	Natural climate solutions
NO_x	Nitrogen oxides
OEM	Original equipment manufacturer
ORE	Optimistic Renewable Electricity scenario
PPA	Power purchase agreement
PRU	Prudent scenario
PSC	Point source capture
PtL	Power-to-Liquids
PV	Photovoltaic
R&D	Research and development
RD&D	Research, development, and demonstration
RPK	Revenue passenger kilometre
RSB	Roundtable on Sustainable Biomaterials
SAF	Sustainable Aviation Fuel
SBTi	Science Based Targets initiative
SOAK	Second of a kind
SPK	Synthetic paraffinic kerosene
TCO	Total cost of ownership
t CO_2	Tonne carbon dioxide
TRL	Technology readiness level
TTW	Tank-to-wake, covers Scope 1 emissions from jet fuel
TTZ	Target True Zero initiative
TW	Terawatt
TWh	Terawatt-hour
UNFCCC	United Nations Framework Convention on Climate Change
WTT	Well-to-tank, covers Scope 3 emissions from jet fuel
WTW	Well-to-wake, covers full value chain of jet fuel emissions

ENDNOTES

1 Air Transport Action Group, *Waypoint 2050*, September 2021, **https://aviationbenefits.org/media/167417/w2050_v2021_27sept_full.pdf**; and ICF, *Fueling Net Zero*, September 2021, **https://aviationbenefits.org/media/167495/fueling-net-zero_september-2021.pdf**.

2 International Civil Aviation Organization, *Report on the Feasibility of a Long-Term Aspirational Goal (LTAG) for International Civil Aviation CO_2 Emission Reductions*, March 2022, **https://www.icao.int/environmental-protection/LTAG/Documents/REPORT%20ON%20THE%20FEASIBILITY%20OF%20A%20LONG-TERM%20ASPIRATIONAL%20GOAL_en.pdf**.

3 International Transport Forum (ITF) and the Organisation for Economic Co-operation and Development (OECD), *Decarbonising Air Transport: Acting Now for the Future*, 2021, **https://www.itf-oecd.org/sites/default/files/docs/decarbonising-air-transport-future.pdf**.

4 Aerospace Industries Association (AIA) and Accenture, *Horizon 2050: A Flight Plan for the Future of Sustainable Aviation*, 2022, **https://www.aia-aerospace.org/report/horizon-2050-new-report-from-aia-accenture-details-strategic-plan-for-the-future-of-sustainable-aviation/**.

5 Airlines for Europe (A4E), Civil Air Navigation Services Organisation (CANSO), European Regions Airline Association (ERA), Airports Council International-Europe (ACI), and Aerospace & Defence Industries Association of Europe (ASD), *Destination 2050: A Route to Net Zero European Aviation*, February 2021, **https://www.destination2050.eu/wp-content/uploads/2021/02/Destination2050_Report.pdf**.

6 US Federal Aviation Administration (FAA), *United States: 2021 Aviation Climate Action Plan*, November 2021, **https://www.faa.gov/sites/faa.gov/files/2021-11/Aviation_Climate_Action_Plan.pdf**.

7 Federal Government of Germany, *PtL Roadmap: Sustainable Aviation Fuel from Renewable Energy Sources for Aviation in Germany*, 2021, **https://www.bmvi.de/SharedDocs/DE/Anlage/G/ptl-roadmap-englisch.pdf?__blob=publicationFile**.

8 Sustainable Aviation, *Decarbonisation Road-Map: A Path to Net Zero – A Plan to Decarbonise UK Aviation*, 2020, **https://www.sustainableaviation.co.uk/wp-content/uploads/2020/02/SustainableAviation_CarbonReport_20200203.pdf**.

9 Transport & Environment, *Roadmap to Climate Neutral Aviation in Europe*, March 2022, **https://www.transportenvironment.org/wp-content/uploads/2022/03/TE-aviation-decarbonisation-roadmap-FINAL.pdf**.

10 IEA, *Net Zero by 2050: A Roadmap for the Global Energy Sector*, May 2021; Hannah Ritchie, "Cars, Planes, Trains: Where Do CO_2 Emissions from Transport Come From?", Our World in Data, October 6, 2020, **https://ourworldindata.org/co2-emissions-from-transport**; and Hannah Ritchie, Max Roser, and Pablo Rosado, "CO_2 and Greenhouse Gas Emissions", Our World in Data, last revised August 2020, **https://ourworldindata.org/co2-and-other-greenhouse-gas-emissions**.

11 IEA, *Net Zero by 2050: A Roadmap for the Global Energy Sector*, May 2021; and Hannah Ritchie, "Climate Change and Flying: What Share of Global CO_2 Emissions Come from Aviation?", Our World in Data, October 22, 2020, **https://ourworldindata.org/co2-emissions-from-aviation**.

12 European Parliament, *Emission Reduction Targets for International Aviation and Shipping*, 2015, **https://www.europarl.europa.eu/RegData/etudes/STUD/2015/569964/IPOL_STU(2015)569964_EN.pdf**.

13 D. S. Lee et al., "The Contribution of Global Aviation to Anthropogenic Climate Forcing for 2000 to 2018", *Atmospheric Environment* 244, 117834 (2021); Hannah Ritchie, Max Roser, and Pablo Rosado, "CO_2 and Greenhouse Gas Emissions", Our World in Data, last revised August 2020, **https://ourworldindata.org/co2-and-other-greenhouse-gas-emissions**; and Hannah Ritchie, "Climate Change and Flying: What Share of Global CO_2 Emissions Come from Aviation?", Our World in Data, October 22, 2020, **https://ourworldindata.org/co2-emissions-from-aviation**.

14 ATAG, *Aviation: Benefits Beyond Borders*, September 2020, **https://aviationbenefits.org/media/167517/aw-oct-final-atag_abbb-2020-publication-digital.pdf**.

15 ATAG, *Aviation Benefits Beyond Borders: Global Fact Sheet*, September 2020, **https://aviationbenefits.org/media/167144/abbb20_factsheet_global.pdf**.

16 Andreas W. Schäfer et al., "Technological, Economic and Environmental Prospects of All-Electric Aircraft", *Nature Energy* 4 (2019): 160–6, **https://www.nature.com/articles/s41560-018-0294-x**.

17 IATA, *20-year Air Passenger Forecast Infographic: Current Trends*, 2021, **https://www.iata.org/contentassets/fe5b20e8aae147c290fc4880f120c969/4679_passenger-forecast-infographic-update_v2.pdf**.

18 Hannah Ritchie, "Short-Haul vs. Long-Haul; Rich vs. Poor Countries: Where Do Global CO_2 Emissions from Aviation Come From?", Our World in Data, October 23, 2020, **https://ourworldindata.org/breakdown-co2-aviation**.

19 Andreas Schäfer, "The Global Demand for Motorized Mobility", *Transportation Research Part A: Policy and Practice* 32, no. 6 (1998): 455–77, **https://doi.org/10.1016/S0965-8564(98)00004-4**.

20 Stefan Gössling and Andreas Humpe, "The Global Scale, Distribution and Growth of Aviation: Implications for Climate Change", *Global Environmental Change* 65, 102194 (November 2020), **https://doi.org/10.1016/j.gloenvcha.2020.102194**.

21 D. S. Lee et al., "The Contribution of Global Aviation to Anthropogenic Climate Forcing for 2000 to 2018", *Atmospheric Environment* 244, 117834 (2021), **https://doi.org/10.1016/j.atmosenv.2020.117834**.

22 Clean Skies for Tomorrow Initiative (CST), World Economic Forum, Energy Transitions Commission (ETC), and Mission Possible Partnership (MPP), *Clean Skies for Tomorrow: Sustainable Aviation Fuel Policy Toolkit*, November 2021, **https://www.energy-transitions.org/wp-content/uploads/2021/11/Clean_Skies_for_Tomorrow_Sustainable_Aviation_Fuel_Policy_Toolkit_2021.pdf**.

23 IPCC, "Summary for Policymakers", in *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty*, eds. Valérie Masson-Delmotte et al. (2018), **https://www.ipcc.ch/sr15/chapter/spm/**; IEA, *Net Zero by 2050: A Roadmap for the Global Energy Sector*, May 2021, **https://www.iea.org/reports/net-zero-by-2050**; and BloombergNEF, *New Energy Outlook 2021*, 2021, **https://about.bnef.com/new-energy-outlook/**.

24 European Commission, *Proposal for a Regulation on Ensuring a Level Playing Field for Sustainable Air Transport, COM/2021/561 Final*, 2021, **https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX:52021PC0561**; ICAO, *CORSIA Default Life Cycle Emissions Values for CORSIA Eligible Fuels*, March 2021, **https://www.icao.int/environmental-protection/CORSIA/Documents/ICAO%20document%2006%20-%20Default%20Life%20Cycle%20Emissions%20-%20March%202021.pdf**; Boris Stolz et al., "Techno-Economic Analysis of Renewable Fuels for Ships Carrying Bulk Cargo in Europe", *Nature Energy* 7 (2022): 1–10, **https://www.nature.com/articles/s41560-021-00957-9**; McKinsey & Company, Clean Sky 2 JU, and FCH 2 JU, *Hydrogen-Powered Aviation: A Fact-Based Study of Hydrogen Technology, Economics, and Climate Impact by 2050*, May 2020, **https://www.fch.europa.eu/sites/default/files/FCH%20Docs/20200720_Hydrogen%20Powered%20Aviation%20report_FINAL%20web.pdf**.

25 Clean Skies for Tomorrow Initiative (CST), World Economic Forum, and McKinsey & Company, *Clean Skies for Tomorrow: Sustainable Aviation Fuels as a Pathway to Net-Zero Aviation*, November 2020, **https://www3.weforum.org/docs/WEF_Clean_Skies_Tomorrow_SAF_Analytics_2020.pdf**; Andreas W. Schäfer et al., "Costs of Mitigating CO_2 Emissions from Passenger Aircraft", *Nature Climate Change* 6 (2016): 412–7, **https://www.nature.com/articles/nclimate2865**; ICAO, *CORSIA Default Life Cycle Emissions Values for CORSIA Eligible Fuels*, March 2021, **https://www.icao.int/environmental-protection/CORSIA/Documents/ICAO%20document%2006%20-%20Default%20Life%20Cycle%20Emissions%20-%20March%202021.pdf**.

26 European Commission, *Proposal for a Regulation on Ensuring a Level Playing Field for Sustainable Air Transport, COM/2021/561 Final*, 2021, **https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX:52021PC0561**; M. Prussi, A. O'Connell, and L. Lonza, "Analysis of Current Aviation Biofuel Technical Production Potential in EU28", *Biomass and Bioenergy* 130, 105371 (November 2019), **https://doi.org/10.1016/j.biombioe.2019.105371**; and Energy Transitions Commission, *Mind the Gap: How Carbon Dioxide Removals Must Complement Deep Decarbonisation to Keep 1.5°C Alive*, March 2022, **https://www.energy-transitions.org/wp-content/uploads/2022/03/ETC-CDR-Report-Mind-the-Gap.pdf**.

27 IATA, *20-year Air Passenger Forecast Infographic: Current Trends*, 2021, **https://www.iata.org/contentassets/fe5b20e8aae147c290fc4880f120c969/4679_passenger-forecast-infographic-update_v2.pdf**.

28 European Environment Agency (EEA), "Energy Efficiency and Specific CO_2 Emissions", last modified May 2021, **https://www.eea.europa.eu/data-and-maps/indicators/energy-efficiency-and-specific-co2-emissions/energy-efficiency-and-specific-co2-9**.

29 IEA, *Net Zero by 2050: A Roadmap for the Global Energy Sector,* May 2021, **https://www.iea.org/reports/net-zero-by-2050**.

30 European Commission, *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions: Sustainable and Smart Mobility Strategy – Putting European Transport on Track for the Future (COM/2020/789 final)*, 2020, **https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52020DC0789**.

31 Oxera, *Short-Haul Flying and Sustainable Connectivity*", March 2022, **https://canso.fra1.digitaloceanspaces.com/uploads/2022/03/Short-haul-flying-and-sustainable-connectivity.pdf**.

32 Richard Holden, "Find Flights with Lower Carbon Emissions", Google, October 6, 2021, **https://blog.google/products/travel/find-flights-with-lower-carbon-emissions/**; and Jessica Stobaugh, "$CO_{2:}$ Every Kilogram Counts", ETH Zurich, 2021, **https://mavt.ethz.ch/news-and-events/d-mavt-news/2021/03/CO2-every-kilogram-counts.html**.

33 Vivid Economics, *A Study to Estimate Ticket Price Changes for Aviation in the EU ETS: A Report for Defra and DfT,* November 2007, **https://www.vivideconomics.com/wp-content/uploads/2019/05/Aviation_Tickets.pdf**.

34 Andreas W. Schäfer et al., "Technological, Economic and Environmental Prospects of All-Electric Aircraft", *Nature Energy* 4 (2019): 160–6, **https://www.nature.com/articles/s41560-018-0294-x**.

35 Andreas W. Schäfer et al., "Costs of Mitigating CO_2 Emissions from Passenger Aircraft", *Nature Climate Change* 6 (2016): 412–7, **https://www.nature.com/articles/nclimate2865**.

36 Ibid.

37 International Council on Clean Transportation (ICCT, *Fuel Burn of New Commercial Jet Aircraft: 1960 to 2019*, September 2020, **https://theicct.org/wp-content/uploads/2021/06/Aircraft-fuel-burn-trends-sept2020.pdf**.

38 Andreas W. Schäfer et al., "Costs of Mitigating CO_2 Emissions from Passenger Aircraft", *Nature Climate Change* 6 (2016): 412–7, **https://www.nature.com/articles/nclimate2865**; SBTi, *Science-Based Target Setting for the Aviation Sector: Version 1.0*, August 2021, **https://sciencebasedtargets.org/resources/files/SBTi_AviationGuidanceAug2021.pdf**; and Jonathan A. Lovegren and R. John Hansman, *Estimation of Potential Aircraft Fuel Burn Reduction in Cruise Via Speed and Altitude Optimization Strategies*, MIT International Center for Air Transportation, February 2011, **https://dspace.mit.edu/handle/1721.1/62196**.

39 Andreas W. Schäfer et al., "Costs of Mitigating CO_2 Emissions from Passenger Aircraft", *Nature Climate Change* 6 (2016): 412–7, **https://www.nature.com/articles/nclimate2865**; and IATA, *Aircraft Technology Roadmap to 2050*, 2020, **https://www.iata.org/contentassets/8d19e716636a47c184e7221c77563c93/Technology-roadmap-2050.pdf**.

40 Aerospace Industries Association (AIA) and Accenture, *Horizon 2050: A Flight Plan for the Future of Sustainable Aviation,* 2022, **https://www.aia-aerospace.org/report/horizon-2050-new-report-from-aia-accenture-details-strategic-plan-for-the-future-of-sustainable-aviation/**.

41 Airlines for Europe (A4E), Civil Air Navigation Services Organisation (CANSO), European Regions Airline Association (ERA), Airports Council International-Europe (ACI), and Aerospace & Defence Industries Association of Europe (ASD), *Destination 2050: A Route to Net Zero European Aviation,* February 2021, **https://www.destination2050.eu/wp-content/uploads/2021/02/Destination2050_Report.pdf**.

42 International Council on Clean Transportation (ICCT), *CO_2 Emissions from Commercial Aviation: 2013, 2018, and 2019*, October 2020, **https://theicct.org/publication/co2-emissions-from-commercial-aviation-2013-2018-and-2019/**.

43 World Bank, World Bank Commodity Price Data, 2021, **https://databank.worldbank.org/databases/commodity-price-data**; ICCT, *Fuel Burn of New Commercial Jet Aircraft: 1960 to 2019*, September 2020, **https://theicct.org/wp-content/uploads/2021/06/Aircraft-fuel-burn-trends-sept2020.pdf**.

44 IATA, *Fact Sheet 2: Sustainable Aviation Fuel: Technical Certification*, 2021, **https://www.iata.org/contentassets/d13875e9ed784f75bac90f000760e998/saf-technical-certifications.pdf**.

45 Rolls-Royce, "Accelerating the Transition of Long-Haul Aviation towards Net Zero", October 14, 2021, **https://www.rolls-royce.com/media/press-releases.aspx**; The Boeing Company, "Boeing Commits to Deliver Commercial Airplanes Ready to Fly on 100% Sustainable Fuels", January 22, 2021, **https://boeing.mediaroom.com/2021-01-22-Boeing-Commits-to-Deliver-Commercial-Airplanes-Ready-to-Fly-on-100-Sustainable-Fuels**; and The Boeing Company, "Aviation Industry Chief Technology Officers Issue Joint Call to Action to Deliver Sustainable Aviation Plans", October 26, 2021, **https://investors.boeing.com/investors/investor-news/press-release-details/2021/Aviation-Industry-Chief-Technology-Officers-Issue-Joint-Call-to-Action-to-Deliver-Sustainable-Aviation-Plans/default.aspx**; "Embraer's Aviation Flight to Net Zero Includes Making Its Current Aircraft Portfolio 100% SAF Capable", *GreenAir*, August 16, 2021, **https://www.greenairnews.com/?p=1505**.

46 Clean Skies for Tomorrow Initiative (CST), World Economic Forum, and McKinsey & Company, *Clean Skies for Tomorrow: Sustainable Aviation Fuels as a Pathway to Net-Zero Aviation*, November 2020, **https://www3.weforum.org/docs/WEF_Clean_Skies_Tomorrow_SAF_Analytics_2020.pdf**.

47 Airbus, "ZEROe Concept Aircraft", 2021, **https://www.airbus.com/en/innovation/zero-emission/hydrogen/zeroe**.

48 Robert Thomson, "Hydrogen: A Future Fuel for Aviation?", Roland Berger, March 11, 2020, **https://www.roland-berger.com/en/Insights/Publications/Hydrogen-A-future-fuel-for-aviation.html**; IATA, *Aircraft Technology Roadmap to 2050*, 2020, **https://www.iata.org/contentassets/8d19e716636a47c184e7221c77563c93/Technology-roadmap-2050.pdf**; and ICAO, *2019 Environmental Report: Aviation and Environment – Destination Green: The Next Chapter*, 2019, **https://www.icao.int/environmental-protection/pages/envrep2019.aspx**.; and Embraer, "Embraer Presents the Energia Family – Four New Aircraft Concepts Using Renewable Energy Propulsion Technologies", November 8, 2021, **https://www.prnewswire.com/news-releases/embraer-sa-embraer-presents-the-energia-family--four-new-aircraft-concepts-using-renewable-energy-propulsion-technologies-301418630.html**.

49 US Federal Aviation Administration (FAA), "Airworthiness Certification", last modified March 2021, **https://www.faa.gov/aircraft/air_cert/airworthiness_certification/**.

50 ICAO, *2019 Environmental Report: Aviation and Environment – Destination Green: The Next Chapter*, 2019, **https://www.icao.int/environmental-protection/pages/envrep2019.aspx**.

51 SBTi, *Science-Based Target Setting for the Aviation Sector: Version 1.0*, August 2021, **https://sciencebasedtargets.org/resources/files/SBTi_AviationGuidanceAug2021.pdf**.

52 Energy Transitions Commission, *Mind the Gap: How Carbon Dioxide Removals Must Complement Deep Decarbonisation to Keep 1.5°C Alive*, March 2022, **https://www.energy-transitions.org/wp-content/uploads/2022/03/ETC-CDR-Report-Mind-the-Gap.pdf**.

53 Ibid.

54 Ibid.

55 Christiane Voigt et al., "Cleaner Burning Aviation Fuels Can Reduce Contrail Cloudiness", *Communications Earth & Environment* 2 (2021), **https://www.nature.com/articles/s43247-021-00174-y**; and Bernd Kärcher, "Formation and Radiative Forcing of Contrail Cirrus", *Nature Communications* 9, 1824 (2018), **https://www.nature.com/articles/s41467-018-04068-0**.

56 Energy Transitions Commission, *Mind the Gap: How Carbon Dioxide Removals Must Complement Deep Decarbonisation to Keep 1.5°C Alive*, March 2022, **https://www.energy-transitions.org/wp-content/uploads/2022/03/ETC-CDR-Report-Mind-the-Gap.pdf.**

57 Air Transport Action Group, *Waypoint 2050*, September 2021, **https://aviationbenefits.org/media/167417/w2050_v2021_27sept_full.pdf**; and IATA, "Developing Sustainable Aviation Fuel (SAF)", 2021, **https://www.iata.org/en/programs/environment/sustainable-aviation-fuels/**.

58 IATA, "Developing Sustainable Aviation Fuel (SAF)", 2021, **https://www.iata.org/en/programs/environment/sustainable-aviation-fuels/; IATA**, "Net-Zero Carbon Emissions by 2050", October 4, 2021, **https://www.iata.org/en/pressroom/2021-releases/2021-10-04-03/**; ICAO, *Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA)*, 2016, **https://www.icao.int/environmental-protection/Documents/Assembly/Resolution_A40-19_CORSIA.pdf**; ATAG, *Aviation Benefits Beyond Borders: Global Fact Sheet*, September 2020, **https://aviationbenefits.org/media/167144/abbb20_factsheet_global.pdf**; European Commission, *Proposal for a Regulation on Ensuring a Level Playing Field for Sustainable Air Transport*, *COM/2021/561 Final*, 2021, **https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX:52021PC0561**; The White House, "Fact Sheet: Biden Administration Advances the Future of Sustainable Fuels in American Aviation", September 9, 2021, **https://www.whitehouse.gov/briefing-room/statements-releases/2021/09/09/fact-sheet-biden-administration-advances-the-future-of-sustainable-fuels-in-american-aviation/**; First Movers Coalition, "Aviation Commitment", **https://www3.weforum.org/docs/WEF_Aviation_2021.pdf**.

59 European Commission, *Proposal for a Regulation on Ensuring a Level Playing Field for Sustainable Air Transport*, *COM/2021/561 Final*, 2021, **https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX:52021PC0561**.

60 Statista, "Total Fuel Consumption of U.S. Airlines from 2004 to 2020", 2021, **https://www.statista.com/statistics/197690/us-airline-fuel-consumption-since-2004/**.

61 The White House, "Fact Sheet: Biden Administration Advances the Future of Sustainable Fuels in American Aviation", September 9, 2021, **https://www.whitehouse.gov/briefing-room/statements-releases/2021/09/09/fact-sheet-biden-administration-advances-the-future-of-sustainable-fuels-in-american-aviation/**.

62 IEA Bioenergy Task 39, *Progress in Commercialization of Biojet /Sustainable Aviation Fuels (SAF): Technologies, Potential and Challenges*, May 2021, **https://www.ieabioenergy.com/wp-content/uploads/2021/06/IEA-Bioenergy-Task-39-Progress-in-the-commercialisation-of-biojet-fuels-May-2021-1.pdf**.

63 ICCT, *The cost of supporting alternative jet fuels in the European Union*, March 2019, **https://theicct.org/publication/the-cost-of-supporting-alternative-jet-fuels-in-the-european-union/**.

64 IEA Bioenergy Task 39, *Progress in Commercialization of Biojet /Sustainable Aviation Fuels (SAF): Technologies, Potential and Challenges*, May 2021, **https://www.ieabioenergy.com/wp-content/uploads/2021/06/IEA-Bioenergy-Task-39-Progress-in-the-commercialisation-of-biojet-fuels-May-2021-1.pdf**.

65 Jim Spaeth, "Sustainable Aviation Fuels from Low-Carbon Ethanol Production", US Department of Energy, October 20, 2021, **https://www.energy.gov/eere/bioenergy/articles/sustainable-aviation-fuels-low-carbon-ethanol-production**.

66 IEA, "Transport Biofuels – Renewables 2020 – Analysis", 2020, **https://www.iea.org/reports/renewables-2020/transport-biofuels**.

67 Agora Energiewende and Guidehouse, *Making Renewable Hydrogen Cost-Competitive: Policy Instruments for Supporting Green H_2*, 2021, **https://static.agora-energiewende.de/fileadmin/Projekte/2020/2020_11_EU_H2-Instruments/A-EW_223_H2-Instruments_WEB.pdf**.

68 Ibid.

69 Florian Egli, Bjarne Steffen, and Tobias Schmidt, "Learning in the Financial Sector Is Essential for Reducing Renewable Energy Costs", *Nature Energy* 4, no. 10 (2019): 835–6, **https://www.nature.com/articles/s41560-019-0482-3**.

70 Energy Transitions Commission (ETC), *Making the Hydrogen Economy Possible: Accelerating Clean Hydrogen in an Electrified Economy*, April 2021, **https://energy-transitions.org/wp-content/uploads/2021/04/ETC-Global-Hydrogen-Report.pdf**.

71 Agora Energiewende and Guidehouse, *Making Renewable Hydrogen Cost-Competitive: Policy Instruments for Supporting Green H_2*, 2021, **https://static.agora-energiewende.de/fileadmin/Projekte/2020/2020_11_EU_H2-Instruments/A-EW_223_H2-Instruments_WEB.pdf**.

72 Johan Lilliestam et al., "Understanding and Accounting for the Effect of Exchange Rate Fluctuations on Global Learning Rates", *Nature Energy* 5, no. 1 (2020): 71–8, **https://www.nature.com/articles/s41560-019-0531-y**.

73 Timo Wassermann et al., "Supply Chain Optimization for Electricity-Based Jet Fuel: The Case Study Germany", *Applied Energy* 307, 117683 (2022), **https://doi.org/10.1016/j.apenergy.2021.117683**.

74 IEA, *Net Zero by 2050: A Roadmap for the Global Energy Sector,* May 2021, **https://www.iea.org/reports/net-zero-by-2050**.

75 ATAG, *Aviation Benefits Beyond Borders: Global Fact Sheet*, September 2020, **https://aviationbenefits.org/media/167144/abbb20_factsheet_global.pdf**.

76 Ibid.

77 IEA, *Net Zero by 2050: A Roadmap for the Global Energy Sector,* May 2021, **https://www.iea.org/reports/net-zero-by-2050**.

78 Energy Transitions Commission (ETC), *Making Clean Electrification Possible: 30 Years to Electrify the Global Economy*, April 2021, **https://www.energy-transitions.org/wp-content/uploads/2021/04/ETC-Global-Power-Report-.pdf**; Hannah Ritchie and Max Roser, "Renewable Energy", Our World in Data, 2021, **https://ourworldindata.org/renewable-energy**; Energy Transitions Commission (ETC), *Making the Hydrogen Economy Possible: Accelerating Clean Hydrogen in an Electrified Economy*, April 2021, **https://energy-transitions.org/wp-content/uploads/2021/04/ETC-Global-Hydrogen-Report.pdf**; and Energy Transitions Commission (ETC), *Bioresources within a Net-Zero Emissions Economy: Making a Sustainable Approach Possible*, July 2021, **https://www.energy-transitions.org/wp-content/uploads/2021/07/ETC-bio-Report-v2.5-lo-res.pdf**.

79 Yvonne Y. Deng et al., Quantifying a Realistic, Worldwide Wind and Solar Electricity Supply", *Global Environmental Change* 31 (March 2015): 239–52, **https://doi.org/10.1016/j.gloenvcha.2015.01.005**.

80 Energy Transitions Commission (ETC), *Making Clean Electrification Possible: 30 Years to Electrify the Global Economy*, April 2021, **https://www.energy-transitions.org/wp-content/uploads/2021/04/ETC-Global-Power-Report-.pdf**.

81 IRENA, *Renewable Capacity Statistics 2021*, 2021, **https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2021/Apr/IRENA_RE_Capacity_Statistics_2021.pdf**.

82 Energy Transitions Commission (ETC), *Making Clean Electrification Possible: 30 Years to Electrify the Global Economy*, April 2021, **https://www.energy-transitions.org/wp-content/uploads/2021/04/ETC-Global-Power-Report-.pdf**.

83 IRENA, *Renewable Capacity Statistics 2021*, 2021, **https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2021/Apr/IRENA_RE_Capacity_Statistics_2021.pdf**.

84 Energy Transitions Commission (ETC), *Making Clean Electrification Possible: 30 Years to Electrify the Global Economy*, April 2021, **https://www.energy-transitions.org/wp-content/uploads/2021/04/ETC-Global-Power-Report-.pdf**.

85 Aurora Energy Research, *Hydrogen market attractiveness rating (HyMAR) report – October 2021*, November 2021, **https://auroraer.com/insight/hydrogen-market-attractiveness-rating-hymar-report-october-2021/**.

86 Ibid.

87 Energy Transitions Commission (ETC), *Bioresources within a Net-Zero Emissions Economy: Making a Sustainable Approach Possible*, July 2021, **https://www.energy-transitions.org/wp-content/uploads/2021/07/ETC-bio-Report-v2.5-lo-res.pdf**; and McKinsey & Company, *McKinsey ACRE model: Global sustainable biomass availability,* 2021, **https://www.mckinsey.com/industries/agriculture/how-we-help-clients/acre**.

88 National Petroleum Council (NPC), "Capture Facility Reference Costs (Gaffney Cline Model)", **https://www.gaffney-cline.com/calculator/npc-scenarios-table**.

89 National Petroleum Council (NPC), "Capture Facility Reference Costs (Gaffney Cline Model)", **https://www.gaffney-cline.com/calculator/npc-scenarios-table**; and Coalition for Negative Emissions, *The Case for Negative Emissions: A Call for Immediate Action,* June 2021, **https://coalitionfornegativeemissions.org/wp-content/uploads/2021/06/The-Case-for-Negative-Emissions-Coalition-for-Negative-Emissions-report-FINAL-2021-06-30.pdf**.

90 Ryan Hanna et al., "Emergency Deployment of Direct Air Capture as a Response to the Climate Crisis", *Nature Communications* 12, 368 (2021), **https://www.nature.com/articles/s41467-020-20437-0**.

91 IEA, *The Future of Petrochemicals – Methodological Annex*, 2018; and IEA, *The Future of Trucks: Implications for Energy and the Environment,* July 2017, **https://www.iea.org/reports/the-future-of-trucks**.

92 Energy Transitions Commission, *Mind the Gap: How Carbon Dioxide Removals Must Complement Deep Decarbonisation to Keep 1.5°C Alive*, March 2022, **https://www.energy-transitions.org/wp-content/uploads/2022/03/ETC-CDR-Report-Mind-the-Gap.pdf**.

93 UNFCCC, *Glasgow Climate Pact (Decision -/CMA.3)*, 2021, **https://unfccc.int/sites/default/files/resource/cma3_auv_2_cover%20decision.pdf**.

94 Sustainable Aviation, *Decarbonisation Road-Map: A Path to Net Zero – A Plan to Decarbonise UK Aviation*, 2020, **https://www.sustainableaviation.co.uk/wp-content/uploads/2020/02/SustainableAviation_CarbonReport_20200203.pdf**; European Commission, *Proposal for a Regulation on Ensuring a Level Playing Field for Sustainable Air Transport*, *COM/2021/561 Final*, 2021, **https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX:52021PC0561**; First Movers Coalition, "Aviation Commitment", **https://www3.weforum.org/docs/WEF_Aviation_2021.pdf**; 117th US Congress, Sustainable Skies Act, 2021; Clean Aviation Joint Undertaking, *1st Call for Proposals: List and description of topics*, 2022, **https://clean-aviation.eu/sites/default/files/2022-03/CAJU-GB-2022-03-16%20Annex-Call-1-topics-descriptions_published.pdf**; Federal Ministry for Digital and Transport of Germany (BMVI), *Förderung der Produktion von Power-to-Liquid-Kraftstoffen (PtL) mit Fokus auf Kerosin*, August 2021, **https://www.bmvi.de/SharedDocs/DE/Anlage/G/ptl-kerosin-foerdersystem-markttest.pdf?__blob=publicationFile**; Kristin L. Brandt, Lina Martinez-Valencia, and Michael P. Wolcott, "Cumulative Impact of Federal and State Policy on Minimum Selling Price of Sustainable Aviation Fuel", *Frontiers in Energy Research* 10 (March 2022), **https://doi.org/10.3389/fenrg.2022.828789**; Poseidon Principles, *Poseidon Principles for Financial Institutions*, 2021, **https://www.poseidonprinciples.org/finance/**; US Department of Energy, "Energy Earthshots: Hydrogen Shot", **https://www.energy.gov/eere/fuelcells/hydrogen-shot**; ArcelorMittal, "ArcelorMittal Expands Partnership with Carbon Capture and Re-Use Specialist LanzaTech through US$30 Million Investment", December 9, 2021, **https://corporate.arcelormittal.com/media/press-releases/arcelormittal-expands-partnership-with-carbon-capture-and-re-use-specialist-lanzatech-through-us-30-million-investment/**.

95 ICAO, *Convention on International Civil Aviation Done at Chicago on the 7th Day of December 1944*, 1944, **https://www.icao.int/publications/documents/7300_orig.pdf**.

96 Clean Skies for Tomorrow Initiative (CST), World Economic Forum, Energy Transitions Commission (ETC), and Mission Possible Partnership (MPP), *Clean Skies for Tomorrow: Sustainable Aviation Fuel Policy Toolkit*, November 2021, **https://www.energy-transitions.org/wp-content/uploads/2021/11/Clean_Skies_for_Tomorrow_Sustainable_Aviation_Fuel_Policy_Toolkit_2021.pdf**.

97 International Civil Aviation Organization, *Report on the Feasibility of a Long-Term Aspirational Goal (LTAG) for International Civil Aviation CO_2 Emission Reductions*, March 2022, **https://www.icao.int/environmental-protection/LTAG/Documents/REPORT%20ON%20THE%20FEASIBILITY%20OF%20A%20LONG-TERM%20ASPIRATIONAL%20GOAL_en.pdf**.

98 European Commission, *Proposal for a Regulation on Ensuring a Level Playing Field for Sustainable Air Transport*, *COM/2021/561 Final*, 2021, **https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX:52021PC0561**.

99 The White House, "Fact Sheet: Biden Administration Advances the Future of Sustainable Fuels in American Aviation", September 9, 2021, **https://www.whitehouse.gov/briefing-room/statements-releases/2021/09/09/fact-sheet-biden-administration-advances-the-future-of-sustainable-fuels-in-american-aviation/**; and The White House, "Executive Order on Catalyzing Clean Energy Industries and Jobs Through Federal Sustainability", December 8, 2021, **https://www.whitehouse.gov/briefing-room/presidential-actions/2021/12/08/executive-order-on-catalyzing-clean-energy-industries-and-jobs-through-federal-sustainability/**.

100 UK Government, "Jet Zero Council", 2021, **https://www.gov.uk/government/groups/jet-zero-council**.

101 Breakthrough Energy, "The Catalyst Program", 2021, **https://www.breakthroughenergy.org/scaling-innovation/catalyst**.

102 Federal Ministry for Digital and Transport of Germany (BMVI), *Förderung der Produktion von Power-to-Liquid-Kraftstoffen (PtL) mit Fokus auf Kerosin*, August 2021, **https://www.bmvi.de/SharedDocs/DE/Anlage/G/ptl-kerosin-foerdersystem-markttest.pdf?__blob=publicationFile**.

103 Aerospace Technology Institute, "FlyZero", 2021, **https://www.ati.org.uk/flyzero/**.

104 European Commission, *Proposal for a Regulation on Ensuring a Level Playing Field for Sustainable Air Transport*, *COM/2021/561 Final*, 2021, **https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX:52021PC0561**.

105 117th US Congress, Sustainable Skies Act, 2021, **https://www.congress.gov/bill/117th-congress/house-bill/3440?s=1&r=3**.

106 Kristin L. Brandt, Lina Martinez-Valencia, and Michael P. Wolcott, "Cumulative Impact of Federal and State Policy on Minimum Selling Price of Sustainable Aviation Fuel", *Frontiers in Energy Research* 10 (March 2022), https://doi.org/10.3389/fenrg.2022.828789.

107 Aviation Benefits Beyond Borders, "KLM and Microsoft Join Forces to Advance Sustainable Air Travel", October 3, 2019, https://aviationbenefits.org/newswire/2019/10/klm-and-microsoft-join-forces-to-advance-sustainable-air-travel/

108 Board Now, Coalition for Sustainable Flying, 2021, https://boardnow.org/.

109 Commercial Aviation Alternative Fuels Initiative (CAAFI), "Aviation's Market Pull for SAF", September 2021, https://www.caafi.org/focus_areas/docs/CAAFI_SAF_Market_Pull_from_Aviation_September2021.pdf.

110 DHL and Eviation, "DHL Express Shapes Future for Sustainable Aviation with the Order of First-Ever All-Electric Cargo Planes from Eviation", August 3, 2021, https://www.dpdhl.com/content/dam/dpdhl/en/media-relations/press-releases/2021/pr-dhl-express-eviation-zero-emission-aircraft-20210803.pdf; and Jeremy Bogaisky, "Amazon and UPS Are Betting This Electric Aircraft Startup Will Change Shipping", *Forbes*, December 16, 2021, https://www.forbes.com/sites/jeremybogaisky/2021/12/16/beta-technologies-amazon-ups-evtol/

111 ICAO, "Global Framework for Aviation Alternative Fuels: SAF Offtake Agreements", http://datastudio.google.com/reporting/8e9488a2-1811-4b13-b7eb-b3fc2e970160/page/FTHXC?feature=opengraph.

112 First Movers Coalition, "Aviation Commitment", https://www3.weforum.org/docs/WEF_Aviation_2021.pdf.

113 RSB, "RSB Launches First SAF Book & Claim Pilot with Air bp to Enable Certified SAF Claims from Microsoft and United Airlines", November 16, 2021, https://rsb.org/2021/11/16/rsb-launches-first-saf-book-claim-pilot-with-air-bp-to-enable-certified-saf-claims-from-microsoft-and-united-airlines/.

114 SAF+ Consortium, webpage of consortium with Airbus, Air transat, ADM, Aero Montreal, and others as partners, 2021, https://safplusconsortium.com/.

115 US Department of Energy, Office of Energy Efficiency & Renewable Energy, *Sustainable Aviation Fuel: Review of Technical Pathways*, September 2020, https://www.energy.gov/sites/prod/files/2020/09/f78/beto-sust-aviation-fuel-sep-2020.pdf.

116 Poseidon Principles, *Poseidon Principles for Financial Institutions*, 2021, https://www.poseidonprinciples.org/finance/.

117 Breakthrough Energy, "The Catalyst Program", 2021, https://www.breakthroughenergy.org/scaling-innovation/catalyst.

118 Clean Aviation Joint Undertaking, *1st Call for Proposals: List and description of topics*, 2022, https://clean-aviation.eu/sites/default/files/2022-03/CA-JU-GB-2022-03-16%20Annex-Call-1-topics-descriptions_published.pdf; and Goda Naujokaitytė, "Clean Aviation Industrial Partnership Lifts Off", *Science/Business*, March 24, 2022, https://sciencebusiness.net/climate-news/news/clean-aviation-industrial-partnership-lifts.

MISSION POSSIBLE PARTNERSHIP

The Mission Possible Partnership is an alliance of climate leaders focused on supercharging efforts to decarbonise some of the world's highest-emitting industries in the next 10 years.