MAKING NET-ZERO AVIATION POSSIBLE

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

AVIATION TRANSITION STRATEGY / JULY 2022

MISSION POSSIBLE PARTNERSHIP

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Technical Appendix

of

MAKING NET-ZERO AVIATION POSSIBLE

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July 2022

Table of Content

This technical appendix accompanies the Mission Possible Partnership's and Clean Skies for Tomorrow's Aviation Transition Strategy "Making Net-Zero Aviation Possible: An industry-backed, 1.5°C-aligned Transition Strategy".

It provides background information on:

- Benefits and the climate impact of aviation
- Decarbonisation measures
    - Demand-side measures
    - Efficiency improvements
    - Renewable fuels (SAFs, hydrogen fuel cell, hydrogen combustion and battery-electric aircraft)
    - Carbon dioxide removal (CDR) solutions
- Overview of the model (i.e., a discussion of the model setup and its limitations)
- Methodology for sectoral allocation of 1.5°C carbon budget
- The cost of inaction

1 Benefits and climate impact of aviation

Aviation is an economic powerhouse, supporting millions of jobs worldwide and accounting for around $2 trillion p.a. (incl. the aviation industry supply chain), or 2% of global GDP.[1] Air travel is also more than a lever of the economy. It is associated with fundamental human impulses around connection, exploration, and discovery. As we fly, our imaginations soar.

However, global aviation accounts for around 2.8% of anthropogenic CO_2 emissions (1.02 Gt CO_2 tank-to-wake emissions out of 36.7 Gt CO_2 globally), **2.0% of GHG emissions** (out of roughly 50 Gt CO_2e globally)**, and 3.5–4.0% of anthropogenic climate impact** (measured in net effective radiative forcing).[2–5] Given increased momentum in the battle against climate change, aviation faces growing scrutiny from consumers, the media, regulators, and investors.

In reaction to the increasing sense of urgency to transition to carbon-neutrality, IATA and ATAG have published a resolution for the global aviation industry to achieve net-zero CO_2 emissions by 2050.

2 Demand-side measures

In this report, the impact of the following demand-side measures has been assessed in sensitivity analyses:

- **Behaviour change:** In contrast to the demand reduction impact assessment in the IEA's *Net Zero by 2050* report, which assumes that business and long-haul leisure air travel does not exceed 2019 levels, we modelled a linearly ramped up 10% demand reduction by 2050, assuming a more conservative assumption of the potential impact of video conferencing as alternatives to in-person meetings, and reduced leisure travel due to increased climate awareness of end customers.
- **Mode shift:** We modelled a mode shift of short-haul flights to high-speed rail in line with the IEA's *Net Zero by 2050* report, linearly ramped up until 2050 when the maximum potential (which is regionally different) is achieved. Considering that future short-haul aircraft are likely going to feature new propulsion systems (battery-electric/ hybrid/ hydrogen aircraft) with substantially lower emissions, the GHG emissions advantage of mode shift could diminish from a total life cycle emissions perspective.
- **Elasticity on ticket price increases:** Given the high uncertainty of the impact of potential cost increases per RPK on demand, the impact of reduced demand as a response to increased ticket prices has not been modelled.

We have not included any demand reduction measures in the core net-zero scenarios to not undermine the magnitude of the renewable fuel volume requirements if demand reduction does not materialise.

However, demand reduction measures should be implemented wherever possible and reasonable in regional contexts and while ensuring a just transition towards climate-neutral flying. While developed countries should implement demand reduction measures, developing countries will still rely on some demand increase to unlock all the positive impact that aviation can have on these economies and societies.

3 Efficiency improvements

The fuel efficiency gain assumptions in this report are in line with the ICAO's aspirational goal of a 2% annual fuel efficiency improvement through 2050 and in the range of other studies' assumptions on fuel efficiency gains (Exhibit 1).[6–9]

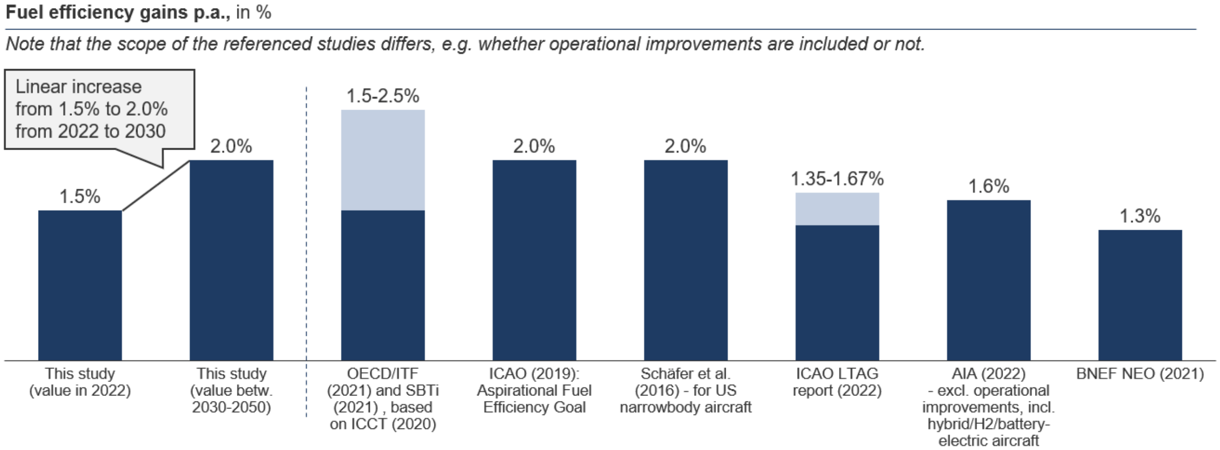


Exhibit 1: Fuel efficiency gains assumed in this study, compared with assumptions of other reports.[6,8–15]

To reduce the complexity of the model, it also applies some simplifications to reality: New efficiency improvement measures like the introduction of new turbines are not modelled as discrete events but rather evened out as continuous improvements across the whole aircraft fleet and all efficiency measures.

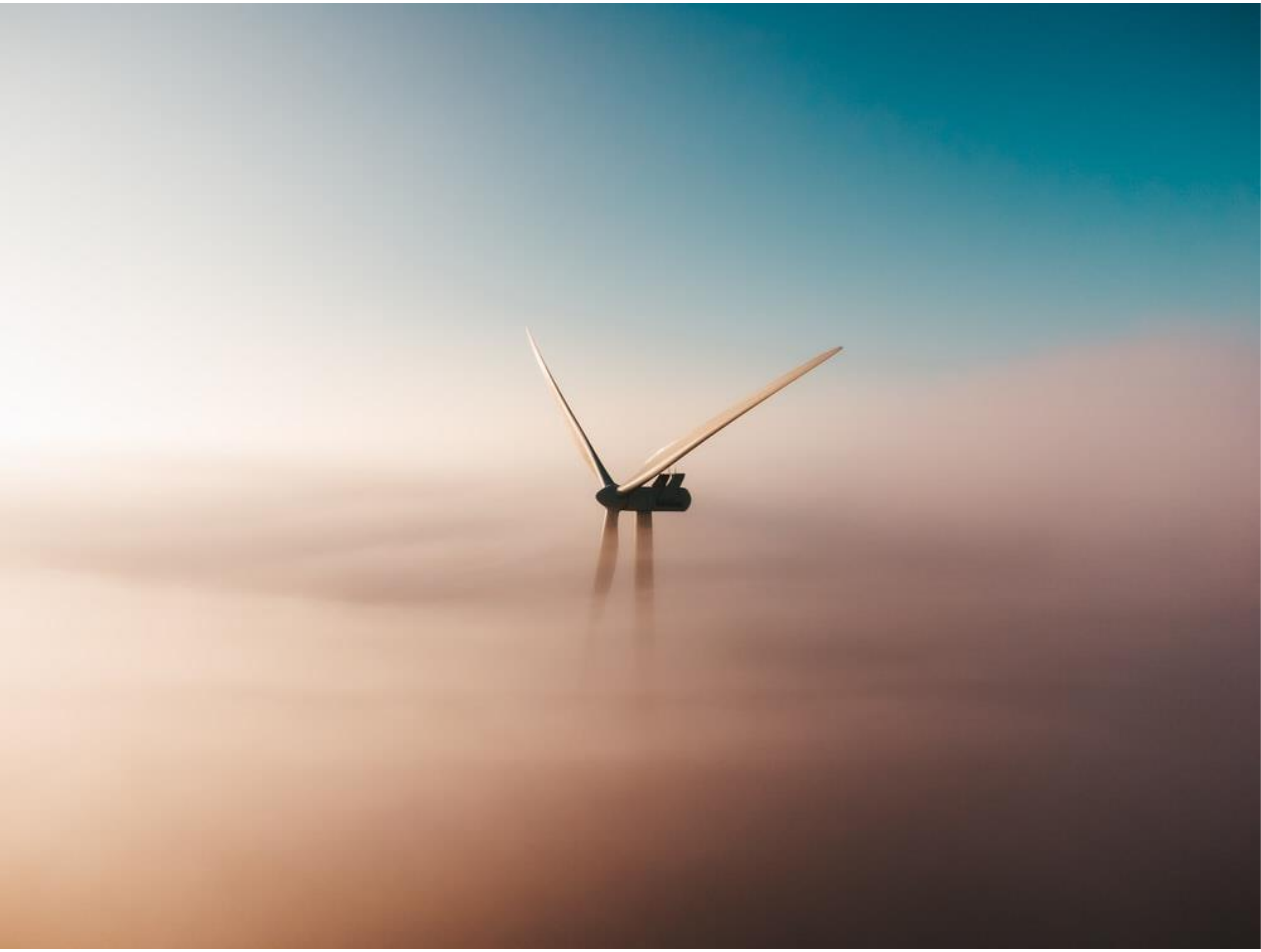
Fuel efficiency measures are only applied to conventional jet aircraft. Hydrogen and battery-electric aircraft are assumed to have a constant fuel burn given the currently large uncertainties of future technology developments. Therefore, the GHG reduction impact of fuel efficiency measures is less prominent the more hydrogen and battery-electric aircraft enter the fleet.

4 Renewable fuels: Market potential, costs and GHG reduction impact

This report considers SAFs, green hydrogen and renewable electricity as renewable energy carriers. Lower-Carbon Aviation Fuels (LCAFs), i.e. fossil jet fuel with certain GHG savings (e.g., from the use of renewable energy in oil refineries or the use of CCS), are excluded from this study because they only offer minor GHG reduction potentials. LCAFs could assist the transition but must under no circumstances substitute SAFs.

4.1 Electricity, hydrogen and fossil jet fuel costs assumptions

The considered renewable energy carriers (SAFs, hydrogen for hydrogen combustion and hydrogen fuel cell aircraft, and electricity for battery-electric aircraft) are based on the cost assumptions for renewable electricity and hydrogen shown in Exhibit 2 and Exhibit 3.



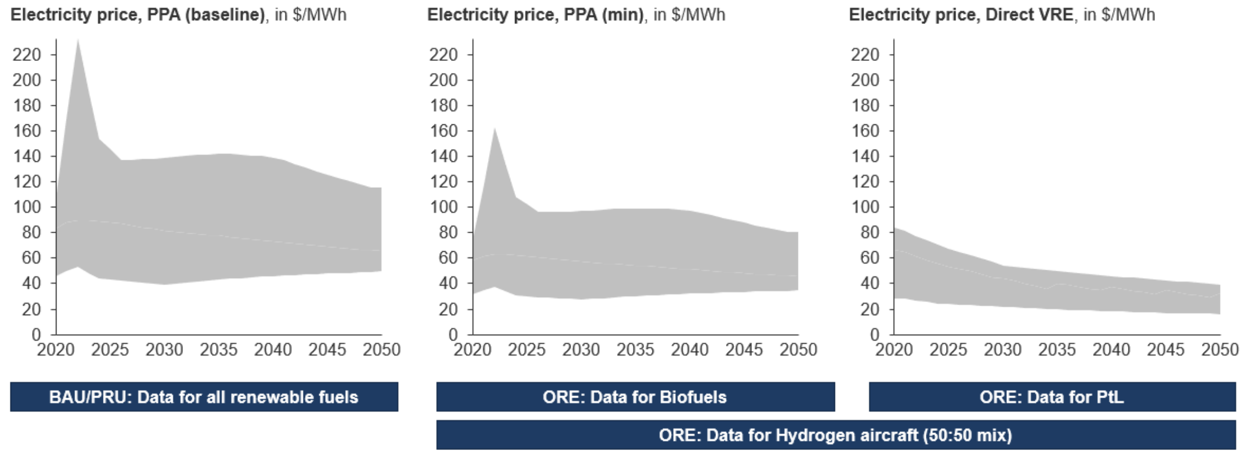


Exhibit 2: Renewable electricity cost projections and their mapping to the BAU/PRU and ORE scenarios. Ranges stem from regional differences. PPA = Power Purchase Agreement. VRE = Variable Renewable Electricity. The recent price spikes for oil, natural gas and coal feed through to power prices since the PPA prices are modelled to follow grid prices with a discount.

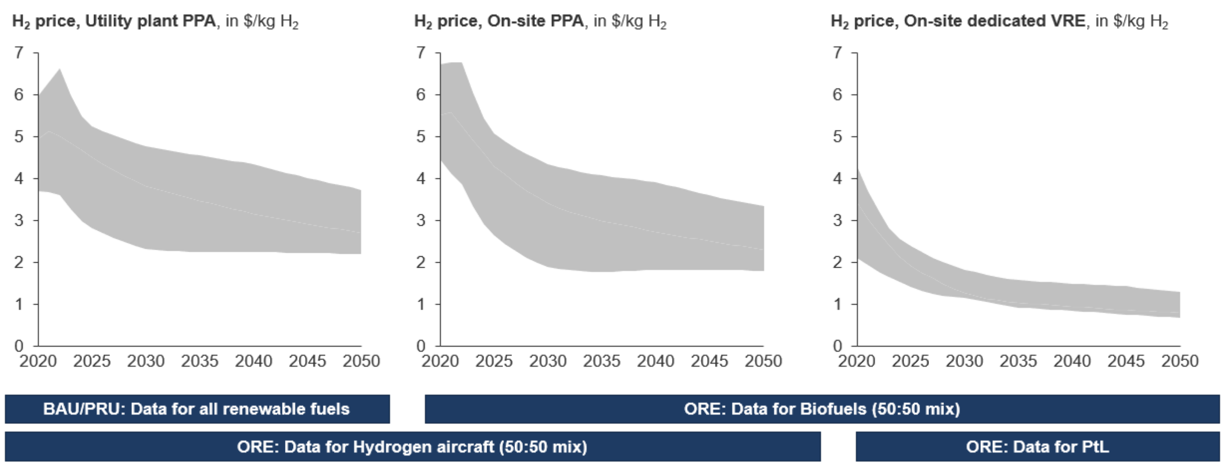
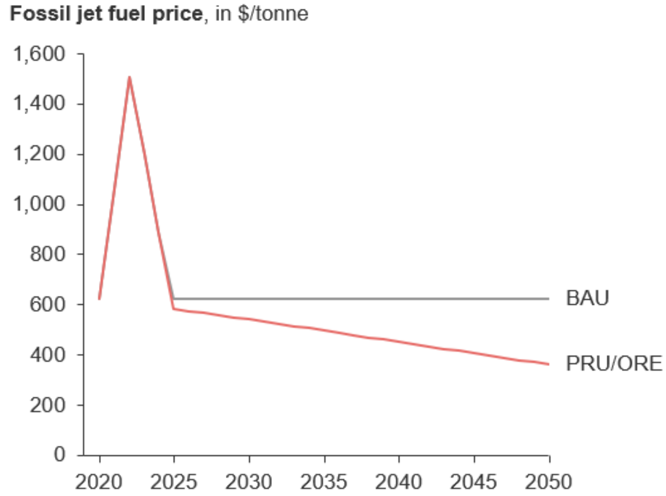


Exhibit 3: Hydrogen cost projections and their mapping to the BAU/PRU and ORE scenarios. Ranges stem from regional differences. PPA = Power Purchase Agreement. VRE = Variable Renewable Electricity. The recent price spikes for oil, natural gas and coal feed through to power prices since the PPA prices are modelled to follow grid prices with a discount.

For fossil jet fuel, we assume the cost trajectories depicted in Exhibit 4.



Underlying assumptions

- The fossil jet fuel prices are modelled to follow oil prices. Both scenarios have included **recent price spikes** (in particular the World Bank's forecast for 2022) which are modelled to return to 2019 levels until 2024.
- The price of fossil jet fuel decreases in the **net-zero scenarios (PRU and ORE)**, assuming an over-supply of oil in a decarbonising global economy. This is **in line with the IEA's NZE report**. Any carbon pricing schemes are not included here for the price of fossil jet fuel, but are accounted for in the assumed green premium that is accepted by the aviation industry to get to net zero. This is equivalent to modelling a carbon price on top of fossil jet fuel (and not including a green premium).
- The price of fossil jet fuel stays constant in the **BAU scenario**.

Exhibit 4: Fossil jet fuel price projections and underlying assumptions. The historical fossil jet fuel price is taken as the average market price of the last 20 years. It has, however, fluctuated substantially around that average during that time period, with a minimum price of $135/tonne and a maximum of $1590/tonne.

4.2 Background information for Sustainable Aviation Fuels (SAFs)

All modelling assumptions for SAFs are informed by industry expertise across the value chain (from the industry community of the Clean Skies for Tomorrow Initiative and the Mission Possible Partnership) as well as recent academic insights and reports from other organisations like IATA, ATAG, IEA, AIA or ACI.

Current use case: Blending limits

Regulatory blending limit*:* Currently, most certified SAFs can be blended to conventional fossil jet fuel up to 50 volume%, as regulated by the ASTM D7566 standard from ASTM International.[16] The 50% limits are expected to be lifted before a system-wide SAF blending rate of 50% is actually reached which is projected to happen only in the late 2030s.

Technical blending limit: Several aviation companies are already experimenting with scaling of SAFs in commercial settings. Rolls-Royce announced that all its 'Trent' engines will have been proven compatible with 100% SAF by 2023.[17] GE, Safran, and Pratt & Whitney have announced that they are aiming for 100% SAF compatibility[18], while Airbus, Boeing and Embraer are also targeting certification of 100% unblended SAF by 2030. [17,19,20]

Fuel production pathways

SAFs can either be produced from sustainable biomass (biofuels), electricity (e-fuels, PtL) or via thermo-chemical processes from solar irradiation (solar fuels).[21,22] While non-HEFA biofuels are modelled to enter the market in 2022 and PtL in 2025, solar fuels have lower TRLs and are therefore excluded in this analysis.

Biofuel and PtL pathways produce either synthesis gas (consisting primarily of hydrogen and carbon monoxide), methanol, or ethanol. These in turn are converted into renewable jet fuel (SAF) and byproducts (Exhibit 5).

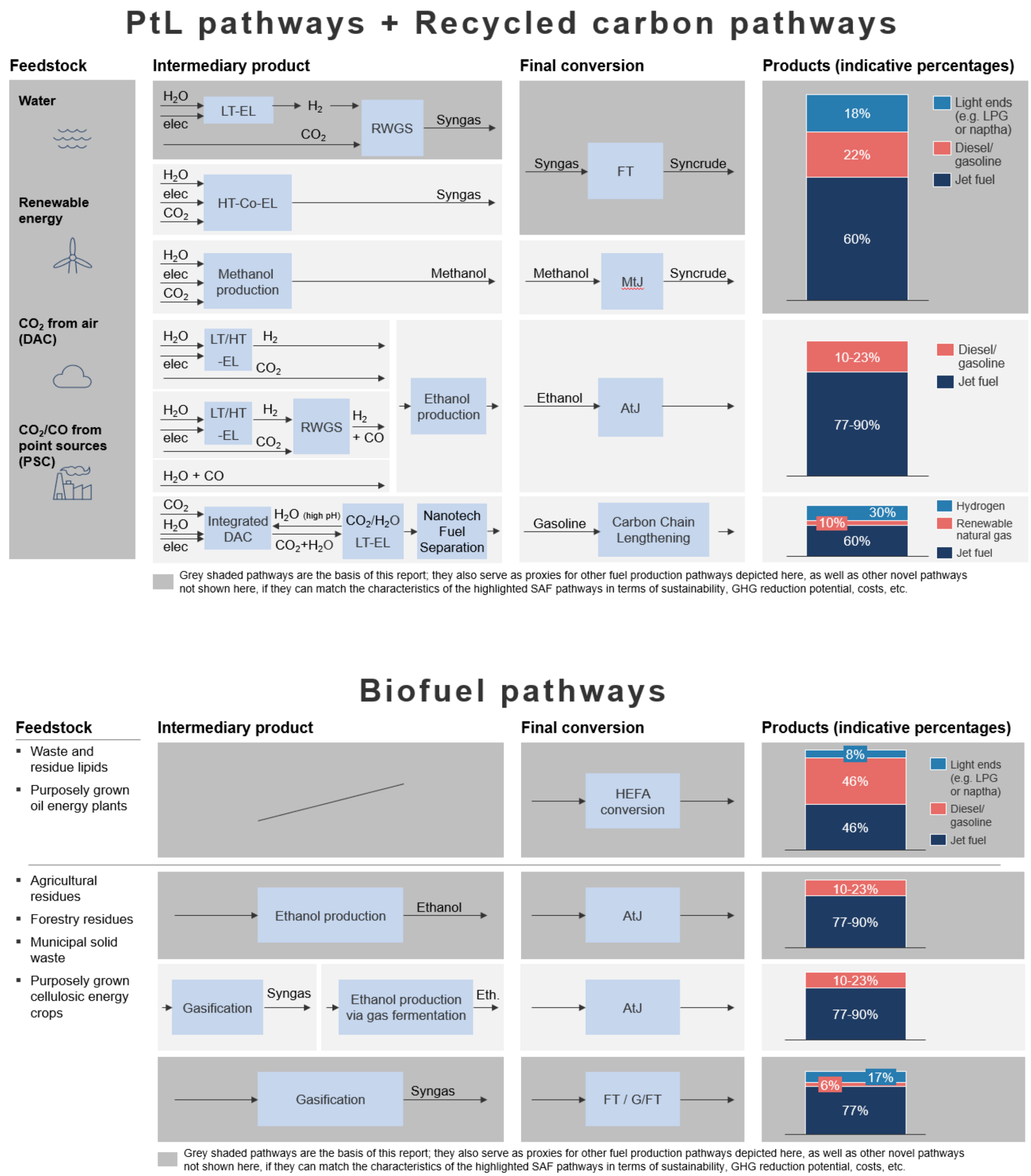


Exhibit 5: Overview of main SAF production pathways. There are other potential SAF production pathways like pyrolysis that are not illustrated but could play a role in the supply of SAFs in the future if they can be brought to market at competitive costs, climate impact reduction levels and high standards of feedstock sustainability. With more technological innovation and fine-tuning, the specificity towards individual product slates (like jet fuel) could be increased. The shown product slates are only indicative and vary depending on regional differences and policy incentives (e.g., the current incentives to produce bio-diesel for road transport rather than jet fuel for aviation). RWGS = Reverse Water Gas Shift; HT/LT-EL = High-/Low-temperature electrolysis; Co-EL = Co-electrolysis; MtJ = Methanol-to-Jet; FT = Fischer-Tropsch; G/FT = Gasification/Fischer-Tropsch; AtJ = Alcohol-to-Jet; DAC = Direct Air Capture of CO_2.

Feedstock constraints

The model accounts for regional limits to the availability of feedstock of sustainable biomass for HEFA and other biofuels. The global limit for sustainable biomass is assumed to be 50 EJ in a Prudent scenario and up to 110 EJ in a Maximum Potential scenario.[23]

Exhibit 6 shows the underlying assumptions for the **Prudent scenario**, based on a report of the Energy Transitions Commission.[23]

Exhibit 7 shows the underlying assumptions for the **Maximum Potential scenario**,[23] which describes as follows how additional sustainable biomass could be made available on top of the Prudent scenario:

"Three possible, but highly uncertain, future developments could increase the sustainable supply of biomass. Two could be driven by business model and cost developments with:

(1) Improved waste management and collection of organic wastes potentially providing an additional c. 5 EJ/year of supply.

(2) The development and scaling of a seaweed-for-energy industry of much larger scale than current macroalgae production (primarily for other, high value, uses, e.g., food additives). This could allow for a possible additional c. 10 EJ/year, though with the caveat that it may always make sense to devote increased macroalgae (and microalgae) production to high value uses such as food and feed supply rather than to energy production. This would deliver the indirect benefit of less pressure on land for food production.

***The largest and most uncertain upside (3)** relates to the availability of land for dedicated biomass production. At present about 3,300 million hectares (3.3m km^2) of land is devoted to pasture or to cropland, with a significant share of the latter producing feed for livestock. Analysis by the Food and Land Use (FOLU) coalition, suggests that a combination of major changes in diet and/or the development of new cultured and synthetic meat technology, alongside improved agricultural productivity and reduced food waste, could release as much as c. 1,310 Mha from food production, of which about c. 1,100 Mha might be suitable for either managed forests or energy crop cultivation. While the optimal use of this land – both for biodiversity and climate mitigation purposes – may be to return much of it to permanent forest or other natural ecosystems, devoting 800 Mha or 250 Mha of it to managed forestry or energy crops, respectively, could deliver another c. 45 EJ/year of sustainable biomass supply.*

***Our 'maximum potential scenario' therefore adds c. 60 EJ/year of additional supply** to the upper end of the c.40–60 EJ/ year assumed in the 'prudent scenario'. It is important to note however that even if this additional supply eventually becomes available, it will only do so gradually, with changes in diet and synthetic meat production – levers which make additional land available – in particular likely to take time. Even our maximum potential scenario is significantly less than some other estimates of total sustainable supply, but it is broadly in line with the estimate presented in the International Energy Agency's recent "Net Zero by 2050" report, though with a different specific mix.*

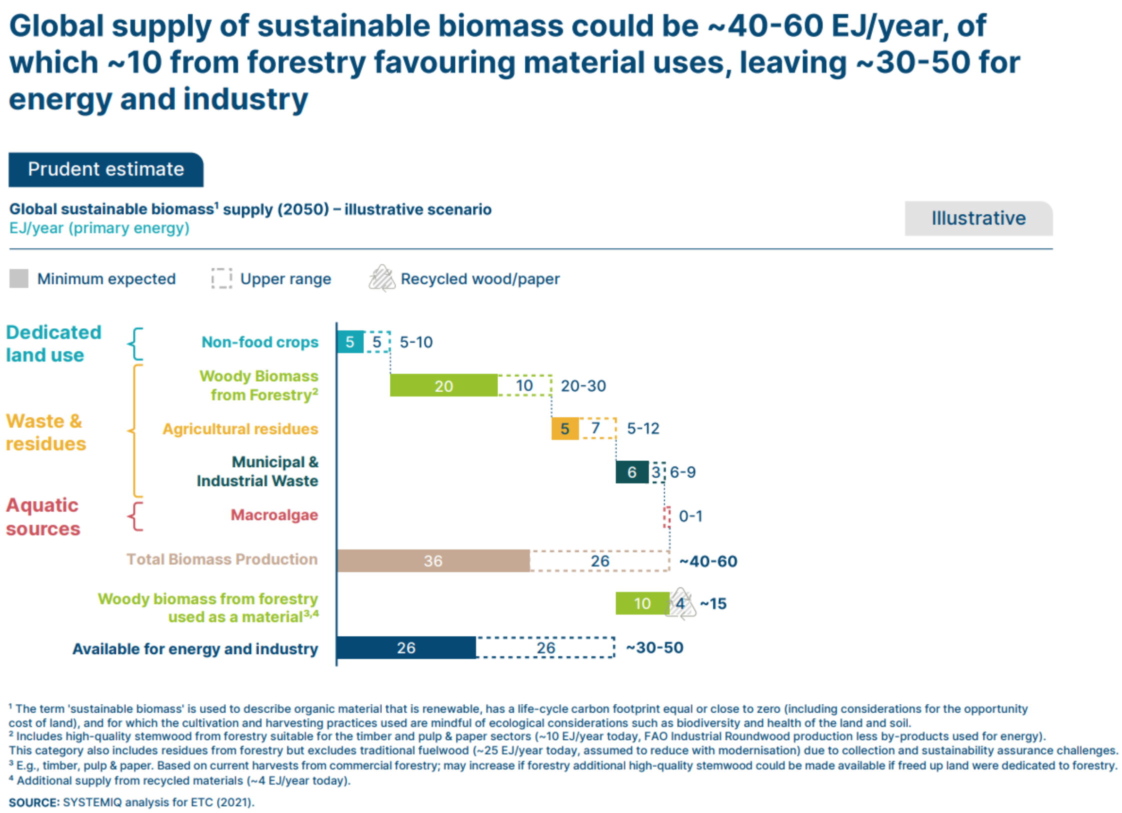


Exhibit 6: Indicative estimates of global sustainable biomass availability (Prudent estimate), based on analysis from the Energy Transitions Commission[23]

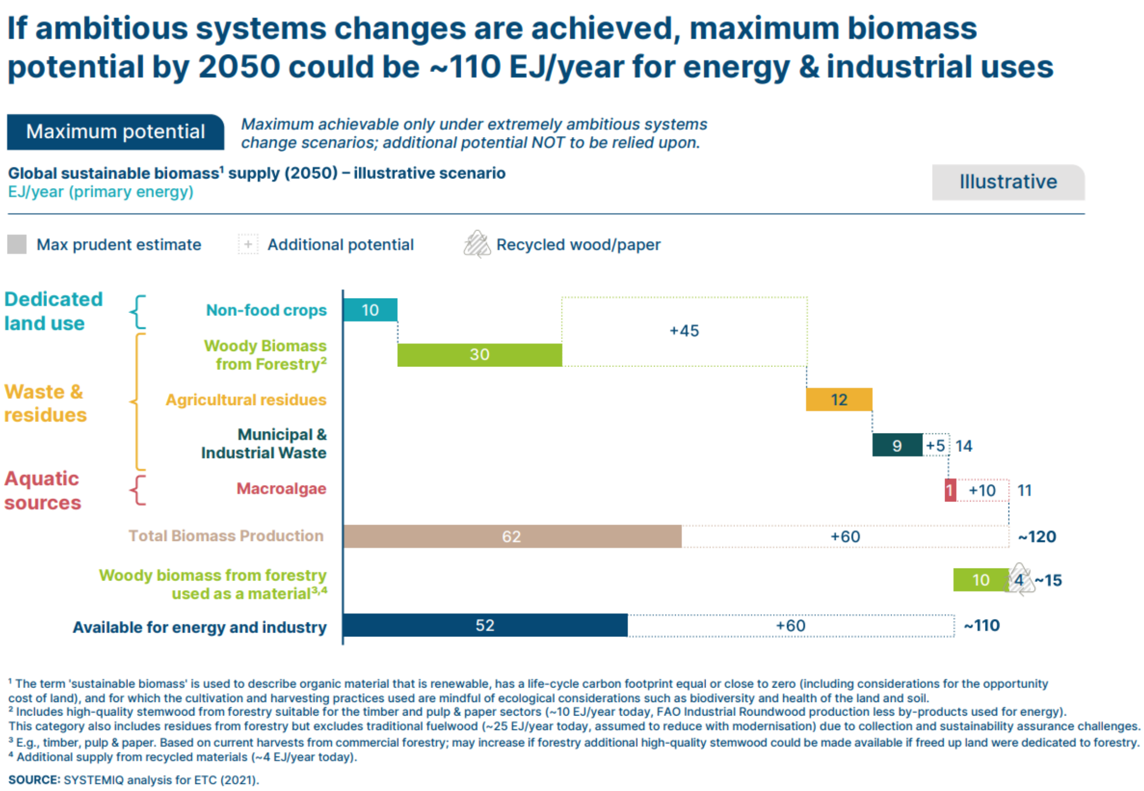


Exhibit 7: Indicative estimates of global sustainable biomass availability (Maximum potential estimate), based on analysis from the Energy Transitions Commission[23]

According to a prioritisation framework developed by MPP, which analyses the merit order of biomass use for different biomass-demanding sectors, the amount of biomass ending up in jet fuel should not exceed about 15 EJ. Considering that the production of bio-jet fuel will always come with the production of byproducts, overall more sustainable biomass will be used in SAF production facilities.

The global feedstock limits are broken down to individual regions based on McKinsey's ACRE model and an analysis by MPP, and include a more restrictive sublimit for HEFA feedstock compared with other feedstock types like MSW, forestry residues or agricultural residues.

For renewable electricity generation assets and electrolysers, we assume that supply will follow demand in the long run, even if in the short-run the ramp-up of PtL might encounter supply bottlenecks.

For electrolysers, the availability of raw materials might induce a shift to other electrolyser chemistries. Iridium, PGMs (platinum-group metals) and nickel are key metals required for fuel cells and electrolysers in the hydrogen economy. The ETC projects a maximum of 800 Mt of H_2 of demand by 2050 across sectors, which can be supplied using primary nickel.[24] Less than a third of known reserves would be required. However, iridium supply is almost entirely from South Africa, which accounts for 81% of global production, suggesting the potential for supply bottlenecks. Finally, South Africa and Russia account or 91% of global PGM reserves.[25] IRENA suggests current supplies of iridium and platinum would only support 3–7 GW of electrolyser production annually[26] (yielding a yearly addition in hydrogen output of 0.5–1.0 Mt).

SAF project pipeline: Capacity and production

Currently, around 0.05–0.10 Mt SAF is produced annually,[27,28] almost exclusively stemming from HEFA. The current production volumes compare to a total product output capacity (including byproducts) of 8.9 Mt today. However, most of that biofuel volume is directed to the road transport sector as biodiesel/gasoline.

Until 2030, the SAF production from HEFA will increase to 7 Mt, and also first volumes of other biofuels (AtJ, G/FT) and e-fuels are expected, representing a total of 1.2 Mt by 2030 (Exhibit 8).

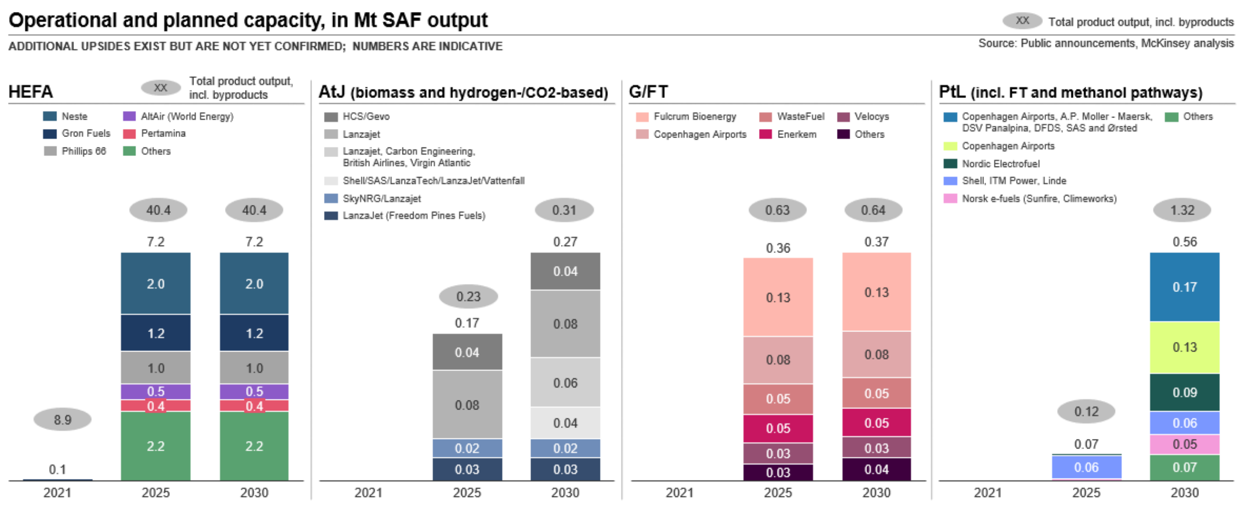


Exhibit 8: Operational and planned SAF production capacity in 2020, 2025 and 2030 (additional upsides exist but are not yet confirmed, numbers are indicative; source: public announcements, McKinsey analysis). Note that the projected SAF output of 8.4 Mt does not include announcements but only concrete SAF plant plans. However, other announcements and production targets represent significant potential upsides, see e.g. [29–31]

SAF cost projections

Exhibit 9-Exhibit 13 provide an overview of the assumed SAF production costs up to 2050, including a breakdown of individual cost components. These are indicative numbers that differ for individual regions and feedstock types.

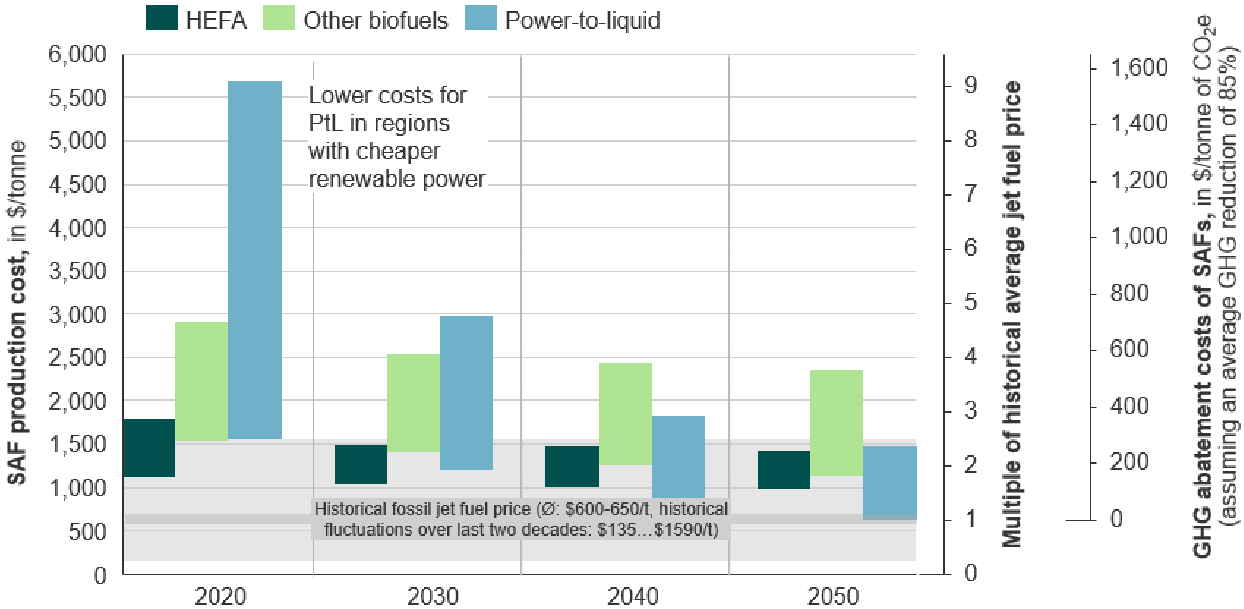


Exhibit 9: Indicative GHG Abatement costs for SAFs. The cost of fossil jet fuel is taken as the average market price of the last 20 years. It has, however fluctuated substantially around that average during that time period, with a minimum price of $135/tonne and a maximum of $1590/tonne. This report's 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.

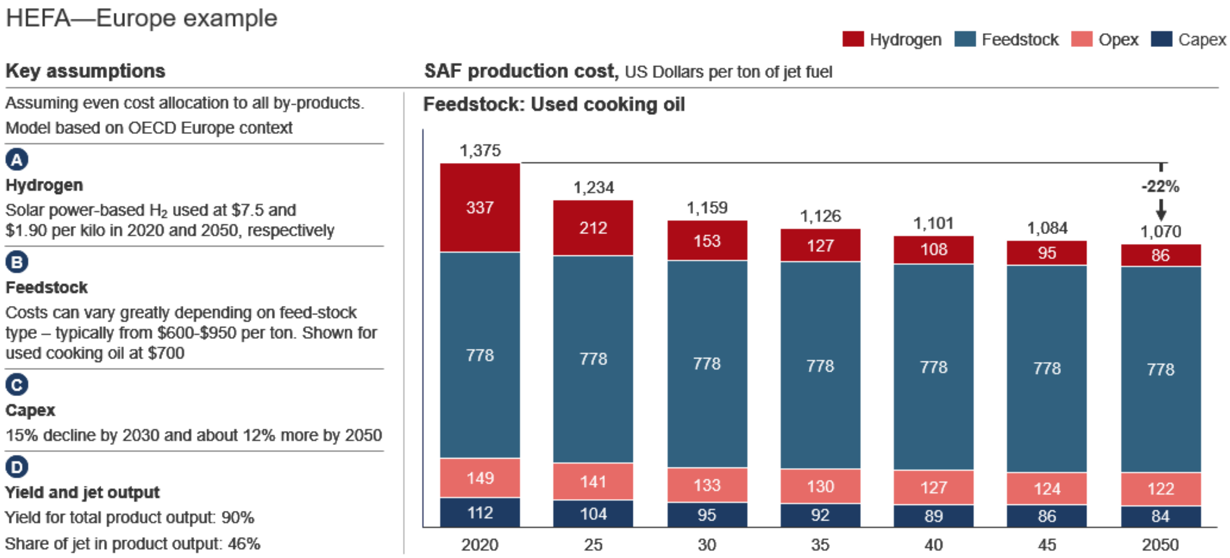


Exhibit 10: Indicative HEFA fuel production costs. CAPEX values reflect a greenfield plant. The share of jet fuel in the product output of 46% is conservative and could be up to 70%. Values are based on ENERGINET[32], expert input and WEF Clean Skies for Tomorrow Insight Report[21]

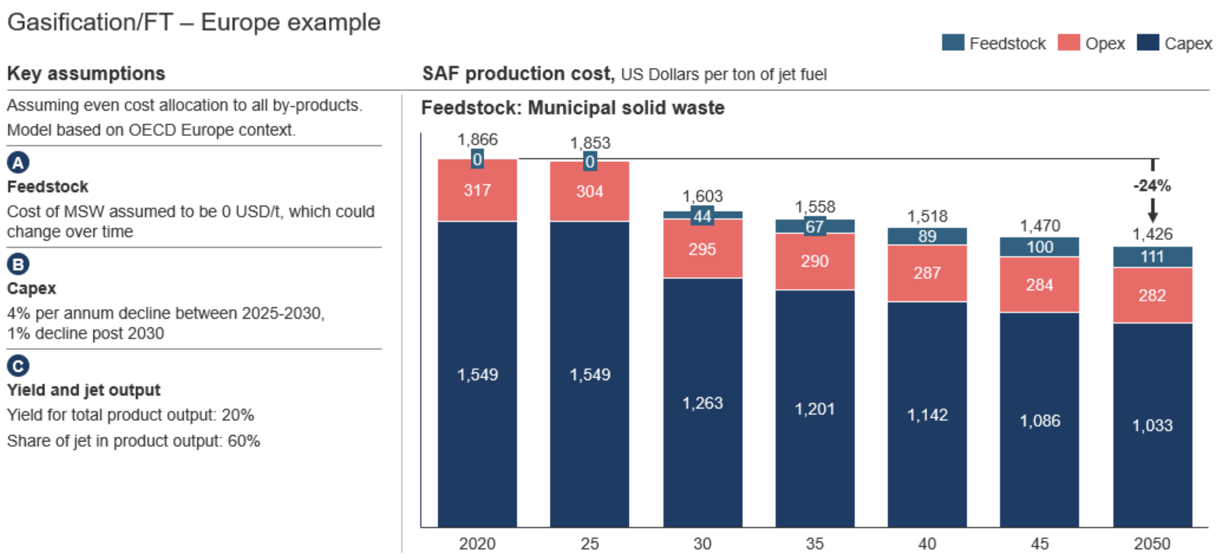


Exhibit 11: Indicative G/FT fuel production costs. CAPEX values reflect a greenfield plant. The share of jet fuel in the product output of 60% is conservative and could be up to 70%. Values are based on IVL report "Investment cost estimates for gasification based biofuel production systems"[33], expert input and WEF Clean Skies for Tomorrow Insight Report[21] MSW feedstock is a mix of organic wastes (e.g., food waste) and plastics.

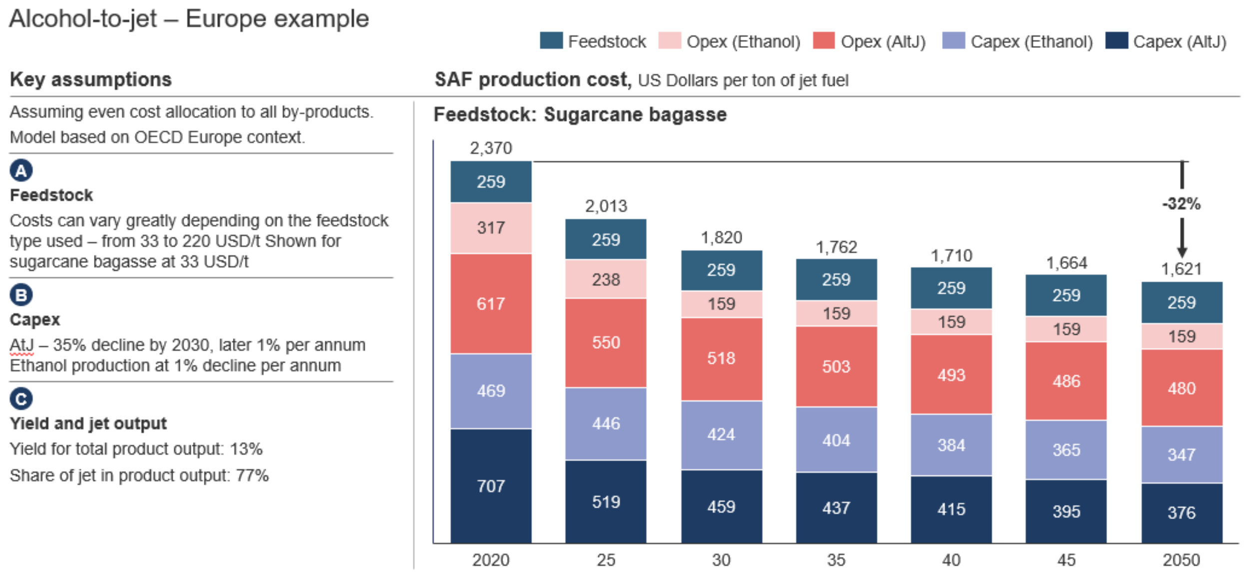


Exhibit 12: Indicative G/FT fuel production costs. CAPEX values reflect a greenfield plant. The share of jet fuel in the product output of 46% is conservative and could be up to 90%. Values are based on Suresh et. al. "Life cycle greenhouse gas emissions and costs of production of diesel and jet fuel from municipal solid waste"[34], ENERGINET[32], expert input, and WEF Clean Skies for Tomorrow Insight Report.[21] If existing ethanol plants are used to produce jet fuel, the CAPEX for the ethanol production plant would be smaller.

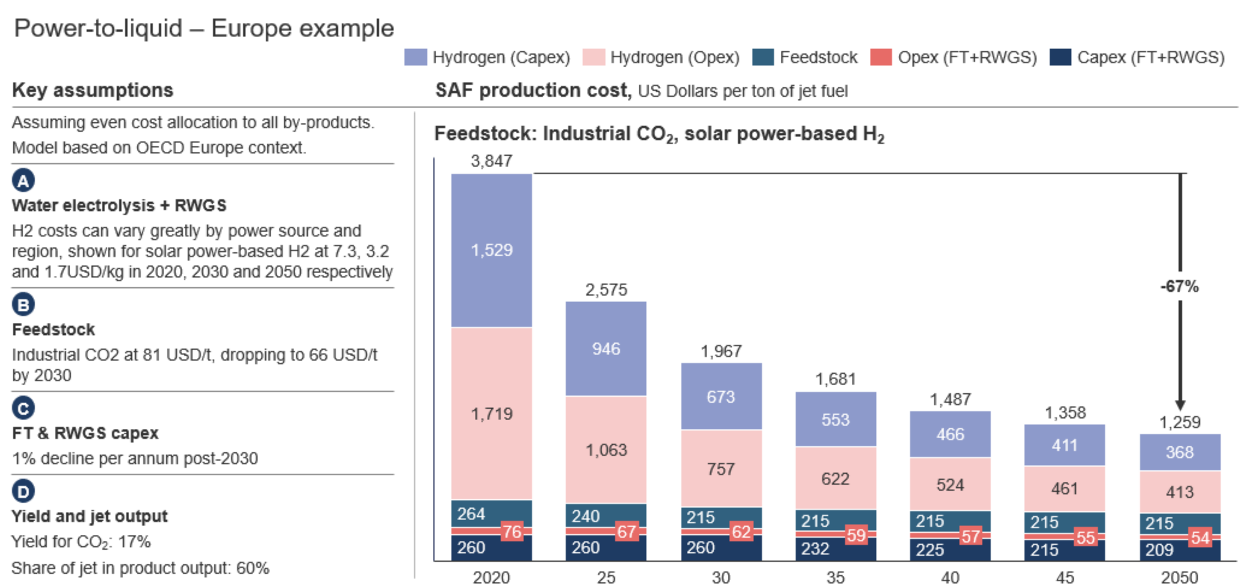


Exhibit 13: Indicative G/FT fuel production costs. CAPEX values reflect a greenfield plant. The share of jet fuel in the product output of 46% is conservative and could be up to 70%. Values are based on McKinsey Energy Insights' Global Energy Perspective, expert input, and WEF Clean Skies for Tomorrow Insight Report[21]

4.3 Background information for hydrogen and battery-electric aircraft

All modelling assumptions for hydrogen and battery-electric are informed by industry expertise across the value chain (from the industry community of the Target True Zero Initiative and the Mission Possible Partnership) as well as recent academic insights.

Benefits:

- Non-CO_2 benefits: Hydrogen and battery-electric aircraft have the potential to reduce the non-CO_2 climate impact of aviation (see details about aviation induced cloudiness in the next section), improve local air quality and reduce noise levels at airports.
- Market opportunity: While battery-electric aircraft only contribute a tiny fraction of the overall GHG emission reduction required to get to net zero, they offer a large market. Since they operate on low-distances, the share of battery-electric aircraft on the global fleet is notedly higher than their GHG emission reduction contribution. Electrical take-off and landing aircraft (eVTOLs) can even unlock new markets for flight routes that are currently not being catered by regional airports.

Challenges:

- Infrastructure needs: Airport infrastructure for recharging (or battery swapping) and hydrogen refueling needs to be set up to cater the energy demand of hydrogen and battery-electric aircraft.[35] "Green corridors" could kick-off the introduction of novel propulsion aircraft, providing the necessary infrastructure at two dedicated airports with regular operations between them. In the longer-term, interoperability needs to be ensured, i.e. the supply, handling and refueling of hydrogen, electricity and SAFs at airports around the globe, when the aircraft fleet is going to consist of a mix of conventional jet, hydrogen and battery-electric aircraft.
- Certification: To unfold their full potential, the airframe of hydrogen and battery-electric aircraft will likely need to be redesigned to achieve higher glide ratios, more lightweight structures and a tailor-made storage of the hydrogen/batteries inside the aircraft. This will come with new certification and safety requirements.
- Range of battery-electric aircraft: For batteries to be viable for flights up to 1,000 km, they will need to increase their energy density by a factor of 4 compared with today's levels, to at least 800 Wh/kg. This will require a breakthrough in battery chemistries beyond the currently dominant lithium-ion (Li-ion). However, Li-air or Li-metal batteries are still at a relatively early stage of development and lack durability and longevity. [36,37]

Applicability: Market entry and maximum ranges

Hydrogen and battery-electric aircraft are limited in their maximum range by their maximum energy density of their storage systems, i.e. liquefied hydrogen tanks or batteries (Exhibit 14), but could experience technological improvements to achieve drastically higher energy densities towards 2050. Until these technology innovations materialise, hybrid-electric aircraft could combine the range advantages of SAF-powered aircraft with the efficiency of electric aircraft.

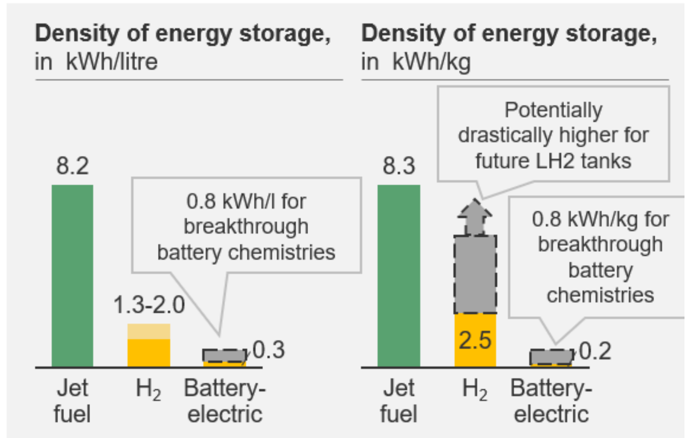


Exhibit 14: Indicative energy densities of hydrogen storage systems and batteries compared with jet fuel (References: Stolz et al., 2021[38]; McKinsey 2021, Target True Zero Initiative) – today and future potential

Exhibit 15 to Exhibit 17 illustrate the assumed market entry dates and maximum ranges of hydrogen fuel cell (FC), hydrogen combustion and battery-electric aircraft for different segments of global aviation. The moderate assumptions are used in the BAU and PRU scenario, the progressive assumptions in the ORE scenario. For battery-electric and hydrogen aircraft, the market entry dates highlight the market entry at large scales rather than the market entry of first-of-a-kind aircraft.

The range of those aircraft is aligned with the model granularity of 500 nm (926 km) bins. Below this ~1000 km limit, CO_2 emissions from commercial aircraft operating flights between 0–500 km amount to about 5% of total commercial aviation emissions, whereas flights in the range of 501–1,000 km emit about 10% of total emissions.[39] While not resolving for these "sub-bins", the implicit modelling assumption is that battery-electric and hydrogen-fuel cell aircraft will first enter the market in the lower-range, fewer-seats segment and then over time penetrate the market into the second "sub-bin" as well if more technological advancements are materialised.

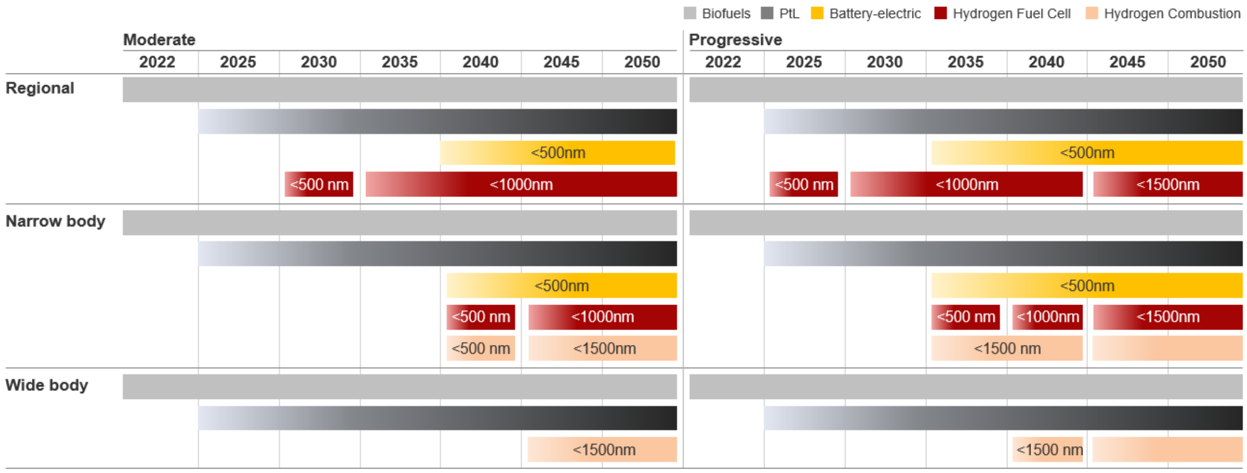


Exhibit 15: Projection of market entry and maximum range of commercial passenger and commercial cargo aircraft

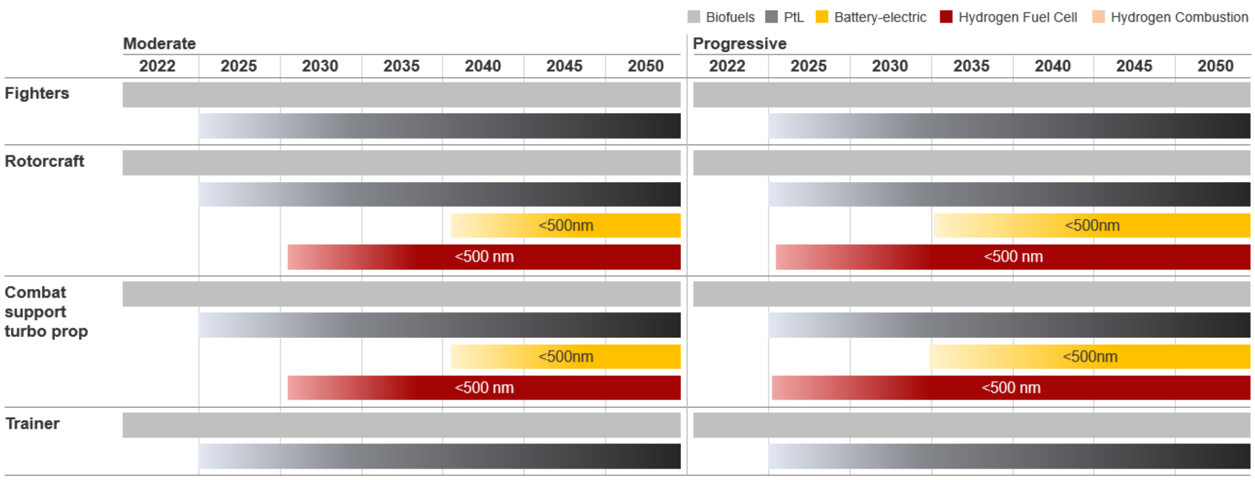


Exhibit 16: Projection of market entry and maximum range of aircraft in the public sector

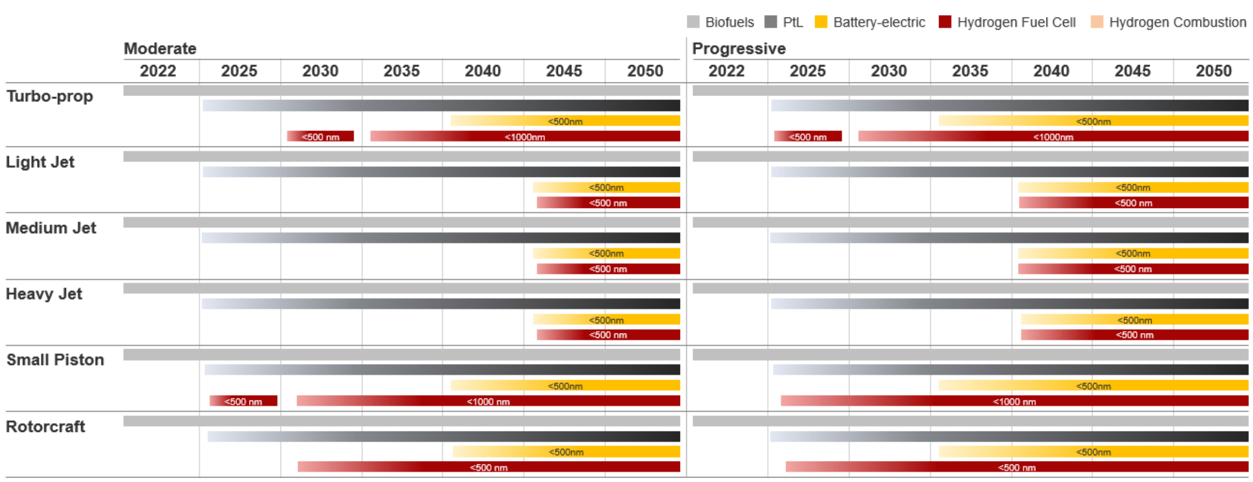


Exhibit 17: Projection of market entry and maximum range of general aviation aircraft

4.4 Climate impact of renewable fuels

Exhibit 18 shows the GHG emission reduction potential of all considered energy carriers, coupled with their respective propulsion systems. Exhibit 19 shows what emissions are in and out of scope for this study.

The emission reduction potential of biofuels largely depends on the used feedstock and the emissions from indirect land use change. Therefore, they show a broad range of potential GHG reduction values.

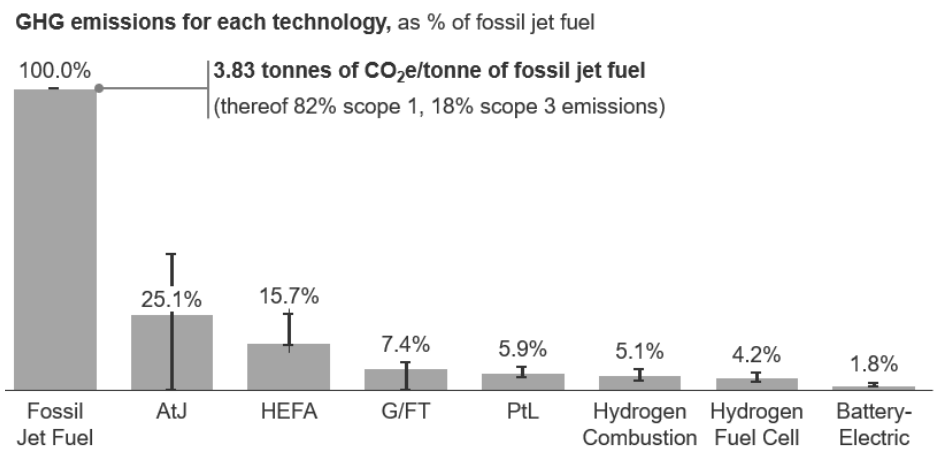


Exhibit 18: Emission reduction potential of SAFs, hydrogen and battery-electric aircraft following the emissions scope of Exhibit 19. The GHG emission reduction potentials of biofuels are taken from ICAO's CORSIA Eligible Fuels methodology as the median of all feedstock types excl. edible crops and those feedstocks that would entail an increase in emissions.[40] All values include the impact of indirect land use change (ILUC). The error bars correspond to the minimum and maximum CORSIA values. The GHG emission reduction potential of PtL, hydrogen and battery-electric aircraft is estimated using GHG emissions of renewable electricity generation[41] and fuel production efficiencies (Exhibit 20). The indicative figures in this graph do not necessarily represent real-world numbers which can differ depending on feedstock types, regional differences and technology advancements. Emission reduction factors could be smaller in the early applications of the fuels and reduce over time.

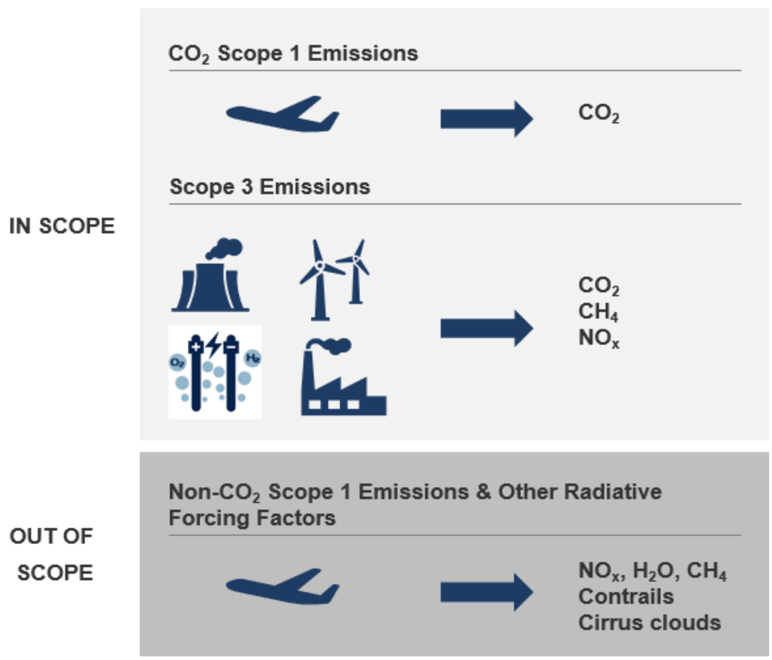


Exhibit 19: Scope of emissions in this study

Emissions from jet fuel span across the full value chain, from production and refining to combustion, and can be broken down into the following scopes:[42]

- Scope 1: This covers direct emissions from operations, and in the case of jet fuel includes emissions from fuel combustion. Emissions from the combustion of fuel are commonly referred to as “tank-to-wake” (TTW).
- Scope 2: This includes emissions from the electricity consumed by operations, and are considered negligible in the case of jet fuel.
- Scope 3 category 3: This scope accounts for emissions relating to the extraction, production, transportation and distribution of jet fuel and electricity consumed. This component is referred to as “well-to-tank” (WTT).

The model accounts for emissions from scope 1 (jet fuel combustion, TTW) and scope 3 category 3 (production and transport of jet fuel, WTT). This is in line with the Science-based target setting for the aviation sector.[6]

All emissions calculations account for GHG emissions of CO_2, CH_4, and N_2O from WTT activities (scope 3) and CO_2 emissions from TTW activities (scope 1). Following ICAO’s CORSIA methodology, GHG emissions of CH_4, N_2O, and H_2O from combustion are excluded.[43]

- The emissions of fossil jet fuel are based on CORSIA’s lifecycle assessment (LCA) methodology at 89g CO_2e/MJ, or 3.84 t CO_2e per tonne of jet fuel. From that, CO_2 emissions from fuel combustion amount to 3.16 t CO_2 per tonne of jet fuel, the rest being upstream GHG emissions.
- The abatement potential of biofuels includes the impact of indirect land use change (ILUC) as estimated by ICAO. However, the reduction potential is limited to 100% versus emissions of the fossil jet baseline, following SBTi guidance.
- The GHG emission reduction potential of PtL, hydrogen and battery-electric aircraft is estimated via GHG emissions of renewable electricity generation[41] and fuel production efficiencies (see indicative well-to-wake efficiency comparison in Exhibit 20).

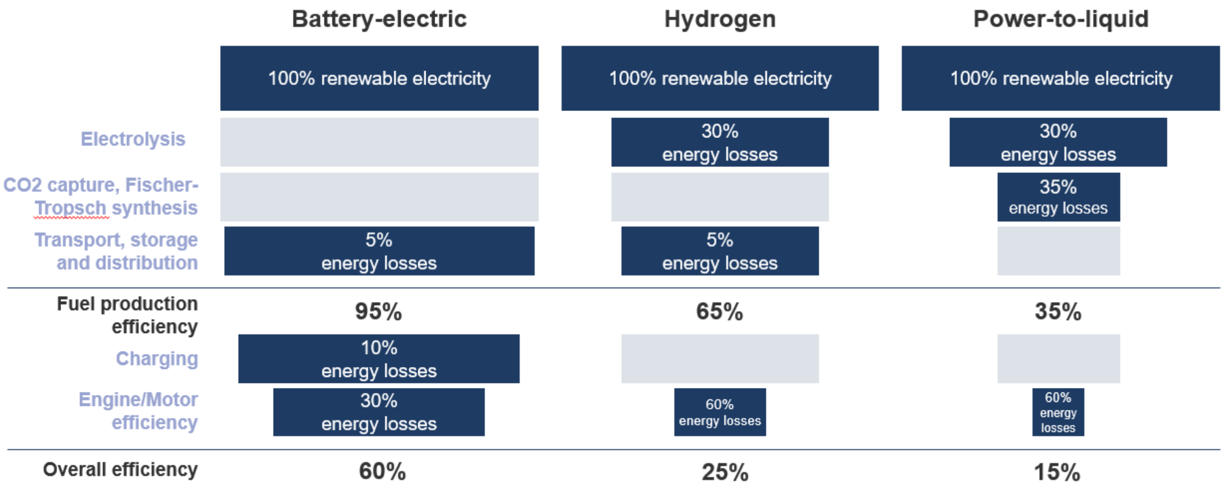


Exhibit 20: Indicative comparison of energy losses in the production and on-board use of electricity in battery-electric aircraft, and hydrogen or PtL in combustion turbines.

The model does not account for the effective radiative forcing (ERF) of non-CO_2 impacts from NOx, contrails, and cirrus clouds. They are, however, estimated to have significant impact: taking those effects into account, aviation could have a share of about 3.5% of the "net anthropogenic ERF."[5] The total climate impact of aviation is estimated to be roughly three times higher than that of CO_2 alone (however, subject to large uncertainties).

Currently, there is no standard way to include aviation induced cloudiness in net-zero pathway modelling. A mere multiplier on top of CO_2 emissions does not necessarily do justice to the complexity of this issue since the "use of a multiplier does not incentivise reductions of non-CO_2 emissions independently of CO_2 emissions",[44] More research is needed to reduce the uncertainties around the impact of short-lived climate forcers. First new concepts are already arising, like replacing a Global Warming Potential (GWP) with a new GWP* concept that better captures the impact of both long- and short-lived climate forcers, where normal GWPs fail.[45]

The role of non-CO_2 climate forcers in aviation

Fossil-based jet fuel contains aromatic hydrocarbons. When an aircraft burns fuel, its aromatic content produces aerosol particles (soot). Under certain atmospheric conditions, the soot can trigger ice nucleation (from the water in the aircraft's exhaust plume or the ambient air) and create contrails. From persistent contrails, cirrus clouds can form. This phenomenon is called *aviation induced cloudiness* and has a warming effect on the atmosphere.

Recent insights point towards a considerable reduction of aviation induced cloudiness through the use of certain SAF types, so called synthetic paraffinic kerosenes (SPKs), or hydrogen. This would not be the case for the continued use of fossil jet fuel, coupled with DACCS.

SPK does not consist of any aromatic hydrocarbons. Therefore, burning SPK produces drastically less soot particles compared with fossil jet fuel. As a consequence, ice crystal formation is reduced. As uncertainties are high around the exact reduction in aviation induced cloudiness when using SPK instead of fossil jet fuel, more research is required to quantify this effect.

Hydrogen aircraft do not emit particulate matter during flights, but emit more water. This could potentially lead to an increase in aviation induced cloudiness if the background particle concentration in the atmosphere is high. If the atmospheric particle concentration is low, aviation induced cloudiness could be reduced – all subject to high scientific uncertainties.

In contrast, there is more certainty about the positive climate impact hydrogen fuel cell and battery-electric aircraft can have: Both have the potential to largely omit any warming impact on the atmosphere during flight – battery-electric aircraft having no in-flight emissions and hydrogen fuel cell aircraft having the possibility of active water release management during flight, i.e. to store the exhaust water from the fuel cells on board and release it in batches as liquids rather than vapour, preventing contrails and cirrus cloud formation.

Besides this uncertain short-lived climate forcing, burning hydrogen in a combustion turbine produces NOx, whereas hydrogen fuel cell aircraft don't. Without any emissions during flight, battery-electric aircraft avoid 100% of aviation induced cloudiness.

Box 1: The role of non-CO_2 climate forcers in aviation, based on refs.[5,16,46–50]

5 Carbon dioxide removal (CDR) solutions

CDR solutions are needed to neutralise the final 5–10% of GHG emissions that cannot be mitigated by in-sector decarbonisation. They also need to counter-balance the warming impact of unmitigated short-lived climate forcers like aviation induced cloudiness (Box 1). CDR solutions include[51]

- Natural climate solutions (NCS): Restoring natural ecosystems (e.g. forests, peatlands) and better managing current use of land
- Hybrid solutions: Biochar (burning biomass in the absence of oxygen to slow decomposition) and bioenergy, carbon capture, and storage (BECCS, to produce energy from biomass and then capturing and storing the CO_2 produced)
- Engineered solutions: Direct air carbon capture and storage (DACCS)

CDR solutions will be required to close the emissions gap that remains even under ambitious sectoral decarbonisation scenarios. Globally, a 1.5°C carbon budget of 500 Gt CO_2 between 2020 and 2050 compares to cumulative emissions of 570–725 Gt CO_2 even under ambitious in-sector CO_2 reduction scenarios, leaving a gap of 70–225 Gt CO_2. This overshoot needs to be covered by CDR solutions, but the overall potential and in particular the short-term ramp-up of CDR solutions are limited. Scaling CDR to such levels will require current funding of <$10 bn/year to increase by a factor of 20 until 2030. On such a trajectory, CDR solutions could remove about 165 Gt CO_2 from the atmosphere between 2020 and 2050.[51] Over the next years, measurement and accounting of CDR solutions need to improve in a currently immature market.[52]

6 Model overview

As with any model, the approach taken in this report is an imperfect representation of the complex decision-making processes at play in the aviation sector. This report uses bottom-up modelling of individual aircraft flows and the introduction of decarbonisation levers to showcase pathways how the aviation sector could achieve net-zero GHG emissions by 2050 under the constraint of a 1.5°C carbon budget. It provides a perspective how the pathways change if you change the beliefs of future developments (of technology, demand, etc.), which are input assumptions to the model.

The model does not prescribe how the future will look like but rather provides multiple conceivable futures. Due to the uncertainty around the development of new technologies, the future availability of feedstocks, the future behaviour of corporate and private travellers, and the future decisions of policymakers, financial institutions and industry, this model is an imperfect representation of reality. It cannot reflect all regional varieties, for example that some business cases are exceptionally good for one location, and suboptimal for others (e.g., depending on the availability of renewable electricity, CO_2 point sources, etc.).

The model evaluates the business case for technology switches, constrained by achieving net-zero GHG emissions by 2050 and adhering to a 1.5°C carbon budget. Critically, it is not a market or full environment impact model: It does not consider the impact of different speeds of transition on trade flows between geographies, nor does it assess environmental impacts unrelated to GHG emissions. Exhibit 21 presents a simplified overview of the model structure, key inputs, constraints, the model/decision logic and outputs of the model, which are further explained below.

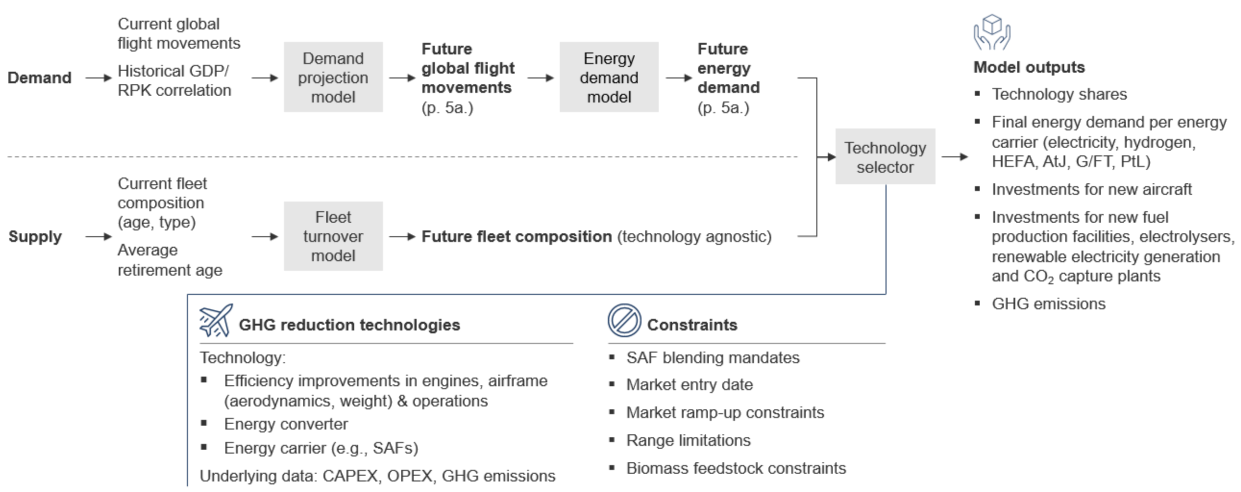


Exhibit 21: High-level model structure

A **demand model** forecasts future flight demand and energy required through 2050. Current flight movements and forecasts of Revenue Passenger Kilometres (RPKs) serve as inputs, and fleet fuel consumption information is used to project future energy demand in 2019-jet fuel equivalents (JFE). A demand of 1 tonne JFE in 2050 can be converted to the real final energy demand in 2050 by considering fuel efficiency gains between 2019 and 2050 and–in the case of novel propulsion aircraft–the difference in propulsion efficiency of a jet to e.g. a battery-electric aircraft. The demand model is detailed further in *Section 6.2 Demand model*.

In a **fleet turnover model**, aircraft are retired when they reach a certain age. New aircraft enter the fleet to replace retired aircraft and to cater to any demand increase. Our model estimates how demand will be met by supply for every year between 2019 and 2050. For new aircraft, the model selects a propulsion technology (jet turbine, hydrogen turbine, hydrogen fuel cell, or electric motor) and energy carrier (fossil jet fuel, SAFs, hydrogen or electricity). For new and existing aircraft, it updates the blending rate of SAFs at each increment. Assumptions are summarised in *Section 6.3 Fleet turnover model*.

The **technology selector model** selects technologies based on total costs of ownership, subject to several constraints and assumptions further described in *Section 6.4 Technology selector model.* In the case of the net-zero scenarios, a "green premium" is applied. In this case, 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. 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 when 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.

In a final postprocessing step, **sector-wide investment requirements** are estimated – including aircraft, fuel production and upstream feedstock supply capacity – as further described in *Section 6.5 Investment cost assumptions*.

Exhibit 22 provides the **model dimensions and granularity** across technologies, industry segments, aircraft categories, regions for flight movements, and aircraft stage lengths. Understanding the critical regional dimensions of the aviation sector's transition will be vital for industry players and policymakers alike.

Technologies	Industry segments	Aircraft categories	Regions for Flight Movements	Stage lengths
Fossil jet fuel	Commercial pax	Regional	Europe	< 500 NM
Biofuels:	Commercial cargo	Narrow-body	Asia	501 - 1000 NM
• HEFA	Public sector	Wide-body	North America	1001 - 1500 NM
• AtJ	General aviation	Small piston	South America	1051 - 2000 NM
• G/FT		Turboprop	Central America	> 2000 NM
E-fuel*		Light jet	Middle East	
Hydrogen:		Medium jet	Africa	
• Combustion turbine		Heavy jet	Australasia	
• Fuel cell		Fighters	Carribean	
Battery-electric propulsion		Rotorcraft		
		Trainer		
		Combat support		

***E-fuel:** PtL with PSC at 100% in 2019, being replaced by DAC towards 2050 via S-curve

Exhibit 22: Model dimensions (NM refers to nautical miles, 1 NM = 1.852 km)

6.1 Key assumptions and scenarios

The model is based on a number of underlying assumptions outlined in Exhibit 23 and further discussed in other sections of the appendix.

	Topic	Assumptions
General	Boundary of aviation emissions	Scope 1 and Scope 3 category 3 emissions (well-to-wake, WTW)
	Aviation demand growth rate[i]	• Impact of COVID modelled in line with IATA's assumption that global air travel will be back to 2019 levels by 2024[53] • 3.0% p.a. between 2024 and 2050 • The two assumptions above yield a CAGR of ~2.5% p.a. between 2019 and 2050

Decarbonisation levers	Investments considered	• Aircraft
		• Renewable energy carriers:
		  o Production of HEFA, other biofuels, and PtL
		  o CO_2 capture as feedstock for SAF production (only "renewable" if captured via DAC; PSC can support the initial ramp-up of PtL)
		  o Green hydrogen to power hydrogen aircraft and as feedstock for SAF production
		  o Renewable electricity to power battery-electric aircraft and SAF production
		• Airport infrastructure investments are required for hydrogen and battery electric aircraft, but only hydrogen is accounted for. Battery electric infrastructure is estimated at investment requirements of less than $2 billion and is not included.

Exhibit 23: Key assumptions

[i] Directionally in line with estimates from ATAG (2021) and ICAO (2022)[13,27]

The parameters of the model as shown in
Exhibit 24 are varied based on the different scenarios within the Aviation Transition Strategy.

	Business-as-Usual (BAU) Scenario	**Prudent scenario**	**Optimistic RE scenario**
Selection criterium for renewable energy carrier	Lowest total cost of ownership (TCO)	Lowest GHG-abatement costs emissions within defined green premium range	Lowest GHG emissions within defined green premium range
Green premium[ii]	No	Yes (37.5%)	Yes (25%)
Market entry and range of hydrogen and battery-electric propulsion systems	Moderate	Moderate	Progressive
Levelized cost of renewable electricity (LCOE)	Moderate	Moderate	Progressive
Green hydrogen costs	Moderate	Moderate	Progressive
HEFA technology costs	Assumed feedstocks are waste oils and lipids.		
Alcohol to Jet technology costs	Costs as average between cellulosic feedstock (forestry residues) and MSW		
Gasification/ Fischer-Tropsch technology costs	Costs as average between cellulosic feedstock (forestry residues) and MSW		
Power-to-liquids technology costs	Low-temperature electrolysis, point source capture of CO_2 in 2019, being fully replaced by direct air capture of CO_2 towards 2050 (see Exhibit 26)		

Exhibit 24: Key assumptions of MPP's Aviation Transition Strategy model

[ii] The green premium is defined on a total cost of ownership basis with a 15-year investment horizon.

6.2 Demand model

Exhibit 25 shows the jet fuel demand per modelled region in 2019 and corresponding growth rates between 2019 and 2050.

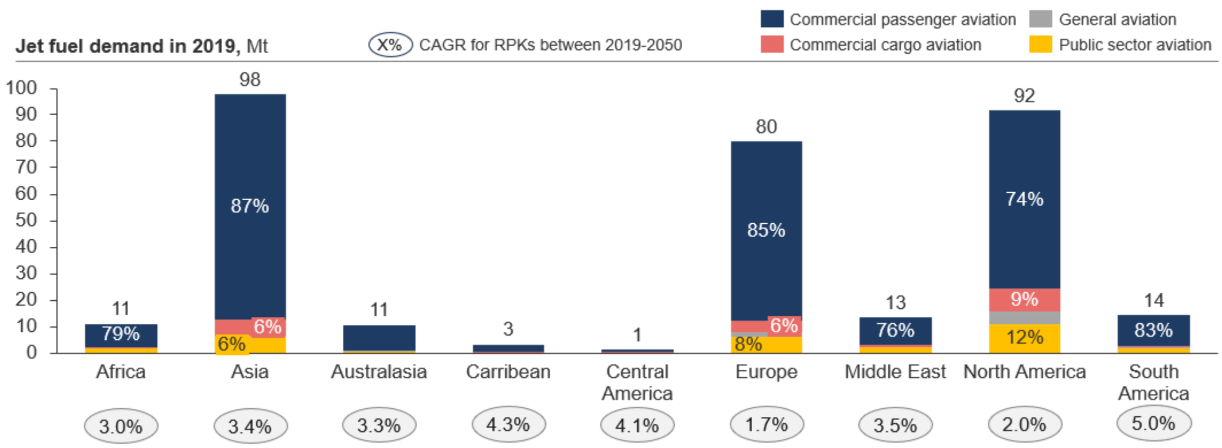


Exhibit 25: Energy demand of global aviation pre-COVID (2019) per region and CAGR projected for regions between 2019 and 2050

The demand model forecasts tonnes of 2019-jet fuel-equivalent (2019-JFE) required through 2050. For the commercial passenger model, the output is informed by forecasts of Revenue Passenger Kilometres (RPKs) through 2050 and uses fleet fuel consumption information to convert RPKs into jet fuel required:

- The model uses the 2019 IATA PaxIS RPK database.[54] The RPK data is broken down by region and by distance, and RPKs are accounted for as origin and destination pairs, irrespective of any intermediate stops.
- RPKs for 2019 are broken down into geographical flows and forecasted through 2050 by growing RPKs in tandem with GDP growth, based on historical regressions between GDP growth and RPK growth.
- Flows are further broken down by aircraft type, using LexisNexis and Cirium's DiioMi schedule data[55] and IATA's PaxIS data to calculate the share of aircraft family for each geographical flow. The energy required (in 2019 JFE) per aircraft family per stage length is then applied to forecast the jet fuel required for each flow, each stage length, and each aircraft family through 2050.

For the commercial cargo segment, the calculation is based on forecasts of Cargo Tonne Kilometres (CTKs) through 2050:

- Flightradar24 data[56] from 2019 is used as the basis for flight hours by aircraft type, region, and distance.
- IATA WATS cargo data[57] is leveraged to develop a linear relationship between hours flown and 2019 CTKs. The data also determine what percentage of CTKs were belly cargo (omitted), as opposed to dedicated freighters.
- CTKs are forecast with a regression of past CTK growth against historical GDP growth.

- Simultaneously, we calculate a linear relationship between CTKs and flight hours. The CTK forecasts are multiplied by CTK-flight hour ratios to ascertain the annual hour requirements for each aircraft type, geography, and distance. The hourly fuel requirements of each aircraft type is then applied to calculate the amount of jet fuel (2019-JFE) required up to 2050.

For General Aviation (GA), the model forecasts flight hours for each aircraft type through 2050 and uses proxy burn rates to determine the volume of jet fuel required:

- For light GA (piston/turboprop/helicopter), the model leverages various data points to triangulate the global fleet and mitigate the limited availability of data. For small piston aircraft, Flightradar24 data[56] and FAA data is used. Turboprop and Rotorcraft aircraft baselines are based on data sets from GAMA and BART.[58,59] Using FAA flight hours, the model estimates annual hours flown for each aircraft type and region.
- The business jets baseline uses ADS-B Radar Data from the WingX Advance database.[60] All 2019 jet movements in flight hours are grouped into regional flows, broken down by journey length and aircraft type. Flight hours for all aircraft families are multiplied by proxy burn rates, resulting in total 2019-JFE required.

For public sector aviation, the model utilizes a proprietary fleet forecast model and fuel proxies:

- Based on the AWIN (Aviation Week Intelligence Network[61]) forecast of military fleets through 2029, a relationship between GDP and fleet growth is derived. Percentage breakdowns of the current fleet are applied across each country and each aircraft type.
- To calibrate current fuel demand and usage rates, US government sources which report the jet fuel acquisitions of the US Military (2019 numbers) are compared with known US fleet numbers for 2019.
- By applying proxy burn rates, we derive annual fuel requirements for each aircraft type. This relationship, established for the US fleet, is applied as a proxy across regions to determine regional and global fuel demand for public sector aviation through 2050.

6.3 Fleet turnover model

- The model creates a technology-agnostic fleet projection for each five-year step, by each origin-destination region, aircraft category, and stage length.
- Aircraft retirement ages are assessed with a cumulative survival probability curve defined for each aircraft category as reported in Dray (2013).[62] The model assumes no early retirements.
- In each year, the model retires aircraft that reach retirement age and estimates the number of new aircraft needed to (a) fill the gap created by retired aircraft, and (b) meet increasing demand.

6.4 Technology selector model

The technology selection within the Aviation Transition Strategy model works as follows:

- After blending mandates and technology constraints are accounted for, the model selects the technology with the lowest GHG abatement costs from the list of technologies that are within the given maximum accepted green premium.
- This option is then deployed up to the level of market ramp-up constraints. These constraints represent a limit on a maximum year-to-year growth for each technology. The chosen technology is deployed up to these constraints, and any remaining demand to be filled is calculated. The model then selects the next-best technology option and the procedure is repeated.
- 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 when 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.

In the following, the used methodology for the total costs of ownership (TCO) calculation, market ramp-up constraints and modelled blending mandates are described.

Total Costs of Ownership (TCO)

- The TCO of each propulsion technology and associated energy carrier allows the model to optimize for lowest costs or GHG abatement costs under a given set of constraints.
- The TCO of aircraft operations are calculated across the different segments and aircraft types, for all energy carriers. It includes the required capital for new aircraft purchases, as well as fees, maintenance, crew costs, and fuel expenses.[iii]
  - The **capital cost** of aircraft is based on the annualised aircraft upfront investment, considering depreciation, residual value, interest, and insurance rates.
  - **Fees** include landing fees, departure fees, passenger departure and security fees, and terminal charges. Fees differ between technologies and are defined from a fossil propulsion baseline. Fees are adjusted to stage length and assumed to stay constant over time.
  - **Maintenance costs** differ between technologies, and are compared with maintenance costs of fossil propulsion, which serves as a baseline. Maintenance costs are adjusted to stage length and are assumed to stay constant over time.
  - **Crew costs** include flight attendants and pilots, and are known for different aircraft types today. For a given aircraft type, crew costs are assumed to stay constant across technologies, due to an expectation of similar levels of service – independent

[iii] As public sector aviation is not a well-documented segment, its operational costs are calculated in relative terms: fossil jet fuel propulsion is considered the baseline, to which costs for other technologies are compared.

of the aircraft type or propulsion system. Crew costs are adjusted to stage length and are assumed to stay constant over time.

- For **fuel costs**, the following assumptions have been made:

  - All renewable energy carriers are assumed to be produced from renewable electricity or sustainable biomass.

  - For PtL, the CO_2 source is either (1) industrial PSC, as an average between CO_2 capture appliances from power, cement, pulp & paper, biomass, and ethanol plants, based on cost data from the National Petroleum Council / the Gaffney Cline model[63], or (2) DAC, as an average between liquid and solid direct air capture of CO_2, based on cost data from the Coalition of Negative Emissions.[64] Both technologies are consolidated into a single cost for PtL by projecting a shift in technology penetration over time from PSC to DAC, which has been adapted from ref.[65] to achieve 100% of new-built CO_2 capture plants from DAC by 2050.

  - As cost proxies for the variety of sustainable biomass feedstocks, HEFA is assumed to be produced from used cooking oil, alcohol-to-jet from sugarcane bagasse, gasification Fischer-Tropsch is considered as an average between MSW gasification (available at no cost) and cellulosic gasification from forestry residues.

  - Fossil jet fuel and the related production and distribution infrastructure is considered commoditised, with the model only accounting for a feedstock market price. SAFs are assumed to use existing fossil distribution and refueling infrastructure.

  - For fuel production plants, operational expenditures (OPEX) include feedstock, utilities, operations, and maintenance costs, and differ between regions due to differing prices of feedstock and utilities. Capital expenditures (CAPEX) include production infrastructure and are assumed to be global.

- The TCO of all energy carriers and the related production infrastructure is calculated across the different segments and aircraft types, for all regions.

- TCOs are calculated using a discount factor of 8% and an investment horizon of 15 years.

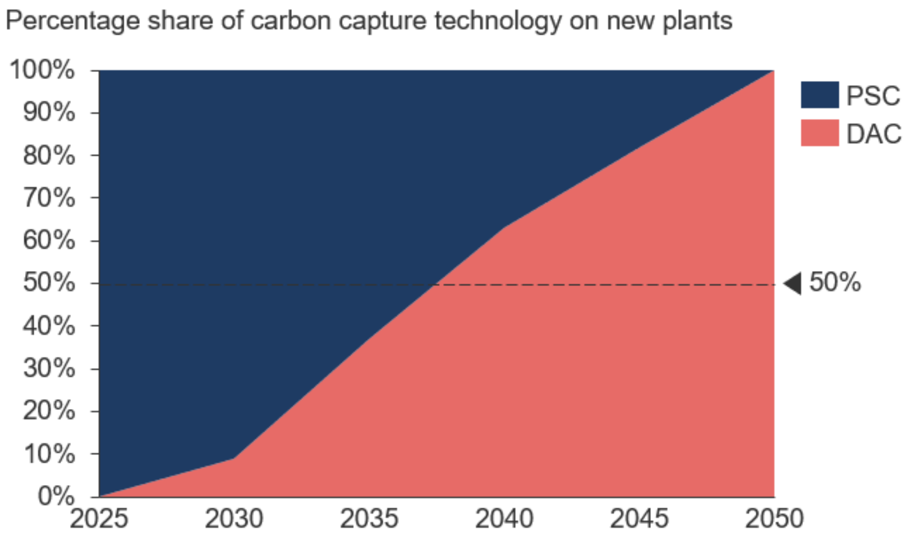


Exhibit 26: Technology mix of new-built carbon capture plants between 2025 and 2050. Point-source capture (PSC) of CO_2–e.g. at cement or natural gas plants–is used to scale up PtL production due to its lower costs compared with direct air capture (DAC). New-built CO_2 capture plants are increasingly DAC plants in the 2030s and 2040s due to the expected end date for large CO_2 emitters. Data adapted from ref.[65] to achieve 100% of new-built CO_2 capture plants from DAC by 2050.

Market ramp-up constraints

For new technologies entering the market for the first time, the model uses a “market kick-off" limit defined as the share the new technology can take of a market segment in its year of market introduction. In the BAU and PRU scenario, this initial market share (defined as percentage of total final energy demand) of a specific SAF type is capped at 1% in the PRU scenario. In the ORE scenario, this limit is set higher with 1.75%, enabling a faster market uptake of SAFs. For all scenarios, hydrogen and battery-electric aircraft are assumed to have a maximum initial market share of 0.5% in the PRU scenario and 1% in the ORE scenario. This limit is set lower for hydrogen and battery-electric aircraft, based on the assumption that airport infrastructure needs to be set up in addition to the fuel production and aircraft development, compared with just blending SAFs into existing aircraft.

After the market entry of new technologies, the model assumes a limit to maximum year-to-year ramp-up of 20% for a technology’s market share.

Government regulation

Within a recent publication by the Clean Skies for Tomorrow Initiative and the Energy Transitions Commission (the "SAF Policy Toolkit"[66]), policy options to increase the ramp-up of SAF demand and supply, while ensuring feedstock sustainability, are discussed. Currently, the two biggest demand signals from policy makers come from the *ReFuel EU Aviation* policy proposal of the European commission, envisaging a SAF blending mandate, and from the *SAF Grand Challenge* of the United States, aspiring SAF supply volumes by 2030 and 2050. We have included both in the two net-zero scenarios.

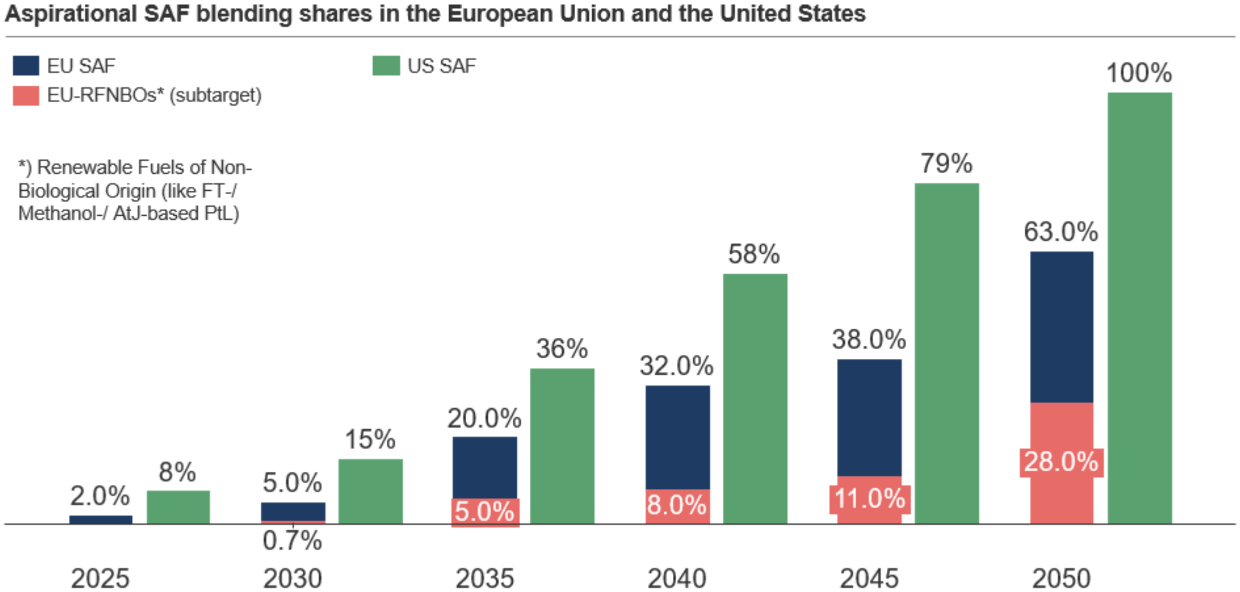


Exhibit 27: Proposed blending mandate from the European Commission in the EU[67] and intended SAF use from the SAF Grand Challenge in the US[68] as share of SAFs or PtL on total final jet fuel demand. SAF targets include all types of SAF. The RFNBO target is a subtarget specifying that a certain share of the overall SAF target needs to come from Renewable Fuels of Non-Biological Origin like PtL.

The European Commission has proposed blending mandates for SAFs in its *ReFuel EU Aviation* initiative,[69] with a minimum required quantity of biofuls and renewable fuels of non-biological origin (RFNBOs), RFNBOs would be reflected as PtL in the model. While these blending mandates are still to pass legislation within the European Parliament, we assume they will become mandatory and define them as lower limits for use of SAFs for flights departing from Europe.

For the US, the model implements their SAF Grand Challenge[29] to supply at least 3 billion gallons (9 Mt) of SAF a year by 2030 which represents about 15% of pre-COVID US jet fuel demand from airlines.[70] By 2050, the US aspires to supply 100% of their projected aviation fuel demand with SAFs. The targets are modelled similarly to EU mandates, ramping up linearly between 2022 and 2030 – and between 2030 and 2050.
In contrast to the blending mandate in the EU, the US SAF Grand Challenge is not strictly mandated and will therefore be complemented by SAF production incentives like the Blenders Tax Credit (BTC).[71]

6.5 Investment cost assumptions

The model offers a sector-wide view on investments required at certain points in time, both in terms of aircraft and energy carrier production:

- **New aircraft**: Upfront CAPEX for new conventional aircraft entering the market are available in industry databases for all segments, with the assumption that airframe constitutes 80% of the aircraft cost, while the propulsion turbine accounts for 20%.[iv] Low-carbon technologies are compared with fossil propulsion, which serves as a baseline. For parts of new propulsion technologies (e.g., H2 tank, battery), cost degressions are assumed over time due to learning rates.
- **Fuel production capacity**: Upfront CAPEX for fuel production plants are assumed to be constant across geographies but decrease over time as the available capacity and efficiency of plants increases.
- **Renewable electricity generation capacity**: Upfront CAPEX for new renewable electricity generation assets (e.g., solar PV, or wind off-/onshore parks) are based on the renewable electricity requirements of biofuels, PtL and hydrogen production, as well as battery-electric aircraft. Regional investment requirements are modelled for either dedicated variable renewable electricity plants or power purchase agreements (PPAs).
- **Electrolyser capacity**: Upfront CAPEX for green hydrogen production plants are based on the hydrogen required for PtL production, hydrogen aircraft and hydrocracking of biofuels. Regional investment requirements are modelled for low-temperature electrolysers.
- **CO_2 capture capacity**: Upfront CAPEX for CO_2 capture plants changes over time according to the ratio between PSC and DAC (Exhibit 26).
- Investment requirements for additional fossil fuel infrastructure are not included.

[iv] Based on average costs of regional/single aisle airframes & turbines. Airframe costs are based on "The Aircraft Value Reference", Apr 30th 2021 Issue 58.1 Turboprops / Issue 60, 2020; turbine costs on TEAL group analysis[72]

7 The 1.5°C carbon budget

Exhibit 28 documents how the carbon budget to limit global warming to 1.5°C with a probability of 50% has been derived for all MPP sectors. The IPCC's carbon budget of 580 Gt CO_2[73] from the beginning of 2018 has been updated to about 500 Gt CO_2 from the beginning of 2020.

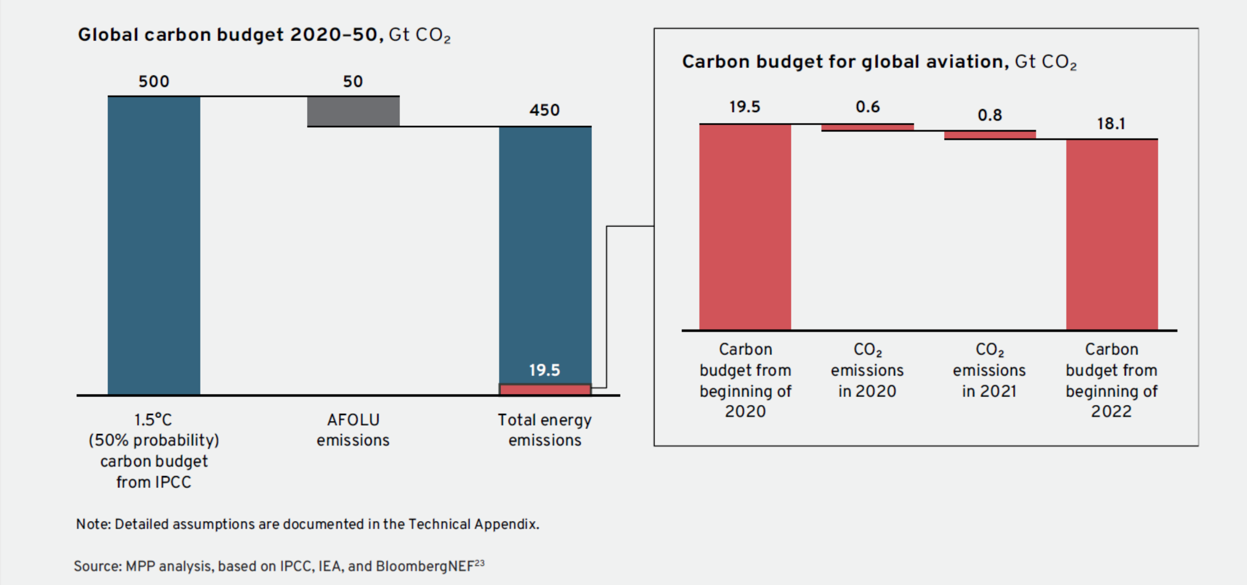


Exhibit 28: Allocation of global carbon budget to limit global warming to 1.5°C to the aviation sector.

7.1 Assumptions on AFOLU emissions

Based on Roe et al. (2019)[74] and ETC analysis, 50 Gt CO_2 have been subtracted to account for the cumulative net anthropogenic emissions between 2020 and 2050 from Agriculture, Forestry, and Other Land Use (AFOLU). This scenario assumes a rapid and steep end to deforestation with 90% reduction in emissions from deforestation by 2030 and 95% by 2050. In addition, it assumes a 65% reduction in process emissions from agriculture by 2030 and a 50% shift towards plant-dominant diets by 2050, in line with the recommendations of the EAT-Lancet Review (2019)[75]. Emissions figures include net human-driven land use change but do not include the terrestrial sink or CDR through restoration efforts.

7.2 Sectoral allocation of energy-related carbon budget

The sectoral allocation is defined by the average of the cumulative emissions of aviation in IEA NZE and BloombergNEF NEO.[2,76] The following assumptions have been made:

- For IEA NZE, scope 2 emissions were estimated by each subsector's share in total industry or transport scope 1 emissions.
- For NEO, scope 2 emissions were estimated from final electricity consumption multiplied by carbon intensity of grid electricity.
- For IEA NZE, a return to pre-COVID emissions until 2024 was assumed according to IATA[53] and the remaining emissions data was interpolated linearly between the given years.

Based on this methodology, the 1.5°C carbon budget for global aviation from the beginning of 2020 amounted to about roughly 19.5 Gt CO_2. Subtracting the CO_2 emissions from global aviation in 2020 and 2021 leaves a remaining carbon budget from the beginning of 2022 of about 18 Gt CO_2. Given the variety of different methodologies to allocate a global carbon budget to individual sectors and the inherent uncertainty around the global carbon budget itself, the 18 Gt CO_2 should be understood as an indicative point of reference, not as a precise single truth.

8 The cost of inaction

Carbon emissions cause an economic damage that is currently not internalized in the use of fossil fuels. The so-called social cost of carbon (SCC) quantifies this economic damage. In a 2018 study, the SCC has been estimated to be $417 (177–805) per tonne of CO_2.[77]

However, there is mounting scientific evidence that inaction on climate change will be even more expensive than decarbonising our economies, with a new 2021 study suggesting social costs of carbon of over $3,000 per tonne of CO_2.[78,79] Large uncertainties exist around the impact of climate change on long-term economic growth "and how far societies can adapt to reduce these damages; depending on how much growth is affected, the economic costs of warming this century could be up to 51% of global GDP."[78]

Using the SCC estimates above, the cumulative investments of $5 trillion required for transitioning global aviation to net zero compare to a social cost of carbon of $9 (4–18) trillion if the sector were to be unmitigated until 2050. This is based upon the SCC values of the 2018 study. Using the 2021 study's estimates, this number could be as high as $66 trillion.

From a socio-economic perspective, the upsides of the transition outweigh its cost; decarbonising aviation would have a net-positive financial impact on the global economy. Despite all uncertainties inherent to such estimates, this comparison indicates that inaction is not an option: regarding climate change, in terms of long-term economic growth[79] as well as with regards to pollution and human health[80]. Human well-being will benefit from decisive action in terms of all these aspects.

Endnotes

1. ATAG. Aviation: Benefits Beyond Borders. https://aviationbenefits.org/media/167517/aw-oct-final-atag_abbb-2020-publication-digital.pdf (2020).
2. IEA. *Net Zero by 2050 - A Roadmap for the Global Energy Sector*. 224 (2021).
3. Ritchie, H. & Roser, M. CO_2 and Greenhouse Gas Emissions. *Our World in Data* https://ourworldindata.org/co2-and-other-greenhouse-gas-emissions (2020).
4. Ritchie, H. Climate change and flying: what share of global CO2 emissions come from aviation? *Our World in Data* https://ourworldindata.org/co2-emissions-from-aviation.
5. Lee, D. S. *et al.* The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018. *Atmospheric Environment* **244**, 117834 (2021).
6. SBTi. Science-based target setting for the Aviation Sector: Version 1.0. (2021).
7. ICAO. Environmental Protection: Climate Change. https://www.icao.int/environmental-protection/pages/climate-change.aspx (2021).
8. ICAO. *2019 Environmental Report: Aviation and Environment - Destination Green: The Next Chapter*. (2019).
9. ICCT. *Standards to promote airline fuel efficiency*. https://theicct.org/wp-content/uploads/2021/06/Airline-fuel-efficiency-standard-2020.pdf (2020).
10. International Transport Forum (ITF) & OECD. *Decarbonising Air Transport: Acting Now for the Future*. https://www.itf-oecd.org/sites/default/files/docs/decarbonising-air-transport-future.pdf (2021).
11. Schäfer, A. W., Evans, A. D., Reynolds, T. G. & Dray, L. Costs of mitigating CO2 emissions from passenger aircraft. *Nature Clim Change* **6**, 412–417 (2016).
12. AIA & accenture. *Horizon 2050: A Flight Plan for the Future of Sustainable Aviation*. (2022).
13. ICAO. *Report on the Feasibility of a Long-Term Aspirational Goal (LTAG) for International Civil Aviation CO2 Emission Reductions*. https://www.icao.int/environmental-

protection/LTAG/Documents/REPORT%20ON%20THE%20FEASIBILITY%20OF%20A%20LONG-TERM%20ASPIRATIONAL%20GOAL_en.pdf (2022).

14. BloombergNEF. *New Energy Outlook 2021*. (2021).
15. BloombergNEF. *New Energy Outlook 2020 - Executive Summary*. https://assets.bbhub.io/professional/sites/24/928908_NEO2020-Executive-Summary.pdf (2020).
16. IATA. *Fact Sheet 2: Sustainable Aviation Fuel: Technical Certification*. 3 https://www.iata.org/contentassets/d13875e9ed784f75bac90f000760e998/saf-technical-certifications.pdf (2021).
17. Rolls-Royce. Press release: Accelerating the transition of long-haul aviation towards net zero. https://www.rolls-royce.com/media/press-releases.aspx (2021).
18. The Boeing Company. Aviation Industry Chief Technology Officers Issue Joint Call to Action to Deliver Sustainable Aviation Plans. 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 (2021).
19. The Boeing Company. Boeing Commits to Deliver Commercial Airplanes Ready to Fly on 100% Sustainable Fuels. *MediaRoom* https://boeing.mediaroom.com/2021-01-22-Boeing-Commits-to-Deliver-Commercial-Airplanes-Ready-to-Fly-on-100-Sustainable-Fuels (2021).
20. GreenAir News. Embraer’s aviation flight to net zero includes making its current aircraft portfolio 100% SAF capable. https://www.greenairnews.com/?p=1505 (2021).
21. Clean Skies for Tomorrow Initiative (CST), World Economic Forum & McKinsey & Company. *Clean Skies for Tomorrow: Sustainable Aviation Fuels as a Pathway to Net-Zero Aviation*. https://www3.weforum.org/docs/WEF_Clean_Skies_Tomorrow_SAF_Analytics_2020.pdf (2020).
22. Schäppi, R. *et al.* Drop-in fuels from sunlight and air. *Nature* **601**, 63–68 (2022).
23. Energy Transitions Commission (ETC). *Bioresources within a Net-Zero Emissions Economy: Making a Sustainable Approach Possible*. https://www.energy-transitions.org/wp-content/uploads/2021/07/ETC-bio-Report-v2.5-lo-res.pdf (2021).
24. Energy Transitions Commission (ETC). *Making the Hydrogen Economy Possible: Accelerating Clean Hydrogen in an Electrified Economy*. https://energy-transitions.org/wp-content/uploads/2021/04/ETC-Global-Hydrogen-Report.pdf (2021).
25. Heraeus & SFA Oxford. *Paladium Standard 2020*.
26. IRENA. *Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5^{0}C Climate Goal*. (International Renewable Energy Agency, 2020).
27. ATAG. *Waypoint 2050*. https://aviationbenefits.org/media/167417/w2050_v2021_27sept_full.pdf (2021).

28. IATA. Developing Sustainable Aviation Fuel (SAF). https://www.iata.org/en/programs/environment/sustainable-aviation-fuels/ (2021).
29. The White House. FACT SHEET: Biden Administration Advances the Future of Sustainable Fuels in American Aviation. (2021).
30. Shell. Shell calls for more action on aviation emissions and announces ambition to produce around 2 million tonnes of sustainable aviation fuel a year | Shell Global. https://www.shell.com/business-customers/aviation/news-and-media-releases/news-and-media-2021/shell-calls-for-more-action-on-aviation-emissions.html (2021).
31. Argus. Global SAF capacity Map. (2022).
32. Danish Energy Agency and Energinet. *Technology Data Renewable fuels*. https://ens.dk/sites/ens.dk/files/Analyser/technology_data_for_renewable_fuels.pdf.
33. Holmgren, K. *Investment cost estimates for gasification based biofuel production systems*.
34. Suresh, P. *et al.* Life Cycle Greenhouse Gas Emissions and Costs of Production of Diesel and Jet Fuel from Municipal Solid Waste. *Environ. Sci. Technol.* **52**, 12055–12065 (2018).
35. ACI. *Integration of Hydrogen Aircraft into the Air Transport System*. https://www.ati.org.uk/wp-content/uploads/2021/08/aci-ati-hydrogen-report-1.pdf.
36. Nguyen, T. Batteries Need a Boost To Fly the Friendly Skies. *ACS Cent. Sci.* **5**, 1738–1740 (2019).
37. Bills, A., Sripad, S., Fredericks, W. L., Singh, M. & Viswanathan, V. Performance Metrics Required of Next-Generation Batteries to Electrify Commercial Aircraft. *ACS Energy Lett.* **5**, 663–668 (2020).
38. Stolz, B., Held, M., Georges, G. & Boulouchos, K. Techno-economic analysis of renewable fuels for ships carrying bulk cargo in Europe. *Nat Energy* 1–10 (2022) doi:10.1038/s41560-021-00957-9.
39. ICCT. *CO2 emissions from commercial aviation: 2013, 2018, and 2019*. 36 (2020).
40. ICAO. CORSIA Default Life Cycle Emissions Values for CORSIA Eligible Fuels. (2021).
41. IPCC. *Climate Change 2014 Mitigation of Climate Change: Working Group III - Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change - Annex III: Technology-specific Cost and Performance Parameters*. (Cambridge University Press, 2014). doi:10.1017/CBO9781107415416.
42. Rutherford, D. *et al.* Science-based target setting for the Aviation Sector.
43. ICAO. CORSIA Eligible Fuels – Life Cycle Assessment Methodology. (2019).
44. EASA. *Updated analysis of the non-CO2 climate impacts of aviation and potential policy measures pursuant to the EU Emissions Trading System Directive Article 30(4)*. https://eur-lex.europa.eu/resource.html?uri=cellar:7bc666c9-2d9c-11eb-b27b-01aa75ed71a1.0001.02/DOC_1&format=PDF (2020).
45. Allen, M. R. *et al.* A solution to the misrepresentations of CO2-equivalent emissions of short-lived climate pollutants under ambitious mitigation. *npj Clim Atmos Sci* **1**, 1–8 (2018).

46. McKinsey, Clean Sky 2 JU, & FCH 2 JU. *Hydrogen-powered aviation: A fact-based study of hydrogen technology, economics, and climate impact by 2050*. https://www.fch.europa.eu/sites/default/files/FCH%20Docs/20200720_Hydrogen%20Powered%20Aviation%20report_FINAL%20web.pdf (2020).
47. Voigt, C. *et al.* Cleaner burning aviation fuels can reduce contrail cloudiness. *Communications earth & environment* **2**, (2021).
48. Klöwer, M. *et al.* Quantifying aviation's contribution to global warming. *Environ. Res. Lett.* **16**, 104027 (2021).
49. European Commission. *Updated analysis of the non-CO2 climate impacts of aviation and potential policy measures pursuant to EU Emissions Trading System Directive Article 30(4)*. https://eur-lex.europa.eu/resource.html?uri=cellar:7bc666c9-2d9c-11eb-b27b-01aa75ed71a1.0001.02/DOC_1&format=PDF (2020).
50. Kärcher, B. Formation and radiative forcing of contrail cirrus. *Nat Commun* **9**, 1824 (2018).
51. Energy Transitions Commission. *Mind the Gap: How Carbon Dioxide Removals Must Complement Deep Decarbonisation to Keep 1.5°C Alive*. https://www.energy-transitions.org/wp-content/uploads/2022/03/ETC-CDR-Report-Mind-the-Gap.pdf (2022).
52. Joppa, L. *et al.* Microsoft's million-tonne CO2-removal purchase - lessons for net zero. *Nature* **597**, 629–632 (2021).
53. IATA. *20-year Air Passenger Forecast Infographic: Current Trends*. https://www.iata.org/contentassets/fe5b20e8aae147c290fc4880f120c969/4679_passenger-forecast-infographic-update_v2.pdf (2021).
54. IATA. Passenger Intelligence Services (PaxIS). https://www.iata.org/en/services/statistics/intelligence/paxis/ (2021).
55. Cirium. Diio Mi. *Cirium* https://www.cirium.com/products/views/diio-mi/ (2021).
56. Flightradar24. Corporate Website. https://www.flightradar24.com/ (2022).
57. IATA. World Air Transport Statistics. https://www.iata.org/en/publications/store/world-air-transport-statistics/ (2021).
58. Gama Aviation. Corporate Website. *Gama Aviation* https://www.gamaaviation.com/ (2021).
59. Seagil Software Company. Business Aircraft Records & Tracking (BART). *BART Seagil Software* https://seagilbart.com/ (2021).
60. WingX Advance. WingX Advance Webpage. https://wingx-advance.com/ (2021).
61. Aviation Week. *AWIN 2021 MRO and Military Forecast*. https://aviationweek.com/awin-knowledge-center/2021-military-fleet-mro-forecast (2021).

62. Dray, L. M. An analysis of the impact of aircraft lifecycles on aviation emissions mitigation policies. *Journal of Air Transport Management* **28**, 62–69 (2013).
63. National Petroleum Council (NPC). Capture Facility Reference Costs (Gaffney Cline Model). https://www.gaffneycline.com/calculator/npc-scenarios-table.
64. Coalition for Negative Emissions. *The Case for Negative Emissions: A call for immediate action.* https://coalitionfornegativeemissions.org/wp-content/uploads/2021/06/The-Case-for-Negative-Emissions-Coalition-for-Negative-Emissions-report-FINAL-2021-06-30.pdf (2021).
65. Breyer, C. & Crone, K. Powerfuels in a Renewable Energy World. (2020).
66. Clean Skies for Tomorrow Initiative (CST), World Economic Forum, Energy Transitions Commission (ETC) & Mission Possible Partnership (MPP). *Clean Skies for Tomorrow: Sustainable Aviation Fuel Policy Toolkit*. https://www.energy-transitions.org/wp-content/uploads/2021/11/Clean_Skies_for_Tomorrow_Sustainable_Aviation_Fuel_Policy_Toolkit_2021.pdf (2021).
67. European Commission. *Proposal for a Regulation on ensuring a level playing field for sustainable air transport*. *COM(2021) 561 final* (2021).
68. The White House. Fact Sheet: Biden Administration Advances the Future of Sustainable Fuels in American Aviation. *The White House* https://www.whitehouse.gov/briefing-room/statements-releases/2021/09/09/fact-sheet-biden-administration-advances-the-future-of-sustainable-fuels-in-american-aviation/ (2021).
69. European Commission. Proposal for a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on ensuring a level playing field for sustainable air transport. (2021).
70. Statista. Total fuel consumption of U.S. airlines 2004-2020. *Statista* https://www.statista.com/statistics/197690/us-airline-fuel-consumption-since-2004/ (2021).
71. Brandt, K. L., Martinez-Valencia, L. & Wolcott, M. P. Cumulative Impact of Federal and State Policy on Minimum Selling Price of Sustainable Aviation Fuel. *Frontiers in Energy Research* **10**, (2022).
72. TEAL Group Corporation. Corporate Website. https://www.tealgroup.com/ (2021).
73. 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* (Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.), 2018).
74. Roe, S. *et al.* Contribution of the land sector to a 1.5 °C world. *Nature Climate Change* **9**, (2019).

75. EAT-Lancet Commission. Food Planet Health: Healthy Diets From Sustainable Food Systems. https://eatforum.org/content/uploads/2019/01/EAT-Lancet_Commission_Summary_Report.pdf (2019).
76. BloombergNEF. NEO 2021 Executive Summary. 16 (2021).
77. Ricke, K., Drouet, L., Caldeira, K. & Tavoni, M. Country-level social cost of carbon. *Nature Clim Change* **8**, 895–900 (2018).
78. University College London. Economic cost of climate change could be six times higher than previously thought. https://phys.org/news/2021-09-economic-climate-higher-previously-thought.html (2021).
79. Kikstra, J. S. *et al.* The social cost of carbon dioxide under climate-economy feedbacks and temperature variability. *Environ. Res. Lett.* **16**, 094037 (2021).
80. Shindell, D. *et al.* Temporal and spatial distribution of health, labor, and crop benefits of climate change mitigation in the United States. *PNAS* **118**, (2021).