Technologies and fuels for decarbonising global aviation — the opportunities and challenges

This article provides a summary of a recent study undertaken on behalf of Concawe to investigate the challenges faced by the aviation industry when trying to reduce CO_2 emissions. The study explored the options available to reduce emissions, including improvements in aircraft technology and the use of alternative aviation fuels, and a modelling approach was used to determine which options would be required to achieve future emissions targets under a range of scenarios.

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Introduction

In 2019, the global aviation industry consumed around 363 billion litres of jet fuel and was responsible for 914 $MtCO_2$ in direct emissions.[1,2] Passenger aviation, including aircraft carrying belly freight, accounted for 92% of these emissions, with the remaining 8% being attributable to freighter flights.[3] If future fuel use and emissions growth is only half the historical (1980–2019) rate of 2.8% per year, global aviation fuel demand and CO_2 emissions would increase by around 50% by 2050.

In 2009, the International Air Transport Association (IATA) — the aviation industry's trade body — set a sector target of reducing CO_2 emissions by 50% by 2050, compared to 2005 levels. Such drastic abatement requires a radical transformation of the entire aviation sector, affecting each determinant of CO_2 emissions. This article and the associated report illustrate how such strong reductions could be achieved, along with the implications for stakeholders of the aviation value chain, particularly the fuels industry.

Strong demand growth

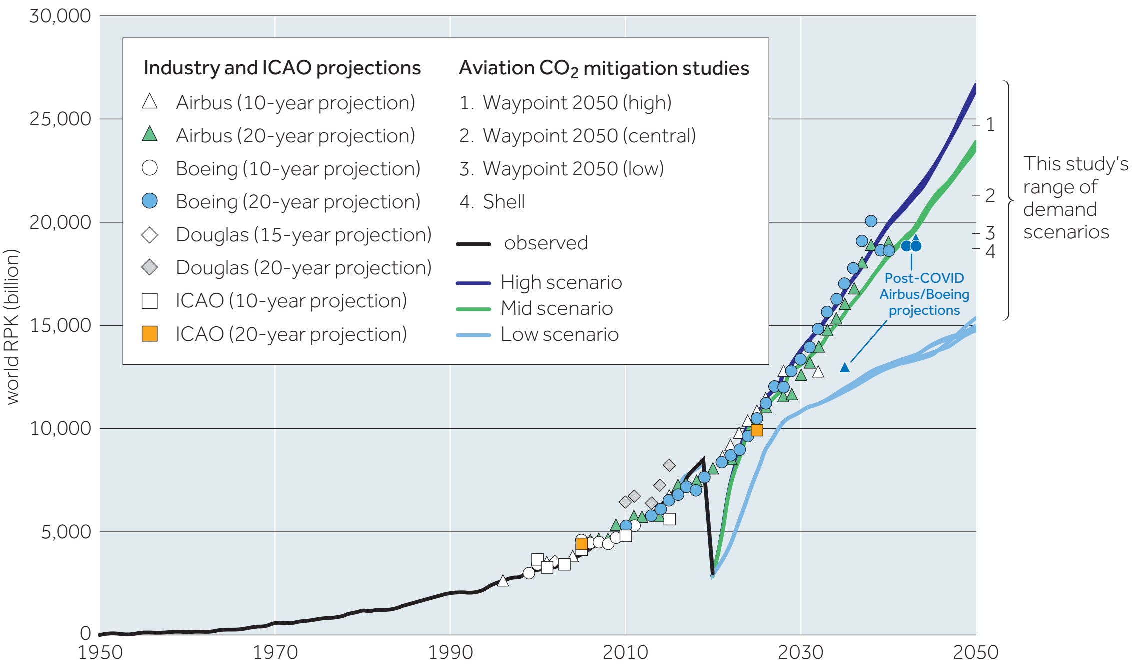
Historical aviation growth has mainly been the result of income growth, followed by declining airfares and the growing population.

Figure 1 on page 49 depicts the study's range of demand scenarios, which span a larger range compared to demand scenarios considered in the Waypoint 2050 study[4] and a study undertaken by Shell. Each utilises different global scenarios for income, population and energy prices, leading to a 'High' scenario (dark blue curve) which implies that demand growth will return to pre-COVID-19 growth rates, a 'Mid' scenario (green curve) where growth rates are close to post-COVID-19 industry projections, and a 'Low' scenario (light blue line) where growth rates diverge from historical trends.

These differences are driven mainly by differences in income growth between the scenarios, which are derived from the IPCC's[1] Shared Socioeconomic Pathways (SSP) scenarios;[5] for the Low scenario, demand growth is additionally assumed to decouple from income growth due to ongoing changes in attitudes to aviation.

Figure 1: World revenue passenger-kilometres travelled (RPK), observed (black continuous line), and projections by industry and ICAO[2] (symbols) and this study (coloured continuous lines).

Adapted from Schäfer and Waitz, 2014.[6]



Long time constants

Developing a new aircraft is a long (10–20 years) and capital-intensive (USD 20–30 billion) process. In light of the roughly 15 years development time for a new aircraft model, the four reference aircraft considered in this study, with entry-into-service dates between 2011 and 2017, are likely to represent two successive generations, one in 2030–35 and another one in 2045–50.

The average operating lifetime of today's commercial aircraft — the time span by which 50% of an aircraft cohort is retired — is about 30 years.[7,8] This implies that around half of those aircraft introduced today will still be operating in 2050. Combined, these long time constants mean that the time between identifying promising concept technology bundles and their significant market impact is around 40–50 years.

[1] Intergovernmental Panel on Climate Change

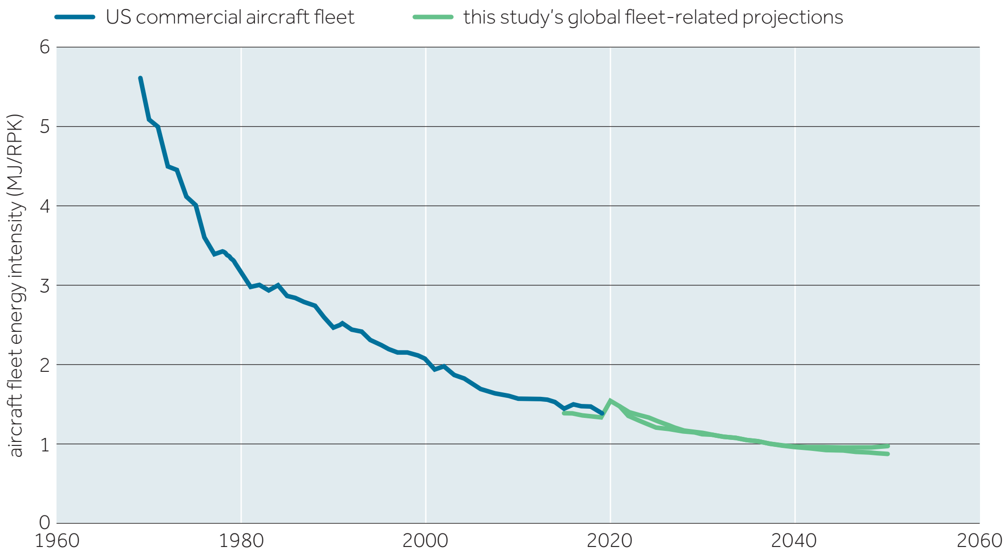
[2] International Civil Aviation Organization

Fuel efficiency improvements

Overall, the energy intensity of the US aircraft fleet has declined from 5.6 MJ per RPK in 1969 to 1.4 MJ per RPK in 2019, a 75% reduction which translates into an average of 2.7% per year. As the life-cycle CO_2 intensity of jet fuel has historically remained largely unchanged, the depicted decline in aircraft fleet energy intensity corresponds with a decline in CO_2 intensity.

Figure 2: Historical trend in aircraft fleet energy intensity, US (1969–2019) and global projections (2020–2050)

Data source: Lee *et al.*, 2001 and US Form 41[9]



Technologies and fuels

Aircraft technologies

Three key factors affect aircraft range and energy use, and are captured in the Breguet range equation: the aircraft lift-to-drag ratio or aerodynamic efficiency; engine-specific fuel consumption or the amount of fuel burnt per unit of thrust; and the empty weight of the aircraft. The higher the lift-to-drag ratio, the lower the engine-specific fuel consumption, and the lower the empty weight of the aircraft, the lower the aircraft energy intensity.

The menu of options for reducing aircraft fuel burn consists of:

- airframe-related technologies, which directly address the lift-to-drag ratio, aircraft drag or aircraft empty weight;
- engine-related technologies, which aim to increase engine efficiency;
- fuel-related technologies that reduce aircraft CO_2 emissions directly;
- air traffic management-related technologies that improve flight procedures; and
- operational technologies and techniques, i.e. measures that the airlines themselves can apply when operating their fleet in the air and on the ground.

As shown in Table 1, this study uses four reference aircraft to assess technology characteristics, jointly covering all major market segments. Aircraft with year-2000 technology form the basis of this classification. The 2015 aircraft types were modelled based on available data about specific aircraft model performance and costs in each size class for this generation (e.g. Airbus A320neo; see the full study report for tables of assumptions for these aircraft).

Table 1: Reference aircraft and projected fuel burn reductions compared with year-2000 performance

Market segment	Representative aircraft for year 2000 (2015)	Seat count	Average stage length (nm)[a]	% fuel burn change compared with year-2000 technology, EIS[b]	
				2030–35	2045–50
Regional	E190-E2	98	500	-28.6	-35.5
Short haul	A320-200 (A320neo)	150	1,000	-30.4	-38.3
Medium hall	A330-300 (B787-9)	295	3,500	-23.6	-57.0
Long hall	B777-300ER (A350-1000)	368	4,500	-25.7	-52.5

[a] nm = nautical miles; 1 nm = 1,852 km
[b] EIS = entry into service

The fuel burn reductions for the next (2030–2035) aircraft generation are similar across all aircraft types, as they build upon similar technologies. In contrast, the generation after next (2045–2050) rely on different technologies particularly between the two smaller and the two larger aircraft size classes, which leads to marked differences in fuel burn reduction.

Alternative aviation fuels

These alternatives can be categorised as drop-in liquid fuels and non-drop-in fuels. Drop-in fuels have similar properties to fossil jet fuel, meaning that no significant modifications to existing infrastructure, aircraft and engines are required. On the other hand, uptake of non-drop-in fuels will require significant modifications and investment.

Drop-in fuels

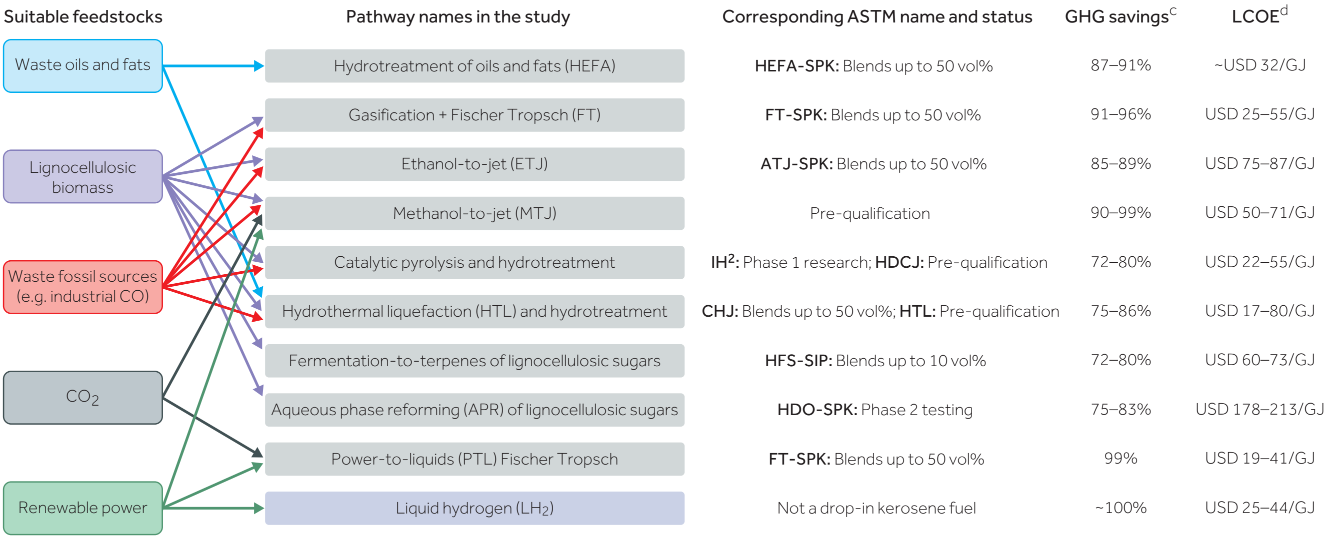
Drop-in sustainable aviation fuels (SAFs) are produced from renewable feedstocks, including biomass and renewable hydrogen, as well as recycled waste fossil carbon (if it leads to sufficient CO_2 emissions reduction), and have a similar composition and performance to that of fossil jet fuel.

Currently, most SAF technology pathways are at an early stage of development, with HEFA[3] the only commercialised route. Nonetheless, a number of routes are already certified under ASTM International's D7566 standard (D1655 for co-processed fuels), which are highlighted in Figure 3 on page 52.

[3] Hydroprocessed esters and fatty acids

Figure 3: Schematic of the alternative aviation fuels considered in this analysis

(GHG savings are given relative to the CORSIA[a] benchmark. LCOE[b] represents production costs, in 2020 USD)



[a] Carbon Offsetting and Reduction Scheme for International Aviation [b] Levelised cost of electricity

[c] Compared to the fossil jet benchmark of 89 $g/CO_2eq/MJ$ [d] LCOE cost ranges between 2025–2050; some pathway variation based on feedstock used

Figure 3 provides an estimate of the range of levelised costs of production for the different fuel routes between 2025 and 2050.[10,11,12,13] Due to the early stage of development of these routes, the production costs of alternative aviation fuels are much higher than fossil jet prices. Over time, the production costs will decrease, owing to scale-up efficiencies and process improvements. Furthermore, routes which rely on renewable electricity — PTL-FT,[4] liquid hydrogen and e-methanol-to-jet — might see a dramatic reduction in feedstock cost as the availability of low-cost renewable power increases. Nonetheless, some routes will remain expensive in 2050, and will likely require policies that support the uptake of alternative aviation fuels in order to effectively penetrate into the fuel mix.

Non-drop-in fuels

There is scope for the use of liquid hydrogen as an aviation fuel (in contrast to liquefied natural gas (LNG) and electrification). Although significant infrastructure and aircraft modifications would be required, many industries are investigating hydrogen supply chains and technologies, which could accelerate development. Hydrogen production costs from renewable energy are projected to decrease from ~28–63 USD/GJ in 2019 to ~10–28 USD/GJ in 2050.[14]

[4] Power-to-liquids via Fischer Tropsch synthesis

Hydrogen can be produced with minimal emissions through the electrolysis of water using a renewable power source. Importantly, hydrogen combustion does not directly generate CO or CO_2 emissions. In addition, although the combustion of hydrogen produces NO_x, it is unclear to what extent it does so relative to burning kerosene.

Technology packages

Table 2 summarises the selected technology and fuel combinations explored in this study. Building upon four reference aircraft and using the most promising technologies from Table 1, two distinct aircraft families are considered: a drop-in fuel family that can use either fossil kerosene or SAF, and a liquid hydrogen (LH_2) family. The characteristics of both aircraft families are projected for two future generations, being 15 years apart.

Whereas the entry-into-service date of the next evolutionary aircraft generation is expected to be 2030, liquid hydrogen aircraft are unlikely to be available before 2035. It is assumed that LH_2 would be introduced first on less complex, smaller aircraft and then progress to larger aircraft later.

Airlines are interested in new aircraft designs that offer significant reductions in operating costs compared to those vehicles already in their fleet. Of particular interest are the direct operating costs (DOCs), which consist of crew, fuel, maintenance, ownership or depreciation, and other expenditures.

Table 2: Chosen aircraft technologies for the drop-in fuel and LH_2 aircraft families

Technology	2030	2035	2040	2045	2050	2055
	Generation N+1			Generation N+2		
Drop-in fuel family	Regional, short haul	Medium and long haul		Regional, short haul	Medium and long haul	
Hydrogen family		Regional, short haul	Medium and long haul		Regional, short haul	Medium and long haul
Wing	15 AR[a]			20 AR[a]	BWB[b] (drop-in) 20 AR[a] (LH_2)	BWB[b] (LH_2)
Engines	UHBR[c]			UHBR[c] and flying slower		
Composite materials	Apply to 50% of components by weight			Apply to 100% of components by weight		

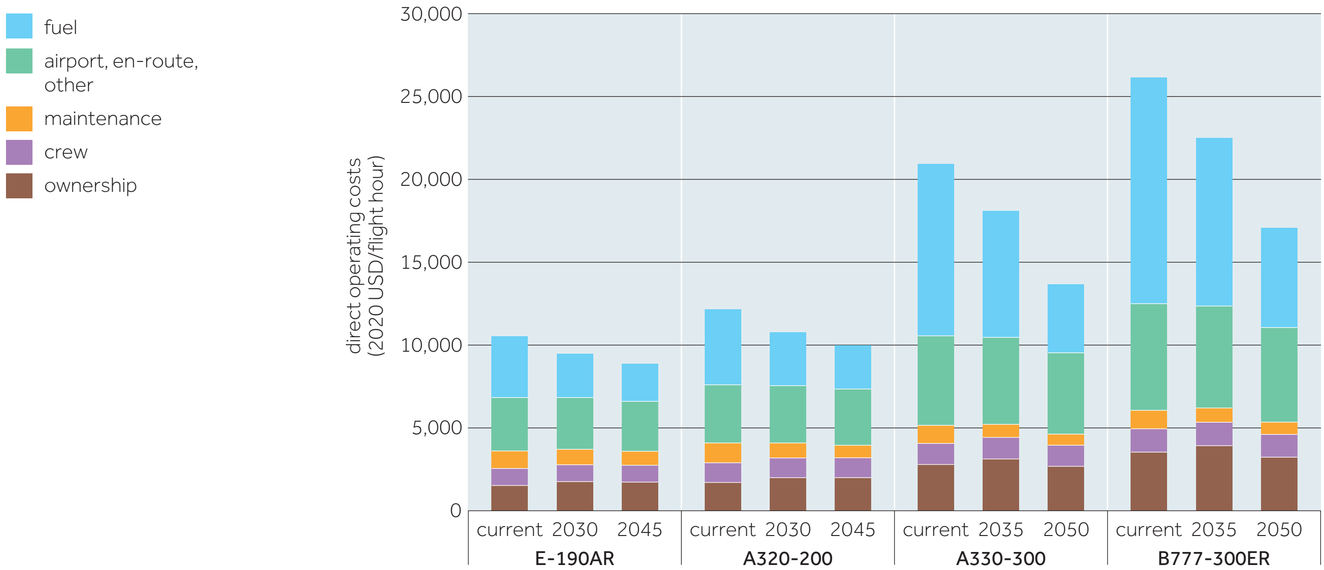
[a] Wing aspect ratio [b] Blended wing body aircraft [c] Ultra-high bypass ratio engines

Figure 4 depicts the resulting DOCs in USD (2020) per flight hour by DOC category for the four aircraft size classes using (synthetic) liquid fuels for today's conditions, for Generation N+1 (2030–2035) and for Generation N+2 (2045–2050). Fuel costs are based on a fuel price of USD 5 per gallon. Although capital costs of the Generation N+1 aircraft are projected to increase above those of the current generation of aircraft, the savings in all other expenditure items are anticipated to increase more strongly (particularly for fuel costs), thus leading to a decline in total DOC.

Because of the projected strong reduction in aircraft energy intensity, the share of fuel costs to total DOC declines from one generation to the next. For example, for the medium-haul A330 type of aircraft, fuel costs account for around 50% in the reference case, around 42% in the Generation N+1 aircraft, and only around 30% in Generation N+2. See the full study report for the estimated DOCs of hydrogen aircraft.

Figure 4: Estimated DOCs (2020 USD) per flight hour for the four aircraft size classes using synthetic liquid fuels for today's generation, Generation N+1 (2030–2035) and Generation N+2 (2045–2050)

(The underlying jet fuel price is USD 5 per gallon)



Modelling results

Methodology and scenarios

The Aviation Integrated Model (AIM)[5] was used to project the potential global impact of the uptake of the various technologies and fuels. Six different scenarios for combinations of demand, fuel supply, policy and aircraft technology were explored using AIM.

These scenarios are intended to be aspirational, highlighting the effort that will be required to meet different aviation emissions targets: as such, they are not projections. Each scenario consists of a set of technology roll-outs defined by the technology analysis; a demand case, including policy ambitions, various demand drivers and trends; and a SAF supply case aimed at meeting the projected demand.

- Technology roll-out
  - **'Drop-in'** technology: New aircraft generations enter service on the expected industry schedule and drop-in SAF is part of the fuel supply, with uptake stimulated by blending mandates.
  - **'H_2'** technology: New aircraft launches are delayed by five years with the first hydrogen-fuelled aircraft entering service in 2035. Both drop-in SAF and liquid hydrogen are part of the fuel supply, with uptake stimulated by blending mandates (for SAF) and aircraft design/purchase standards (for hydrogen aircraft).
- Demand cases
  - **High demand:** assumes high income growth, low oil prices, and limited long-term impact of the COVID-19 pandemic.
  - **Mid demand:** assumes that population and income follow central-case trends, leading to aviation demand growth that is close to the post-COVID-19 industry projections.
  - **Low demand:** assumes that economic growth is on the low end of the projections and, additionally, that aviation passenger demand growth is suppressed by changes in attitudes to aviation arising from societal changes in the wake of the COVID-19 pandemic and/or from increased environmental concerns about flying.
- Supply cases
  - **Low supply:** results in a SAF supply of 10.8 EJ (~250 Mt) in 2050, increasing from ~1 EJ (~25 Mt) in 2030. Both biofuels and PTL routes make up this supply but biofuels are relied upon up to 2030, accounting for 92% of the total SAF supply. Post-2030, as PTL pathways reach commercialisation, biofuels account for 67% of the SAF supply.
  - **Mid supply:** results in a SAF supply of 17.5 EJ (~400 Mt) in 2050, with a supply of 1.2 EJ (~27 Mt) in 2030. Roughly 90% of the 2030 supply is from biofuels, decreasing to 56% in 2050.
  - **High supply:** results in a SAF supply of 30.6 EJ (~700 Mt) in 2050, from a supply of 1.2 EJ (~27 Mt) in 2030. The ramp-up phase to 2030 remains the same as for the mid supply case, with reduced project development timelines, where biofuels account for 90% of SAF in the first decade. However, market expansion after commercialisation occurs at a much faster rate, mostly due to the rapid scale-up of PTL-FT, which accounts for roughly 63% of SAF in 2050.

[5] The Aviation Integrated Model (AIM) is a global aviation systems model which simulates interactions between passengers, airlines, airports and other system actors into the future, with the goal of providing insight into how policy levers and other projected system changes will affect aviation's externalities and economic impacts.

Figure 5: Sustainable aviation fuel (SAF) supply comparison

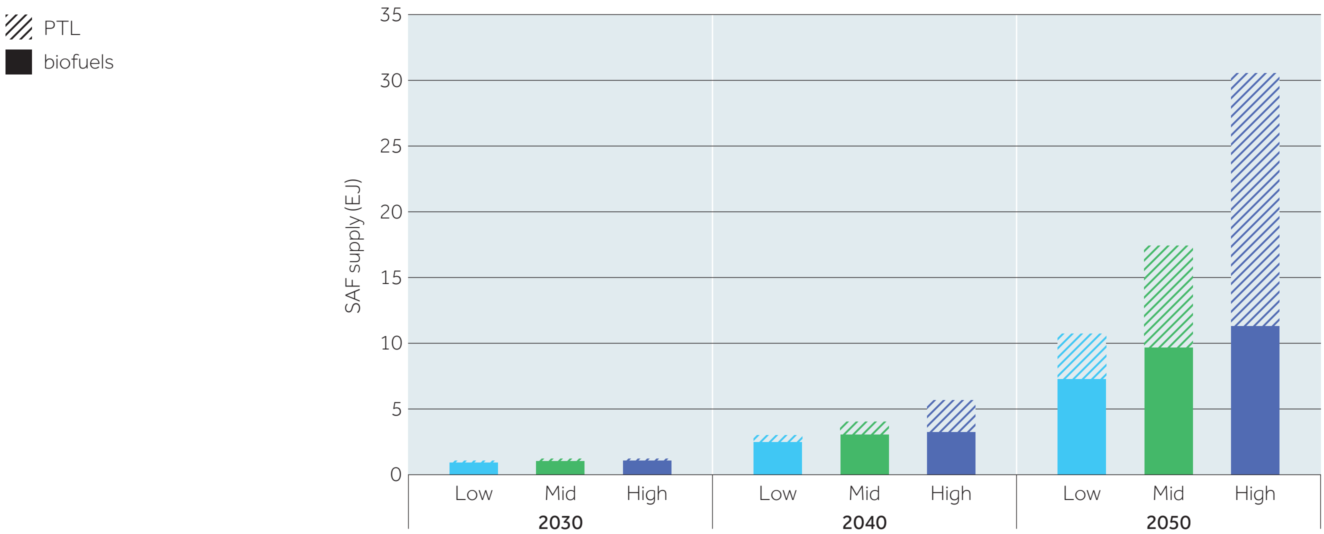


Table 3: Summary of the modelled scenarios

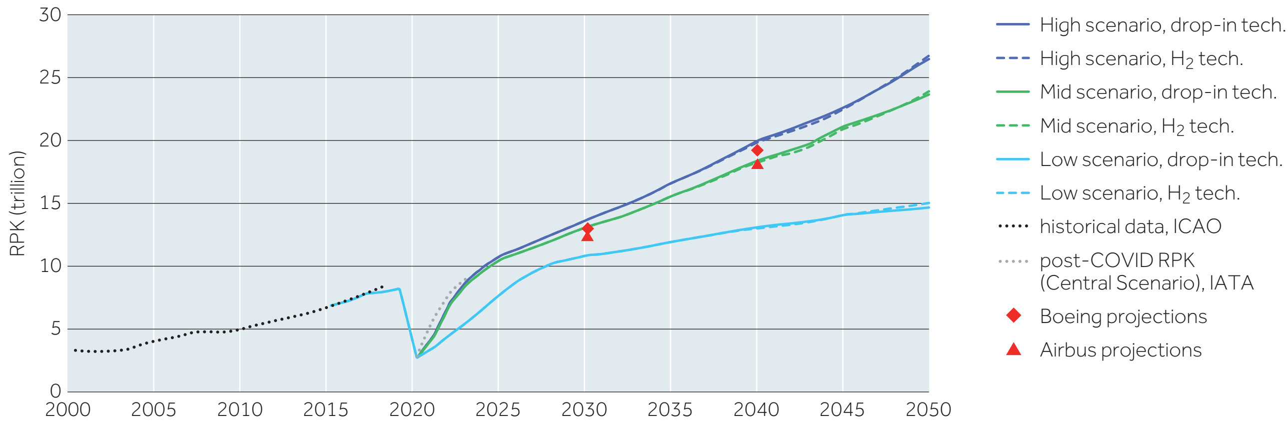
Scenario	Technology roll-out	Technology roll-out	Supply case
Low (drop-in)	New aircraft, drop-in SAF, and operational measures	Long-term economic growth and demand growth is suppressed. High oil prices, ReFuelEU[a] SAF mandate applied globally.	Standard project development timelines during ramp-up phase. 15% CAGR[c] for biofuels, 21% CAGR for PTL fuels during market expansion phase.
Low (H_2)	New aircraft, drop-in SAF, hydrogen and operational measures. Hydrogen aircraft mandates introduced as part of the demand case.		
Mid (drop-in)	New aircraft, drop-in SAF, and operational measures	Economic growth follows central-case trends, aviation demand trends follow post-COVID-19 industry projections. Low oil prices, following IEA SDS[b] scenario. ReFuelEU[a] SAF mandate applied globally.	Accelerated project development timelines during ramp-up phase. 15% CAGRc for biofuels, 23% CAGR for PTL fuels during market expansion phase.
Mid (H_2)	New aircraft, drop-in SAF, hydrogen and operational measures. Hydrogen aircraft mandates introduced as part of the demand case.		
High (drop-in)	New aircraft, drop-in SAF, and operational measures	High economic growth: high income growth, aviation demand trends follow pre-COVID-19 industry projections. Low oil prices, following IEA SDS scenario. Ambitious global SAF mandate, rising to 100% in 2050.	Accelerated project development timelines during ramp-up phase. 16% CAGRc for biofuels, 36% market growth CAGR between 2030–2040, 23% CAGR between 2040–2050 during market expansion phase.
High (H_2)	New aircraft, drop-in SAF, hydrogen and operational measures. Hydrogen aircraft mandates introduced as part of the demand case.		

[a] ReFuelEU is a European Commission initiative that aims to boost the supply and demand for sustainable aviation fuels in the EU.
[b] International Energy Agency (IEA) Sustainable Development Scenario (SDS). [c] Compound annual growth rate.

- **Demand and fleet evolution**

  Figure 6 shows the demand for aviation, from 2000 to 2050, under the various scenarios considered in the study, together with projections from Airbus and Boeing.

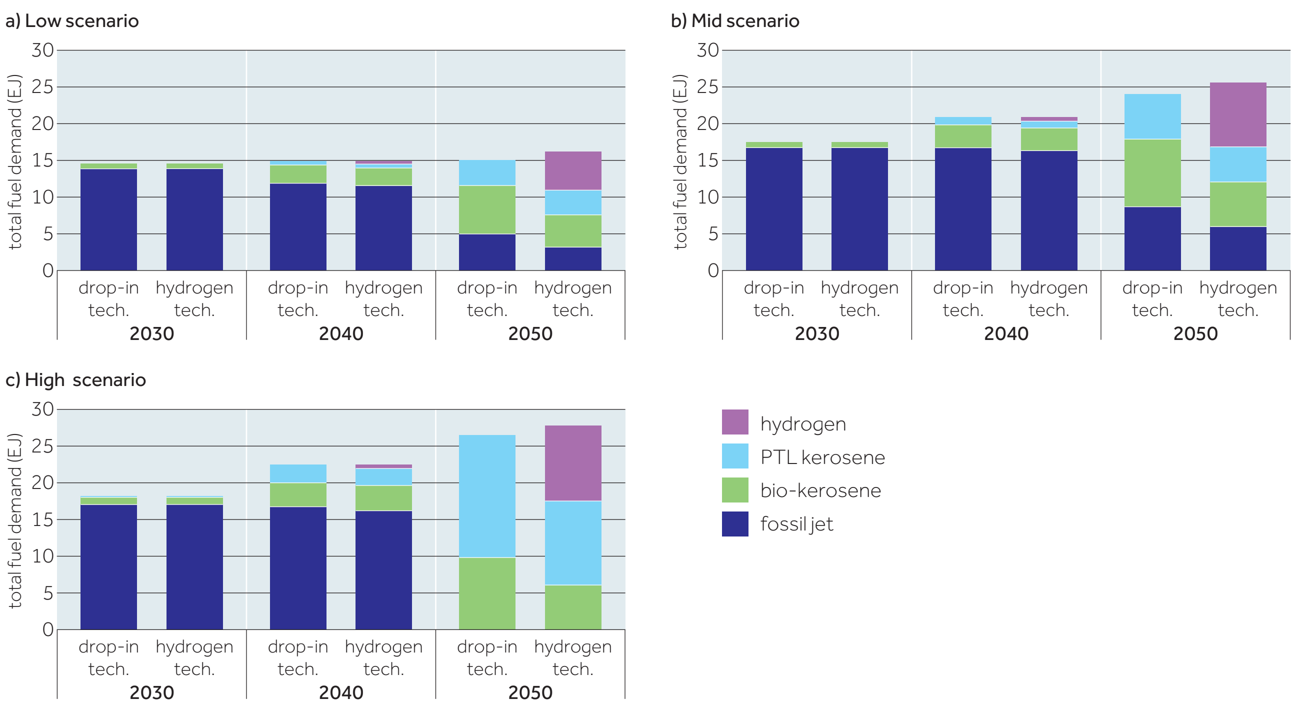
Figure 6: Demand for aviation expressed in revenue passenger-kilometres (RPK)



- **Fuel supply composition**

  Figure 7 presents the overall composition of fuel supply, showing the ramping up of SAF (biofuels and PTL fuels) and liquid hydrogen through to 2050.

Figure 7: Total fuel demand (energy basis) in each scenario



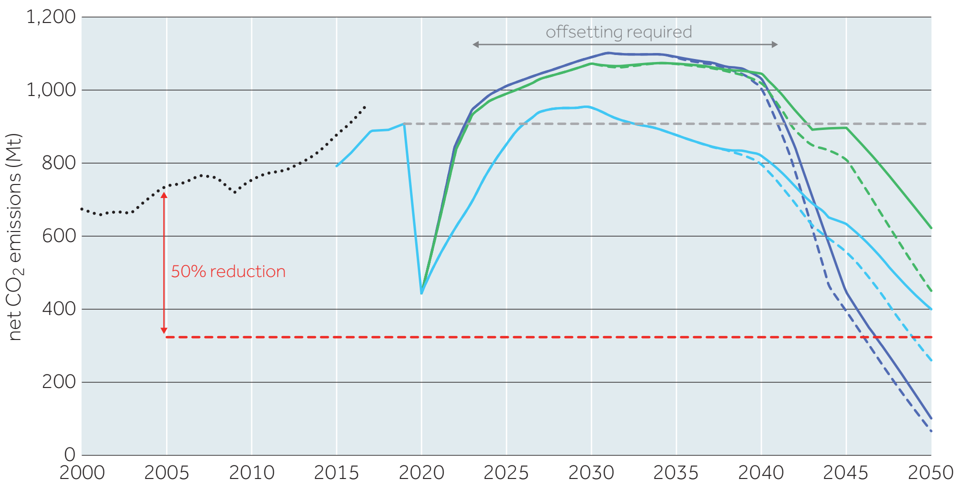
- **CO_2 savings**

  The decarbonisation ambition level for the aviation sector has been evolving towards a net zero target by 2050:

  - Since 2009, IATA has had an ambition to achieve a 50% reduction, compared with 2005 levels, by 2050.
  - In 2016, ICAO adopted CORSIA, with the (current) ambition of stabilising aviation's net CO_2 emissions at 2019 levels, from 2021 (carbon neutral growth).
  - However, in October 2021, IATA approved a revamped goal of achieving net-zero carbon emissions by 2050, in alignment with the Paris Agreement.

Figure 8 indicates the net CO_2 emissions from the aviation sector under a range of scenarios from 2000 to 2050.

Figure 8: Net CO_2 emissions from the aviation sector



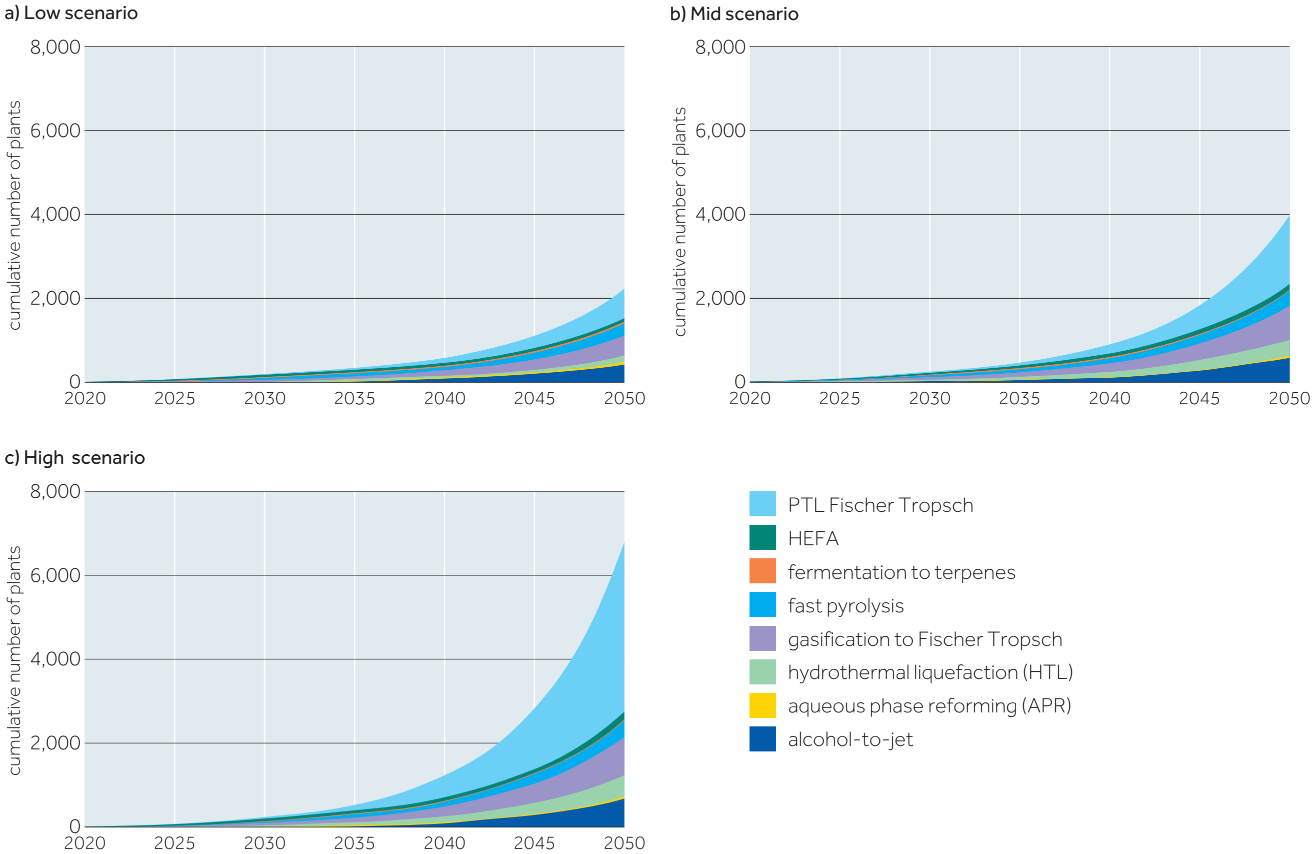
- High scenario, drop-in tech.
- High scenario, H_2 tech.
- Mid scenario, drop-in tech.
- Mid scenario, H_2 tech.
- Low scenario, drop-in tech.
- Low scenario, H_2 tech.
- historical data, IEA
- carbon-neutral growth
- IIATA target, 50% reduction compared to 2005 levels

Note: IEA's data includes military flights, which are excluded from this analysis.

The hydrogen scenarios result in slightly reduced emissions compared with their corresponding SAF-only counterparts. However, limited additional mitigation occurs until 2040, due to uptake constraints. From 2040 onwards, significant numbers of hydrogen aircraft enter the fleet: this reduces the amount of drop-in fuels required, and hence drives sectoral emissions down.

The number of operational plants under each of the three main scenarios studied are shown in Figure 9. Based on nameplate plant capacities and 'nth plant' specific capital investment costs taken from literature, a high-level estimate of the required capital investment costs can be calculated.

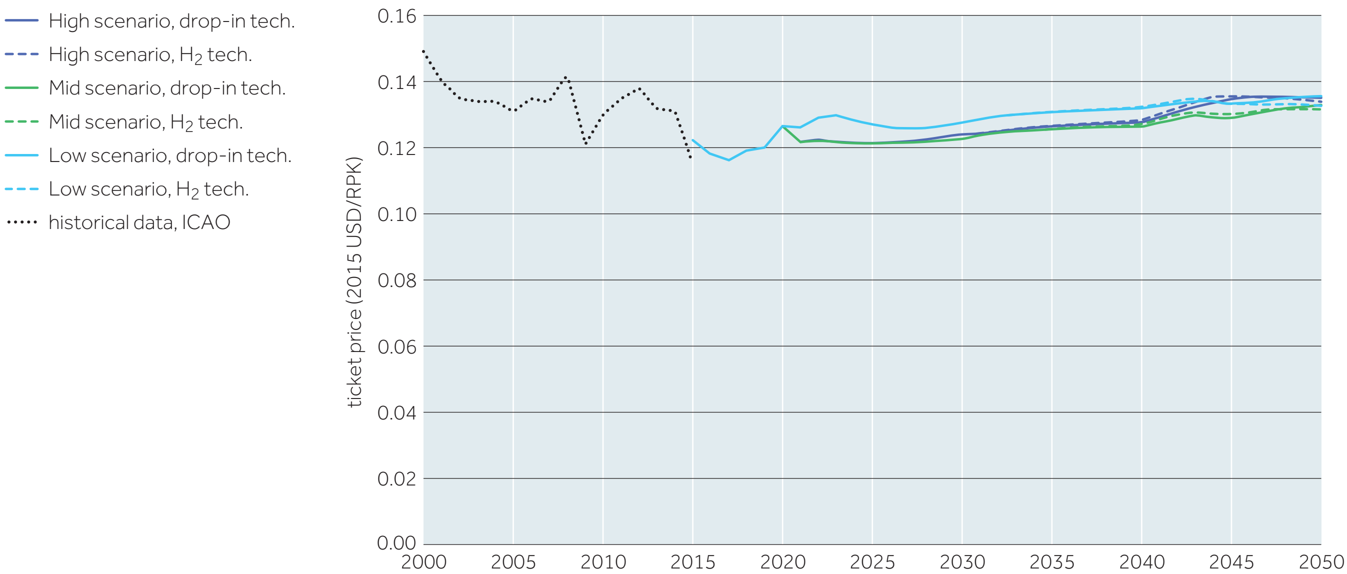
Figure 9: Number of operational plants in each scenario
(typical plant capacity ranges from 30 kta to 250 kta for current developments)



- **Ticket price**

  As shown in Figure 10 on page 60, the model analysis suggests that there will be minimal variation in ticket price across all scenarios between 2020 and 2050. The largest impact on ticket price arises from the variation in oil prices assumed across the 2020–2040 period. Due to all scenarios imposing a significant mandate (minimum 63% SAF by 2050), the uptake of SAF is high in each scenario, with SAF prices assumed to be broadly similar in each (USD 4–6/gallon). The uptake of SAF increases the airline operating cost. Historically, fuel costs have accounted for 10–30% of airline direct operating costs (ICAO, 2020). However, aircraft performance improvements are projected to drive down the proportion of operating costs attributable to fuel, while increases in the effective fuel price from SAF uptake are projected to increase it. The net result, at typical rates of cost passthrough which are close to 100%, is a modest increase in ticket price.

Figure 10: Ticket price from 2000 to 2050 in 2015 USD per RPK



Conclusion

- Technological improvements to aircraft alone will not be sufficient to reduce the aviation sector's CO_2 emissions, due to anticipated increases in demand.
- Bio-based kerosene can contribute substantially to aviation fuel, but supplying the aviation industry with 100% SAF would require vast quantities of biomass feedstock.
- Decarbonising the aviation sector strongly depends on the success of PTL technology and an abundance of low-cost renewable power.
- The speed of hydrogen aircraft fleet introduction will be constrained by technology development, fleet turnover, cost and production line capacity.
- Life-cycle CO_2 emissions still arise from the production of sustainable aviation fuel, therefore market-based measures and/or greenhouse gas removal technology will be needed in the long term to achieve net-zero targets.

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