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Analysis

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Cost and emissions pathways towards net-zero climate impacts in aviation

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Aviation emissions are not on a trajectory consistent with Paris Climate Agreement goals. We evaluate the extent to which fuel pathways—synthetic fuels from biomass, synthetic fuels from green hydrogen and atmospheric CO_2, and the direct use of green liquid hydrogen—could lead aviation towards net-zero climate impacts. Together with continued efficiency gains and contrail avoidance, but without offsets, such an energy transition could reduce lifecycle aviation CO_2 emissions by 89–94% compared with year-2019 levels, despite a 2–3-fold growth in demand by 2050. The aviation sector could manage the associated cost increases, with ticket prices rising by no more than 15% compared with a no-intervention baseline leading to demand suppression of less than 14%. These pathways will require discounted investments on the order of US$0.5–2.1 trillion over a 30 yr period. However, our pathways reduce aviation CO_2-equivalent emissions by only 46–69%; more action is required to mitigate non-CO_2 impacts.

Reducing climate impacts is particularly challenging for aviation, a sector with high growth rates, long-lived assets, non-CO_2 impacts of similar magnitude to those from CO_2[1,2], and no commercially available, scalable carbon-neutral technology.

Previous studies investigating aviation pathways towards zero CO_2 and/or climate impacts have highlighted the difficulty of meeting emissions goals[3–5], particularly when considering non-CO_2 climate impacts[3]. Most mitigation scenarios project net positive aviation CO_2 in 2050[6–8]. For studies looking at net zero within the aviation sector, substantial scale-up in alternative fuel use (either drop-in fuels[9–11] or hydrogen[12]) and potentially demand-reducing measures[13,14] are widely identified as necessary conditions. Most studies investigating pathways towards zero climate impacts explore limited regional scopes;[5,7,9,15] exclude non-drop-in fuels, such as hydrogen;[3,6,7,9–11,13] do not examine transition costs;[8,10,11] or do not quantify non-CO_2 impacts[6,7,9–13,15]. Moreover, none of these studies considers additional measures to avoid non-CO_2 impacts, such as contrail avoidance. Here we evaluate hypothetical greenhouse gas mitigation pathways, including drop-in and non-drop-in fuels in addition to air transport efficiency improvements, and explore non-CO_2 impact mitigation through operational changes. We consider tank-to-wake (TTW) fuel combustion CO_2 and a range of non-CO_2 TTW impacts (direct warming from black carbon; semi-direct sulfate aerosol cooling; direct warming from stratospheric water vapour; indirect warming from contrails; and indirect NOx impacts including short-lived nitrate aerosol cooling, short-lived ozone warming, and cooling from destruction of atmospheric methane (CH_4) and reduction of tropospheric ozone). For well-to-tank (WTT) emissions from the fuel supply chain (including feedstock production or extraction, land use change, feedstock conversion and transportation), we consider direct warming impacts from CO_2, CH_4 and nitrous oxide (N_2O), and indirect impacts from CH_4 (warming from tropospheric ozone, stratospheric water vapour and additional CO_2). In addition, we provide estimates of the costs and demand impacts associated with this transition.

Mitigation measures

A net-zero emissions pathway requires anthropogenic sources of climate forcing emissions, including both direct emissions and the emissions of the supporting energy system, to ultimately become equal

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Table 1 | Characteristics of energy carriers suitable for commercial aviation

	Jet-A	Drop-in fuels			Cryogenic fuels			Electricity
		Low-cost biofuels[a]	High-cost biofuels[a]	Power-to-liquids	Low-cost SLNG[b]	High-cost SLNG	Liquid hydrogen	
Feedstock	**Crude oil**	**Waste and plant oils; FTL from MSW**	**Cellulosic biomass**	**Hydrogen and atmosph. CO_2[c]**	**Animal manure, municipal wastewater**	**Hydrogen and atmosph. CO_2**	**Water and renewable electricity**	**Solar, wind**
Fuel supply characteristics								
Electricity intensity in 2020 (2050), kWh(el)/kWh(fuel)[d]	~0	0.02	<0.01	2.1 (1.9)	0.05	2.0 (1.8)	1.8 (1.5)	1.0
Capital intensity, million $/boe/d in 2020 (2050)[e]	0.01–0.03	0.03–0.13	0.13–0.20	1.0 (0.3)	0.3	1.0 (0.3)	1.3 (0.4)	0.14 (0.07)
Production costs in 2020 (2050), $/bbl(JFE)	6–22 (6–110)	150–230 (130–210)	180–290 (160–260)	380 (100/200)[f]	110–230 (110–230)	390 (110)	440 (130/195)[f]	60–150 (30–70)
Fuel resource potential, EJ	24,000–98,000	0.3–20.5[g]	60–110[g]	Unlimited	30[g]	Unlimited	Unlimited	Unlimited
Climate impact intensity, $gCO_2(eq)\ MJ^{-1}$								
Upstream (WTT)	14.3	−61.7 to −36.1	−62.7 to −51.0	−70.4	−104.7 to −45.8	−56.4	0.0	0.0
of which CO_2	11.9	−65.9 to −48.0	−63.0 to −58.8	−70.4	−75.1 to −57.0	−56.4	0.0	0.0
of which non-CO_2[h]	2.4	1.3–23.1	0.4–11.4	0.0	−29.6 – 11.2	0–13.9	0.0	0.0
Combustion (TTW)	104.0	94.1	94.1	94.1	95.5	95.5	35.1	0.0
of which CO_2	73.2	70.4	70.4	70.4	56.4	56.4	0.0	0.0
of which non-CO_2, central value (uncertainty)[h]	30.8 (9.4–54)	23.7 (6–47)	23.7 (6–47)	23.7 (6–47)	39.1 (13–73)	39.1 (13–73)	35.1 (11–68)	0.0
Lifecycle (WTT+TTW)	118.3	32.4–58.0	31.4–43.1	23.7	−9.2–40.5	39.1	35.1	0.0
of which CO_2	85.1	4.5–22.4	7.4–11.6	0.0[e]	−18.7 to −10.6	0.0	0.0	0.0
of which non-CO_2[h]	33.2	25.0–46.8	24.1–35.1	0.0	9.5–50.3	39.1–53.0	35.1	0.0
% of lifecycle Jet-A	100	27–49	27–36	20	−8–34	33	30	0

[a]The biofuels production cost range is determined by feedstock and conversion pathways; lower end: HEFA fuels and waste; higher end: energy crops. [b]The cost range of low-cost SLNG is determined by feedstock; lower end: agricultural residues; higher end: energy crops. [c]See Supplementary Section 1.3. [d]The electricity intensity captures external electricity input. Therefore, the electricity intensity of refineries is around zero, as nearly all electric power is produced onsite. [e]Capital intensity is measured in million dollars of investments per barrel of oil equivalent (boe) per day. [f]Higher number: sensitivity case. In the case of PTL, consistent with DAC costs of US$280 per tonne CO_2 at hydrogen production costs of US$1 per kg. [g]Resource potential of low-cost biofuels from ref. [34]. High-cost biofuels resource potential corresponds to the lower end and higher end in Table 7.34 (ref. [39]), assuming a 50% biomass to fuel conversion efficiency. The low-cost SLNG potential is based on ref. [40]. [h]The CO_2eq values in this table were derived using GWP_{100}. The relative impact of CO_2 to non-CO_2 is sensitive to time horizon (Supplementary Sections 3.2 and 3.3). CO_2eq emissions of renewable electricity are assumed to be zero. FTL from MSW, Fischer–Tropsch liquids from municipal solid waste; bbl(JFE), barrel of jet fuel equivalent.

to or less than their sinks[16]. We disaggregate factors that affect aviation's climate forcing emissions using equation (1). These emissions are driven by: aviation's level of activity (in revenue tonne-km, RTK); energy intensity (Energy/RTK); and CO_2-equivalent emissions intensity per unit energy, where CO_2eq includes CO_2 and non-CO_2 impacts on both WTT and TTW scopes. Offsets can be used as an instrument to balance impacts from emissions which cannot be avoided.

$$\mathrm{CO_2eq} = \mathrm{RTK}\,\frac{\mathrm{Energy}}{\mathrm{RTK}}\,\frac{\mathrm{CO_2eq}}{\mathrm{Energy}} - \mathrm{offsets} \tag{1}$$

Technology and policy solutions for each of these variables can contribute towards reducing aviation's emissions towards the net-zero goal.

RTK: air transportation demand

The demand for air transportation depends mainly upon urban populations, associated per person income, and airfares. We expect the world to become wealthier (Supplementary Section 5) and larger shares of the global population to gain access to air transportation. As such, in the absence of a transition towards low-carbon energy carriers and/or additional policy measures, we project demand for air transportation (measured in RTK) to grow by 2.4–4.1% per year, corresponding to a doubling or tripling of 2019 demand by 2050. This is in line with established market forecasts[17–19]. We do not consider policies that directly reduce air transportation demand (for example, French government policy aiming at displacing short-haul flights with high-speed rail[14]). However, our integrated aviation systems model AIM2015 considers

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Table 2 | Scenario variables and outcomes in the reference scenarios and single-pathway abatement scenarios

	Low demand		Middle demand		High demand	
	Baseline (fossil Jet-A)	Single alternative fuel scenarios	Baseline (fossil Jet-A)	Single alternative fuel scenarios	Baseline (fossil Jet-A)	Single alternative fuel scenarios
RTK growth, % yr^{-1} (2019–2050)	2.4	1.8–2.4[a]	3.7	3.1–3.7[a]	4.1	3.5–4.0[a]
Aviation direct energy use in 2050, EJ (compare to 13 EJ in 2019)	17.7	15.0–17.6[b]	26.4	22.3–25.8[b]	29.4	24.9–28.6[b]
of which EJ provided by alternative fuel	N/A	7.9–17.2[c]	N/A	12.9–25.6[c]	N/A	14.9–28.5[c]
WTW CO_2 emissions in 2050, Mt (compare to 1,070 million tonnes in 2019)	1,510	0–822[a]	2,240	0–1,100[a]	2,490	0–1,170[a]
Cumulative (2019–2050) WTW CO_2 emissions, Gt	40.1	24.9–35.3[d]	50.0	28.0–42.3[d]	53.4	29.5–44.7[d]
Cumulative discounted climate costs, trillion US$(2020) [(10)]	13.1	9.9–12.1[e]	15.9	11.7–14.3[f]	16.9	12.3–15.1[g]
Cumulative discounted (2019–2050) alternative fuel supply investments, trillion US$(2020)	N/A	0.54–1.36[h]	N/A	0.83–1.93[h]	N/A	0.94–2.12[h]
Change over 2019 constant-price airfare in 2050, % (per RPK)	−4.0	−2.1–14[i]	−2.3	−0.8–16[i]	−1.3	0.4–17[i]

[a]Lower end PTL, higher end LH2. [b]Lower end biofuels, higher end LH2. [c]Lower end LH2, higher end PTL. [d]Lower end biofuels, higher end LH2. [e]Central values and 95% CI: 13.1 (3.2–32.9, baseline); 10.1 (2.5–25.4, PTL); 9.9 (2.5–24.9, biofuel); 12.1 (3.0–30.4, hydrogen). For comparison purposes, climate costs are calculated using RCP2.4 and SSP2. [f]Central values and 95% CI: 15.9 (4.0 - 40.1, baseline); 12.2 (3.0–30.6, PTL); 11.7 (3.0–30.6, biofuel); 14.3 (3.6–36.1, hydrogen). [g]Central values and 95% CI: 16.9 (4.2 - 42.6, baseline); 13.0 (3.3–32.7, PTL); 12.3 (3.1–30.8, biofuel); 15.1 (3.8–38.0, hydrogen). [h]Lower end biofuels, higher end PTL. Discount rate, 2%. [i]Lower end LH2, higher end biofuels.

that cost-increasing technologies, such as synthetic fuels, will lead to demand feedbacks[19,20].

Energy/RTK: energy intensity of the air transport system

The energy intensity of the air transportation system is driven by the fuel efficiency of individual aircraft, operational efficiency (for example, the air traffic management (ATM) system) and capacity utilization of flights. When combining our projected energy intensity reductions for new aircraft[21] with age distributions and retirement schedules of the current fleet, average passenger load factor growth, ATM improvements and market growth projections, system-level energy intensity per RTK declines by 1.3% per year (around 33% total) between 2019 and 2050; in combination with a doubling or tripling of RTK demand, aviation CO_2 emissions would increase by a factor of 1.3 to 2. Consequently, energy efficiency improvements alone are unlikely to reach even the carbon-neutral growth goal of the International Civil Aviation Organization (ICAO)[22].

CO_2eq/energy: climate intensity of fuels

Currently, the aviation sector relies on fossil hydrocarbon Jet-A, which generates 73 g of combustion CO_2 per MJ, with an additional 14 g CO_2eq per MJ (using global warming potential with a 100 yr time horizon (GWP_{100})) from CO_2, CH_4 and N_2O emissions arising from WTT processes (oil extraction, refining, and crude oil and fuel logistics; Table 1)[23]. Alternative energy carriers, which partly or entirely mitigate fuel GHG emissions, include 'drop-in' fuels usable in existing aircraft and 'non-drop-in' fuels, for example, cryogenic fuels such as liquid hydrogen (LH2) and electricity, which require novel fuel infrastructure and aircraft designs (Table 1). Drop-in fuels are synthetic hydrocarbons produced from sequestered carbon atoms, for example, from biomass (biofuels) or from the atmosphere (power-to-liquid fuels), so that direct CO_2 emissions are offset over the fuel lifecycle. Several other non-drop-in solutions are omitted due to low energy density and high toxicity (ammonia), low availability for aviation (low-cost synthetic liquefied natural gas [SLNG]), dominance by drop-in pathways (high-cost SLNG), or severely limited range and payload performance (all-electric aircraft). The capital requirements, inputs, costs, resource potential and lifecycle GHG emissions vary between the fuel pathways (Table 1). Several underlying key technologies (for example, CO_2 capture from the atmosphere) are still under development. In such cases, Table 1 represents ambitious future states of the technology.

CO_2eq/energy: climate intensity of TTW non-CO_2 emissions

Aviation's CO_2 emissions footprint is exacerbated by WTT and TTW non-CO_2 impacts from onboard fuel combustion. While WTT non-CO_2 emissions are accounted for in the previous section, jointly, soot, stratospheric water vapour, contrails and contrail-cirrus, oxides of nitrogen, and sulfur TTW emissions contribute 30–67% to aviation's total radiative forcing impacts[1,2]. The largest contribution, 41–57% of in-flight climate impacts, has been attributed to contrail-cirrus[1,2].

The different chemical compositions of alternative fuels lead to differences in their non-CO_2 climate impact. Using GWP_{100}, we estimate TTW non-CO_2 impacts of drop-in alternative fuels to be 23% lower (range: 67% lower to 38% higher) than that of Jet-A (Table 1). This decline is due to a 35% decrease in the contrail impact[24–26], partially counteracted by an assumed reduction in sulfur-related cooling. For LH2, we estimate non-CO_2 impacts to be 14% higher per unit energy (range 52% lower to 120% higher) than from Jet-A, as a result of: (1) a 2.6-fold increase in warming from stratospheric water vapour emissions; (2) elimination of sulfur-related cooling; and (3) a 15% reduction in contrail warming. Results for alternative GWP time horizons are presented in Supplementary Section 3.3.

Contrails form in regions with ice-supersaturated atmospheric conditions, which have large horizontal (up to 400 km) extent and a small vertical height (typically less than 600 m)[27,28], and can thus be avoided through cruise altitude adjustments. Studies suggest this strategy to result in a small fuel burn penalty at the benefit of a large, avoided contrail impact[24,29–31]. Using results from our meta-analysis of contrail avoidance (Methods), we assume that 50% of contrail length can be avoided at a 1% increase in fuel burn (Extended Data Fig. 1).

Offsets

Instead of directly reducing their own emissions, airlines can purchase certificates for CO_2 emissions reductions in other sectors or carbon sequestration measures. Such an approach is implemented as part of ICAO's Carbon Offsetting and Reduction Scheme for International

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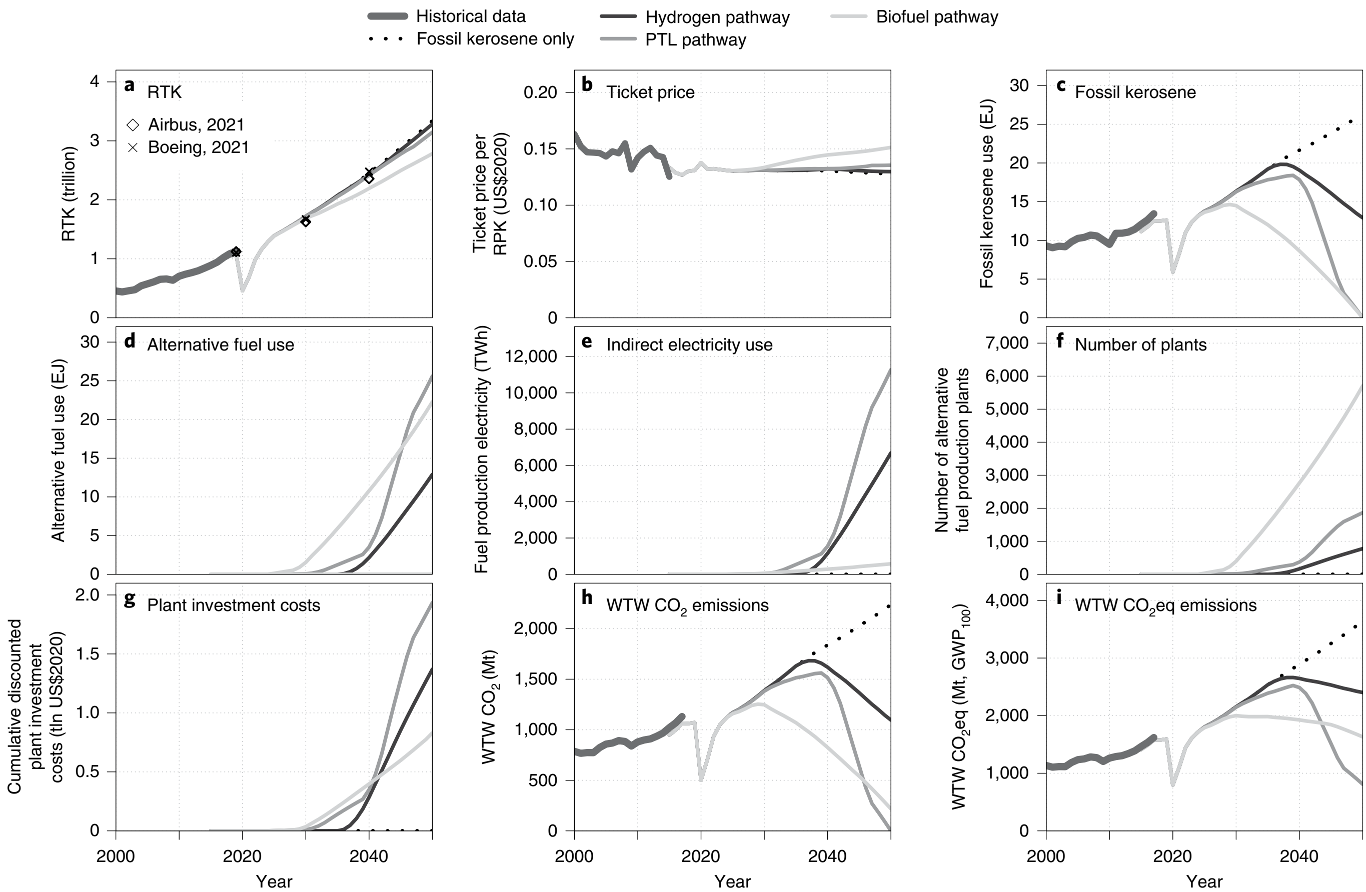

Fig. 1 | Model outputs for single-fuel pathways in the middle-demand scenario. a–**i**, RTK (**a**), average ticket price (**b**), fossil jet fuel use (**c**), alternative fuel use (**d**), low-carbon electricity required for fuel production (**e**), number of synfuel plants in operation (**f**), cumulative discounted synfuel plant investment costs (**g**), combined WTW CO_2 emissions (**h**) and combined WTW CO_2 equivalent GHG emissions including non-CO_2 effects on a GWP_{100} basis (**i**). Additional panels showing non-CO_2 effects by GWP_{20}, GWP_{500}, radiative forcing and global mean surface temperature change are included in Supplementary Information. Historical RTK and ticket revenue data are from ICAO[41]. See Supplementary Section 6 for other demand scenarios.

Aviation (CORSIA). However, offset schemes may not fully ensure that emissions reductions would not have occurred otherwise, are permanent, are not double-counted, and are verified[32]. For these reasons, we do not consider offsetting in this study.

Results

Potentials and costs of single-fuel pathways

The path towards a net-zero aviation system requires a potentially costly transition to low-carbon fuels. The most suitable fuels identified are biofuels, power-to-liquid fuels (PTL) and LH2. Their climate impact mitigation potential is limited by available supply, how fast production can be ramped up, how ramp-up interacts with demand growth and, for LH2 as a non-drop-in fuel, the rate of fleet turnover. To explore the boundaries of mitigation from each candidate fuel, we first analyse emissions reductions, fuel production infrastructure investment costs, and market response over time if each fuel is individually regulated into the market at maximum rates through mandates without supply limitations ('single-fuel pathways').

The integrated aviation systems model AIM2015[19,20] allows modelling of these fuel pathways and a no-intervention baseline under different demand scenarios, defined by socioeconomic development, oil prices, technological change and other factors (derived from IPCC's Shared Socioeconomic Pathways [SSP] scenarios adjusted for the impact of the COVID-19 pandemic[19]). Due to their cost-effectiveness, future conventional aircraft generations are adopted without additional policy intervention. For the hydrogen pathway, LH2 aircraft are mandated into the fleet from 2035 onwards following AIM2015's fleet turnover model. For drop-in fuels, mandates reaching 100% in 2050 are assumed. These runs build upon the World Economic Forum ambition of 10% biofuel share (around 1.5 x 10^{18}J [1.5 EJ]) in 2030 and imply drop-in fuel supply of nearly 26 EJ in 2050[33]. However, it is unclear to what extent the associated biomass of ~52 EJ yr^{-1} would be available for aviation use[33–35] (Methods and Supplementary Section 1).

In the baseline scenarios, aviation direct energy use is projected to increase from 13 EJ in 2019 to 18–29 EJ in 2050, depending on the demand scenario (Table 2). Associated lifecycle ('well-to-wake', WTW) CO_2 emissions increase from 1.1 to 1.5–2.5 Gt. Mitigating these CO_2 emissions requires discounted investments from US$0.5 trillion to US$2.1 trillion, depending on the pathway. Airfares increase by no more than 17% from year-2019 values and demand growth slows by no more than 0.6 percentage points per year.

Following the single-fuel pathways, only PTL could reduce aviation lifecycle CO_2 emissions to zero as shown for the middle-demand scenario in Fig. 1 (additional metrics in Extended Data Fig. 2, high-demand scenario in Extended Data Fig. 3, low-demand scenario in Extended Data Fig. 4). Despite the unconstrained 2050 energy supply, the single-LH2 pathway cannot achieve full market share due to fleet turnover constraints (Fig. 1c,d). Biofuels could be adopted at large scale earlier than PTL and LH2 since production capacity is already being ramped up today. By 2050, under the assumptions of this study, the biofuel pathway would release around 220 million tonnes of CO_2 due to remaining fuel production WTT CO_2 emissions (Fig. 1h). In addition, substantial

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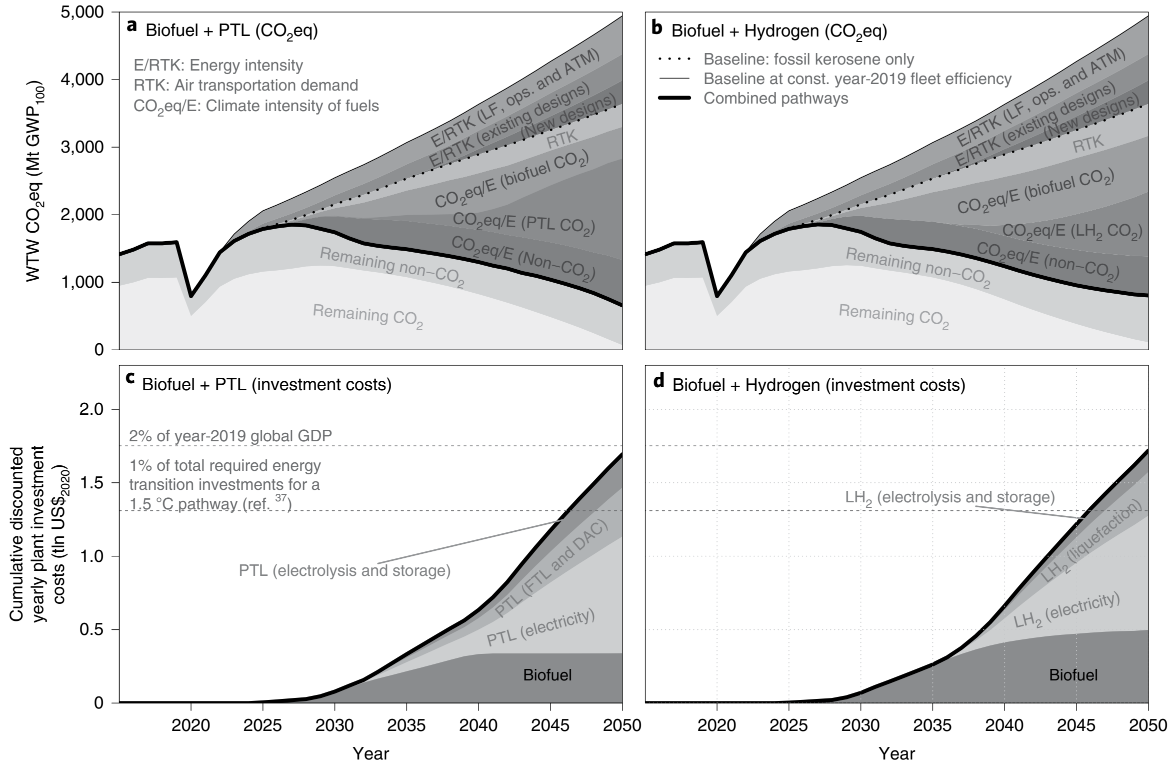

Fig. 2 | Middle-demand scenario related model outputs for two combined pathways aimed at minimizing year-2050 aviation climate impact. **a**,**b**, Reduction in CO_2eq (GWP_{100}) emissions by type of mitigation strategy: biofuels + PTL pathway (**a**); biofuels + hydrogen pathway (**b**). **c**,**d**, Cumulative discounted plant investment costs: biofuels + PTL pathway (**c**); biofuels + hydrogen pathway (**d**). The contribution of each source to emissions reductions is approximate, as there is interdependency between mitigation measures. E/RTK (existing designs) includes changes in CO_2eq from aircraft designs with pre-2025 entry into service. E/RTK (LF, ops. and ATM) includes the impact of changes in load factor, operational mitigation measures (for example, reduced taxi time) and changes in CO_2eq from network change over time (for example, longer average flight length). RTK reduction results from higher airfares induced by the energy transition. Non-CO_2 impacts include contrail avoidance and non-CO_2 impacts of alternative fuel use. A CO_2-only version of this figure, metrics for high- and low-demand scenario runs, and results including GWP_{20} and GWP_{500}, radiative forcing and temperature change are in Supplementary Section 6.

non-CO_2 impacts remain for all single-fuel pathways because alternative fuels still cause non-CO_2 impacts (Table 1), and no action to avoid contrails is included.

Owing to the comparatively high electricity intensity of PTL and LH2 (Table 1), power generation accounts for 59% and 64%, respectively, of the investment required in each pathway. By 2050, around 11,000 TWh and 6,700 TWh of electric power would be needed for PTL and LH2, respectively (Fig. 1e), equivalent to 41% and 25% of year-2020 world electricity generation[36]. For the biofuel pathway, almost 6,000 fuel production plants would have to be built globally over the study period.

For each single-fuel pathway, air transportation continues to grow but at a lower rate compared with the reference development (Fig. 1a) due to higher operating costs raising airfares (Fig. 1b). The ramp-up of PTL production coincides with the cost of PTL declining sharply under aggressive assumptions for cost reductions in direct air capture, renewable electricity and electrolysis. To assess the sensitivity of outcomes, we also simulated the middle-demand scenario with 50% higher projected LH2 costs and twice the projected PTL costs in 2050 (Table 1 and ref. [18]). Compared with the projected 2–6% increase in the average 2050 airfare over year-2019 values, the higher fuel costs result in an 8 and 16% ticket price rise for the LH2 and PTL case, respectively, and a 7–18% reduction in year-2050 RTK over baseline values (Extended Data Fig. 5).

Potentials and costs of combined pathways

PTL and LH2 pathways have limited scale-up potential before the 2030 s, whereas biofuels are likely to experience long-term supply constraints. Therefore, we define combined pathways, which include supply-constrained biofuels in combination with either LH2 or PTL. Furthermore, to address non-CO_2 impacts, the combined pathways consider contrail avoidance (Methods).

Cost-effective reductions in air transport system energy intensity reduce middle-demand scenario year-2050 WTW CO_2eq emissions from 4,900 to 3,600 Mt, addressing around 26% of the potential CO_2eq emissions in 2050 (Fig. 2a,b). Over 40% of CO_2eq emissions reductions result from low-carbon fuels, whereas demand effects, from higher airfares, lead to an additional decline of up to 10%. Altogether, the combined pathways can reduce year-2050 WTW CO_2 emissions by around 95% relative to baseline runs that include aircraft energy intensity improvements only, and by over 89% relative to 2019 levels. These reductions are enabled by year-2050 biofuel use of 6.6 EJ (biofuel + PTL pathway) and 11.2 EJ (biofuel + LH2 pathway); year-2050 PTL and LH2 use is 17.9 and 11.5 EJ, respectively. However, year-2050 non-CO_2 impacts are around 10% higher than those in 2019 because only 60% of the cumulative non-CO_2 impacts compared to baseline runs can be addressed. This reflects that contrail avoidance is assumed to reduce contrail radiative forcing by only 50%, with additional benefits available from fuel composition changes. Other non-CO_2 impacts, for example from water vapour emissions, remain unaddressed (Extended Data Figs. 6 and 7).

The required discounted investments associated with the aviation energy transition are around US\$1.7 trillion over the 30 yr study period (12% lower than in the corresponding single-fuel PTL pathway), of which around 45% is associated with renewable power generation. In the context of a broader transition of a net-zero global energy system,

middle-demand scenario non-discounted investments are around 2.2% of those required in the global energy and industrial system[37].

Aircraft operating costs increase at most by 10–16% relative to the baseline Jet-A scenario over the study period. These increases are relatively small because alternative fuel costs decrease and aircraft energy efficiency increases over time, mitigating the cost increase associated with higher levels of alternative fuel mandate in later years. Almost the entire cost increase is passed on through ticket prices, leading to 0.3–0.4% per year lower average RTK growth rates for the middle-demand scenario (Extended Data Figs. 8–10).

Discussion

An energy transition towards synthetic low-carbon fuels is a necessary condition for the aviation sector to achieve the net-zero goal. Improvements in air transport fuel efficiency, driven largely by market forces, can address about a quarter of the projected 2050 lifecycle WTW CO_2eq emissions. These cost-effective reductions will also be an important enabler for the needed energy transition since they reduce investment requirements for fuel production, limit the need for higher-cost fuels, and thus mitigate increases in airline operating costs and airfares.

Low-carbon alternative fuels can reduce 2050 lifecycle CO_2eq emissions by an additional 40% and, in combination with reduced air transport demand due to the higher costs of these fuels, bring aviation 2050 CO_2 emissions close to zero. This requires LH2 and PTL fuels with zero lifecycle CO_2eq emissions, that is, the embedded emissions of power generation should be zero (Supplementary Information). Drop-in biofuels could play a critical role in the fuel transition over the coming decade, given their near-term availability. However, as biofuel production is scaled up over time, constrained biomass availability could limit production volumes and increase costs (Supplementary Section 1). Thus, biofuels could be supplemented by a second wave of fuels that use renewable electricity as a major feedstock, that is, LH2 and drop-in PTL. PTL could fully displace other fuel sources by 2050; due to fleet turnover limitations, 100% use of LH2 is unlikely before 2080. The choice of either PTL or LH2 will depend on the cost of atmospheric CO_2 capture and syngas-to-fuel conversion, the upfront cost and practicability of hydrogen aircraft and fuel infrastructure, and potentially these fuels' non-CO_2 impacts. The extent and timing of the introduction of PTL and LH2 over biofuels depend on their cost relative to biofuels and technology readiness. Our analysis relies on optimistic assumptions from the literature; later technology readiness or higher costs could delay or reduce the scale of PTL or LH2 adoption.

The non-CO_2 effects are harder to abate and still have substantial impact in 2050. Contrail avoidance partly addresses the non-CO_2 impact of aviation by reducing contrail impacts—perhaps conservatively estimated—by 50% for a 1% fuel burn penalty or 0.2% increase in aircraft direct operating cost. However, the reduction in non-CO_2 emissions is incomplete. Further research is needed to address the remaining gap, along with other impacts currently not considered in this analysis (for example, climate impacts of hydrogen leakage[38]).

The scale of the energy transition, requiring 1,000 GW-scale LH2 plants or 5,000–6,000 MW-scale-biofuel plants in 2050, as well as build-up of power generation infrastructure, requires investments of the order of US$1–2 trillion (discounted to 2019). Without policy intervention, there does not seem to be a business case, as the alternative fuels are not projected to reach cost parity with fossil Jet-A. Large-scale, long-term and globally coordinated political incentives are needed to drive this transition.

At the same time, our models of market feedbacks suggest that the aviation sector could be able to fully cover the cost of the transition. The projected airfare increases associated with the transitions in the combined pathways are limited to 10–15% compared with a baseline without energy transition, with increasing fuel costs partly offset by energy efficiency improvements. As such, the air transport sector could continue to grow through this transition, thereby enabling larger shares of the global population to use and benefit from air transportation. However, in light of low airline profitability, less profitable carriers could be forced to exit markets. Our model cannot capture such changes to sector structure.

Our analysis shows that the aviation sector could move towards a zero-impact CO_2 system if predictable, long-term incentives are created. Such measures do not require shifting the cost of the transition away from the aviation sector but can be absorbed by airlines and customers. However, the required technologies (that is, biofuels, PTL, LH2 aircraft and contrail avoidance) to achieve these goals still require development and scale-up. Additional measures, such as encouraging mode shifts, as well as measures to reduce non-CO_2 impacts, may further improve the viability of the transition. For the aviation sector to contribute substantially towards the goals of the Paris Agreement by mid-century, the transition needs to start now.

Online content

Any methods, additional references, Nature Research reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information, details of author contributions and competing interests, and statements of data and code availability are available at https://doi.org/10.1038/s41558-022-01485-4.

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Methods

We assess technology adoption scenarios towards a net-zero aviation sector through a system-level approach. The model builds on combining (1) the global aviation integrated model (AIM) to model future market development, demand feedbacks and technology adoption in a consistent framework; (2) the reduced-order climate model Aviation environmental Portfolio Management Tool - Impacts Climate (APMT-IC) to capture CO_2 and non-CO_2 impacts of aviation emissions under current and future scenarios; (3) detailed assessments of techno-economic characteristics and lifecycle GHG emissions of alternative fuel pathways; (4) a meta-study for assessing the opportunities and costs of contrail avoidance through flight route adjustments; and (5) a detailed scenario approach.

AIM

AIM is an open-source global aviation systems model simulating future passenger and freight demand for trips between 878 city regions worldwide (1,169 airports; 40,264 distinct flight segments); airline fleets and operations; operating costs and impact on itinerary-level ticket prices, freight rates and technology choices; airport schedules and delay; emissions outcomes including CO_2, NOx and particulate matter (PM); and how outcomes change in the presence of different policies or new technologies. AIM2015 and its component modules have been widely used for policy assessment, including for the European Commissions (EC)[32] and UK Department for Transport (DfT)[42]. Details of model structure, methodology and validation are given in refs. [19,20].

AIM2015 allows us to capture second-order impacts of energy transition-related policies. For example, AIM2015's cost model includes a detailed flight segment-level model of fuel and non-fuel operating costs by aircraft and route type[20]. If a technology with higher operating costs is used on that segment, the model projects impacts on itinerary ticket prices and freight rates, and subsequent impacts on demand and required amounts of fuel. For this study, global fuel blending mandates, beginning in 2025 and rising to 100% in 2050, were simulated and, in the case of hydrogen aircraft, a mandatory hydrogen requirement for new purchases was simulated (phased in over 5 yr from hydrogen aircraft first entry into service). A net present value (NPV) model was used to assess uptake of other new aircraft technologies and technology-fuel combinations within those consistent with mandate requirements. For drop-in fuels, adoption was based on the lowest cost to airlines once any mandate requirements, carbon, NOx or contrail-related costs were factored in, with other fuels additionally used where supply or blending limits prevent satisfaction of demand. These models are further described in ref. [43], including assumptions about airline costs and performance modelling.

The characteristics of future generations of conventional aircraft and operational emissions mitigation measures or retrofits to existing aircraft were taken from refs. [9,21,43]. For electric aircraft, performance characteristics, including range limitations, were taken from ref. [44] for single-aisle aircraft and ref. [45] for regional jets. Operating cost characteristics were derived from ref. [46]. For this study, LH2 aircraft were added to the model. Literature LH2 aircraft performance characteristics range from more to less energy-efficient than conventional designs (for example, refs. [47,48]), depending mainly on assumptions about tank design. In addition, considerable uncertainty exists about hydrogen aircraft capital and maintenance costs. For simplicity, we assumed energy intensity and non-fuel operating costs of LH2 aircraft equal those of conventional aircraft of a comparable generation and size, that is, that the operating cost difference between conventional and hydrogen aircraft is dominated by fuel costs. We assumed hydrogen combustion rather than fuel cell-powered propulsion, as the extra weight of fuel cells reduces their feasibility for mid- and long-haul flights[48]. A detailed fuels module was also developed for this study to simulate alternative fuel costs and characteristics over time. The assumptions used in this module are documented separately below ('Fuel modelling'). Model scenario-related inputs are discussed in 'Scenario modelling' below.

Climate impact modelling

We model the climate impacts of aviation emissions using the APMT-IC as described in refs. [1,49]. APMT-IC probabilistically evaluates the physical climate impacts from global aviation emissions and estimates the associated monetary damages. Our use of this model is twofold. First, we used it to derive global warming potentials (GWP) for each of the precursor emissions (Supplementary Section 3.2). These GWP values were used convert non-CO_2 emissions to CO_2eq emissions. Second, we used it to calculate radiative forcing and atmospheric surface temperature change response for each of the future emissions pathways generated by AIM.

The implementation of APMT-IC used here is described in refs. [1,49]. The model has been updated to capture recent research results on (1) the contrail-cirrus forcing and subsequent expected atmospheric temperature response to this forcing;[2,50] (2) the NOx-related methane forcing; (3) the cost of global warming; and (4) updates to account for non-CO_2 impacts of drop-in alternative fuels, LNG and LH2.

Following ref. [2], we updated the contrail-cirrus radiative forcing (RF) in APMT-IC to explicitly separate the estimation of RF and effective RF (ERF, the change in energy forcing after certain short-term climate feedbacks have occurred). For RF, we applied a triangular uncertainty distribution with a minimum value of 20.9 mW m^{-2}, mid-value of 69.78 mW m^{-2} and upper bound of 118.62 mW m^{-2} for distance flown in 2006[51–54]. We also aligned with the ERF/RF adjustment from ref. [2] and applied a triangular uncertainty distribution with a mid-value of 0.417, minimum value of 0.31 and maximum value of 0.59[50,55,56]. This adjustment allowed us to capture the expected temperature change associated with the updated contrail-cirrus RF.

We note that some unquantified uncertainties are not captured in this approach. First, while this ERF/RF adjustment captures the difference in temperature change from short-term RF, this ERF/RF may not necessarily provide an accurate measure of long-term temperature response[50,57]. Second, the adjustment factors from refs. [55,56] represent long-term climate feedbacks for linear contrails only, derived using contrail formation more than 50 times the expected contrail coverage in 2050. This upscaling may cause saturation of feedback effects such as cloud formation[58–60]. After these adjustments, we found a 33% net reduction in temperature change associated with contrail-cirrus per distance flown as compared with ref. [1]. Additionally, we normalized contrail impacts by the Aviation Environmental Design Tool (AEDT) distance for flights in 2006 as reported in ref. [2].

The second update aligns the NOx-related methane forcing with more recent literature on the radiative interaction of methane. Following the method of ref. [2], we increased the forcing of NOx-related methane forcing by 14%. This accounts for additional short-wave RF previously not accounted for in the methane radiative transfer function calculations[61]. Except for contrails, ERF/RF adjustment factors from ref. [2] were not included for in-flight emissions. These factors remain highly uncertain, and remain a research need for in-flight aviation emissions[58].

The third update aligns estimated costs of global warming with more recent literature values. Previously, APMT-IC used the damage function from the Dynamic Integrated Climate-Economy (DICE) model[62], which is consistent with the social cost of carbon as proposed by the US Interagency Working Group on Social Cost of Carbon[63]. This damage function was based on a meta-analysis of 17 studies quantifying market and non-market damages[62]. Recent reports indicate that traditional integrated assessment models, including DICE, lag recent research on climate damages[64,65]. In this study, we applied the damage function from ref. [66], as described in ref. [67]. This damage function is based on a meta-analysis of a larger number of damage estimates from the literature and explicitly treats dependencies between different underlying studies to avoid overrepresentation of results from specific studies. This change leads to a social cost of carbon of US\$246 (USD_{2020}) per tonne CO_2 (90% confidence interval 61.4 to 624) for RCP2.6 and SSP2 background scenarios and a 2% discount rate. For a 3% discount rate,

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RCP4.5 and SSP1, the social cost of carbon in 2020 is US$158 ($USD_{2020}$) per tonne CO_2 (90% confidence interval 46.4 to 352). While this represents a ~2.8-fold increase above the previous APMT-IC social cost of carbon, these values are in line with recent literature on global social cost of carbon estimates of US$80–805[67–69].

Finally, due to changes in the non-CO_2 emissions footprint of LH2, LNG and drop-in fuels, the subsequent climate impacts are also expected to differ[70,71]. For each fuel considered, we derived adjustment factors by emission species on the basis of a literature survey. These factors capture changes in RF per unit fuel energy for each fuel relative to conventional Jet-A. A summary of adjustment factors is provided in Supplementary Section 3.

Alternative fuel pathways

The following fuel and fuel production pathways were considered in this analysis:

- LH2: we considered liquid hydrogen produced via water electrolysis and subsequent liquefaction, both powered by renewable electricity. The electrolysis of water is modelled on the basis of the proton-exchange membrane technology and follows the varying load of renewable electricity. The produced hydrogen gas is stored in a compressed-gas tank to enable continuous operation downstream. Liquefaction of hydrogen is performed at continuous load and the liquid product is stored for further use.
- PTL: we considered power-to-liquids based on hydrogen from water electrolysis and CO_2 from direct air capture. Hydrogen is produced at varying loads from proton-exchange membrane water electrolysis and stored in a compressed-gas tank. CO_2 is continuously extracted from the atmosphere via physical adsorption in a direct air capture process (DAC). CO_2 and H_2 are continuously converted to syngas (H_2 + CO) via the reverse water gas shift process (RWGS). The syngas is converted into hydrocarbons via the Fischer-Tropsch process, where the gaseous fraction is cycled back to the RWGS reaction to be turned into syngas. The resulting synthetic crude is converted into jet fuel and by-products using refining process steps.
- Biofuels: we considered biofuels produced from dedicated biomass and waste streams including the following pathways: HEFA (hydrogenated esters and fatty acids) process using dedicated vegetable oil crops (for example, soybean, rapeseed, jatropha, palm oil) and FOGs (fats, oils, and greases; specifically used cooking oil and tallow), advanced fermentation of sugar crops, and Fischer-Tropsch synthesis of municipal solid waste and lignocellulosic material (forestry residues, agricultural residues, and dedicated feedstock such as switchgrass and miscanthus).
- Synthetic natural gas: hydrogen is produced via water electrolysis using renewable electricity; CO_2 is captured from the atmosphere via low-temperature pressure-swing adsorption. Natural gas is then synthesized from H_2 and CO_2 via the Sabatier process, and the methane is subsequently liquefied for aviation use. Another pathway to synthetic natural gas is via anaerobic digestion of biomass to produce biogas, which is then cleaned and liquefied.

The availability of fuels produced from electricity, water and CO_2 (PTL, SLNG) is in principle unlimited as the feedstock potentials can be leveraged at practically any scale. However, the specific availability at a point in time depends on the rate at which production capacity can be ramped up and the policy priority given to aviation for using scarce input factors such as electricity or biomass. We assumed that the main constraint on LH2 ramp-up is fleet penetration of LH2 aircraft; for PTL and biofuels, maximum ramp-up rates were set using a combination of near-term literature estimates of supply and longer-term estimates of aviation fuel demand (Supplementary Section 1). For single-fuel pathways, biomass availability was modelled after the F1-A1-S2 scenario of ref. [34], assuming full availability of the fuels for aviation such that biofuel potential is essentially unlimited (over twice the expected demand of less than 30 EJ yr^{-1} in 2050). These assumptions were used as the fundamental availability for these pathways, while the specific use of fuels was then determined with the AIM model, taking into account demand effects, mandate levels, scale-up behaviour and prices. For the combined-pathway model runs, a more constrained biomass supply was assumed, rising to a maximum of 21.7 EJ in 2050, based on ref. [33] (Supplementary Section 1).

Production costs. We determined alternative fuel pathway costs (except for biofuel pathways) with the levelized cost of energy approach. To this end, we determined the investment costs of the facilities on the basis of energy and mass balances, and component cost estimates from the literature. We assumed improvements of component efficiencies and energy demands in line with recent publications. The levelized costs of intermittent renewable electricity was assumed to be US$0.04 kWh^{-1} today at a capacity factor of 30% and US$0.02 kWh^{-1} at 50% in 2050, where these estimates are based on a mix of solar photovoltaics and onshore wind technologies. Additionally, we included energy storage for parts of the facilities that must run continuously and thus used a levelised cost of electricity of US$0.10 kWh^{-1} (year 2020) and US$0.05 kWh^{-1} (year 2050) for renewable electricity that is available around the clock. The costs were annualized assuming a lifetime of 20 yr and a discount rate of 10%. The minimum selling price of the different biofuel pathways was based on a discounted cash flow rate of return analysis as shown in ref. [72].

GHG emissions. The lifecycle emissions of electricity from solar photovoltaics and wind are assumed to be zero (see Supplementary Section 1 for estimate on embedded emissions). While currently there are still embedded emissions in the production of photovoltaics modules and wind turbines, these are expected to approach zero with the decarbonization of the economy. For GHG emissions of biofuels, we used literature values from ref. [34] for the different pathways in our study. The authors indicated values for today and for 2050, and we used linear interpolation to get values in between. We neglected embedded emissions of all infrastructure for the fuel pathways due to the expected small impact (see Supplementary Section 1 for estimates). We used literature information on different biofuel pathways to break out different species (CO_2, CH_4, N_2O) in direct emissions of greenhouse gases[23,73–75]. The climate impacts of hydrogen leakage (either from PTL or LH2 production) were not included here and remain highly uncertain due to uncertainties in leakage rates and climate impacts[38,76]. Other non-CO_2 impacts on the atmosphere are discussed in 'Climate impact modelling' above, 'Contrail avoidance modelling' below, and in Supplementary Section 3.

Contrail avoidance modelling

Reaching net-zero climate impacts from aviation will require avoiding contrail formation. One strategy of contrail avoidance relies on small-scale altitude adjustments to avoid flying through atmospheric locations where contrails can form (refs. [29,30,77]). These diversions lead to a small fuel burn penalty (typically less than 5% of fleet-wide fuel consumption) compared with a counterfactual case with fuel-optimal operations. In addition, only 2% of flights have been found to be responsible for 80% of contrail forcing in some regions; hence, less than 2% of flights would have to be diverted to avoid contrail warming impacts[24].

Contrail avoidance was modelled using results from our contrail avoidance meta-analysis based on a literature review of five different studies[31,77–80] (ExtendedData Fig. 1 and Supplementary Section 2). Using these studies, we estimated the relationship between contrail avoidance and fleet-wide fuel burn penalty as shown in equation (2), where $f(x)$ represents the fraction increase in fuel burn for the x fraction

contrail length avoided and C_0, C_1 and C_2 represent the shape parameters to be estimated.

$$f(x) = C_0\left(-1 + \frac{C_1}{C_1 - x}\right)^{C_2} \quad (2)$$

Performing this curve fit yields coefficients of $C_0 = 0.011$, $C_1 = 1.161$ and $C_2 = 0.906$. The resulting route mean square error (RMSE) is 0.0891, leading to a normalized RMSE of 11%, where this normalization is taken to the maximum fuel burn fraction increase. The central estimate of the curve fit indicates that 50% of fleet-wide contrail length can be avoided for a 0.88% fleet-wide fuel burn penalty (5th to 95th percentile range 0 to 2.51). Thereafter, avoiding subsequent contrails becomes more fuel costly, with an additional 20% avoidance requiring double the additional fuel.

Using this meta-analysis, a single mid-range contrail avoidance scenario was selected for our combined technology pathways in which 50% fleet-wide contrail avoidance could be achieved at a 1% fleet-wide fuel burn penalty. This represents a higher fuel burn penalty than the central estimate of the meta-analysis, to account for the range in estimates in the literature. The 50% length avoidance is lower compared with other studies, which calculate maximum contrail impact avoidance of 70–80%. However, this mid-range value of 50% was selected since high rates of avoidance would cause increased strain on airspace and air traffic control[24], and maximum rates of contrail avoidance might be difficult to achieve with current weather prediction data[24]. This contrail avoidance trade-off probably differs for alternative energy carriers such as hydrogen, but data on these differences remain unavailable. Therefore, we applied the same results from equation (2) for alternative fuels (Supplementary Section 2).

Scenario approach

The global potential of technologies and fuels to reduce aviation emissions is limited by supply, ramp-up rate and fleet turnover. These factors interact with demand growth. As such, we examined outcomes across three demand scenarios, as described below. For each demand scenario, we ran: baseline model runs (with operational and efficiency improvements, but no energy transition or additional aviation policy); single-fuel pathways (model runs with operational and efficiency improvements and energy transition to a single alternative fuel (biofuels, PTL and hydrogen) only); and, based on the outcomes of the single-technology scenarios, combined pathways (model runs with operational and efficiency improvements, contrail avoidance and biofuels as a bridging fuel to PTL or hydrogen).

Uncertain AIM scenario inputs include future population, GDP per capita, oil prices, and whether the relationship between demand growth and income growth will change as aviation systems mature. The development of scenarios for input assumptions that take the COVID-19 pandemic into account is described in ref. [19]. Baseline population and GDP per capita growth rates were derived from the IPCC SSP scenarios[81], adjusted for COVID-19 pandemic GDP per capita impacts (ref. [82]), and impacts of movement restrictions on demand and load factors (refs. [83,84]). The scenarios used in this paper (summarized in Supplementary Section 5) are: a high-growth scenario based on IPCC SSP1 socioeconomic factors, leading to aviation demand growth comparable to recent historical trends; a central scenario based on IPCC SSP2 socioeconomic factors, leading to demand growth similar to industry projections; and a low-growth scenario based on IPCC SSP3 socioeconomic factors, leading to post-pandemic demand growth which is lower than historical trends. The low-demand scenario included demand growth decoupling from economic growth, at the level used in ref. [85]. This assumes a gradual trend towards income elasticities of no more than 0.6 over a 70 yr period. For reference cases, we used IEA Sustainable Development Scenario oil price projections[86], which are consistent with a level of policy ambition which falls short of net-zero CO_2 in 2050. Because seeking to achieve net-zero CO_2 emissions in aviation implies a high level of climate ambition in other sectors, we used lower oil prices post-2040 in scenarios where there is large-scale use of alternative technology in aviation (transitioning from the SDS trajectory to the IEA Net Zero Emissions by 2050 Scenario (NZE) projections[6]; Supplementary Fig. 2). Future technology costs and capabilities are also uncertain. For this paper, the key sensitivity is to fuel costs and we addressed this using alternative fuel cost projections, as discussed in the main paper.

Data availability

The datasets generated during the current study are available from the corresponding authors on reasonable request.

Code availability

A version of the open-source code of the Aviation Integrated Model AIM2015, adjusted to remove confidential data, underlying this study can be downloaded at http://www.atslab.org/data-tools/

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Author contributions

A.W.S., L.D., S.R.H.B. and F.A. conceived and conceptualized the study. C.F., A.W.S. and F.A. conducted the fuel pathway analyses. C.G., M.E.J.S. and S.R.H.B. conducted analyses of climate assessments and contrail avoidance. L.D. led the scenario analysis and integration of technologies into AIM2015. All authors commented on the results and contributed to the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

Extended data is available for this paper at https://doi.org/10.1038/s41558-022-01485-4.

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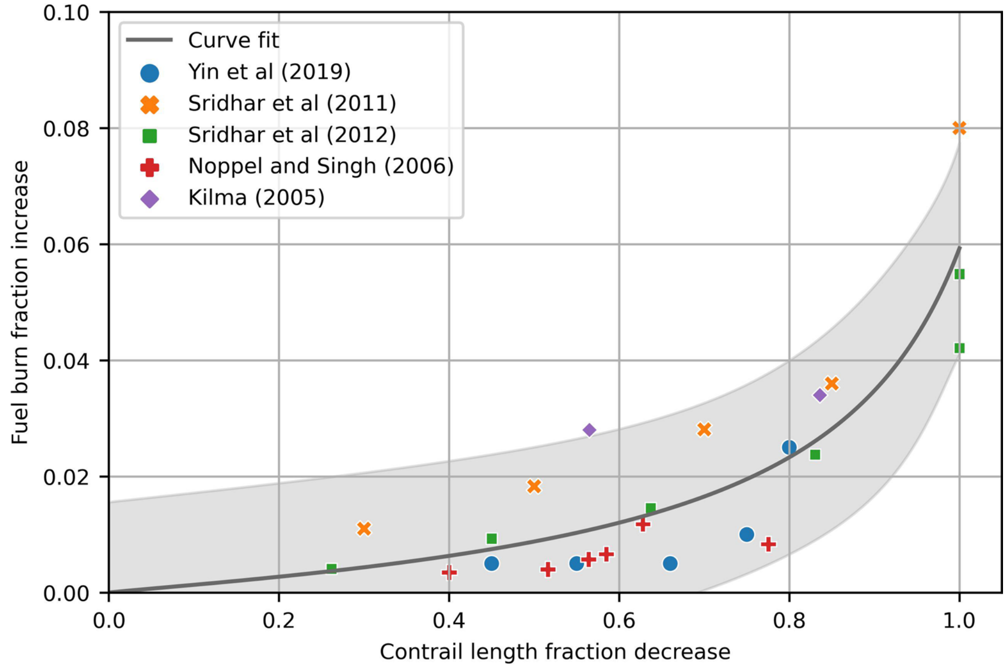

Extended Data Fig. 1 | Fuel burn penalty for contrail length avoided related to a fuel-optimized flight baseline.

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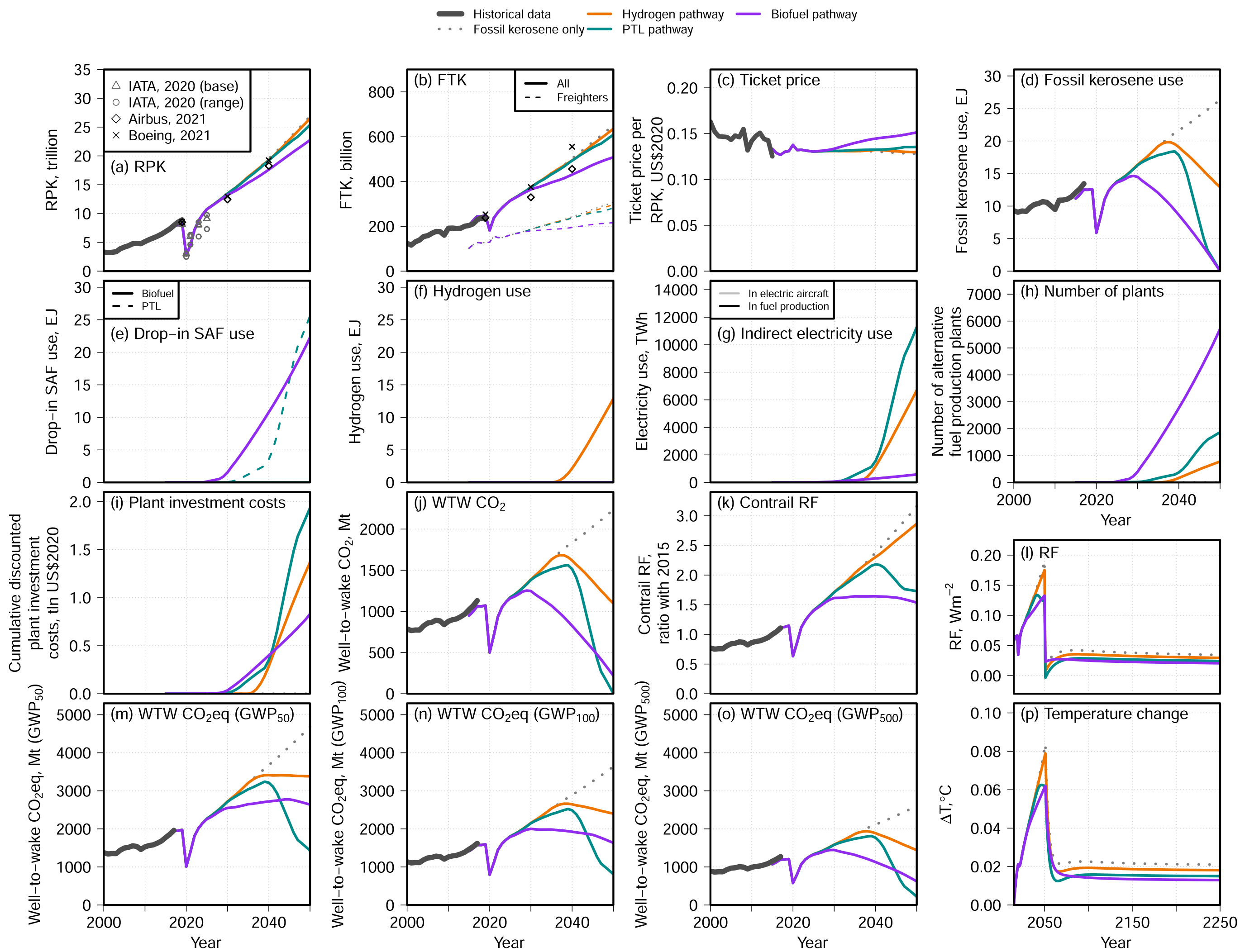

Extended Data Fig. 2 | Middle demand scenario projections of aviation system characteristics with individual technology pathways.

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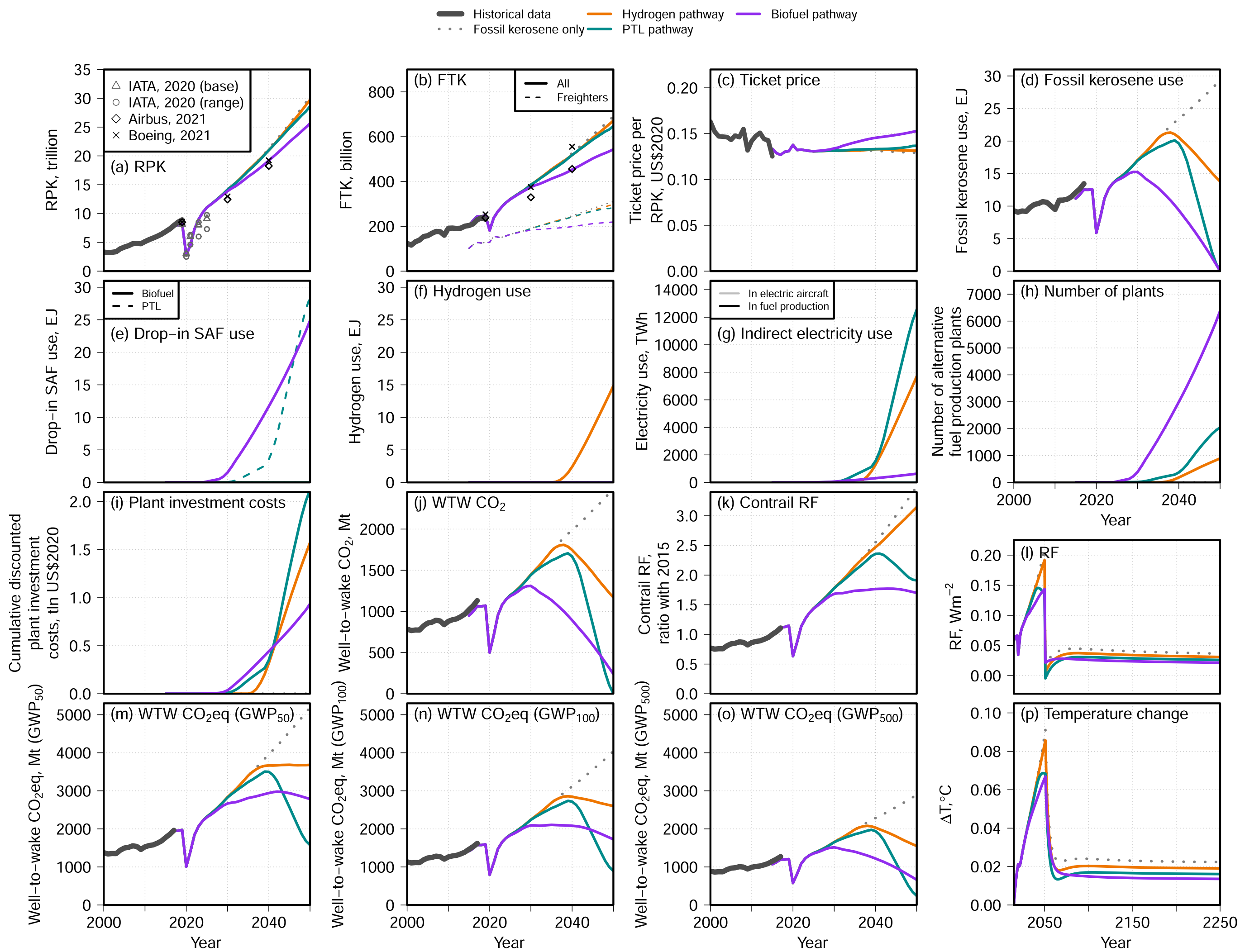

Extended Data Fig. 3 | High demand scenario projections of aviation system characteristics with individual technology pathways.

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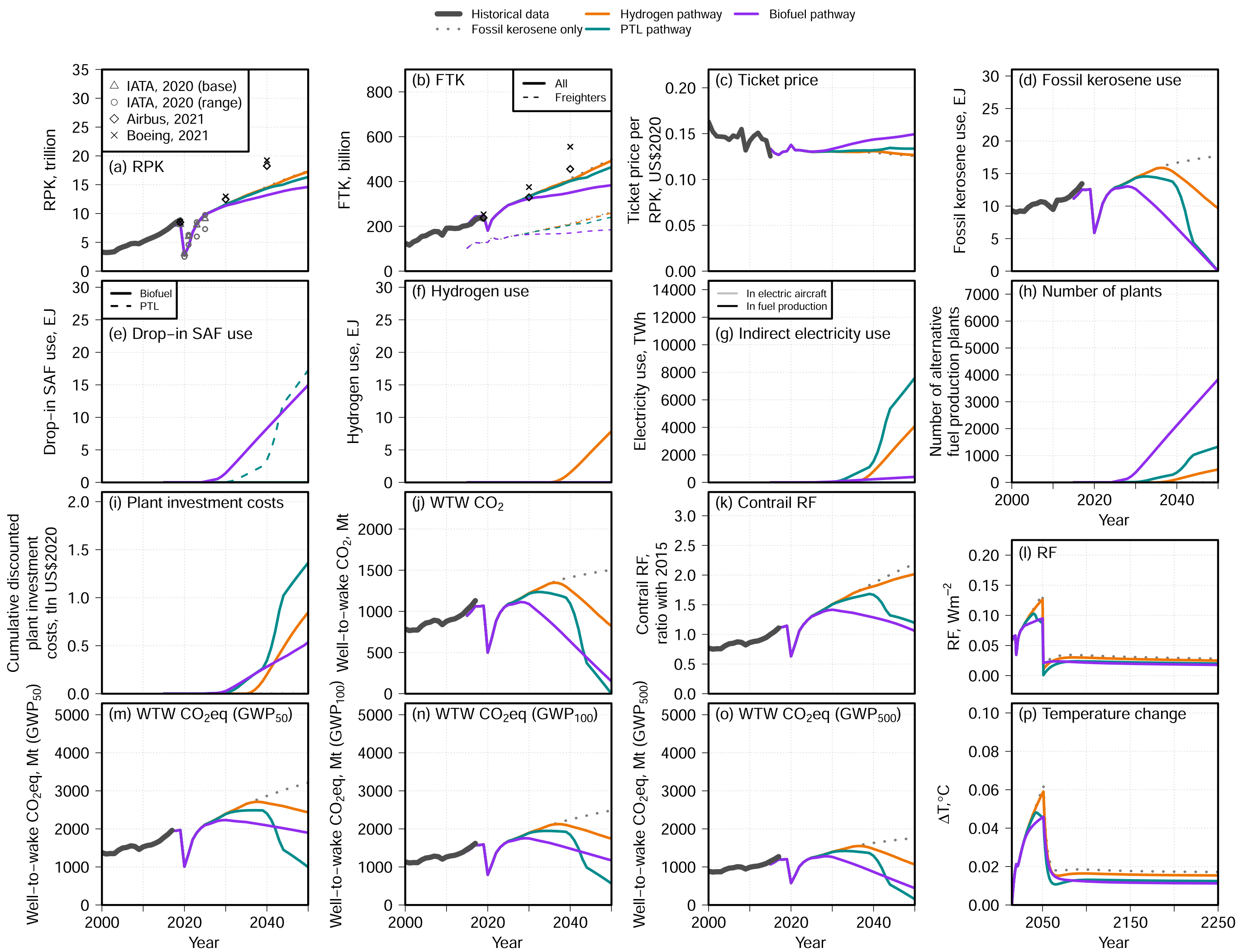

Extended Data Fig. 4 | Low demand scenario projections of aviation system characteristics with individual technology pathways.

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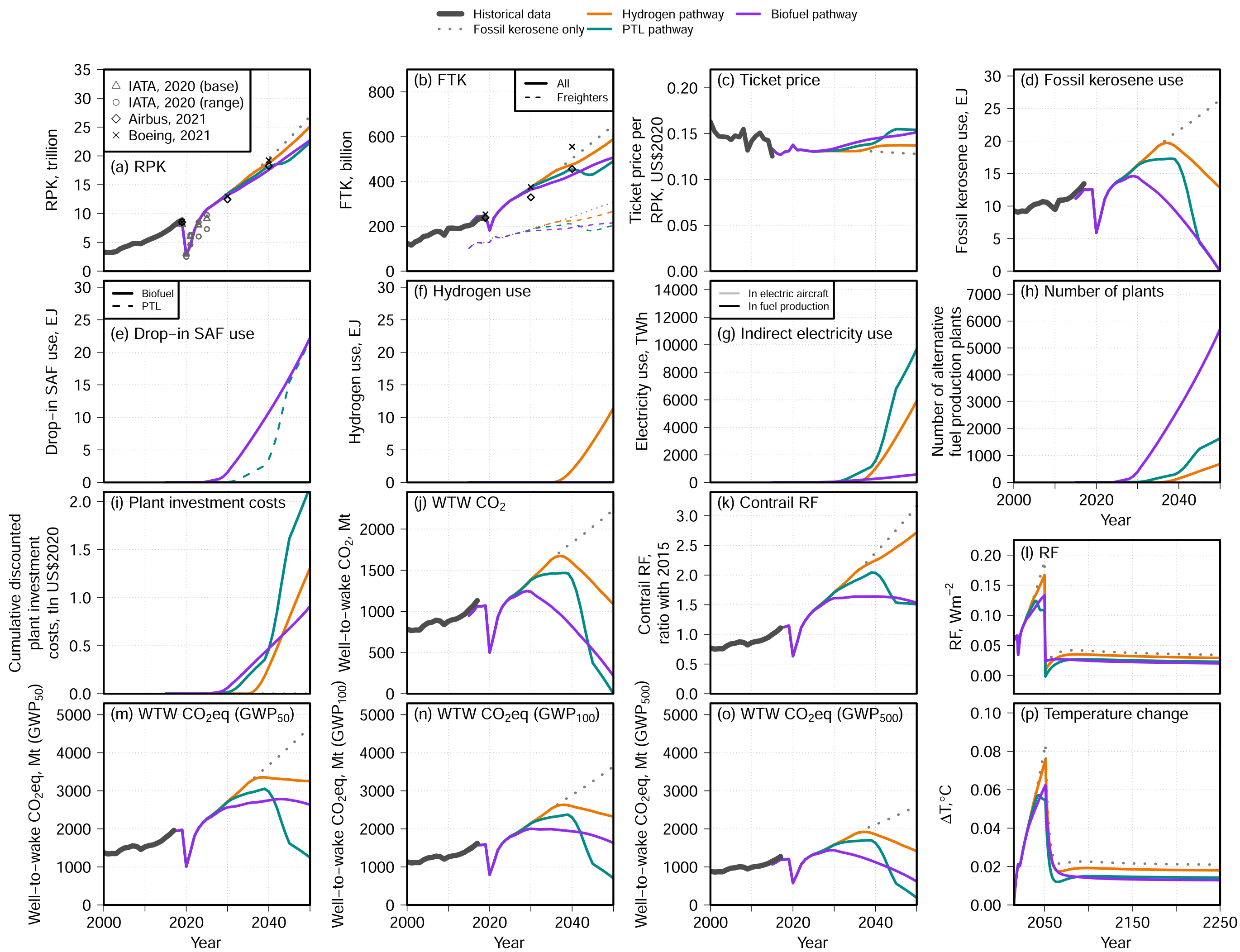

Extended Data Fig. 5 | Middle demand scenario projections of aviation system characteristics with individual technology pathways and fuel mandates, high LH2 and PTL cost sensitivity case.

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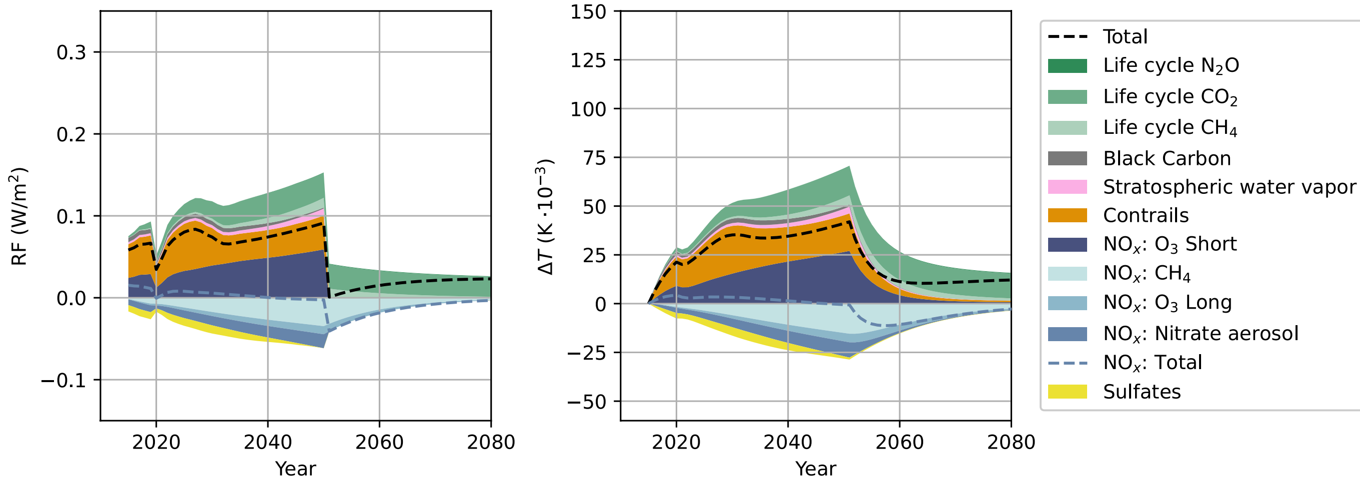

Extended Data Fig. 6 | Relative contribution of each climate forcing pathway for the combined biofuel and LH2 scenario, capturing emissions from 2015 to 2050, radiative forcing (left), temperature change (right).

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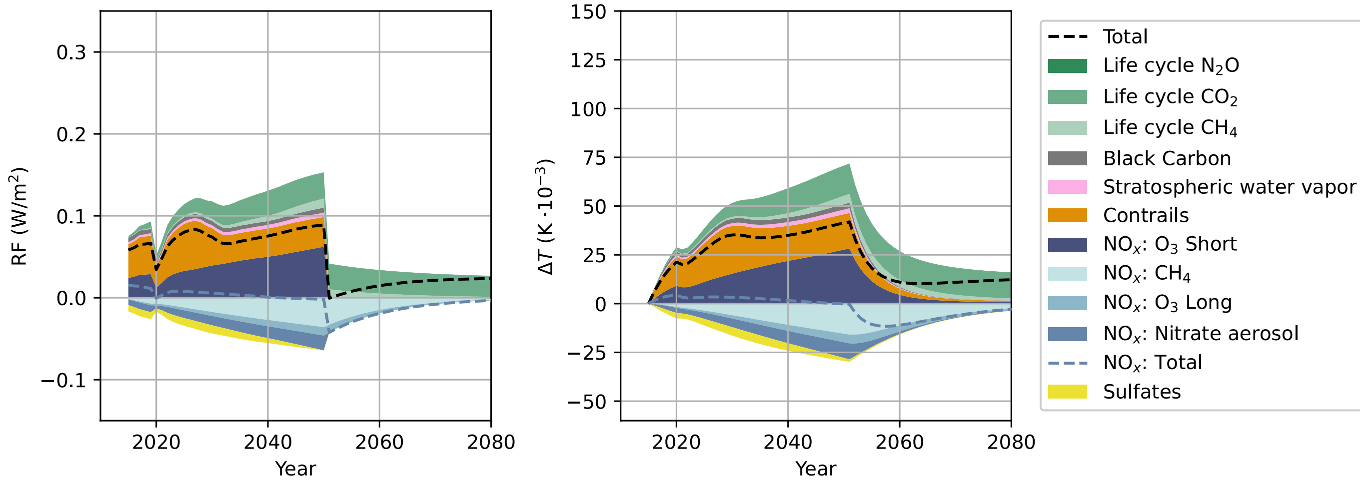

Extended Data Fig. 7 | Relative contribution of each climate forcing pathway for the combined biofuel and PTL scenario, capturing emissions from 2015 to 2050, radiative forcing (left), temperature change (right).

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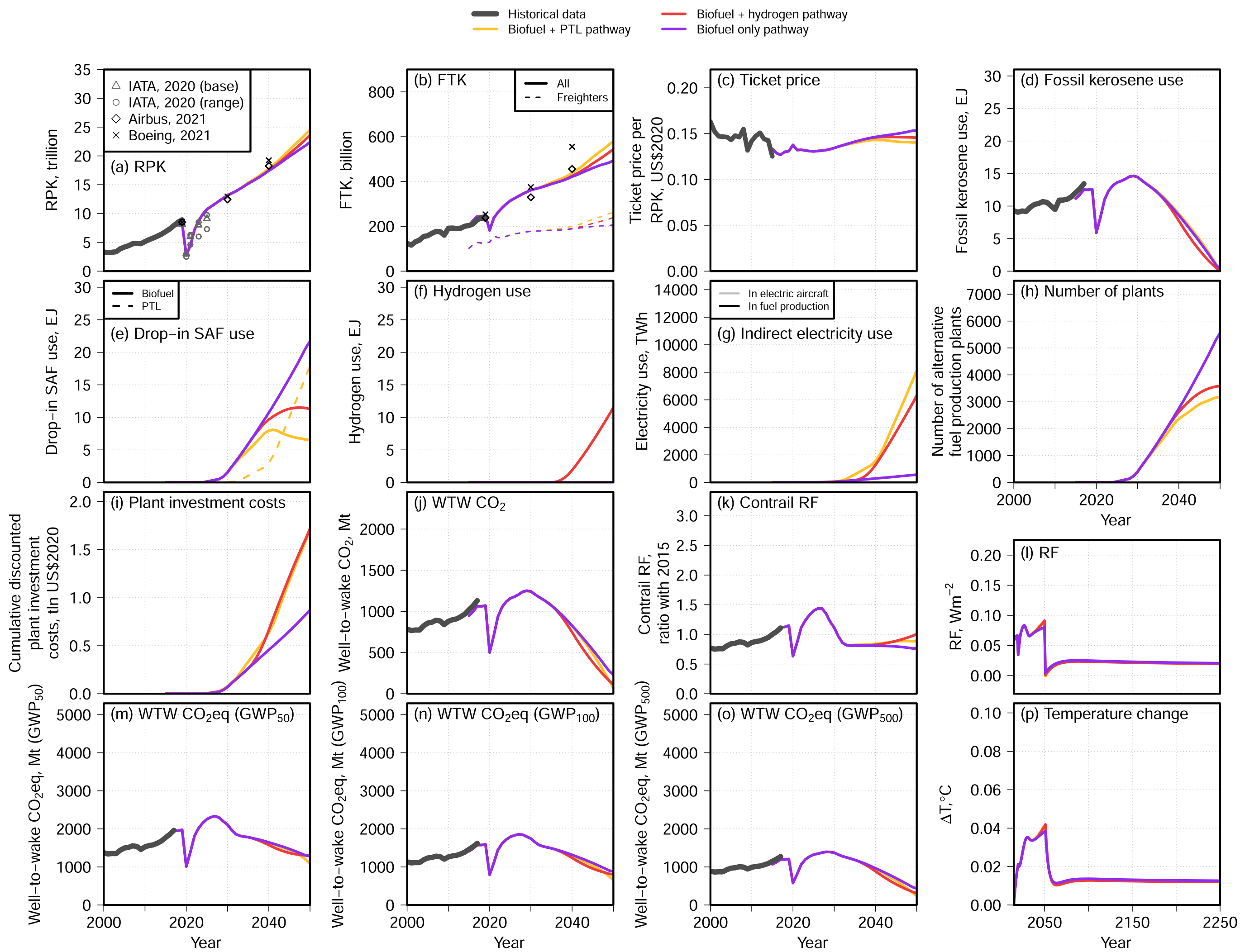

Extended Data Fig. 8 | Middle demand scenario projections of aviation system characteristics with biofuel-only and biofuel as a bridging fuel to PTL and LH2.

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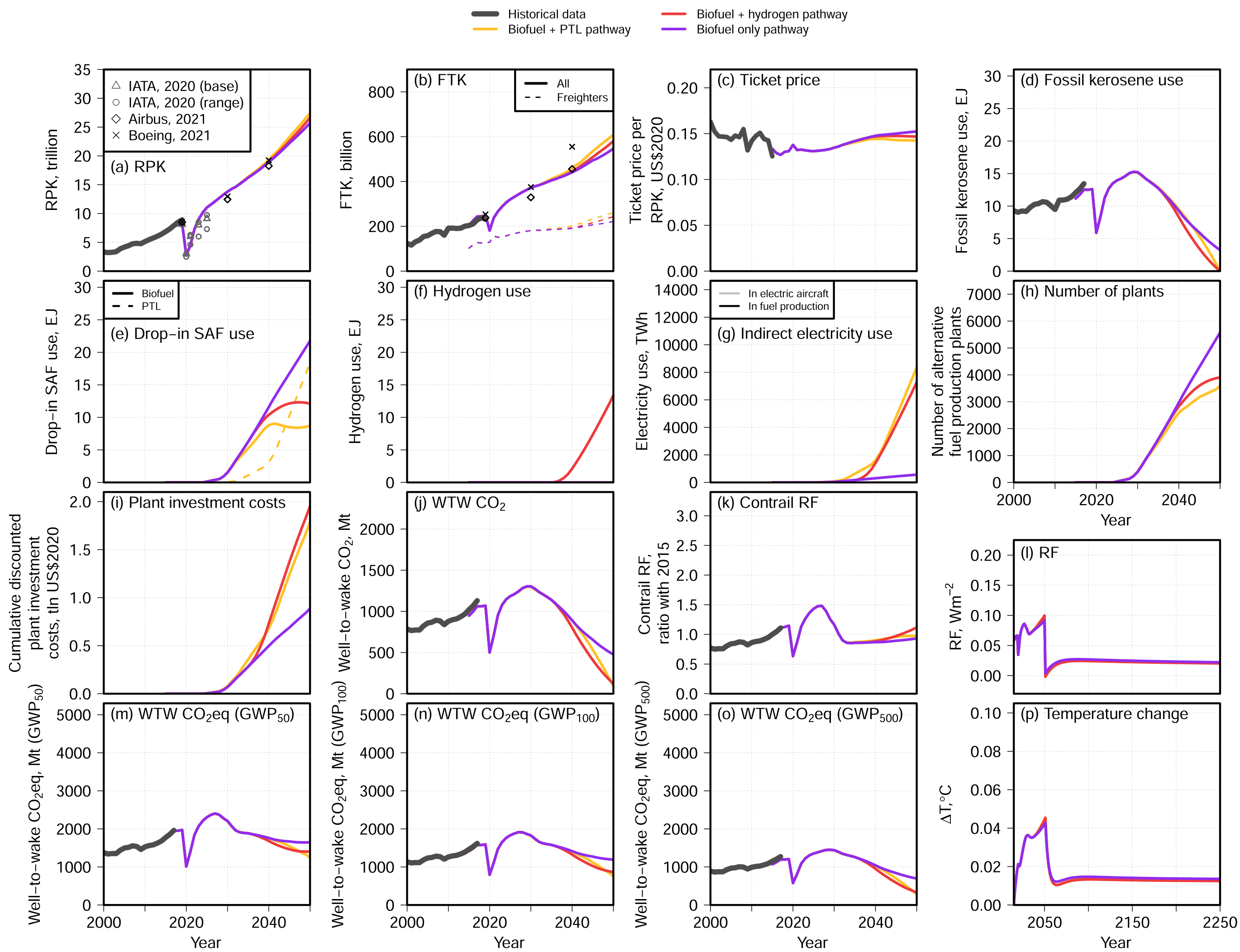

Extended Data Fig. 9 | High demand scenario projections of aviation system characteristics with biofuel-only and biofuel as a bridging fuel to PTL and LH2.

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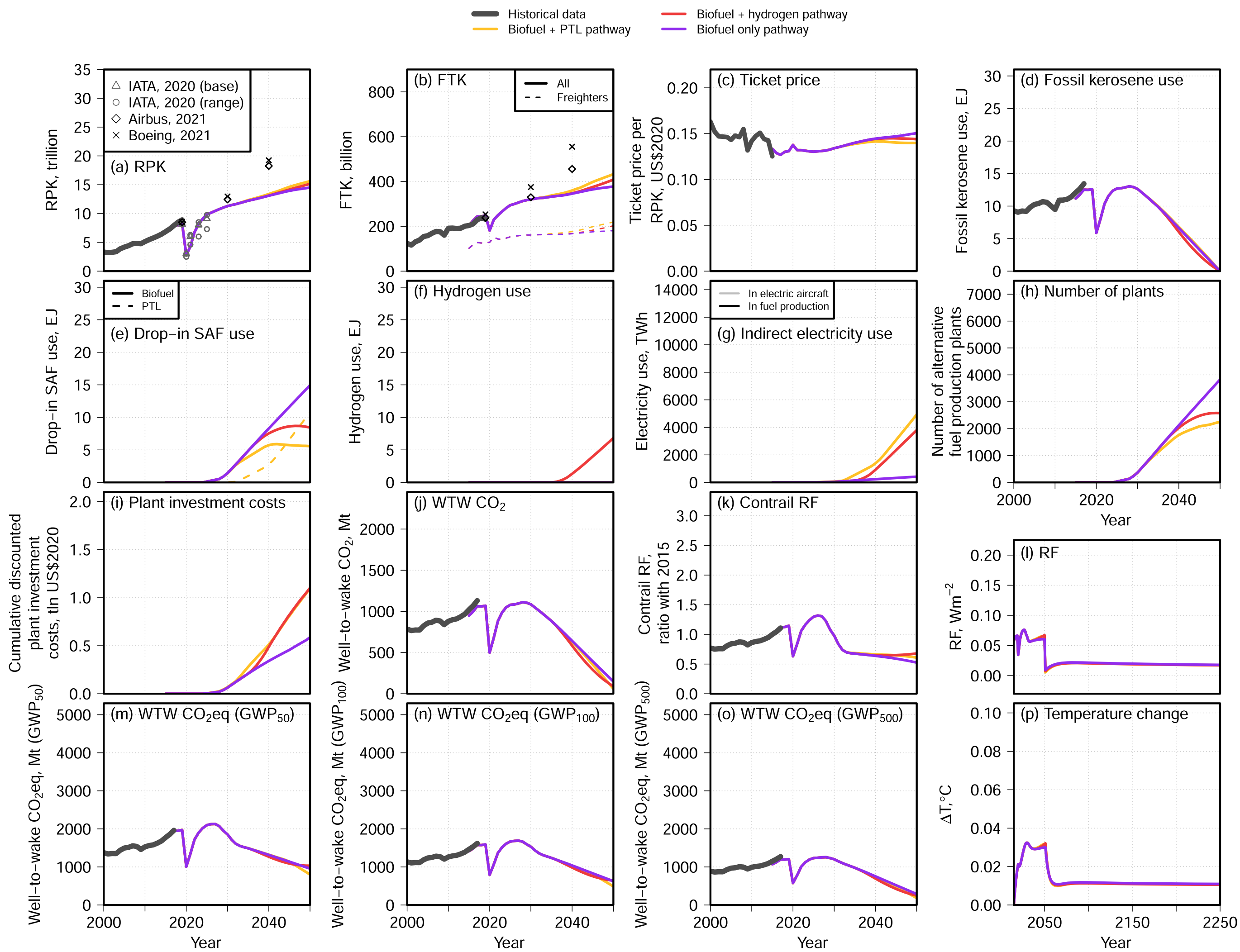

Extended Data Fig. 10 | Low demand scenario projections of aviation system characteristics with biofuel-only and biofuel as a bridging fuel to PTL and LH2.