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

Lynnette Dray(1), Andreas W. Schäfer(1), Carla Grobler(2), Christoph Falter(2),
Florian Allroggen(2), Marc E.J. Stettler(3), Steven R.H. Barrett(2)

(1) Air Transportation Systems Laboratory, School of Environment, Energy and Resources, University College London, London WC1E 6BT

(2) MIT Laboratory for Aviation and the Environment, Department of Aeronautics and Astronautics, Massachusetts Institute of Technology, Cambridge MA, 02139

(3) Department of Civil and Environmental Engineering, Imperial College London, London SW7 2AZ

Corresponding authors: a.schafer@ucl.ac.uk, sbarrett@mit.edu

Abstract: Aviation emissions are not on a trajectory consistent with Paris Climate Agreement goals.[1,2] We evaluate the extent to which fuel pathways could lead aviation towards net-zero climate impacts: synthetic fuels from biomass, synthetic fuels from green hydrogen and atmospheric CO_2, and the direct use of green liquid hydrogen. 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 to 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 to a no intervention baseline leading to

demand suppression less than 14%. These pathways will require discounted investments on the order of \$0.5-2.1 trillion over a 30-year period. However, our pathways reduce aviation CO_2-equivalent emissions by 46-69% only; more action is required to mitigate non-CO_2 impacts.

Main

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[3,4], 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[2,5,6], particularly when considering non-CO_2 climate impacts.[2] Most mitigation scenarios project net positive aviation CO_2 in 2050.[7–9] For studies looking at net zero within the aviation sector, significant scale-up in alternative fuel use (either drop-in fuels[10–12] or hydrogen[13]), and potentially demand-reducing measures[1,14], are widely identified as necessary conditions. Most studies investigating pathways towards zero climate impacts explore limited regional scopes[6,8,10,15]; exclude non-drop-in fuels, such as hydrogen[1,2,7,8,10–12,15]; do not examine transition costs[9,11,12]; or do not quantify non-CO_2 impacts[1,7,8,10–13,15]. 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 vapor; indirect warming from contrails; and indirect NO_x 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 vapor, 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 to or less than their sinks. [16] We disaggregate factors that affect aviation's climate forcing emissions using Eq (1). These emissions are driven by: aviation's level of activity (in revenue tonne-km, RTK); energy intensity (Energy/RTK); and CO_2eq 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.

$$\mathrm{CO_{2eq}} = \mathrm{RTK}\,\frac{\mathrm{Energy}}{\mathrm{RTK}}\,\frac{\mathrm{CO_{2\,eq}}}{\mathrm{Energy}} - \mathrm{offsets} \qquad \text{Eq.1}$$

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 (SI 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% p.a., 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 which directly reduce air transportation demand (e.g., French government policy aiming at displacing short-haul flights with high-speed rail [14]). However, our integrated aviation systems model AIM2015 considers 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 (e.g., 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-year 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, e.g., 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, e.g., 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 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 (e.g., CO_2 capture from the atmosphere) are still under development. In such cases, Table 1 represents ambitious future states of the technology.

[Table 1]

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 vapor, contrails and contrail-cirrus, oxides of nitrogen, and sulfur TTW emissions contribute 30-67% to aviation's total radiative forcing impacts.[3,4] The largest contribution, 41-57% of in-flight climate impacts, has been attributed to contrail-cirrus.[3,4]

The different chemical composition of alternative fuels leads 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[27–29], 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 factor 2.6 increase in warming from stratospheric water vapor emissions; (2) elimination of sulfur related cooling; and (3) a 15% reduction in contrail warming. Results for alternative GWP time horizons are presented in SI 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) [30,31], 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.[27,32–34] Using results from our meta-analysis of contrail avoidance (Methods), we assume 50% of contrail length can be avoided at a 1% increase in fuel burn (ED 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 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.[35] 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, 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 analyze 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 these fuel pathways and a no-intervention baseline under different demand scenarios, defined by socio-economic development, oil prices, technological change, and other factors (derived from IPCC's 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 EJ) in 2030 and imply drop-in fuel supply of nearly 26 EJ in 2050.[36] However, it is unclear to what extent the associated biomass of ~52 EJ/yr would be available for aviation use.[24,36,37] (Methods and SI 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 \$0.5 tln to \$2.1 tln, 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 p.a.

[Table 2]

Following the single-fuel pathways, only PTL could reduce aviation lifecycle CO_2 emissions to zero as shown for the middle demand scenario in Figure 1 (additional metrics ED Fig. 2, high demand scenario ED Fig. 3, low demand scenario ED Fig. 4). Despite the unconstrained 2050 energy supply, the single-LH2 pathway cannot achieve full market share due to fleet turnover constraints (Panels c and d). Biofuels could be adopted at significant 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 (Panel h). In addition, significant 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.

[Figure 1]

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 (panel e), equivalent to 41% and 25% of year-2020 world electricity generation.[38] 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 to the reference development (panel a), due to higher operating costs raising airfares (panel b). 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 to 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 and an 7-18% reduction in year-2050 RTK over baseline values (ED Fig. 5).

Potentials and costs of combined pathways

PTL and LH2 pathways have limited scale-up potential before the 2030s, 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 (Figure 2 a, b). Over 40% of CO_2eq emission 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 50% only, with additional benefits available from fuel composition changes. Other non-CO_2 impacts, e.g. from water vapor emissions, remain unaddressed (ED Fig. 6, 7).

The required discounted investments associated with the aviation energy transition are around $1.7 tln over the 30-year study period (12% lower than in the corresponding single-fuel PTL pathway), of which around 45% are 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. [39]

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 through to ticket prices, leading to 0.3-0.4% p.a. lower average RTK growth rates for the middle demand scenario; ED Figs. 8-10).

[Figure 2]

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, i.e., the embedded emissions of power generation to be zero (SI). 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 (SI Section 1). Thus, biofuels could be supplemented by a second wave of fuels which use renewable electricity as a major feedstock – i.e., 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 depends on their relative cost 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 significant 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 (e.g., climate impacts of hydrogen leakage[40]).

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 order $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 to 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 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 (i.e., 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.

Acknowledgements

A.S. and L.D. acknowledge funding by the UK Engineering and Physical Sciences Research Council, research grant EP/V000772/1. Some MIT contributions to this paper were funded by the U.S. Federal Aviation Administration Office of Environment and Energy through ASCENT, the FAA Center of Excellence for Alternative Jet Fuels and the Environment, project 1, 52 and 58 through FAA Award Number 13-C-AJFE-MIT under the supervision of Anna

Oldani, Daniel Jacob and Nate Brown. Any opinions, findings, conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the FAA. C.G. acknowledges fellowship and travel support from Martin Family Fellowship and the Council for Scientific and Industrial Research (CSIR) in South Africa.

Contributions

A.S., L.D., S.B., and F.A. conceived and conceptualized the study. C.F., A.S., and F.A. conducted the fuel pathway analyses. C.G., M.S. and S.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.

Tables

Table 1 Characteristics of energy carriers suitable for commercial aviation

	Jet A	Drop-in Fuels			Cryogenic Fuels			Electricity
		Low-cost Biofuels (1)	High-Cost Biofuels (1)	Power-to-Liquids	Low-Cost SLNG (2)	High-Cost SLNG	Liquid Hydrogen	
Feedstock	Crude oil	Waste & plant oils; FTL from MSW*	Cellulosic biomass	Hydrogen & atmosph. CO_2 (3)	Animal manure, municipal wastewater	Hydrogen & atmosph. CO_2	Water & renewable electricity	Solar, wind

Fuel Supply Characteristics								
Electricity intensity in 2020 (2050), kWh(el)/kWh(fuel) (4)	~ 0	0.02	<0.01	2.1 (1.9)	0.05	2.0 (1.8)	1.8 (1.5)	1.0
Capital intensity, mln \$/boe/d in 2020 (2050) (5)	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)(8)	110 – 230 (110 – 230)	390 (110)	440 (130/195)(8)	60 – 150 (30 – 70)
Fuel resource potential, EJ	24,000-98,000	0.3 – 20.5 (6)	60 – 110 (6)	unlimited	30 (6)	unlimited	unlimited	unlimited
Climate impact intensity, $gCO_2(eq)/MJ$								
Upstream (WTT)	14.3	-61.7 – -36.1	-62.7 – -51.0	-70.4	-104.7 – -45.8	-56.4	0.0	0.0
of which CO_2	11.9	-65.9 – -48.0	-63.0 – -58.8	-70.4	-75.1 – -57.0	-56.4	0.0	0.0
of which non-CO_2 (7)	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) (7)	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 (5)	-18.7 – -10.6	0.0	0.0	0.0
of which non-CO_2(7)	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

Table Notes:

(1) The biofuels production cost range is determined by feedstock and conversion pathways; lower end: HEFA fuels and waste; higher end: energy crops. (2) The cost range of low-cost SLNG is determined by feedstock; lower end: agricultural residues, higher end: energy crops. (3) See SI Section 1.3. (4) The electricity intensity captures external electricity input. Therefore, the electricity intensity of refineries is around zero, as nearly all electric power is produced onsite. (5) Capital intensity is measured in mln dollars of investments per barrel of oil equivalent (boe) per day. (6) Resource potential of low-cost biofuels from ref.[24]. High-cost biofuels resource potential corresponds to the lower end and higher end in Table 7.34 (ref. [25]), assuming a 50% biomass to fuel conversion efficiency. The low-cost SLNG potential is based upon ref. [26] (7) The CO_2eq values in this table are derived using Global Warming Potential with a 100-year time horizon (GWP_{100}. The relative impact of CO_2 to non-CO_2 is sensitive to time horizon (SI Sections 3.2, 3.3) CO_2-eq emissions of renewable electricity are assumed to be zero. (8) Higher number: sensitivity case. In case of PTL, consistent with DAC costs of \$280 per tonne CO_2 at hydrogen production costs of \$1 per kg.

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 (2019-2050)	2.4	1.8-2.4 (3)	3.7	3.1-3.7 (3)	4.1	3.5-4.0 (3)
Aviation direct energy use in 2050, EJ (c.t. 13 EJ in 2019)	17.7	15.0-17.6 (1)	26.4	22.3-25.8(1)	29.4	24.9-28.6(1)
of which EJ provided by alternative fuel	N/A	7.9-17.2(2)	N/A	12.9-25.6(2)	N/A	14.9-28.5(2)
Well-to-wake CO_2 emissions in 2050, Mt (c.t. 1,070 mln tonnes in 2019)	1,510	0-822 (3)	2,240	0-1,100(3)	2,490	0-1,170 (3)
Cumulative (2019-2050) well-to-wake CO_2 emissions, Gt	40.1	24.9-35.3 (4)	50.0	28.0-42.3(4)	53.4	29.5-44.7(4)
Cumulative discounted climate costs, tln US$(2020) (10)	13.1	9.9-12.1(5)	15.9	11.7-14.3(6)	16.9	12.3-15.1(7)
Cumulative discounted (2019-2050) alternative fuel supply investments, tln US$(2020)	N/A	0.54-1.36 (8)	N/A	0.83-1.93 (8)	N/A	0.94-2.12(8)
Change over 2019 constant-price airfare in 2050, % (per RPK)	-4.0	-2.1-14 (9)	-2.3	-0.8-16 (9)	-1.3	0.4-17 (9)

Table Notes:

(1) Lower end biofuels, higher end LH2. (2) Lower end LH2, higher end PTL.(3) Lower end PTL, higher end LH2. (4) Lower end biofuels, higher end LH2. (5) 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. (6) 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). (7) 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). (8) Lower end biofuels, higher end PTL. Discount rate = 2%. (9) Lower end LH2, higher end biofuels.

Figure Legends

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

Figure 2 Middle demand scenario related model outputs for two combined pathways aimed at minimizing year-2050 aviation climate impact, biofuels + PTL and biofuels + hydrogen. (a) Reduction in CO_2eq (GWP_{100}) emissions by type of mitigation strategy, biofuels + PTL pathway; (b) reduction in CO_2eq emissions by type of mitigation strategy, biofuels + hydrogen pathway; (c) cumulative discounted plant investment costs, biofuels + PTL pathway; (d) cumulative discounted plant investment costs, biofuels + hydrogen pathway. 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. & ATM) includes the impact of changes in load factor, operational mitigation measures (e.g., reduced taxi time), and changes in CO_2eq from network change over time (e.g., longer average flight length). RTK reduction results from higher airfares induced by the energy transition. Non-CO_2 includes 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 SI Section 6.

References

1. Sharmina, M. *et al.* Decarbonising the critical sectors of aviation, shipping, road freight and industry to limit warming to 1.5–2°C. *Climate Policy* **21**, 455–474 (2021).
2. Grewe, V. *et al.* Evaluating the climate impact of aviation emission scenarios towards the Paris agreement including COVID-19 effects. *Nature Communications 2021 12:1* **12**, 1–10 (2021).
3. Grobler, C. *et al.* Marginal climate and air quality costs of aviation emissions. *Environmental Research Letters* **14**, (2019).
4. Lee, D. S. S. *et al.* The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018. *Atmospheric Environment* 117834 (2020) doi:10.1016/j.atmosenv.2020.117834.
5. Ivanovich, C. C., Ocko, I. I., Piris-Cabezas, P. & Petsonk, A. Climate benefits of proposed carbon dioxide mitigation strategies for international shipping and aviation. *Atmospheric Chemistry and Physics* **19**, 14949–14965 (2019).
6. Hassan, M., Pfaender, H. & Mavris, D. Probabilistic assessment of aviation CO2 emission targets. *Transportation Research Part D: Transport and Environment* **63**, 362–376 (2018).
7. IEA. *Net Zero by 2050*. (2021).
8. US Government. *Aviation greenhouse gas emissions reduction plan*. (2015).
9. Leipold, A. *et al. DEPA 2050 Development Pathways for Aviation up to 2050 - Final Report* .
10. Schäfer, A. W., Evans, A. D., Reynolds, T. G. & Dray, L. Costs of mitigating CO2 emissions from passenger aircraft. *Nature Climate Change 2015 6:4* **6**, 412–417 (2015).
11. Gössling, S., Humpe, A., Fichert, F. & Creutzig, F. COVID-19 and pathways to low-carbon air transport until 2050. *Environ. Res. Lett* **16**, 34063 (2021).
12. Kar, R., Bonnefoy, P. A., Hansman, R. J. & Sgouridis, S. Dynamics of Implementation of Mitigating Measures to Reduce Commercial Aviation's Environmental Impacts. in *9th AIAA Aviation Technology, Integration, and Operations Conference (ATIO)* (2009). doi:10.2514/6.2009-6935.
13. Girod, B., van Vuuren, D. P. & Deetman, S. Global travel within the 2°C climate target. *Energy Policy* **45**, 152–166 (2012).
14. Åkerman, J., Kamb, A., Larsson, J. & Nässén, J. Low-carbon scenarios for long-distance travel 2060. *Transportation Research Part D: Transport and Environment* **99**, 103010 (2021).
15. van der Sman, E., Peerlings, B., Kos, J., Lieshout, R. & Boonekamp, T. *A route to net zero European aviation*. (2021).
16. Fuglestvedt, J. *et al.* Implications of possible interpretations of greenhouse gas balance in the Paris Agreement. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* **376**, (2018).
17. Air Transport Action Group. *Waypoint 2050. Second edition: September 2021*. (2021).
18. Shell. *Decarbonizing Aviation: Cleared for Take-off*. (2021).
19. Dray, L. & Schäfer, A. W. Initial Long-Term Scenarios for COVID-19's Impact on Aviation and Implications for Climate Policy: *https://doi.org/10.1177/03611981211045067* 036119812110450 (2021) doi:10.1177/03611981211045067.
20. Dray, L. M. *et al.* AIM2015: Validation and initial results from an open-source aviation systems model. *Transport Policy* **79**, 93–102 (2019).
21. ATA and Ellondee. *Understanding the potential and costs for reducing UK aviation emissions, Report to the Committee on Climate Change and the Department for Transport*. (2018).
22. ICAO. *Resolution A40-18: Consolidated statement of continuing ICAO policies and practices related to environmental protection - Climate change*. (2019).

23. Stratton, R. W., Wong, H. M. & Hileman, J. I. *Life cycle greenhouse gas emissions from alternative jet fuel, PARTNER Project 28 report, Version 1.2, MIT*. (2010).

24. Staples, M. D., Malina, R., Suresh, P., Hileman, J. I. & Barrett, S. R. H. Aviation CO2 emissions reductions from the use of alternative jet fuels. *Energy Policy* **114**, 342–354 (2018).

25. GEA. *Global Energy Assessment – Toward a Sustainable Future*. (Cambridge University Press, Cambridge, UK and New York, NY, USA and and the International Institute for Applied Systems Analysis, Laxenburg, Austria, 2012).

26. IEA. Outlook for biogas and biomethane: Prospects for Organic Growth. in *World Energy Outlook Special Report* (IEA/OECD, 2020).

27. Teoh, R., Schumann, U., Majumdar, A. & Stettler, M. E. J. Mitigating the Climate Forcing of Aircraft Contrails by Small-Scale Diversions and Technology Adoption. *Environmental Science & Technology* **54**, acs.est.9b05608 (2020).

28. Burkhardt, U., Bock, L. & Bier, A. Mitigating the contrail cirrus climate impact by reducing aircraft soot number emissions. *npj Climate and Atmospheric Science* **1**, 37 (2018).

29. Caiazzo, F., Agarwal, A., Speth, R. L. & Barrett, S. R. H. Impact of biofuels on contrail warming. *Environmental Research Letters* **12**, 114013 (2017).

30. Mannstein, H., Spichtinger, P. & Gierens, K. A note on how to avoid contrail cirrus. *Transportation Research Part D: Transport and Environment* **10**, 421–426 (2005).

31. Spichtinger, P., Gierens, K., Leiterer, U. & Dier, H. Ice supersaturation in the tropopause region over Lindenberg, Germany. *Meteorologische Zeitschrift* **12**, 143–156 (2003).

32. Schumann, U., Graf, K. & Mannstein, H. Potential to reduce the climate impact of aviation by flight level changes. (2011) doi:10.2514/6.2011-3376.

33. Avila, D., Sherry, L. & Thompson, T. Reducing global warming by airline contrail avoidance: A case study of annual benefits for the contiguous United States. *Transportation Research Interdisciplinary Perspectives* **2**, 100033 (2019).

34. Yin, F., Grewe, V., Frömming, C. & Yamashita, H. Impact on flight trajectory characteristics when avoiding the formation of persistent contrails for transatlantic flights. *Transportation Research Part D: Transport and Environment* **65**, 466–484 (2018).

35. ICF Consulting. *Assessment of ICAO's Global Market-Based Measure (CORSIA) pursuant to Article 28b and for studying cost pass-through pursuant to Article 3d of the EU ETS Directive*. (2020).

36. WEF. *Clean Skies for Tomorrow: Sustainable Aviation Fuel as a Pathway to Net-Zero Aviation*. (2020).

37. Johansson, T. B., Patwardhan, A., Nakicenovic, N. & Gomez-Echeverri, L. *Global Energy Assessment - Toward a Sustainable Future*. (Cambridge University Press, Cambridge, UK and New York, NY, USA and and the International Institute for Applied Systems Analysis, Laxenburg, Austria, 2012).

38. British Petroleum. BP Statistical Review of World Energy (2022).

39. IRENA. *World Energy Transitions Outlook: 1.5°C Pathway. International Renewable Energy Agency*. (2021).

40. Cooper, J., Dubey, L., Bakkaloglu, S. & Hawkes, A. Hydrogen emissions from the hydrogen value chain-emissions profile and impact to global warming. *Science of The Total Environment* **830**, 154624 (2022).

41. ICAO. *Presentation of 2019 Air Transport Statistical Results*. https://www.icao.int/annual-report-2017/Documents/Annual.Report.2017_Air Transport Statistics.pdf (2020).

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 systems model (AIM) to model future market development, demand feedbacks and technology adoption in a consistent framework; (2) the reduced-order climate model APMT Impacts Climate 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.

Aviation Integrated Model (AIM)

The Aviation Integrated Model (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 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 EC[36] and UK 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, are simulated and, in the case of hydrogen aircraft, a mandatory hydrogen requirement for new purchases is simulated (phased in over 5 years from hydrogen aircraft first entry into service). A Net Present Value (NPV) model is used to assess uptake of other new aircraft technologies and technology-fuel combinations within those consistent with mandate requirements. For drop-in fuels, adoption is based on the lowest cost to airlines once any mandate requirements, carbon, NO_x or contrail-related costs are 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 are taken from refs. [10,21,43]. For electric aircraft, performance characteristics, including range limitations, are taken from ref. [44] for single-aisle aircraft, and ref. [45] for regional jets. Operating cost characteristics are 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 e.g. 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 assume energy intensity and nonfuel operating costs of LH2 aircraft equal to those of conventional aircraft of a comparable generation and size, i.e. that the operating cost difference between conventional and hydrogen aircraft is dominated by fuel costs. We assume 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 modeling

We model the climate impacts of aviation emissions using the Aviation environmental Portfolio Management Tool - Impacts Climate (APMT-IC) as described in refs. [3,49]. APMT-IC probabilistically evaluates the physical climate impacts from global aviation emissions and estimates the associated monetary damages. Our use of this model is two-fold. First, we use it to derive Global Warming Potentials (GWP) for each of the precursor emissions (SI Section 3.2). These GWP values are used convert non-CO_2 emissions to CO_2eq emissions. Second, we use it to calculate radiative forcing and atmospheric surface temperature change response for each the future emissions pathways generated by AIM.

The implementation of APMT-IC used here is described in refs. [3,49]. The model has been updated to capture recent research results (1) on the contrail-cirrus forcing and subsequent expected atmospheric temperature response to this forcing[4,50]; (2) on the NO_x-related methane forcing; (3) on 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. [4], we update 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 apply 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 align with the ERF/RF adjustment from ref. [4] and apply 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 allows us to capture the expected temperature change associated with the updated contrail-cirrus RF.

We note some unquantified uncertainties are not captured in this approach. Firstly, 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] Secondly, the adjustment factors from refs. [55,56] represent long-term climate feedbacks for linear contrails only, derived using contrail formation more than 50 times expected contrail coverage in 2050. This upscaling may cause saturation of feedback effects such as cloud formation.[58–60] After these adjustments, we find a 33% net reduction in temperature change associated with contrail-cirrus per distance flown as compared to ref. [3]. Additionally, we normalize contrail impacts by the AEDT distance for flights in 2006 as reported in ref. [4].

The second update aligns the NO_x-related methane forcing with more recent literature on the radiative interaction of methane. Following the method of ref. [4], we increase the forcing of NO_x 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. [4] are 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 apply 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 literature and explicitly treats dependencies between different underlying studies to avoid overrepresentation of results from specific studies. This change leads to social cost of carbon of 246 USD_{2020}/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, RCP4.5 and SSP1 the social cost of carbon in 2020 is 158 USD_{2020}/tonne CO_2 (90% confidence interval 46.4 to 352) in 2020 USD. While this represents a factor ~2.8 increase above the previous APMT-IC social cost of carbon, these values are in-line with recent literature global social cost of carbon estimates of 80 - 805 USD.[67–69]

Finally, due to changes in the non-CO_2 emissions footprint of LH2, LNG and SAF, the subsequent climate impacts are also expected to differ.[70,71] For each fuel considered, we derive adjustment factors by emission species based on 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 Section 3 of the SI.

Alternative fuel pathways

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

- Liquid hydrogen (LH2): We consider liquid hydrogen produced via water electrolysis and subsequent liquefaction, both powered by renewable electricity. The electrolysis of water is modeled based on the proton-exchange membrane (PEM) 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.

- Power-to-liquid fuels (PTL): We consider power-to-liquids based on hydrogen from water electrolysis and CO_2 from direct air capture. Hydrogen is produced at varying loads from PEM 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 (FT), 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 consider biofuels produced from dedicated biomass and waste streams including the following pathways: HEFA (hydrogenated esters and fatty acids) process using dedicated vegetable oil crops (e.g., 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, 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 assume the main constraint on LH2 ramp-up is fleet penetration of LH2 aircraft; for PTL and biofuels, maximum ramp-up rates are set using a combination of near-term literature estimates of supply and longer-term estimates of aviation fuel demand (SI Section 1). For single-fuel pathways, biomass availability is modeled after ref. [24]'s F1-A1-S2 scenario, 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/y in 2050). These assumptions are used as the fundamental availability for these pathways, while the specific use of fuels is then determined with the AIM model taking into account demand effects, mandate levels, scale-up behavior and prices. For the combined-pathway model runs a more constrained biomass supply is assumed, rising to a maximum of 21.7 EJ in 2050, based on Ref. [37] (SI Section 1).

Production costs: We determine alternative fuel pathway costs (except for biofuel pathways) with the levelized cost of energy approach. To this end, we determine the investment costs of the facilities based on energy and mass balances, and component cost estimates from the literature. We assume improvements of component efficiencies and energy demands in line with recent publications. The levelized costs of intermittent renewable electricity is assumed to be

$0.04/kWh today at a capacity factor of 30% and $0.02/kWh at 50% in 2050, where these estimates are based on a mix of solar PV and onshore wind technologies. Additionally, we include energy storage for parts of the facilities that must run continuously and thus use an LCOE of $0.10/kWh (year 2020) and $0.05/kWh (year 2050) for renewable electricity that is available around the clock. The costs are annualized assuming a lifetime of 20 years and a discount rate of 10%. The minimum selling price of the different biofuel pathways is based on a discounted cash flow rate of return analysis as shown in ref. [72]

GHG emissions: The life cycle emissions of electricity from solar PV and wind are assumed to be zero (see SI Section 1 for estimate on embedded emissions). While currently there are still embedded emissions in the production of PV modules and wind turbines, these are expected to approach zero with the decarbonization of the economy. For GHG emissions of biofuels, we use literature values from ref. [24]. for the different pathways in our study. The authors indicate values for today and for 2050, and we use linear interpolation to get values in between. We neglect embedded emissions of all infrastructure for the fuel pathways due to the expected small impact (see SI Section 1, for estimates). We use 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) are not included here and remain highly uncertain due to uncertainties in leakage rates and climate impacts. [40,76] Other non-CO_2 impacts on the atmosphere are discussed in 'Climate impact modeling' above, 'Contrail avoidance modeling' below, and in Section 3 of the SI.

Contrail avoidance modeling

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 with where contrails can form (refs. [32,33,77]). These diversions lead to a small fuel burn penalty (typically less than 5% of fleetwide fuel consumption) compared to 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; in turn, less than 2% of flights would have to be diverted to avoid contrail warming impacts[27].

Contrail avoidance is modelled using results from our contrail avoidance meta-analysis based on a literature review of five different studies[34,77–80] (SI Section 2). Using these studies, we estimate 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.

$$\mathrm{f(x)} = \mathrm{C}_0 \left(-1 + \frac{\mathrm{C}_1}{\mathrm{C}_1 - \mathrm{x}}\right)^{\mathrm{C}_2} \qquad \text{Eq. 2}$$

Performing this curve fit yields coefficients of $\mathrm{C}_0 = 0.011$, $\mathrm{C}_1 = 1.161$, and $\mathrm{C}_2 = 0.906$. 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 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 is selected for our combined technology pathways in which 50% fleet-wide contrail avoidance can 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 literature. The 50% length avoidance is lower compared to other studies, which calculate maximum contrail impact avoidance of 70-80%. However, this mid-range value of 50% is selected since high rates of avoidance will cause increased strain on airspace and air traffic control[27] and maximum rates of contrail avoidance may be difficult to achieve with current weather prediction data. [27]This contrail avoidance trade-off likely differs for alternative energy carriers such as hydrogen, but data on these differences remains unavailable. Therefore, we apply the same results from Equation 2 for alternative fuels (SI 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 examine outcomes across three demand scenarios, described below. For each demand scenario, we run: 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/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 which take account of the COVID19 pandemic is described in ref. [19]. Baseline population and GDP/capita growth rates are derived from the IPCC SSP scenarios,[81] adjusted for COVID19 pandemic GDP/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 SI 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 scenario based on IPCC SSP3 socioeconomic factors, which leads to post-pandemic demand growth which is lower than historical trends. The low demand scenario includes 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-year period. For reference cases, we use IEA SDS 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 use lower oil prices post-2040 in scenarios where there is significant use of alternative technology in aviation (transitioning from the SDS trajectory to the IEA NZE projections [7] (SI Figure 2). Future technology costs and capabilities are also uncertain. For this paper, the key sensitivity is to fuel costs and we address this through the use of alternative fuel cost projections, as discussed in the main paper.

Data availability

The datasets generated during the current study are available from the corresponding author 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/

References

42. Dray, L. & Doyme, K. Carbon leakage in aviation policy. *Climate Policy* **19**, 1284–1296 (2019).
43. Dray, L. M., Schäfer, A. W. & Al Zayat, K. The Global Potential for CO2 Emissions Reduction from Jet Engine Passenger Aircraft. *Transportation Research Record: Journal of the Transportation Research Board* **2672**, 40–51 (2018).
44. Gnadt, A. R., Speth, R. L., Sabnis, J. S. & Barrett, S. R. H. Technical and environmental assessment of all-electric 180-passenger commercial aircraft. *Progress in Aerospace Sciences* **105**, 1–30 (2019).
45. Hepperle, M. Electric flight – potential and limitations. in *Energy Efficient Technologies and Concepts of Operation* (2012).
46. Schäfer, A. W. *et al.* Technological, economic and environmental prospects of all-electric aircraft. *Nature Energy 2018 4:2* **4**, 160–166 (2018).
47. Brewer, G. *Hydrogen Aircraft Technology*. (CRC Press, 1991).
48. Clean Sky. *Hydrogen-powered aviation: preparing for take-off.* (2020).
49. de Jong, S. *et al.* Using dynamic relative climate impact curves to quantify the climate impact of bioenergy production systems over time. *GCB Bioenergy* **11**, 427–443 (2018).
50. Bickel, M., Ponater, M., Bock, L., Burkhardt, U. & Reineke, S. Estimating the effective radiative forcing of contrail cirrus. *Journal of Climate* **33**, 1991–2005 (2020).
51. Burkhardt, U. & Kärcher, B. Global radiative forcing from contrail cirrus. *Nature Climate Change* **1**, 54–58 (2011).
52. Bock, L. & Burkhardt, U. Reassessing properties and radiative forcing of contrail cirrus using a climate model. *Journal of Geophysical Research* **121**, 9717–9736 (2016).
53. Schumann, U., Penner, J. E., Chen, Y., Zhou, C. & Graf, K. Dehydration effects from contrails in a coupled contrail-climate model. *Atmospheric Chemistry and Physics* **15**, 11179–11199 (2015).
54. Chen, C. C. & Gettelman, A. Simulated radiative forcing from contrails and contrail cirrus. *Atmospheric Chemistry and Physics* **13**, 12525–12536 (2013).
55. Ponater, M., Pechtl, S., Sausen, R., Schumann, U. & Hüttig, G. Potential of the cryoplane technology to reduce aircraft climate impact: A state-of-the-art assessment. *Atmospheric Environment* **40**, 6928–6944 (2006).
56. Rap, A., Forster, P. M., Haywood, J. M., Jones, A. & Boucher, O. Estimating the climate impact of linear contrails using the UK Met Office climate model. *Geophysical Research Letters* **37**, 20703 (2010).
57. Ponater, M., Bickel, M., Bock, L. & Burkhardt, U. Towards determining the contrail cirrus efficacy. *Aerospace* **8**, 1–10 (2021).
58. Wuebbles, D. *et al.* Issues and Uncertainties Affecting Metrics For Aviation Impacts on Climate. *Bull Am Meteorol Soc* **91**, 491–496 (2010).
59. Lund, M. T. *et al.* Emission metrics for quantifying regional climate impacts of aviation. *Earth System Dynamics* **8**, 547–563 (2017).
60. Fuglestvedt, J. S. *et al.* Transport impacts on atmosphere and climate: Metrics. *Atmospheric Environment* **44**, 4648–4677 (2010).
61. Etminan, M., Myhre, G., Highwood, E. J. & Shine, K. P. Radiative forcing of carbon dioxide, methane, and nitrous oxide: A significant revision of the methane radiative forcing. *Geophysical Research Letters* **43**, 614–623 (2016).
62. Nordhaus, W. D. Revisiting the social cost of carbon. *Proceedings of the National Academy of Sciences* **114**, 1518–1523 (2017).
63. US Government. *Technical Support Document: Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis*. (2016).

64. Greenstone, M. A New Path Forward for an Empirical Social Cost of Carbon. Preprint at (2016).

65. US Government. *Technical Support Document: Social Cost of Carbon, Methane, and Nitrous Oxide: Interim Estimates under Executive Order 13990*. (2021).

66. Howard, P. H. & Sterner, T. Few and Not So Far Between: A Meta-analysis of Climate Damage Estimates. *Environmental and Resource Economics* **68**, 197–225 (2017).

67. Hänsel, M. C. *et al.* Climate economics support for the UN climate targets. *Nature Climate Change* **10**, 781–789 (2020).

68. Pindyck, R. S. The social cost of carbon revisited. *Journal of Environmental Economics and Management* **94**, 140–160 (2019).

69. Ricke, K., Drouet, L., Caldeira, K. & Tavoni, M. Country-level social cost of carbon. *Nature Climate Change* **8**, 895–900 (2018).

70. Grewe, V. *et al.* Assessing the climate impact of the AHEAD multi-fuel blended wing body. *Meteorologische Zeitschrift* **26**, 711–725 (2017).

71. Withers, M. R. *et al.* Economic and environmental assessment of liquefied natural gas as a supplemental aircraft fuel. *Progress in Aerospace Sciences* vol. 66 17–36 Preprint at https://doi.org/10.1016/j.paerosci.2013.12.002 (2014).

72. Bann, S. J. *et al.* The costs of production of alternative jet fuel: A harmonized stochastic assessment. *Bioresource Technology* **227**, 179–187 (2017).

73. Seber, G. *et al.* Environmental and economic assessment of producing hydroprocessed jet and diesel fuel from waste oils and tallow. *Biomass and Bioenergy* **67**, 108–118 (2014).

74. Suresh, P. Environmental and economic assessment of transportation fuels from municipal solid waste. (Massachusetts Institute of Technology, 2016).

75. Staples, M. D. *et al.* Lifecycle greenhouse gas footprint and minimum selling price of renewable diesel and jet fuel from fermentation and advanced fermentation production technologies. *Energy & Environmental Science* **7**, 1545–1554 (2014).

76. Ocko, I. B. & Hamburg, S. P. *Climate consequences of hydrogen leakage*. (2022).

77. Sridhar, B., Ng, H. K. & Chen, N. Y. Aircraft trajectory optimization and contrails avoidance in the presence of winds. in *Journal of Guidance, Control, and Dynamics* vol. 34 1577–1583 (American Institute of Aeronautics and Astronautics Inc., 2011).

78. Sridhar, B., Ng, H. K. & Chen, N. Uncertainty quantification in the development of aviation operations to reduce aviation emissions and contrails. in *28th International Congress of the Aeronautical Sciences* (2012).

79. Noppel, F., Singh, R. & Taylor, M. Contrail and cirrus cloud avoidance. in *25th International Congress of the aeronautical sciences* (eds. Noppel, F., Singh, R. & Taylor, M.) (2006).

80. Klima, K. *Assessment of a Global Contrail Modeling Method and Operational Strategies for Contrail Mitigation*. (2005).

81. O’Neill, B. C. *et al.* A new scenario framework for climate change research: The concept of shared socioeconomic pathways. *Climatic Change* **122**, 387–400 (2014).

82. IMF. *World Economic Outlook: April 2021*. (2021).

83. IATA. *COVID-19: Airline industry financial outlook update*. (2021).

84. ICAO. *Effects of Novel Coronavirus on Civil Aviation: Economic Impact Analysis*. (2021).

85. DfT. *UK Aviation Forecasts 2017*. (2017).

86. IEA. *Energy Technology Perspectives*. (2020).

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

Lynnette Dray(1), Andreas W. Schäfer(1), Carla Grobler(2), Christoph Falter(2),
Florian Allroggen(2), Marc E.J. Stettler(3), Steven R.H. Barrett(2)

(1) Air Transportation Systems Laboratory, School of Environment, Energy and Resources, University College London, London WC1E 6BT

(2) MIT Laboratory for Aviation and the Environment, Department of Aeronautics and Astronautics, Massachusetts Institute of Technology, Cambridge MA, 02139

(3) Department of Civil and Environmental Engineering, Imperial College London, London SW7 2AZ

Corresponding authors: a.schafer@ucl.ac.uk, sbarrett@mit.edu

Abstract: Aviation emissions are not on a trajectory consistent with Paris Climate Agreement goals.[1,2] We evaluate the extent to which fuel pathways could lead aviation towards net-zero climate impacts: synthetic fuels from biomass, synthetic fuels from green hydrogen and atmospheric CO_2, and the direct use of green liquid hydrogen. 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 to 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 to a no intervention baseline leading to

demand suppression less than 14%. These pathways will require discounted investments on the order of \$0.5-2.1 trillion over a 30-year period. However, our pathways reduce aviation CO_2-equivalent emissions by 46-69% only; more action is required to mitigate non-CO_2 impacts.

Main

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[3,4], 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[2,5,6], particularly when considering non-CO_2 climate impacts.[2] Most mitigation scenarios project net positive aviation CO_2 in 2050.[7–9] For studies looking at net zero within the aviation sector, significant scale-up in alternative fuel use (either drop-in fuels[10–12] or hydrogen[13]), and potentially demand-reducing measures[1,14], are widely identified as necessary conditions. Most studies investigating pathways towards zero climate impacts explore limited regional scopes[6,8,10,15]; exclude non-drop-in fuels, such as hydrogen[1,2,7,8,10–12,15]; do not examine transition costs[9,11,12]; or do not quantify non-CO_2 impacts[1,7,8,10–13,15]. 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 vapor; indirect warming from contrails; and indirect NO_x 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 vapor, 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 to or less than their sinks. [16] We disaggregate factors that affect aviation's climate forcing emissions using Eq (1). These emissions are driven by: aviation's level of activity (in revenue tonne-km, RTK); energy intensity (Energy/RTK); and CO_2eq 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.

$$\mathrm{CO_{2eq}} = \mathrm{RTK}\,\frac{\mathrm{Energy}}{\mathrm{RTK}}\,\frac{\mathrm{CO_{2\,eq}}}{\mathrm{Energy}} - \mathrm{offsets} \qquad \text{Eq.1}$$

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 (SI 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% p.a., 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 which directly reduce air transportation demand (e.g., French government policy aiming at displacing short-haul flights with high-speed rail [14]). However, our integrated aviation systems model AIM2015 considers 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 (e.g., 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-year 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, e.g., 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, e.g., 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 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 (e.g., CO_2 capture from the atmosphere) are still under development. In such cases, Table 1 represents ambitious future states of the technology.

[Table 1]

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 vapor, contrails and contrail-cirrus, oxides of nitrogen, and sulfur TTW emissions contribute 30-67% to aviation's total radiative forcing impacts.[3,4] The largest contribution, 41-57% of in-flight climate impacts, has been attributed to contrail-cirrus.[3,4]

The different chemical composition of alternative fuels leads 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[27–29], 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 factor 2.6 increase in warming from stratospheric water vapor emissions; (2) elimination of sulfur related cooling; and (3) a 15% reduction in contrail warming. Results for alternative GWP time horizons are presented in SI 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) [30,31], 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.[27,32–34] Using results from our meta-analysis of contrail avoidance (Methods), we assume 50% of contrail length can be avoided at a 1% increase in fuel burn (ED 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 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.[35] 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, 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 analyze 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 these fuel pathways and a no-intervention baseline under different demand scenarios, defined by socio-economic development, oil prices, technological change, and other factors (derived from IPCC's 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 EJ) in 2030 and imply drop-in fuel supply of nearly 26 EJ in 2050.[36] However, it is unclear to what extent the associated biomass of ~52 EJ/yr would be available for aviation use.[24,36,37] (Methods and SI 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 \$0.5 tln to \$2.1 tln, 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 p.a.

[Table 2]

Following the single-fuel pathways, only PTL could reduce aviation lifecycle CO_2 emissions to zero as shown for the middle demand scenario in Figure 1 (additional metrics ED Fig. 2, high demand scenario ED Fig. 3, low demand scenario ED Fig. 4). Despite the unconstrained 2050 energy supply, the single-LH2 pathway cannot achieve full market share due to fleet turnover constraints (Panels c and d). Biofuels could be adopted at significant 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 (Panel h). In addition, significant 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.

[Figure 1]

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 (panel e), equivalent to 41% and 25% of year-2020 world electricity generation.[38] 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 to the reference development (panel a), due to higher operating costs raising airfares (panel b). 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 to 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 and an 7-18% reduction in year-2050 RTK over baseline values (ED Fig. 5).

Potentials and costs of combined pathways

PTL and LH2 pathways have limited scale-up potential before the 2030s, 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 (Figure 2 a, b). Over 40% of CO_2eq emission 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 50% only, with additional benefits available from fuel composition changes. Other non-CO_2 impacts, e.g. from water vapor emissions, remain unaddressed (ED Fig. 6, 7).

The required discounted investments associated with the aviation energy transition are around $1.7 tln over the 30-year study period (12% lower than in the corresponding single-fuel PTL pathway), of which around 45% are 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. [39]

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 through to ticket prices, leading to 0.3-0.4% p.a. lower average RTK growth rates for the middle demand scenario; ED Figs. 8-10).

[Figure 2]

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, i.e., the embedded emissions of power generation to be zero (SI). 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 (SI Section 1). Thus, biofuels could be supplemented by a second wave of fuels which use renewable electricity as a major feedstock – i.e., 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 depends on their relative cost 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 significant 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 (e.g., climate impacts of hydrogen leakage[40]).

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 order \$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 to 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 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 (i.e., 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.

Acknowledgements

A.S. and L.D. acknowledge funding by the UK Engineering and Physical Sciences Research Council, research grant EP/V000772/1. Some MIT contributions to this paper were funded by the U.S. Federal Aviation Administration Office of Environment and Energy through

ASCENT, the FAA Center of Excellence for Alternative Jet Fuels and the Environment, project 1, 52 and 58 through FAA Award Number 13-C-AJFE-MIT under the supervision of Anna Oldani, Daniel Jacob and Nate Brown. Any opinions, findings, conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the FAA. C.G. acknowledges fellowship and travel support from Martin Family Fellowship and the Council for Scientific and Industrial Research (CSIR) in South Africa.

Contributions

A.S., L.D., S.B., and F.A. conceived and conceptualized the study. C.F., A.S., and F.A. conducted the fuel pathway analyses. C.G., M.S. and S.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.

Tables

Table 1 Characteristics of energy carriers suitable for commercial aviation

	Jet A	Drop-in Fuels			Cryogenic Fuels			Electricity
		Low-cost Biofuels (1)	High-Cost Biofuels (1)	Power-to-Liquids	Low-Cost SLNG (2)	High-Cost SLNG	Liquid Hydrogen	
Feedstock	Crude oil	Waste & plant oils; FTL from MSW*	Cellulosic biomass	Hydrogen & atmosph. CO_2 (3)	Animal manure, municipal wastewater	Hydrogen & atmosph. CO_2	Water & renewable electricity	Solar, wind
Fuel Supply Characteristics								
Electricity intensity in 2020 (2050), kWh(el)/kWh(fuel) (4)	~ 0	0.02	<0.01	2.1 (1.9)	0.05	2.0 (1.8)	1.8 (1.5)	1.0
Capital intensity, mln $/boe/d in 2020 (2050) (5)	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)(8)	110 – 230 (110 – 230)	390 (110)	440 (130/195)(8)	60 – 150 (30 – 70)
Fuel resource potential, EJ	24,000-98,000	0.3 – 20.5 (6)	60 – 110 (6)	unlimited	30 (6)	unlimited	unlimited	unlimited
Climate impact intensity, $gCO_2(eq)/MJ$								
Upstream (WTT)	14.3	-61.7 – -36.1	-62.7 – -51.0	-70.4	-104.7 – -45.8	-56.4	0.0	0.0
of which CO_2	11.9	-65.9 – -48.0	-63.0 – -58.8	-70.4	-75.1 – -57.0	-56.4	0.0	0.0
of which non-CO_2 (7)	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) (7)	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 (5)	-18.7 – -10.6	0.0	0.0	0.0
of which non-CO_2(7)	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

Table Notes:

(1) The biofuels production cost range is determined by feedstock and conversion pathways; lower end: HEFA fuels and waste; higher end: energy crops. (2) The cost range of low-cost SLNG is determined by feedstock; lower end: agricultural residues, higher end: energy crops. (3) See SI Section 1.3. (4) The electricity intensity captures external electricity input. Therefore, the electricity intensity of refineries is around zero, as nearly all electric power is produced onsite. (5) Capital intensity is measured in mln dollars of investments per barrel of oil equivalent (boe) per day. (6) Resource potential of low-cost biofuels

from ref.[24]. High-cost biofuels resource potential corresponds to the lower end and higher end in Table 7.34 (ref. [25]), assuming a 50% biomass to fuel conversion efficiency. The low-cost SLNG potential is based upon ref. [26] (7) The CO_2eq values in this table are derived using Global Warming Potential with a 100-year time horizon (GWP_{100}. The relative impact of CO_2 to non-CO_2 is sensitive to time horizon (SI Sections 3.2, 3.3) CO_2-eq emissions of renewable electricity are assumed to be zero. (8) Higher number: sensitivity case. In case of PTL, consistent with DAC costs of $280 per tonne CO_2 at hydrogen production costs of $1 per kg.

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 (2019-2050)	2.4	1.8-2.4 (3)	3.7	3.1-3.7 (3)	4.1	3.5-4.0 (3)
Aviation direct energy use in 2050, EJ (c.t. 13 EJ in 2019)	17.7	15.0-17.6 (1)	26.4	22.3-25.8(1)	29.4	24.9-28.6(1)
of which EJ provided by alternative fuel	N/A	7.9-17.2(2)	N/A	12.9-25.6(2)	N/A	14.9-28.5(2)
Well-to-wake CO_2 emissions in 2050, Mt (c.t. 1,070 mln tonnes in 2019)	1,510	0-822 (3)	2,240	0-1,100(3)	2,490	0-1,170 (3)
Cumulative (2019-2050) well-to-wake CO_2 emissions, Gt	40.1	24.9-35.3 (4)	50.0	28.0-42.3(4)	53.4	29.5-44.7(4)
Cumulative discounted climate costs, tln US$(2020) (10)	13.1	9.9-12.1(5)	15.9	11.7-14.3(6)	16.9	12.3-15.1(7)
Cumulative discounted (2019-2050) alternative fuel supply investments, tln US$(2020)	N/A	0.54-1.36 (8)	N/A	0.83-1.93 (8)	N/A	0.94-2.12(8)
Change over 2019 constant-price airfare in 2050, % (per RPK)	-4.0	-2.1-14 (9)	-2.3	-0.8-16 (9)	-1.3	0.4-17 (9)

Table Notes:

(1) Lower end biofuels, higher end LH2. (2) Lower end LH2, higher end PTL.(3) Lower end PTL, higher end LH2. (4) Lower end biofuels, higher end LH2. (5) 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. (6) 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). (7) 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). (8) Lower end biofuels, higher end PTL. Discount rate = 2%. (9) Lower end LH2, higher end biofuels.

Figure Legends

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

Figure 2 Middle demand scenario related model outputs for two combined pathways aimed at minimizing year-2050 aviation climate impact, biofuels + PTL and biofuels + hydrogen. (a) Reduction in CO_2eq (GWP_{100}) emissions by type of mitigation strategy, biofuels + PTL pathway; (b) reduction in CO_2eq emissions by type of mitigation strategy, biofuels + hydrogen pathway; (c) cumulative discounted plant investment costs, biofuels + PTL pathway; (d) cumulative discounted plant investment costs, biofuels + hydrogen pathway. 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. & ATM) includes the impact of changes in load factor, operational mitigation measures (e.g., reduced taxi time), and changes in CO_2eq from network change over time (e.g., longer average flight length). RTK reduction results from higher airfares induced by the energy transition. Non-CO_2 includes 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 SI Section 6.

References

1. Sharmina, M. *et al.* Decarbonising the critical sectors of aviation, shipping, road freight and industry to limit warming to 1.5–2°C. *Climate Policy* **21**, 455–474 (2021).
2. Grewe, V. *et al.* Evaluating the climate impact of aviation emission scenarios towards the Paris agreement including COVID-19 effects. *Nature Communications 2021 12:1* **12**, 1–10 (2021).
3. Grobler, C. *et al.* Marginal climate and air quality costs of aviation emissions. *Environmental Research Letters* **14**, (2019).
4. Lee, D. S. S. *et al.* The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018. *Atmospheric Environment* 117834 (2020) doi:10.1016/j.atmosenv.2020.117834.
5. Ivanovich, C. C., Ocko, I. I., Piris-Cabezas, P. & Petsonk, A. Climate benefits of proposed carbon dioxide mitigation strategies for international shipping and aviation. *Atmospheric Chemistry and Physics* **19**, 14949–14965 (2019).
6. Hassan, M., Pfaender, H. & Mavris, D. Probabilistic assessment of aviation CO2 emission targets. *Transportation Research Part D: Transport and Environment* **63**, 362–376 (2018).
7. IEA. *Net Zero by 2050*. (2021).
8. US Government. *Aviation greenhouse gas emissions reduction plan*. (2015).
9. Leipold, A. *et al. DEPA 2050 Development Pathways for Aviation up to 2050 - Final Report* .
10. Schäfer, A. W., Evans, A. D., Reynolds, T. G. & Dray, L. Costs of mitigating CO2 emissions from passenger aircraft. *Nature Climate Change 2015 6:4* **6**, 412–417 (2015).
11. Gössling, S., Humpe, A., Fichert, F. & Creutzig, F. COVID-19 and pathways to low-carbon air transport until 2050. *Environ. Res. Lett* **16**, 34063 (2021).
12. Kar, R., Bonnefoy, P. A., Hansman, R. J. & Sgouridis, S. Dynamics of Implementation of Mitigating Measures to Reduce Commercial Aviation’s Environmental Impacts. in *9th AIAA Aviation Technology, Integration, and Operations Conference (ATIO)* (2009). doi:10.2514/6.2009-6935.
13. Girod, B., van Vuuren, D. P. & Deetman, S. Global travel within the 2°C climate target. *Energy Policy* **45**, 152–166 (2012).
14. Åkerman, J., Kamb, A., Larsson, J. & Nässén, J. Low-carbon scenarios for long-distance travel 2060. *Transportation Research Part D: Transport and Environment* **99**, 103010 (2021).
15. van der Sman, E., Peerlings, B., Kos, J., Lieshout, R. & Boonekamp, T. *A route to net zero European aviation*. (2021).
16. Fuglestvedt, J. *et al.* Implications of possible interpretations of greenhouse gas balance in the Paris Agreement. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* **376**, (2018).
17. Air Transport Action Group. *Waypoint 2050. Second edition: September 2021*. (2021).
18. Shell. *Decarbonizing Aviation: Cleared for Take-off*. (2021).
19. Dray, L. & Schäfer, A. W. Initial Long-Term Scenarios for COVID-19’s Impact on Aviation and Implications for Climate Policy: *https://doi.org/10.1177/03611981211045067* 036119812110450 (2021) doi:10.1177/03611981211045067.
20. Dray, L. M. *et al.* AIM2015: Validation and initial results from an open-source aviation systems model. *Transport Policy* **79**, 93–102 (2019).
21. ATA and Ellondee. *Understanding the potential and costs for reducing UK aviation emissions, Report to the Committee on Climate Change and the Department for Transport*. (2018).
22. ICAO. *Resolution A40-18: Consolidated statement of continuing ICAO policies and practices related to environmental protection - Climate change*. (2019).

23. Stratton, R. W., Wong, H. M. & Hileman, J. I. *Life cycle greenhouse gas emissions from alternative jet fuel, PARTNER Project 28 report, Version 1.2, MIT*. (2010).

24. Staples, M. D., Malina, R., Suresh, P., Hileman, J. I. & Barrett, S. R. H. Aviation CO2 emissions reductions from the use of alternative jet fuels. *Energy Policy* **114**, 342–354 (2018).

25. GEA. *Global Energy Assessment – Toward a Sustainable Future*. (Cambridge University Press, Cambridge, UK and New York, NY, USA and and the International Institute for Applied Systems Analysis, Laxenburg, Austria, 2012).

26. IEA. Outlook for biogas and biomethane: Prospects for Organic Growth. in *World Energy Outlook Special Report* (IEA/OECD, 2020).

27. Teoh, R., Schumann, U., Majumdar, A. & Stettler, M. E. J. Mitigating the Climate Forcing of Aircraft Contrails by Small-Scale Diversions and Technology Adoption. *Environmental Science & Technology* **54**, acs.est.9b05608 (2020).

28. Burkhardt, U., Bock, L. & Bier, A. Mitigating the contrail cirrus climate impact by reducing aircraft soot number emissions. *npj Climate and Atmospheric Science* **1**, 37 (2018).

29. Caiazzo, F., Agarwal, A., Speth, R. L. & Barrett, S. R. H. Impact of biofuels on contrail warming. *Environmental Research Letters* **12**, 114013 (2017).

30. Mannstein, H., Spichtinger, P. & Gierens, K. A note on how to avoid contrail cirrus. *Transportation Research Part D: Transport and Environment* **10**, 421–426 (2005).

31. Spichtinger, P., Gierens, K., Leiterer, U. & Dier, H. Ice supersaturation in the tropopause region over Lindenberg, Germany. *Meteorologische Zeitschrift* **12**, 143–156 (2003).

32. Schumann, U., Graf, K. & Mannstein, H. Potential to reduce the climate impact of aviation by flight level changes. (2011) doi:10.2514/6.2011-3376.

33. Avila, D., Sherry, L. & Thompson, T. Reducing global warming by airline contrail avoidance: A case study of annual benefits for the contiguous United States. *Transportation Research Interdisciplinary Perspectives* **2**, 100033 (2019).

34. Yin, F., Grewe, V., Frömming, C. & Yamashita, H. Impact on flight trajectory characteristics when avoiding the formation of persistent contrails for transatlantic flights. *Transportation Research Part D: Transport and Environment* **65**, 466–484 (2018).

35. ICF Consulting. *Assessment of ICAO's Global Market-Based Measure (CORSIA) pursuant to Article 28b and for studying cost pass-through pursuant to Article 3d of the EU ETS Directive*. (2020).

36. WEF. *Clean Skies for Tomorrow: Sustainable Aviation Fuel as a Pathway to Net-Zero Aviation*. (2020).

37. Johansson, T. B., Patwardhan, A., Nakicenovic, N. & Gomez-Echeverri, L. *Global Energy Assessment - Toward a Sustainable Future*. (Cambridge University Press, Cambridge, UK and New York, NY, USA and and the International Institute for Applied Systems Analysis, Laxenburg, Austria, 2012).

38. British Petroleum. BP Statistical Review of World Energy (2022).

39. IRENA. *World Energy Transitions Outlook: 1.5°C Pathway. International Renewable Energy Agency*. (2021).

40. Cooper, J., Dubey, L., Bakkaloglu, S. & Hawkes, A. Hydrogen emissions from the hydrogen value chain-emissions profile and impact to global warming. *Science of The Total Environment* **830**, 154624 (2022).

41. ICAO. *Presentation of 2019 Air Transport Statistical Results*. https://www.icao.int/annual-report-2017/Documents/Annual.Report.2017_Air Transport Statistics.pdf (2020).

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 systems model (AIM) to model future market development, demand feedbacks and technology adoption in a consistent framework; (2) the reduced-order climate model APMT Impacts Climate 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.

Aviation Integrated Model (AIM)

The Aviation Integrated Model (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 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 EC[36] and UK 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, are simulated and, in the case of hydrogen aircraft, a mandatory hydrogen requirement for new purchases is simulated (phased in over 5 years from hydrogen aircraft first entry into service). A Net Present Value (NPV) model is used to assess uptake of other new aircraft technologies and technology-fuel combinations within those consistent with mandate requirements. For drop-in fuels, adoption is based on the lowest cost to airlines once any mandate requirements, carbon, NO_x or contrail-related costs are 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 are taken from refs. [10,21,43]. For electric aircraft, performance characteristics, including range limitations, are taken from ref. [44] for single-aisle aircraft, and ref. [45] for regional jets. Operating cost characteristics are 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 e.g. 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 assume energy intensity and nonfuel operating costs of LH2 aircraft equal to those of conventional aircraft of a comparable generation and size, i.e. that the operating cost difference between conventional and hydrogen aircraft is dominated by fuel costs. We assume 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 modeling

We model the climate impacts of aviation emissions using the Aviation environmental Portfolio Management Tool - Impacts Climate (APMT-IC) as described in refs. [3,49]. APMT-IC probabilistically evaluates the physical climate impacts from global aviation emissions and estimates the associated monetary damages. Our use of this model is two-fold. First, we use it to derive Global Warming Potentials (GWP) for each of the precursor emissions (SI Section 3.2). These GWP values are used convert non-CO_2 emissions to CO_2eq emissions. Second, we use it to calculate radiative forcing and atmospheric surface temperature change response for each the future emissions pathways generated by AIM.

The implementation of APMT-IC used here is described in refs. [3,49]. The model has been updated to capture recent research results (1) on the contrail-cirrus forcing and subsequent expected atmospheric temperature response to this forcing[4,50]; (2) on the NO_x-related methane forcing; (3) on 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. [4], we update 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 apply 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 align with the ERF/RF adjustment from ref. [4] and apply 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 allows us to capture the expected temperature change associated with the updated contrail-cirrus RF.

We note some unquantified uncertainties are not captured in this approach. Firstly, 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] Secondly, the adjustment factors from refs. [55,56] represent long-term climate feedbacks for linear contrails only, derived using contrail formation more than 50 times expected contrail coverage in 2050. This upscaling may cause saturation of feedback effects such as cloud formation.[58–60] After these adjustments, we find a 33% net reduction in temperature change associated with contrail-cirrus per distance flown as compared to ref. [3]. Additionally, we normalize contrail impacts by the AEDT distance for flights in 2006 as reported in ref. [4].

The second update aligns the NO_x-related methane forcing with more recent literature on the radiative interaction of methane. Following the method of ref. [4], we increase the forcing of NO_x 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. [4] are 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 apply 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 literature and explicitly treats dependencies between different underlying studies to avoid overrepresentation of results from specific studies. This change leads to social cost of carbon of 246 USD_{2020}/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, RCP4.5 and SSP1 the social cost of carbon in 2020 is 158 USD_{2020}/tonne CO_2 (90% confidence interval 46.4 to 352) in 2020 USD. While this represents a factor ~2.8 increase above the previous APMT-IC social cost of carbon, these values are in-line with recent literature global social cost of carbon estimates of 80 - 805 USD.[67–69]

Finally, due to changes in the non-CO_2 emissions footprint of LH2, LNG and SAF, the subsequent climate impacts are also expected to differ.[70,71] For each fuel considered, we derive adjustment factors by emission species based on 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 Section 3 of the SI.

Alternative fuel pathways

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

- Liquid hydrogen (LH2): We consider liquid hydrogen produced via water electrolysis and subsequent liquefaction, both powered by renewable electricity. The electrolysis of water is modeled based on the proton-exchange membrane (PEM) 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.

- Power-to-liquid fuels (PTL): We consider power-to-liquids based on hydrogen from water electrolysis and CO_2 from direct air capture. Hydrogen is produced at varying loads from PEM 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 (FT), 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 consider biofuels produced from dedicated biomass and waste streams including the following pathways: HEFA (hydrogenated esters and fatty acids) process using dedicated vegetable oil crops (e.g., 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, 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 assume the main constraint on LH2 ramp-up is fleet penetration of LH2 aircraft; for PTL and biofuels, maximum ramp-up rates are set using a combination of near-term literature estimates of supply and longer-term estimates of aviation fuel demand (SI Section 1). For single-fuel pathways, biomass availability is modeled after ref. [24]'s F1-A1-S2 scenario, 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/y in 2050). These assumptions are used as the fundamental availability for these pathways, while the specific use of fuels is then determined with the AIM model taking into account demand effects, mandate levels, scale-up behavior and prices. For the combined-pathway model runs a more constrained biomass supply is assumed, rising to a maximum of 21.7 EJ in 2050, based on Ref. [37] (SI Section 1).

Production costs: We determine alternative fuel pathway costs (except for biofuel pathways) with the levelized cost of energy approach. To this end, we determine the investment costs of the facilities based on energy and mass balances, and component cost estimates from the literature. We assume improvements of component efficiencies and energy demands in line with recent publications. The levelized costs of intermittent renewable electricity is assumed to be

\$0.04/kWh today at a capacity factor of 30% and \$0.02/kWh at 50% in 2050, where these estimates are based on a mix of solar PV and onshore wind technologies. Additionally, we include energy storage for parts of the facilities that must run continuously and thus use an LCOE of \$0.10/kWh (year 2020) and \$0.05/kWh (year 2050) for renewable electricity that is available around the clock. The costs are annualized assuming a lifetime of 20 years and a discount rate of 10%. The minimum selling price of the different biofuel pathways is based on a discounted cash flow rate of return analysis as shown in ref. [72]

GHG emissions: The life cycle emissions of electricity from solar PV and wind are assumed to be zero (see SI Section 1 for estimate on embedded emissions). While currently there are still embedded emissions in the production of PV modules and wind turbines, these are expected to approach zero with the decarbonization of the economy. For GHG emissions of biofuels, we use literature values from ref. [24]. for the different pathways in our study. The authors indicate values for today and for 2050, and we use linear interpolation to get values in between. We neglect embedded emissions of all infrastructure for the fuel pathways due to the expected small impact (see SI Section 1, for estimates). We use 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) are not included here and remain highly uncertain due to uncertainties in leakage rates and climate impacts. [40,76] Other non-CO_2 impacts on the atmosphere are discussed in ‘Climate impact modeling’ above, ‘Contrail avoidance modeling’ below, and in Section 3 of the SI.

Contrail avoidance modeling

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 with where contrails can form (refs. [32,33,77]). These diversions lead to a small fuel burn penalty (typically less than 5% of fleetwide fuel consumption) compared to 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; in turn, less than 2% of flights would have to be diverted to avoid contrail warming impacts[27].

Contrail avoidance is modelled using results from our contrail avoidance meta-analysis based on a literature review of five different studies[34,77–80] (SI Section 2). Using these studies, we estimate 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.

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

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 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 is selected for our combined technology pathways in which 50% fleet-wide contrail avoidance can 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 literature. The 50% length avoidance is lower compared to other studies, which calculate maximum contrail impact avoidance of 70-80%. However, this mid-range value of 50% is selected since high rates of avoidance will cause increased strain on airspace and air traffic control[27] and maximum rates of contrail avoidance may be difficult to achieve with current weather prediction data. [27]This contrail avoidance trade-off likely differs for alternative energy carriers such as hydrogen, but data on these differences remains unavailable. Therefore, we apply the same results from Equation 2 for alternative fuels (SI 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 examine outcomes across three demand scenarios, described below. For each demand scenario, we run: 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/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 which take account of the COVID19 pandemic is described in ref. [19]. Baseline population and GDP/capita growth rates are derived from the IPCC SSP scenarios,[81] adjusted for COVID19 pandemic GDP/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 SI 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 scenario based on IPCC SSP3 socioeconomic factors, which leads to post-pandemic demand growth which is lower than historical trends. The low demand scenario includes 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-year period. For reference cases, we use IEA SDS 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 use lower oil prices post-2040 in scenarios where there is significant use of alternative technology in aviation (transitioning from the SDS trajectory to the IEA NZE projections [7] (SI Figure 2). Future technology costs and capabilities are also uncertain. For this paper, the key sensitivity is to fuel costs and we address this through the use of alternative fuel cost projections, as discussed in the main paper.

Data availability

The datasets generated during the current study are available from the corresponding author 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/

References

42. Dray, L. & Doyme, K. Carbon leakage in aviation policy. *Climate Policy* **19**, 1284–1296 (2019).
43. Dray, L. M., Schäfer, A. W. & Al Zayat, K. The Global Potential for CO2 Emissions Reduction from Jet Engine Passenger Aircraft. *Transportation Research Record: Journal of the Transportation Research Board* **2672**, 40–51 (2018).
44. Gnadt, A. R., Speth, R. L., Sabnis, J. S. & Barrett, S. R. H. Technical and environmental assessment of all-electric 180-passenger commercial aircraft. *Progress in Aerospace Sciences* **105**, 1–30 (2019).
45. Hepperle, M. Electric flight – potential and limitations. in *Energy Efficient Technologies and Concepts of Operation* (2012).
46. Schäfer, A. W. *et al.* Technological, economic and environmental prospects of all-electric aircraft. *Nature Energy 2018 4:2* **4**, 160–166 (2018).
47. Brewer, G. *Hydrogen Aircraft Technology*. (CRC Press, 1991).
48. Clean Sky. *Hydrogen-powered aviation: preparing for take-off.* (2020).
49. de Jong, S. *et al.* Using dynamic relative climate impact curves to quantify the climate impact of bioenergy production systems over time. *GCB Bioenergy* **11**, 427–443 (2018).
50. Bickel, M., Ponater, M., Bock, L., Burkhardt, U. & Reineke, S. Estimating the effective radiative forcing of contrail cirrus. *Journal of Climate* **33**, 1991–2005 (2020).
51. Burkhardt, U. & Kärcher, B. Global radiative forcing from contrail cirrus. *Nature Climate Change* **1**, 54–58 (2011).
52. Bock, L. & Burkhardt, U. Reassessing properties and radiative forcing of contrail cirrus using a climate model. *Journal of Geophysical Research* **121**, 9717–9736 (2016).
53. Schumann, U., Penner, J. E., Chen, Y., Zhou, C. & Graf, K. Dehydration effects from contrails in a coupled contrail-climate model. *Atmospheric Chemistry and Physics* **15**, 11179–11199 (2015).
54. Chen, C. C. & Gettelman, A. Simulated radiative forcing from contrails and contrail cirrus. *Atmospheric Chemistry and Physics* **13**, 12525–12536 (2013).
55. Ponater, M., Pechtl, S., Sausen, R., Schumann, U. & Hüttig, G. Potential of the cryoplane technology to reduce aircraft climate impact: A state-of-the-art assessment. *Atmospheric Environment* **40**, 6928–6944 (2006).
56. Rap, A., Forster, P. M., Haywood, J. M., Jones, A. & Boucher, O. Estimating the climate impact of linear contrails using the UK Met Office climate model. *Geophysical Research Letters* **37**, 20703 (2010).
57. Ponater, M., Bickel, M., Bock, L. & Burkhardt, U. Towards determining the contrail cirrus efficacy. *Aerospace* **8**, 1–10 (2021).
58. Wuebbles, D. *et al.* Issues and Uncertainties Affecting Metrics For Aviation Impacts on Climate. *Bull Am Meteorol Soc* **91**, 491–496 (2010).
59. Lund, M. T. *et al.* Emission metrics for quantifying regional climate impacts of aviation. *Earth System Dynamics* **8**, 547–563 (2017).
60. Fuglestvedt, J. S. *et al.* Transport impacts on atmosphere and climate: Metrics. *Atmospheric Environment* **44**, 4648–4677 (2010).
61. Etminan, M., Myhre, G., Highwood, E. J. & Shine, K. P. Radiative forcing of carbon dioxide, methane, and nitrous oxide: A significant revision of the methane radiative forcing. *Geophysical Research Letters* **43**, 614–623 (2016).
62. Nordhaus, W. D. Revisiting the social cost of carbon. *Proceedings of the National Academy of Sciences* **114**, 1518–1523 (2017).
63. US Government. *Technical Support Document: Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis*. (2016).

64. Greenstone, M. A New Path Forward for an Empirical Social Cost of Carbon. Preprint at (2016).

65. US Government. *Technical Support Document: Social Cost of Carbon, Methane, and Nitrous Oxide: Interim Estimates under Executive Order 13990*. (2021).

66. Howard, P. H. & Sterner, T. Few and Not So Far Between: A Meta-analysis of Climate Damage Estimates. *Environmental and Resource Economics* **68**, 197–225 (2017).

67. Hänsel, M. C. *et al.* Climate economics support for the UN climate targets. *Nature Climate Change* **10**, 781–789 (2020).

68. Pindyck, R. S. The social cost of carbon revisited. *Journal of Environmental Economics and Management* **94**, 140–160 (2019).

69. Ricke, K., Drouet, L., Caldeira, K. & Tavoni, M. Country-level social cost of carbon. *Nature Climate Change* **8**, 895–900 (2018).

70. Grewe, V. *et al.* Assessing the climate impact of the AHEAD multi-fuel blended wing body. *Meteorologische Zeitschrift* **26**, 711–725 (2017).

71. Withers, M. R. *et al.* Economic and environmental assessment of liquefied natural gas as a supplemental aircraft fuel. *Progress in Aerospace Sciences* vol. 66 17–36 Preprint at https://doi.org/10.1016/j.paerosci.2013.12.002 (2014).

72. Bann, S. J. *et al.* The costs of production of alternative jet fuel: A harmonized stochastic assessment. *Bioresource Technology* **227**, 179–187 (2017).

73. Seber, G. *et al.* Environmental and economic assessment of producing hydroprocessed jet and diesel fuel from waste oils and tallow. *Biomass and Bioenergy* **67**, 108–118 (2014).

74. Suresh, P. Environmental and economic assessment of transportation fuels from municipal solid waste. (Massachusetts Institute of Technology, 2016).

75. Staples, M. D. *et al.* Lifecycle greenhouse gas footprint and minimum selling price of renewable diesel and jet fuel from fermentation and advanced fermentation production technologies. *Energy & Environmental Science* **7**, 1545–1554 (2014).

76. Ocko, I. B. & Hamburg, S. P. *Climate consequences of hydrogen leakage*. (2022).

77. Sridhar, B., Ng, H. K. & Chen, N. Y. Aircraft trajectory optimization and contrails avoidance in the presence of winds. in *Journal of Guidance, Control, and Dynamics* vol. 34 1577–1583 (American Institute of Aeronautics and Astronautics Inc., 2011).

78. Sridhar, B., Ng, H. K. & Chen, N. Uncertainty quantification in the development of aviation operations to reduce aviation emissions and contrails. in *28th International Congress of the Aeronautical Sciences* (2012).

79. Noppel, F., Singh, R. & Taylor, M. Contrail and cirrus cloud avoidance. in *25th International Congress of the aeronautical sciences* (eds. Noppel, F., Singh, R. & Taylor, M.) (2006).

80. Klima, K. *Assessment of a Global Contrail Modeling Method and Operational Strategies for Contrail Mitigation*. (2005).

81. O'Neill, B. C. *et al.* A new scenario framework for climate change research: The concept of shared socioeconomic pathways. *Climatic Change* **122**, 387–400 (2014).

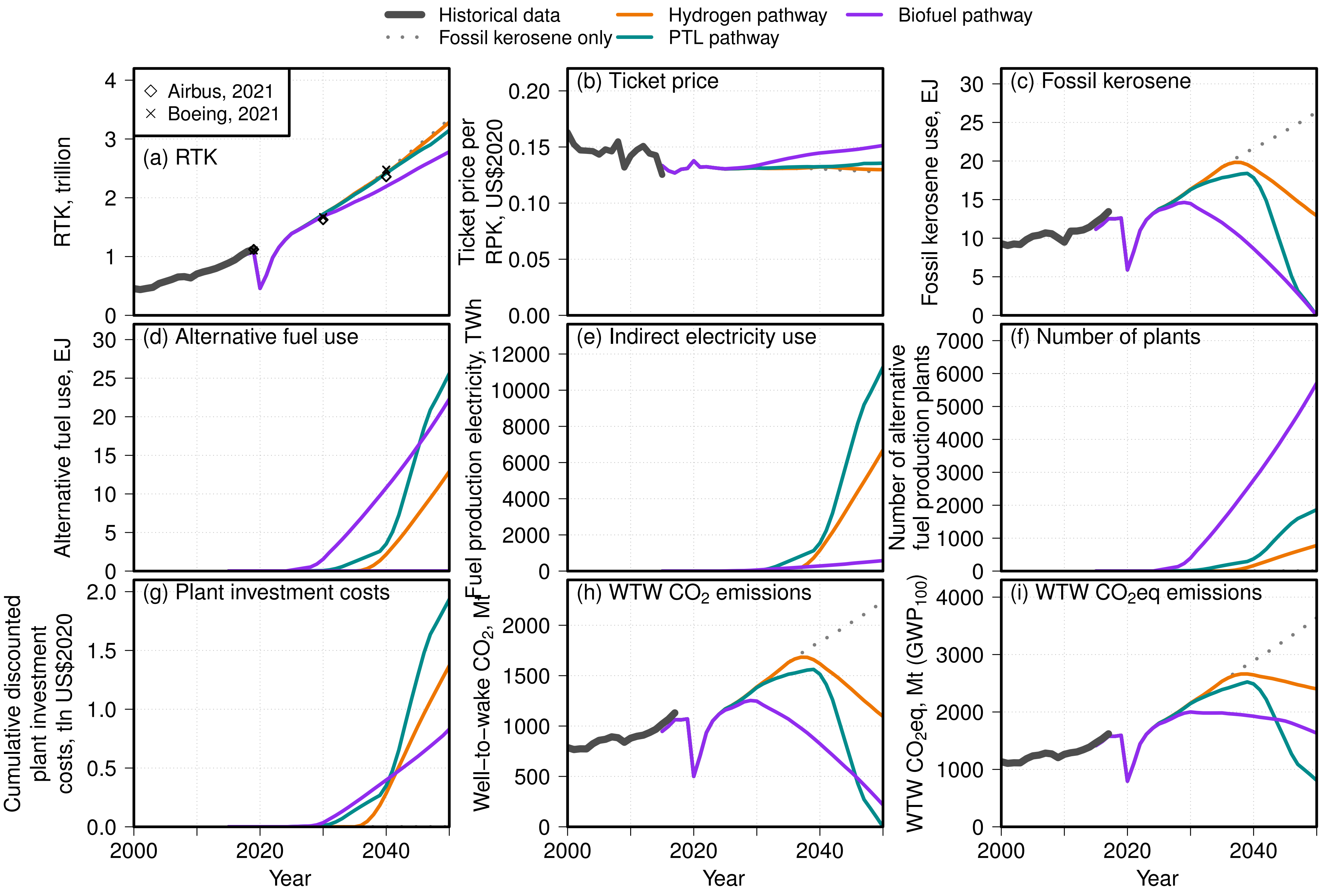
82. IMF. *World Economic Outlook: April 2021.* (2021).

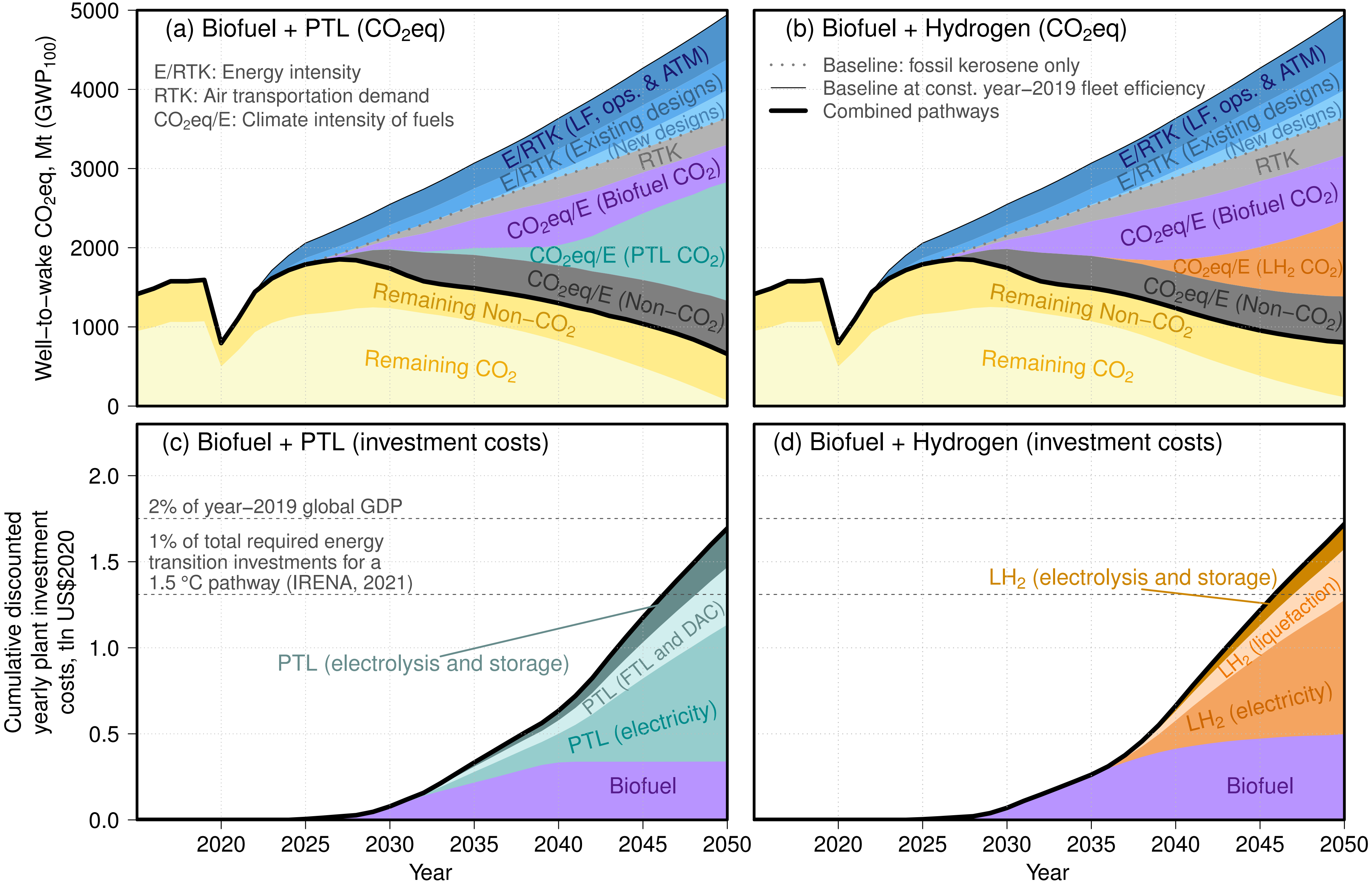
83. IATA. *COVID-19: Airline industry financial outlook update*. (2021).

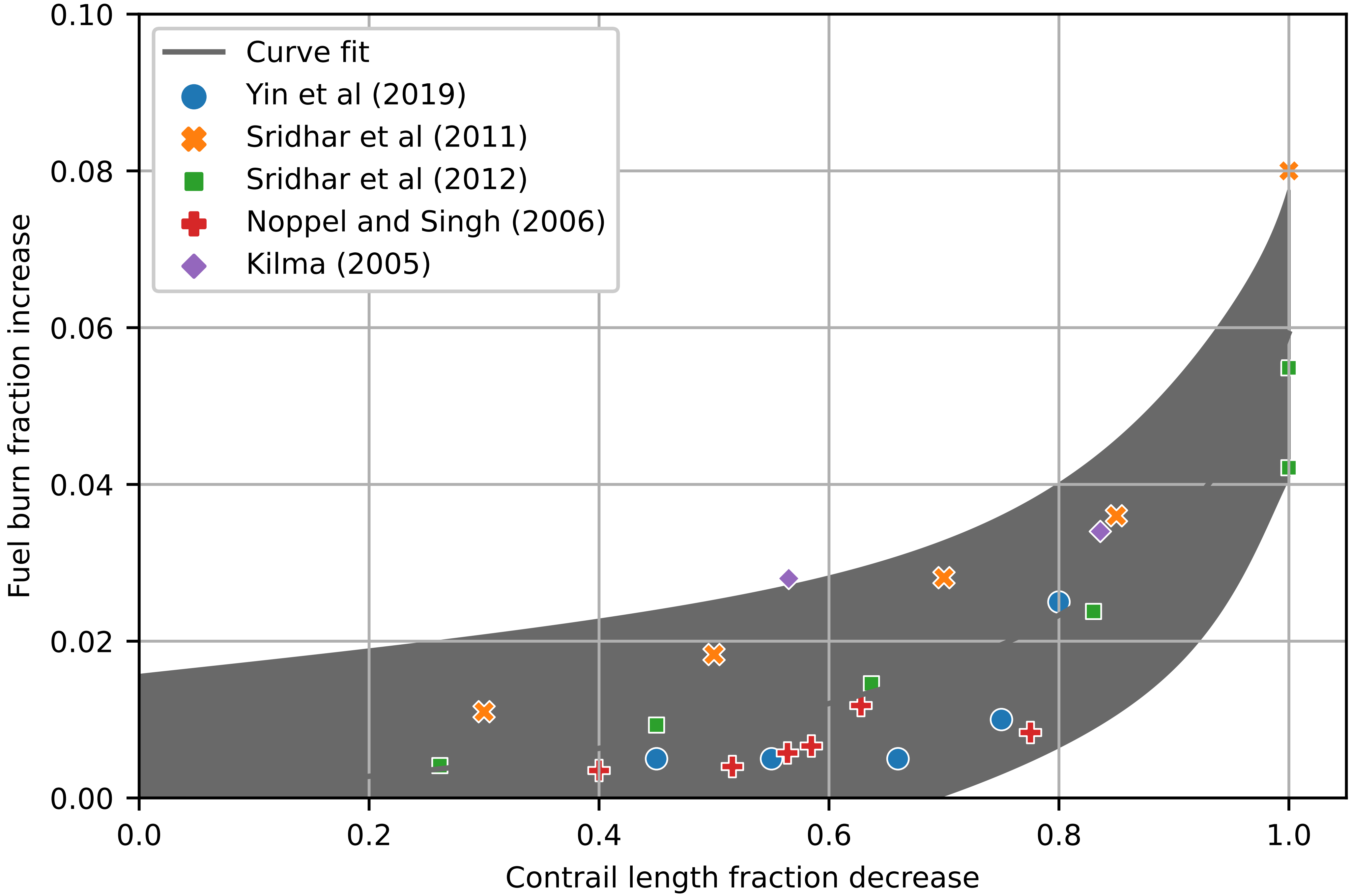
84. ICAO. *Effects of Novel Coronavirus on Civil Aviation: Economic Impact Analysis*. (2021).

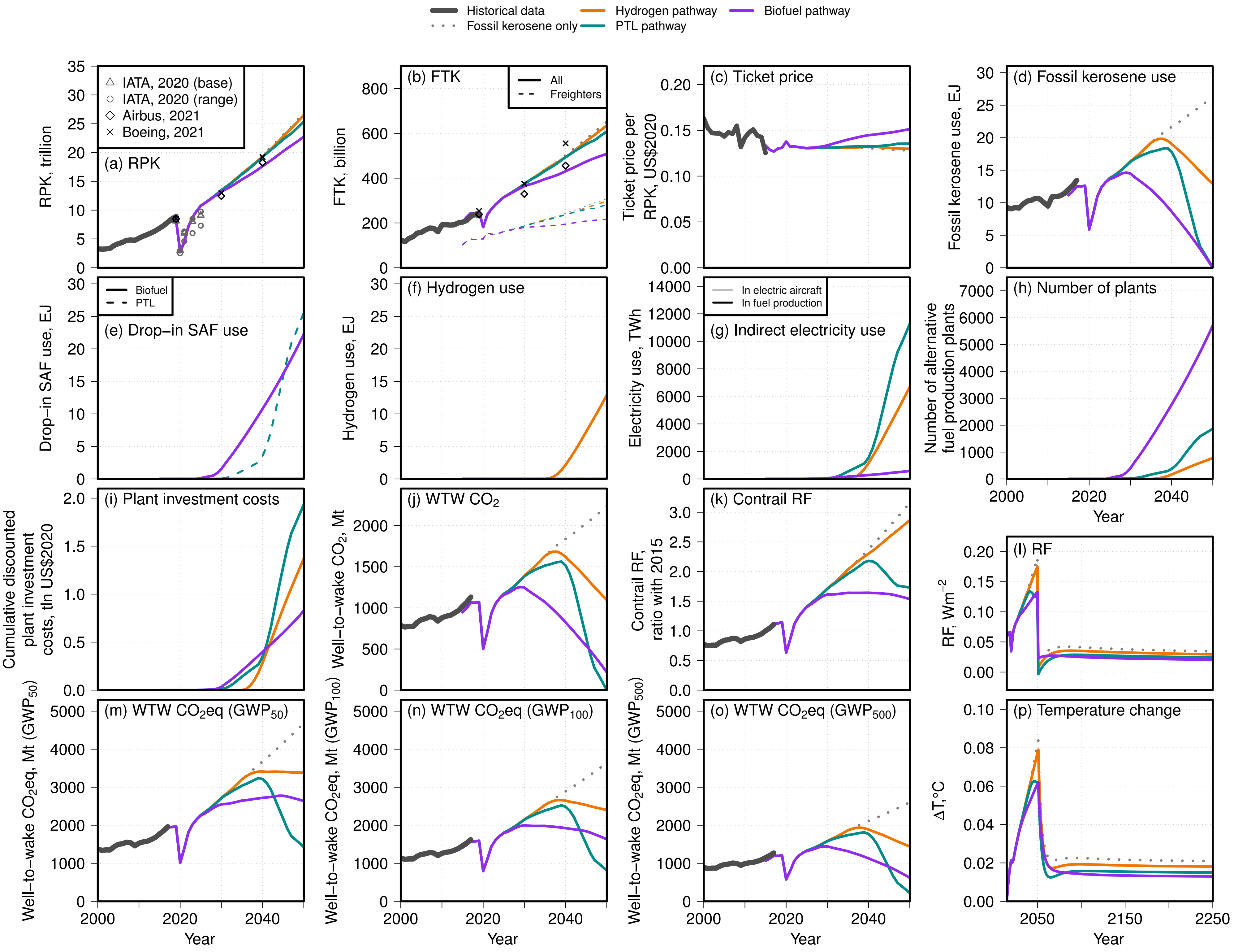
85. DfT. *UK Aviation Forecasts 2017*. (2017).

86. IEA. *Energy Technology Perspectives*. (2020).

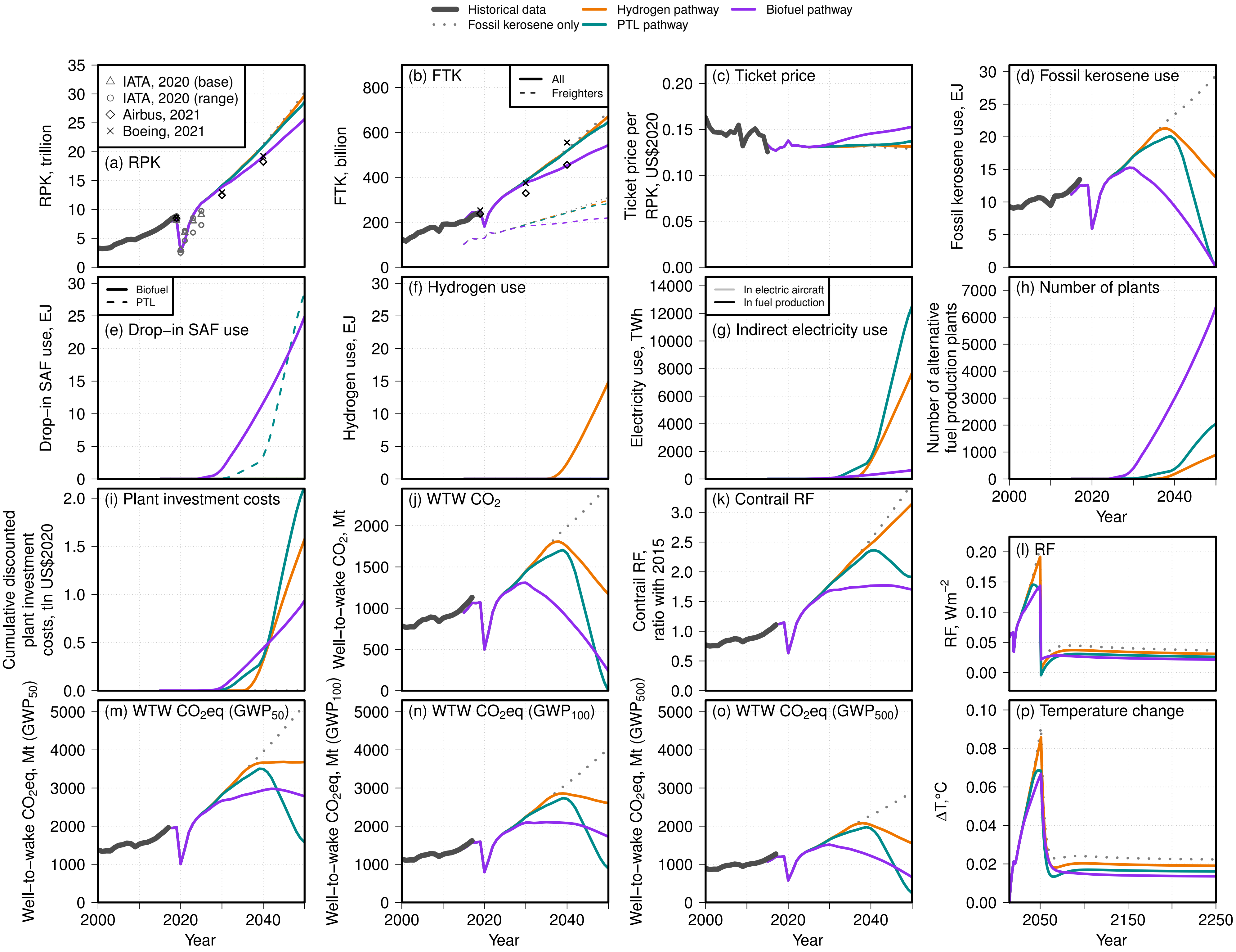

Historical data
Fossil kerosene only
Hydrogen pathway
PTL pathway
Biofuel pathway
(a) RTK
RTK, trillion
Airbus, 2021
Boeing, 2021
(b) Ticket price
Ticket price per RPK, US$2020
(c) Fossil kerosene
Fossil kerosene use, EJ
(d) Alternative fuel use
Alternative fuel use, EJ
(e) Indirect electricity use
Fuel production electricity, TWh
(f) Number of plants
Number of alternative fuel production plants
(g) Plant investment costs
Cumulative discounted plant investment costs, tln US$2020
(h) WTW CO_2 emissions
Well−to−wake CO_2, Mt
(i) WTW CO_2eq emissions
WTW CO_2eq, Mt (GWP_{100})
Year
2000
2020
2040

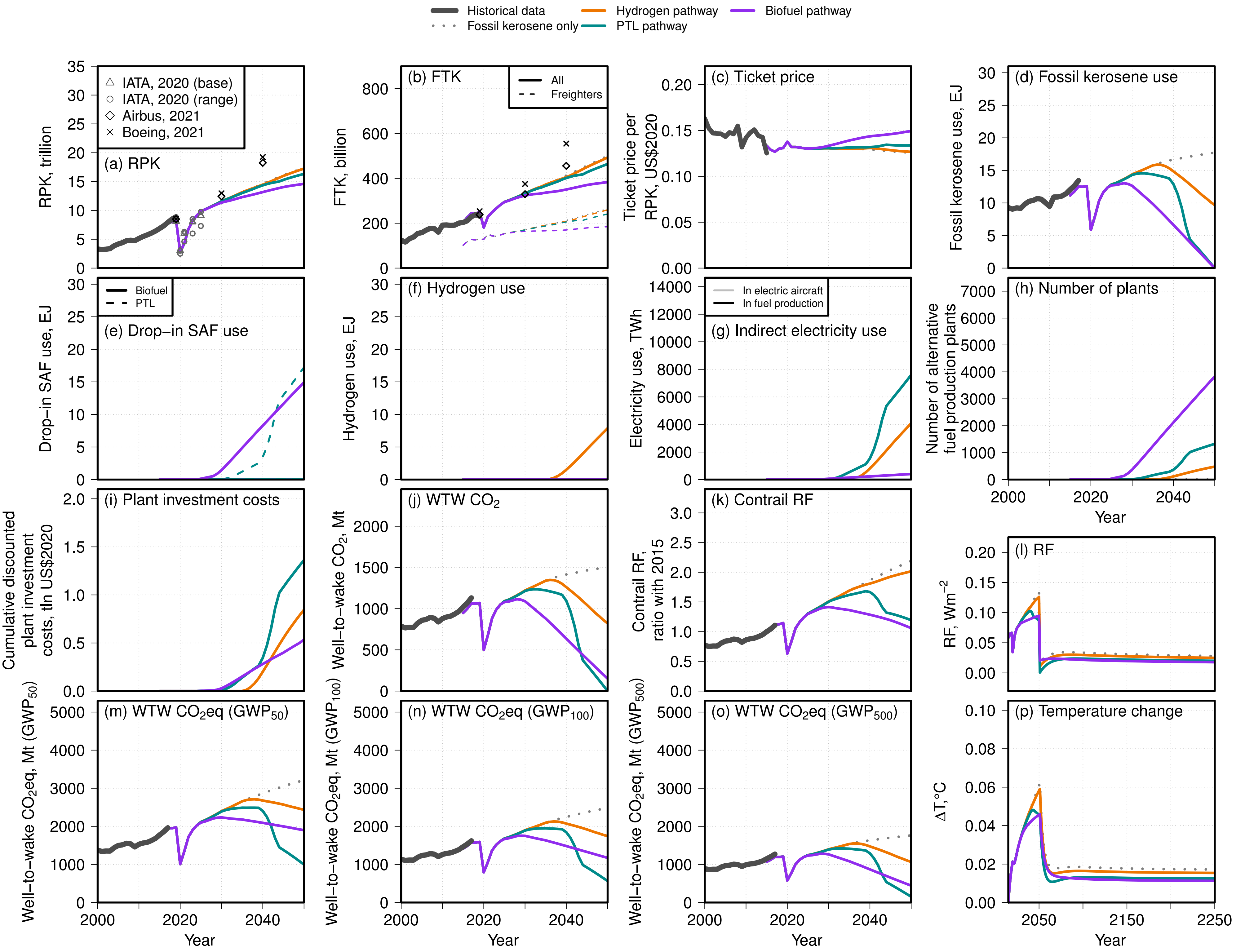

(a) Biofuel + PTL (CO_2eq)
E/RTK: Energy intensity
RTK: Air transportation demand
CO_2eq/E: Climate intensity of fuels
E/RTK (LF, ops. & ATM)
E/RTK (Existing designs)
(New designs)
RTK
CO_2eq/E (Biofuel CO_2)
CO_2eq/E (PTL CO_2)
CO_2eq/E (Non−CO_2)
Remaining Non−CO_2
Remaining CO_2
(b) Biofuel + Hydrogen (CO_2eq)
Baseline: fossil kerosene only
Baseline at const. year−2019 fleet efficiency
Combined pathways
E/RTK (LF, ops. & ATM)
E/RTK (Existing designs)
(New designs)
RTK
CO_2eq/E (Biofuel CO_2)
CO_2eq/E (LH_2 CO_2)
CO_2eq/E (Non−CO_2)
Remaining Non−CO_2
Remaining CO_2
Well−to−wake CO_2eq, Mt (GWP_{100})
0
1000
2000
3000
4000
5000
(c) Biofuel + PTL (investment costs)
2% of year−2019 global GDP
1% of total required energy transition investments for a 1.5 °C pathway (IRENA, 2021)
PTL (electrolysis and storage)
PTL (FTL and DAC)
PTL (electricity)
Biofuel
(d) Biofuel + Hydrogen (investment costs)
LH_2 (electrolysis and storage)
LH_2 (liquefaction)
LH_2 (electricity)
Biofuel
Cumulative discounted yearly plant investment costs, tln US$2020
0.0
0.5
1.0
1.5
2.0
2020
2025
2030
2035
2040
2045
2050
Year
2020
2025
2030
2035
2040
2045
2050
Year

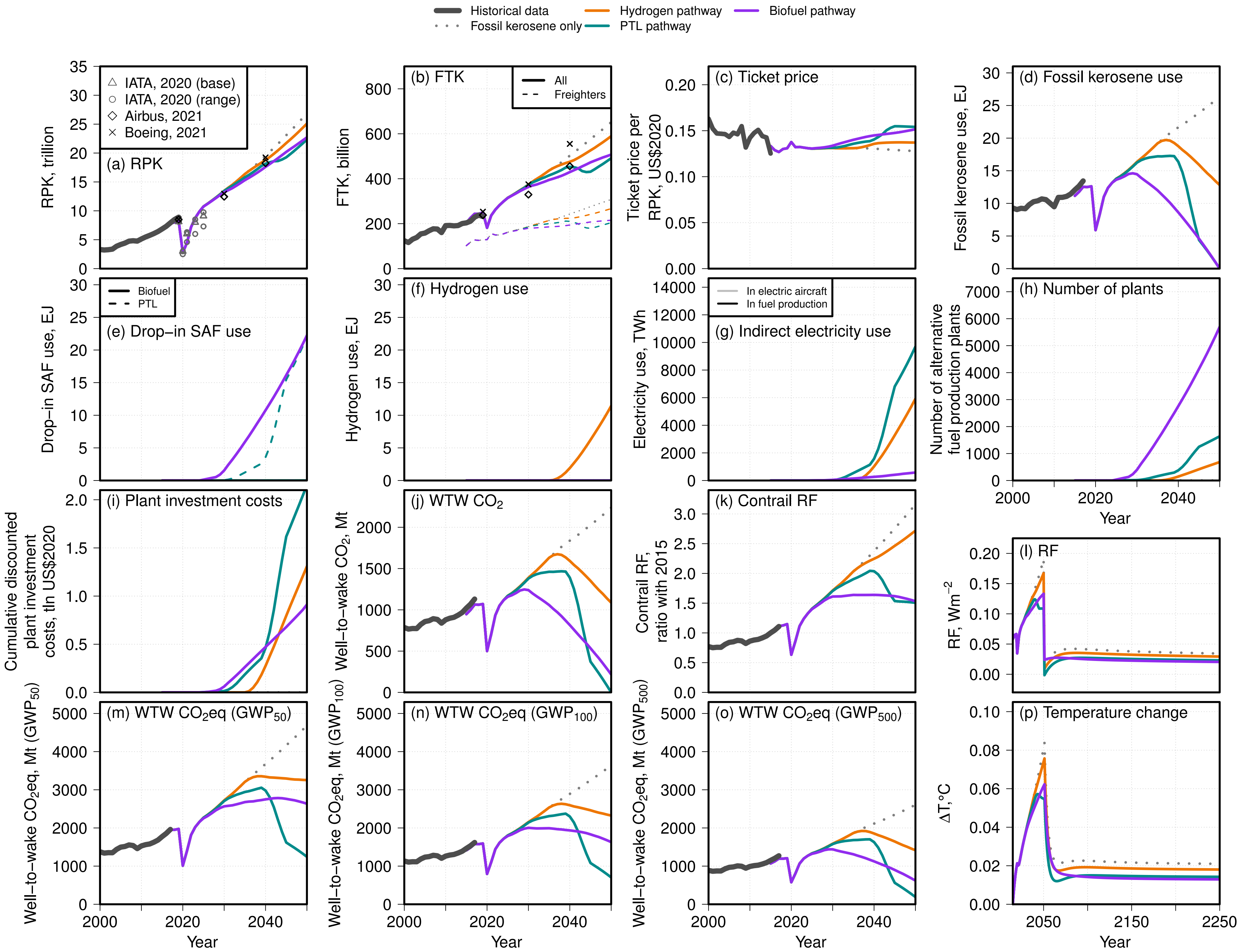

0.10
0.08
0.06
0.04
0.02
0.00
Fuel burn fraction increase
0.0
0.2
0.4
0.6
0.8
1.0
Contrail length fraction decrease
Curve fit
Yin et al (2019)
Sridhar et al (2011)
Sridhar et al (2012)
Noppel and Singh (2006)
Kilma (2005)

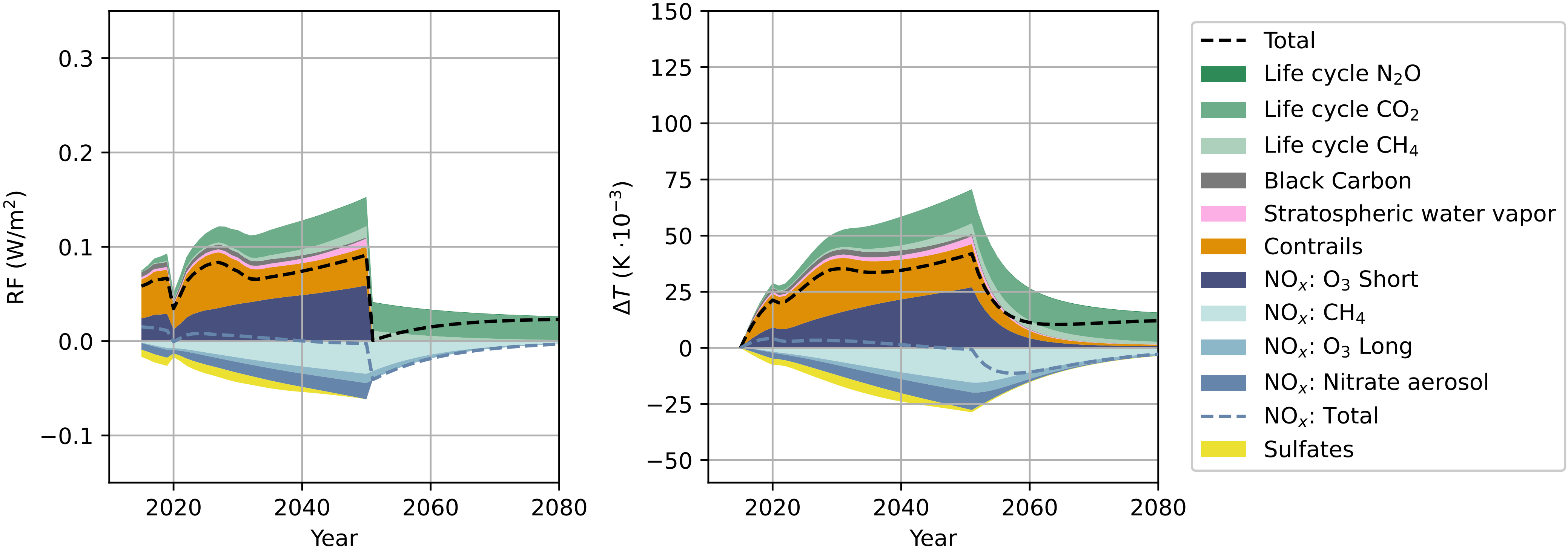


Historical data
Fossil kerosene only
Hydrogen pathway
PTL pathway
Biofuel pathway
(a) RPK
RPK, trillion
IATA, 2020 (base)
IATA, 2020 (range)
Airbus, 2021
Boeing, 2021
0 5 10 15 20 25 30 35
(b) FTK
FTK, billion
All
Freighters
0 200 400 600 800
(c) Ticket price
Ticket price per RPK, US$2020
0.00 0.05 0.10 0.15 0.20
(d) Fossil kerosene use
Fossil kerosene use, EJ
0 5 10 15 20 25 30
(e) Drop−in SAF use
Drop−in SAF use, EJ
Biofuel
PTL
0 5 10 15 20 25 30
(f) Hydrogen use
Hydrogen use, EJ
0 5 10 15 20 25 30
(g) Indirect electricity use
Electricity use, TWh
In electric aircraft
In fuel production
0 2000 4000 6000 8000 10000 12000 14000
(h) Number of plants
Number of alternative fuel production plants
0 1000 2000 3000 4000 5000 6000 7000
2000 2020 2040
Year
(i) Plant investment costs
Cumulative discounted plant investment costs, tln US$2020
0.0 0.5 1.0 1.5 2.0
(j) WTW CO_2
Well−to−wake CO_2, Mt
0 500 1000 1500 2000
(k) Contrail RF
Contrail RF, ratio with 2015
0.0 0.5 1.0 1.5 2.0 2.5 3.0
(l) RF
RF, Wm^{-2}
0.00 0.05 0.10 0.15 0.20
(m) WTW CO_2eq (GWP_{50})
Well−to−wake CO_2eq, Mt (GWP_{50})
(n) WTW CO_2eq (GWP_{100})
Well−to−wake CO_2eq, Mt (GWP_{100})
(o) WTW CO_2eq (GWP_{500})
Well−to−wake CO_2eq, Mt (GWP_{500})
0 1000 2000 3000 4000 5000
2000 2020 2040
Year
(p) Temperature change
ΔT,°C
0.00 0.02 0.04 0.06 0.08 0.10
2050 2150 2250
Year

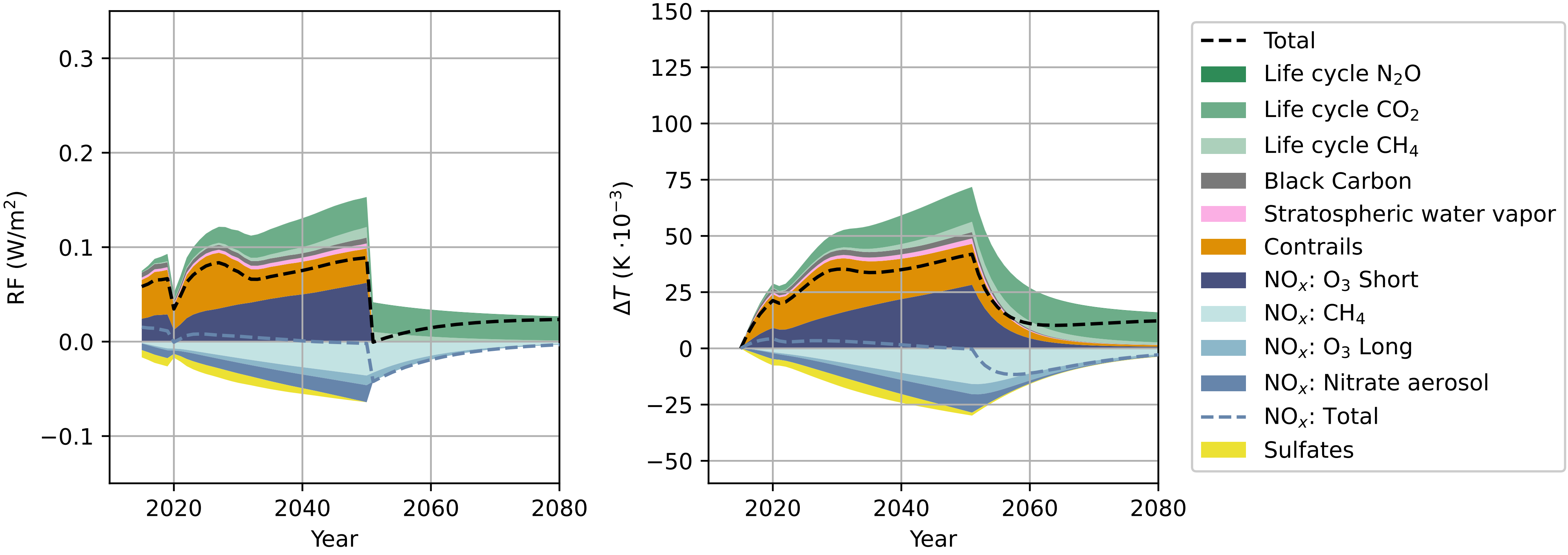

Historical data
Fossil kerosene only
Hydrogen pathway
PTL pathway
Biofuel pathway
(a) RPK
RPK, trillion
IATA, 2020 (base)
IATA, 2020 (range)
Airbus, 2021
Boeing, 2021
0 5 10 15 20 25 30 35
(b) FTK
FTK, billion
All
Freighters
0 200 400 600 800
(c) Ticket price
Ticket price per RPK, US$2020
0.00 0.05 0.10 0.15 0.20
(d) Fossil kerosene use
Fossil kerosene use, EJ
0 5 10 15 20 25 30
(e) Drop−in SAF use
Drop−in SAF use, EJ
Biofuel
PTL
0 5 10 15 20 25 30
(f) Hydrogen use
Hydrogen use, EJ
0 5 10 15 20 25 30
(g) Indirect electricity use
Electricity use, TWh
In electric aircraft
In fuel production
0 2000 4000 6000 8000 10000 12000 14000
(h) Number of plants
Number of alternative fuel production plants
0 1000 2000 3000 4000 5000 6000 7000
2000 2020 2040
Year
(i) Plant investment costs
Cumulative discounted plant investment costs, tln US$2020
0.0 0.5 1.0 1.5 2.0
(j) WTW CO$_2$
Well−to−wake CO$_2$, Mt
0 500 1000 1500 2000
(k) Contrail RF
Contrail RF, ratio with 2015
0.0 0.5 1.0 1.5 2.0 2.5 3.0
(l) RF
RF, Wm^{-2}
0.00 0.05 0.10 0.15 0.20
(m) WTW CO$_2$eq (GWP$_{50}$)
Well−to−wake CO$_2$eq, Mt (GWP$_{50}$)
(n) WTW CO$_2$eq (GWP$_{100}$)
Well−to−wake CO$_2$eq, Mt (GWP$_{100}$)
(o) WTW CO$_2$eq (GWP$_{500}$)
Well−to−wake CO$_2$eq, Mt (GWP$_{500}$)
0 1000 2000 3000 4000 5000
2000 2020 2040
Year
(p) Temperature change
ΔT,°C
0.00 0.02 0.04 0.06 0.08 0.10
2050 2150 2250
Year

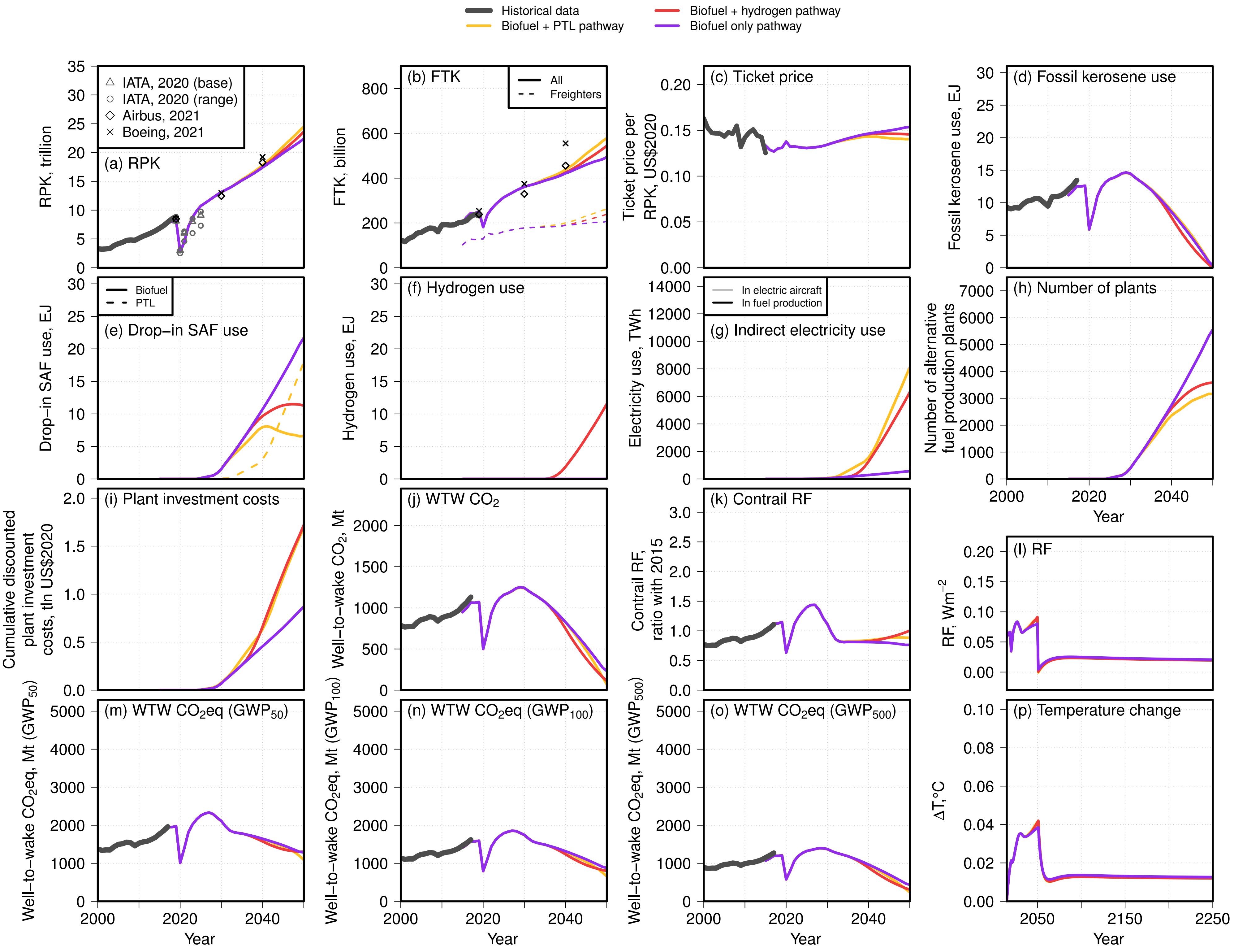

Historical data
Fossil kerosene only
Hydrogen pathway
PTL pathway
Biofuel pathway
IATA, 2020 (base)
IATA, 2020 (range)
Airbus, 2021
Boeing, 2021
(a) RPK
RPK, trillion
(b) FTK
All
Freighters
FTK, billion
(c) Ticket price
Ticket price per RPK, US$2020
(d) Fossil kerosene use
Fossil kerosene use, EJ
Biofuel
PTL
(e) Drop−in SAF use
Drop−in SAF use, EJ
(f) Hydrogen use
Hydrogen use, EJ
In electric aircraft
In fuel production
(g) Indirect electricity use
Electricity use, TWh
(h) Number of plants
Number of alternative fuel production plants
(i) Plant investment costs
Cumulative discounted plant investment costs, tln US$2020
(j) WTW CO_2
Well−to−wake CO_2, Mt
(k) Contrail RF
Contrail RF, ratio with 2015
(l) RF
RF, Wm^{-2}
(m) WTW CO_2eq (GWP_{50})
Well−to−wake CO_2eq, Mt (GWP_{50})
(n) WTW CO_2eq (GWP_{100})
Well−to−wake CO_2eq, Mt (GWP_{100})
(o) WTW CO_2eq (GWP_{500})
Well−to−wake CO_2eq, Mt (GWP_{500})
(p) Temperature change
ΔT,°C
Year
2000
2020
2040
2050
2150
2250

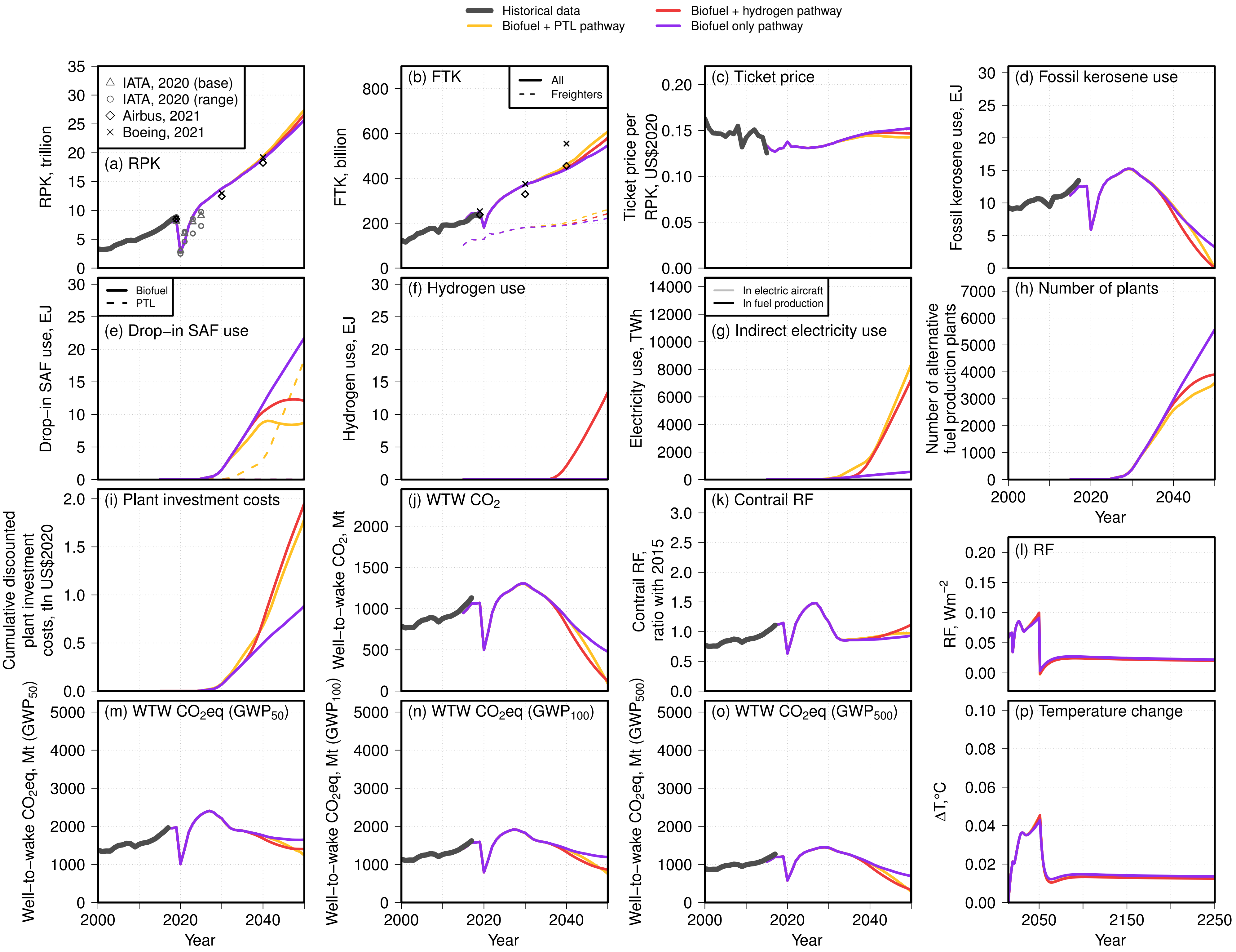

Historical data
Fossil kerosene only
Hydrogen pathway
PTL pathway
Biofuel pathway
(a) RPK
RPK, trillion
IATA, 2020 (base)
IATA, 2020 (range)
Airbus, 2021
Boeing, 2021
(b) FTK
FTK, billion
All
Freighters
(c) Ticket price
Ticket price per RPK, US$2020
(d) Fossil kerosene use
Fossil kerosene use, EJ
(e) Drop−in SAF use
Drop−in SAF use, EJ
Biofuel
PTL
(f) Hydrogen use
Hydrogen use, EJ
(g) Indirect electricity use
Electricity use, TWh
In electric aircraft
In fuel production
(h) Number of plants
Number of alternative fuel production plants
(i) Plant investment costs
Cumulative discounted plant investment costs, tln US$2020
(j) WTW CO_2
Well−to−wake CO_2, Mt
(k) Contrail RF
Contrail RF, ratio with 2015
(l) RF
RF, Wm^{-2}
(m) WTW CO_2eq (GWP_{50})
Well−to−wake CO_2eq, Mt (GWP_{50})
(n) WTW CO_2eq (GWP_{100})
Well−to−wake CO_2eq, Mt (GWP_{100})
(o) WTW CO_2eq (GWP_{500})
Well−to−wake CO_2eq, Mt (GWP_{500})
(p) Temperature change
ΔT,°C
Year
2000
2020
2040
2050
2150
2250



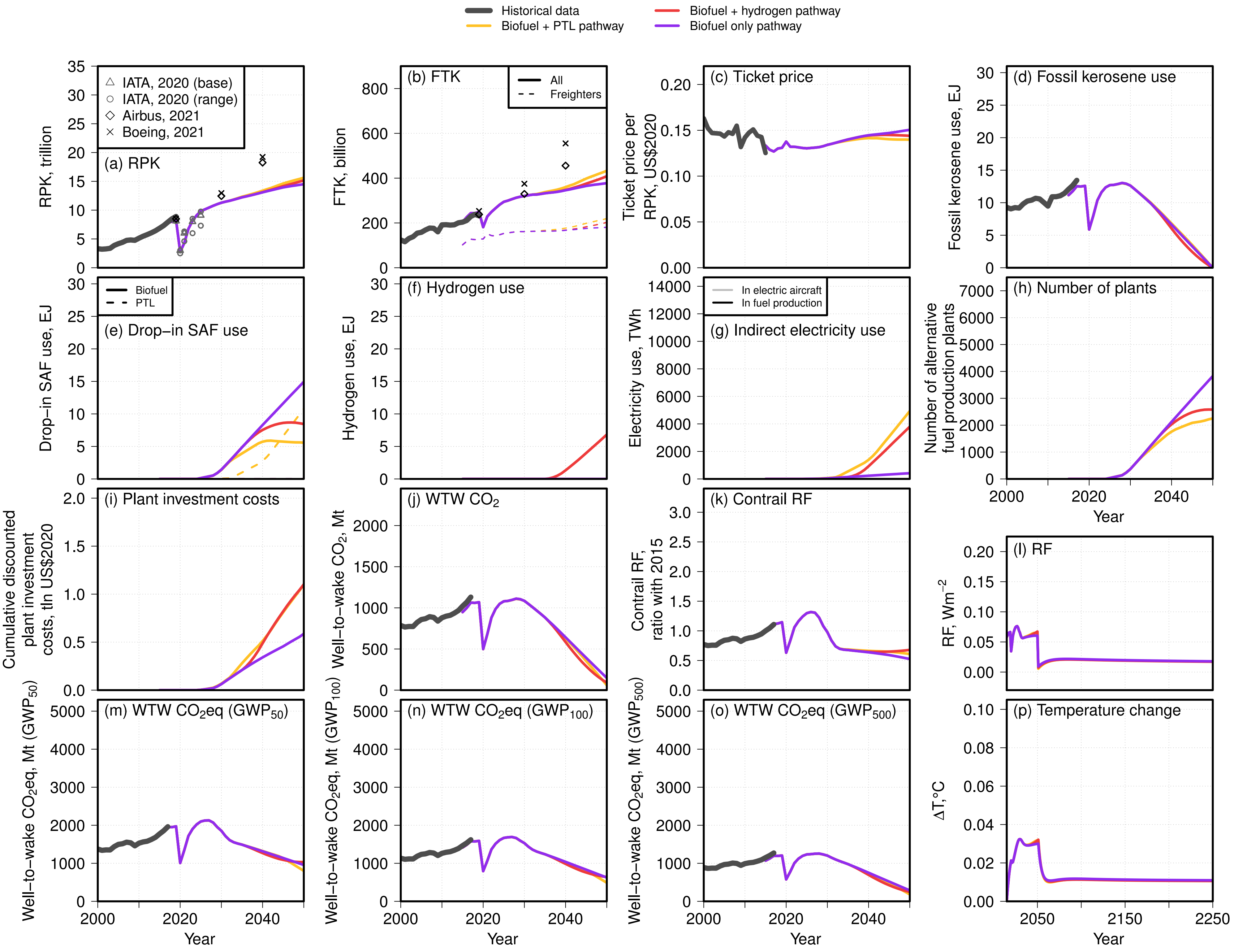
RF (W/m^2)
0.3
0.2
0.1
0.0
−0.1
2020
2040
2060
2080
Year
ΔT (K ·10^{-3})
150
125
100
75
50
25
0
−25
−50
2020
2040
2060
2080
Year
Total
Life cycle N_2O
Life cycle CO_2
Life cycle CH_4
Black Carbon
Stratospheric water vapor
Contrails
NO_x: O_3 Short
NO_x: CH_4
NO_x: O_3 Long
NO_x: Nitrate aerosol
NO_x: Total
Sulfates


RF (W/m^2)
0.3
0.2
0.1
0.0
−0.1
2020
2040
2060
2080
Year
ΔT (K $\cdot 10^{-3}$)
150
125
100
75
50
25
0
−25
−50
2020
2040
2060
2080
Year
Total
Life cycle N_2O
Life cycle CO_2
Life cycle CH_4
Black Carbon
Stratospheric water vapor
Contrails
NO_x: O_3 Short
NO_x: CH_4
NO_x: O_3 Long
NO_x: Nitrate aerosol
NO_x: Total
Sulfates


Historical data
Biofuel + PTL pathway
Biofuel + hydrogen pathway
Biofuel only pathway
(a) RPK
△ IATA, 2020 (base)
○ IATA, 2020 (range)
◇ Airbus, 2021
× Boeing, 2021
RPK, trillion
0
5
10
15
20
25
30
35
(b) FTK
All
Freighters
FTK, billion
0
200
400
600
800
(c) Ticket price
Ticket price per RPK, US$2020
0.00
0.05
0.10
0.15
0.20
(d) Fossil kerosene use
Fossil kerosene use, EJ
0
5
10
15
20
25
30
(e) Drop−in SAF use
Biofuel
PTL
Drop−in SAF use, EJ
0
5
10
15
20
25
30
(f) Hydrogen use
Hydrogen use, EJ
0
5
10
15
20
25
30
(g) Indirect electricity use
In electric aircraft
In fuel production
Electricity use, TWh
0
2000
4000
6000
8000
10000
12000
14000
(h) Number of plants
Number of alternative fuel production plants
0
1000
2000
3000
4000
5000
6000
7000
2000
2020
2040
Year
(i) Plant investment costs
Cumulative discounted plant investment costs, tln US$2020
0.0
0.5
1.0
1.5
2.0
(j) WTW CO$_2$
Well−to−wake CO$_2$, Mt
0
500
1000
1500
2000
(k) Contrail RF
Contrail RF, ratio with 2015
0.0
0.5
1.0
1.5
2.0
2.5
3.0
(l) RF
RF, Wm^{-2}
0.00
0.05
0.10
0.15
0.20
(m) WTW CO$_2$eq (GWP$_{50}$)
Well−to−wake CO$_2$eq, Mt (GWP$_{50}$)
(n) WTW CO$_2$eq (GWP$_{100}$)
Well−to−wake CO$_2$eq, Mt (GWP$_{100}$)
(o) WTW CO$_2$eq (GWP$_{500}$)
Well−to−wake CO$_2$eq, Mt (GWP$_{500}$)
0
1000
2000
3000
4000
5000
2000
2020
2040
Year
(p) Temperature change
ΔT,°C
0.00
0.02
0.04
0.06
0.08
0.10
2050
2150
2250
Year



Historical data
Biofuel + PTL pathway
Biofuel + hydrogen pathway
Biofuel only pathway
(a) RPK
RPK, trillion
IATA, 2020 (base)
IATA, 2020 (range)
Airbus, 2021
Boeing, 2021
0 5 10 15 20 25 30 35
(b) FTK
FTK, billion
All
Freighters
0 200 400 600 800
(c) Ticket price
Ticket price per RPK, US$2020
0.00 0.05 0.10 0.15 0.20
(d) Fossil kerosene use
Fossil kerosene use, EJ
0 5 10 15 20 25 30
(e) Drop−in SAF use
Drop−in SAF use, EJ
Biofuel
PTL
0 5 10 15 20 25 30
(f) Hydrogen use
Hydrogen use, EJ
0 5 10 15 20 25 30
(g) Indirect electricity use
Electricity use, TWh
In electric aircraft
In fuel production
0 2000 4000 6000 8000 10000 12000 14000
(h) Number of plants
Number of alternative fuel production plants
0 1000 2000 3000 4000 5000 6000 7000
2000 2020 2040
Year
(i) Plant investment costs
Cumulative discounted plant investment costs, tln US$2020
0.0 0.5 1.0 1.5 2.0
(j) WTW CO_2
Well−to−wake CO_2, Mt
0 500 1000 1500 2000
(k) Contrail RF
Contrail RF, ratio with 2015
0.0 0.5 1.0 1.5 2.0 2.5 3.0
(l) RF
RF, Wm^{-2}
0.00 0.05 0.10 0.15 0.20
(m) WTW CO_2eq (GWP_{50})
Well−to−wake CO_2eq, Mt (GWP_{50})
(n) WTW CO_2eq (GWP_{100})
Well−to−wake CO_2eq, Mt (GWP_{100})
(o) WTW CO_2eq (GWP_{500})
Well−to−wake CO_2eq, Mt (GWP_{500})
0 1000 2000 3000 4000 5000
2000 2020 2040
Year
(p) Temperature change
ΔT,°C
0.00 0.02 0.04 0.06 0.08 0.10
2050 2150 2250
Year



Historical data
Biofuel + PTL pathway
Biofuel + hydrogen pathway
Biofuel only pathway
(a) RPK
RPK, trillion
0 5 10 15 20 25 30 35
IATA, 2020 (base)
IATA, 2020 (range)
Airbus, 2021
Boeing, 2021
(b) FTK
FTK, billion
0 200 400 600 800
All
Freighters
(c) Ticket price
Ticket price per RPK, US$2020
0.00 0.05 0.10 0.15 0.20
(d) Fossil kerosene use
Fossil kerosene use, EJ
0 5 10 15 20 25 30
(e) Drop−in SAF use
Drop−in SAF use, EJ
0 5 10 15 20 25 30
Biofuel
PTL
(f) Hydrogen use
Hydrogen use, EJ
0 5 10 15 20 25 30
(g) Indirect electricity use
Electricity use, TWh
0 2000 4000 6000 8000 10000 12000 14000
In electric aircraft
In fuel production
(h) Number of plants
Number of alternative fuel production plants
0 1000 2000 3000 4000 5000 6000 7000
2000 2020 2040
Year
(i) Plant investment costs
Cumulative discounted plant investment costs, tln US$2020
0.0 0.5 1.0 1.5 2.0
(j) WTW CO_2
Well−to−wake CO_2, Mt
0 500 1000 1500 2000
(k) Contrail RF
Contrail RF, ratio with 2015
0.0 0.5 1.0 1.5 2.0 2.5 3.0
(l) RF
RF, Wm^{-2}
0.00 0.05 0.10 0.15 0.20
(m) WTW CO_2eq (GWP_{50})
Well−to−wake CO_2eq, Mt (GWP_{50})
(n) WTW CO_2eq (GWP_{100})
Well−to−wake CO_2eq, Mt (GWP_{100})
(o) WTW CO_2eq (GWP_{500})
Well−to−wake CO_2eq, Mt (GWP_{500})
0 1000 2000 3000 4000 5000
2000 2020 2040
Year
(p) Temperature change
ΔT,°C
0.00 0.02 0.04 0.06 0.08 0.10
2050 2150 2250
Year