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Pathways to net-zero emissions from aviation

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International climate goals imply reaching net-zero global carbon dioxide (CO_2) emissions by roughly mid-century (and net-zero greenhouse gas emissions by the end of the century). Among the most difficult emissions to avoid will be those from aviation given the industry's need for energy-dense liquid fuels that lack commercially competitive substitutes and the difficult-to-abate non-CO_2 radiative forcing. Here we systematically assess pathways to net-zero emissions aviation. We find that ambitious reductions in demand for air transport and improvements in the energy efficiency of aircraft might avoid up to 61% (2.8 $GtCO_2$ equivalent ($GtCO_2$eq)) and 27% (1.2 $GtCO_2$eq), respectively, of projected business-as-usual aviation emissions in 2050. However, further reductions will depend on replacing fossil jet fuel with large quantities of net-zero emissions biofuels or synthetic fuels (that is, 2.5–19.8 EJ of sustainable aviation fuels)—which may be substantially more expensive. Moreover, up to 3.4 $GtCO_2$eq may need to be removed from the atmosphere to compensate for non-CO_2 forcing for the sector to achieve net-zero radiative forcing. Our results may inform investments and priorities for innovation by highlighting plausible pathways to net-zero emissions aviation, including the relative potential and trade-offs of changes in behaviour, technology, energy sources and carbon equivalent removals.

Stabilizing global mean temperature at 1.5 °C above pre-industrial times means reaching net-zero CO_2 emissions (that is, balancing any ongoing emissions with removals) by 2050–2060, and net-zero greenhouse gas emissions by 2070–2100[1]. Large—and increasingly affordable—emissions reductions are available by improving energy efficiency, electrifying energy end uses and switching to non-emitting sources of electricity[1], and many countries, subnational jurisdictions and companies have announced net-zero emissions targets[2]. However, flying will be particularly challenging to decarbonize because aircraft rely on energy-dense liquid hydrocarbons and flights also entail non-CO_2 radiative forcing[3,4].

The climate impacts of global aviation are substantial, with one-third of radiative forcing related to CO_2 and two-thirds related mainly to nitrous oxides (NO_x) and water vapour in the form of contrail cirrus clouds[5,6]. According to the IEA, in 2019, aviation accounted for 1.03 $GtCO_2$, or 3.1% of total global CO_2 emissions from fossil fuel combustion[7], and 1.7 $GtCO_2$ equivalent (eq) when non-CO_2 forcing is included (based on a global warming potential of 100 years, or GWP100). Although emissions from air travel dropped 40% in 2020 due to the COVID-19 pandemic, aviation demand is expected to recover and grow in the future[8], with emissions projected to reach as high as 1.9 $GtCO_2$ in 2050[9] (~2.6 times 2021 values) or 3.4 $GtCO_2$eq (GWP100). Demand for air travel across countries and population groups is closely associated with affluence and lifestyle[10] (Supplementary Fig. 1), and flying has become a lightning rod for climate activists who criticize the hypocrisy of climate scientists and climate-concerned policymakers who fly[11].

Many aircraft manufacturers and industry groups aim to meet rising demand while also reducing emissions by improving operational efficiencies, offsetting carbon emissions and switching to net-zero emissions fuels[12–14]. Domestic aviation emissions are included in

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countries' nationally determined contributions under the Paris climate agreement, but international aviation emissions are not. Recently, governments such as the United States (2021 Aviation Climate Action Plan)[15] and the European Union (Aviation Safety Agency report)[16] have addressed the sector's emissions. Though most aviation-related climate targets have not been met[17], in 2016, under the International Civil Aviation Organization (ICAO), 192 countries signed the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) to make post-2020 growth of international aviation carbon neutral, either by fuel switching or by offsetting emissions[14]. Most prominently, the International Air Transport Association (IATA) committed in 2021 that emissions from global aviation would be net-zero by 2050[18].

Recent analyses have evaluated the technological potential of powering aircraft with sustainable aviation fuels (SAFs)[3,19,20], hydrogen or electricity[18] and offsetting aviation emissions by removing equivalent quantities of CO_2 from the atmosphere[21] (Supplementary Fig. 2). SAFs include biofuels and synthetic fuels that are 'drop-in' replacements for jet fuel (that is, they would require little or no changes to existing aircraft and fueling infrastructure) that meet ICAO's sustainability criteria[14] of a net greenhouse gas emissions reduction on a life-cycle basis of at least 10% compared to fossil jet fuel, respecting biodiversity and contributing to local social and economic development.

Here we assess nine possible pathways to achieve net-zero direct emissions from aviation, including changes and trade-offs in demand, energy efficiency, propulsion systems, alternative fuels for both passenger and freight transport and compensatory carbon removals. Details of our analytic approach are in Methods (Supplementary Figs. 3 and 4 and Supplementary Table 1). We develop and analyse a range of mid-century decarbonization scenarios for the aviation industry decomposing historical and future aviation emissions using a sector-specific variant of the Kaya identity:

$$F = D\left(\frac{E}{D}\right)\left(\frac{F}{E}\right) = Def \quad (1)$$

where F represents fossil fuel CO_2 emissions from global aviation (neglecting life-cycle emissions of the aircraft and the supply chain of fuel), D is demand or distance flown and E is the energy consumed by flying aircraft, such that e is energy intensity of air transport and f is the carbon intensity of energy used for air transport. We analyse three pathways of demand (D) and energy intensity (e) based on 'Business-as-usual' (BAU), 'Industry' and 'Ambitious' projections and combine them with three pathways for carbon intensity (f), namely 'Carbon intensive', 'Reduced fossil' and 'Net-zero'.

Demand for aviation

Total aviation demand in 2019 was almost 1 trillion ton-kilometer equivalent (tkm_e or 11.1 trillion passenger-kilometer equivalent, pkm_e), with 78% representing passenger flights and 22% freight (Fig. 1a, black line). Travel advisories and border restrictions during the global pandemic led to a sharp decline in the air transport of passengers[7], driving global demand down to about 0.45 trillion tkm_e (5.0 trillion pkm_e) in 2020: 18% and 65% decreases in freight and passenger transport, respectively. Freight demand fully recovered in 2021[22], but as of July 2022, passenger demand was still about 25% below pre-pandemic levels[23]. While ICAO estimates that it may be several more years before passenger demand recovers to 2019 levels, IATA projects a faster recovery of air travel to 2019 levels by 2023[24]. It is worth noting that demand varies regionally, with about 38%, 24% and 23% of passenger-kilometers being attributed to Asia and the Pacific, Europe and North America, respectively. Although the share of passenger demand is substantially smaller in the Middle East (9%), Latin America and the Caribbean (5%) and Africa (2%), demand in those regions has been rapidly increasing, for example, growing by 234% in the Middle East between 2007 and 2019 (Supplementary Fig. 5).

Despite such short-term uncertainty, industry projections consistently anticipate continued growth in demand of air transport in the coming decades[8], whereas other researchers have argued that substantial reductions in future demand are possible via behavioural changes and shifts to high-speed trains[4]. The demand scenarios in Fig. 1a thus span a wide range of trajectories: 'BAU' increases of 4% per year (to 2.9 trillion tkm_e or 32.1 trillion pkm_e in 2050; orange curve)[8], 'Industry' projections of an average of 2.8% increase per year (2.1 trillion tkm_e or 23.7 trillion pkm_e; blue curve)[8] and 'Ambitious' demand shifts that keep growth to an average of 1% per year (1.1 trillion tkm_e or 12.4 trillion pkm_e; green curve)[25]. It should be noted that the Ambitious scenario implies a sudden and drastic divergence in the historical relationship between aviation demand and expected population and economic growth (Supplementary Fig. 1).

Energy intensity of aviation

The energy intensity of aircraft has declined by an average 1% per year since 1970[26], falling from 31.6 MJ tkm_e^{-1} (2.8 MJ pkm_e^{-1}) in 1990 to about 12.6 MJ tkm_e^{-1} (1.1 MJ pkm_e^{-1}) in 2021 (Fig. 1b, black line). The spike in 2020 is driven by the global pandemic, when the rapid drop-in passenger demand led to decreases in the load factors of flights (that is, the share of seats filled) and thus increases in energy intensity (to 18.3 MJ tkm_e^{-1} or 1.7 MJ pkm_e^{-1}). Improvements since 2010 reflect the release of fuel-efficient aircraft such as the Airbus A320neo and A350 and the Boeing 737 MAX and 787, but the International Council on Clean Transportation does not expect new aircrafts and thus substantial decreases in energy intensity in the next few years[26]. Despite this, the ICAO's A40-18 resolution in 2019 set a goal of improving the fuel efficiency of international flights by 2% per year until 2050[14]. Even more ambitiously, a mid-century net-zero scenario developed by the IEA includes reductions in the energy intensity of international flights of an average 7% from 2019 to 2025, followed by a subsequent 2% yearly reduction to 2030[7].

The scenarios shown in Fig. 1b span the full range of these future energy intensities, from 'BAU' reductions of 1% per year (to 9.4 MJ tkm_e^{-1} or 0.85 MJ pkm_e^{-1} in 2050; orange curve)[26], 'Industry' reduction commitments of 2% per year (7.0 MJ tkm_e^{-1} or 0.63 MJ pkm_e^{-1}; blue curve)[14] and 'Ambitious' reductions of an average of 4% per year (extrapolating the rapid decreases in the IEA net-zero scenario to reach 3.7 MJ tkm_e^{-1} or 0.34 MJ pkm_e^{-1} in 2050; green curve)[7]. Here again, it is not clear that the energy intensities in the most ambitious scenario are physically possible, but some studies have theorized that revolutionary improvements such as open rotors[27], blended wing-body airframes[28] and hybridization[29], and more efficient air traffic management, could bring important efficiency gains[25].

Carbon intensity of energy for aviation

Historically, jet fuel (that is, fossil kerosene-based Jet A/A-1) has been the energy source for almost all commercial aircraft, resulting in a near-constant carbon intensity of ~73.5 gCO_2 MJ^{-1} or 124.9 gCO_2eq MJ^{-1} (including combustion emissions only; Fig. 1c, black curve). In recent years, some airlines have begun using bio-based jet fuel—which could decrease carbon intensity of aviation energy—but uptake has been slow: bio-based jet fuel production was about 140 million liters in 2019. This represented less than 1% of aviation fuel use in that year[30] and was mostly blended with fossil fuels based on standard D7566 from the ASTM, which allows a maximum 50% blend[31]. The first commercial demonstration plane using 100% biofuels flew on December 2021, and few have done it since[32]. Looking forward, industry groups nonetheless project rapid decreases in the carbon intensity of aviation energy. The International Renewable Energy Agency's (IRENA) 1.5 °C scenario assumes that by mid-century, 70% of aviation's energy demand is met by SAFs, while 14% comes from electricity and hydrogen[33]. Similarly, IATA's net-zero commitment projects that 65% of 1.8 $GtCO_2$ (their estimated 2050 emissions) will be abated by using SAFs, with

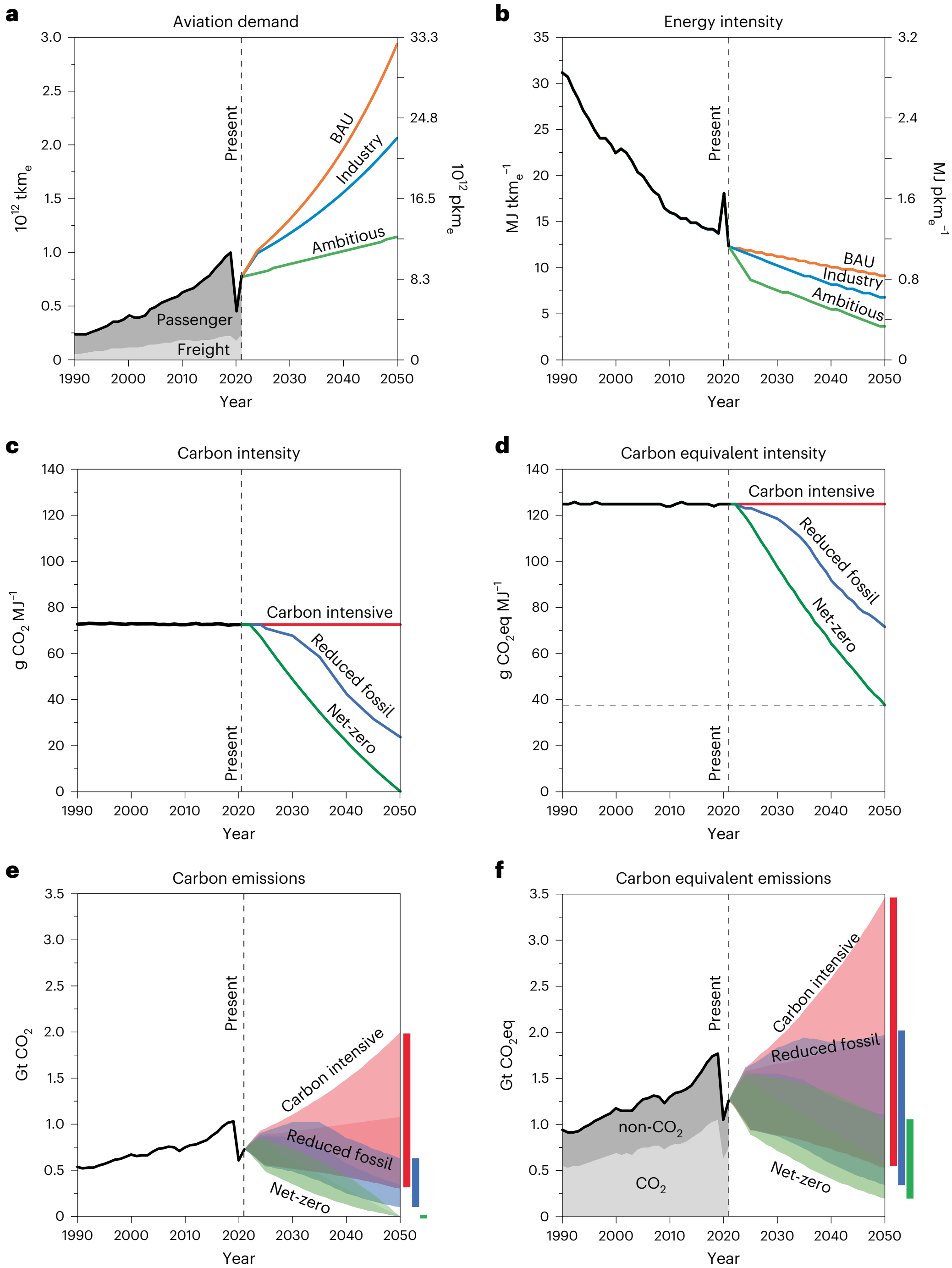

Fig. 1 | Decomposition parameters and emissions trajectories. a, Total global aviation demand (*D*) for BAU (orange), Industry projections (blue) and Ambitious (green) scenarios. **b**, Energy intensity of air transport (*e*) for the same scenarios. **c**, Carbon intensity of aviation energy (*f*) in gCO_2 MJ^{-1} for Carbon Intensive (red), Reduced fossil (blue) and Net-zero (green) scenarios. **d**, Carbon equivalent intensity (*f*) for aviation in gCO_2eq MJ^{-1} based on a GWP100 for the same scenarios. **e**, Carbon dioxide emissions in GtCO_2 from fossil jet fuel burning by combining three carbon intensity scenarios (*f*) with three demand and energy intensity scenarios (BAU *D* with BAU *e*, Industry *D* with Industry *e* and Ambitious *D* with Ambitious *e*). **f**, Carbon-equivalent emissions in GtCO_2eq based on a GWP100 estimate based on Lee et al.[6]. Historical data (black) for each panel are shown for 1990–2021; projections are shown for 2022–2050. Panel **a** shows the breakdown of total demand by passenger and freight aviation. Panels **e** and **f** represent the emissions ranges for each group of demand and energy-intensity scenarios in combination with the different carbon-intensity scenarios. Panel **f** shows the historical breakdown between CO_2 and non-CO_2 emissions. All scenario assumptions and sources are in Supplementary Table 1. For other GWP and GTP, refer to Supplementary Fig. 9.

hydrogen and electricity-powered aircraft abating 13% (ref. [18]). The IEA's net-zero scenario includes 75% of all aviation energy demand being SAF by 2050 but with more modest deployment of electric planes[25]. It is worth noting that given their energy density, only short-haul flights (<3 hours) could be powered by electricity and hydrogen (Supplementary Fig. 6).

There are three carbon-intensity scenarios shown in Fig. 1c,d. First, a 'Carbon intensive' option that continues to rely on fossil jet fuel and thus maintains 73.5 gCO_2 MJ^{-1} or 124.9 gCO_2eq MJ^{-1} (red curve, Supplementary Table 2). Second, a 'Reduced fossil' pathway in which 65% of energy demand by medium- and long-haul aviation in 2050 is met by SAFs (with 35% still met by fossil jet fuel) and 13%, 57% and 30% of short-haul aviation energy demand is met by non-emitting propulsion systems, SAFs and fossil jet fuel, respectively. This leads to 23.9 gCO_2 MJ^{-1} or 71.7 gCO_2eq MJ^{-1} in 2050 (blue curve, Supplementary Table 3). And third, a 'Net-zero' pathway in which, by 2050, there is no combustion of fossil jet fuel. In this scenario, 100% of medium- and long-haul aviation energy in 2050 is supplied by SAFs, and 50% of short-haul fights are powered by other non-emitting propulsion systems, with the rest being SAFs. This leads to 0 gCO_2 MJ^{-1} or 37.6 gCO_2eq MJ^{-1} by 2050 (green curve, Supplementary Table 4). Note that these scenarios assume that the combustion emissions from SAFs are net-zero with respect to atmospheric carbon and have the same non-CO_2 emissions as fossil fuels, assumptions we discuss in more detail below.

Aviation emissions

According to IEA estimates, aviation carbon emissions were 1.03 $GtCO_2$ in 2019[7], 64% of which were related to international flights and 36% from domestic flights. Emissions plunged to 0.61 $GtCO_2$ in 2020 amid COVID-19 lockdowns and rebounded somewhat to 0.7 $GtCO_2$ in 2021[7] (Fig. 1e, black curve). On the basis of GWP100[6], aviation's total equivalent emissions in 2019 were about 1.7 $GtCO_2eq$ and dropped to 1.03 $GtCO_2eq$ in 2020 (Fig. 1f, black curve). Future emissions will reflect the combination of changes in demand, energy intensity of aviation and the carbon intensity of aviation energy, with important regional distinctions. By 2019, the United States represented ~28% of global aviation emissions, followed by China (10%) and larger European nations (18%) (Supplementary Fig. 5).

Combining our scenarios of demand and intensities as described in Supplementary Fig. 3 gives ranges of emissions trajectories shown in Fig. 1e,f. On the upper end, BAU growth in demand (that is, +4% per year) and improvements in energy intensity (that is, −1% per year), with continued use of fossil jet fuel leads to annual aviation emissions of 2.0 $GtCO_2$ (3.4 $GtCO_2eq$) in 2050 (top of red shading in Fig. 1e,f). At the other extreme, phasing out fossil jet fuel entirely would eliminate carbon aviation emissions by 2050 (green shading in Fig. 1e)—but might entail large cost increases (as discussed below). Accounting for non-CO_2 impacts, total equivalent emissions in such an ambitious scenario would be about 0.2 $GtCO_2eq$ by mid-century (Fig. 1f). Notably, replacing 65% of medium- and long-haul aviation fossil jet fuel with SAFs could still result in annual carbon emissions of 0.65 $GtCO_2$ (higher than emissions in 2020) or about 1.9 $GtCO_2eq$ in 2050 under BAU changes in demand and energy intensity (top of blue shading in Fig. 1e,f; Fig. 2d). Accounting for the non-CO_2 impacts from aviation means the sector will not be zero emissions unless carbon dioxide removals (CDR) are included.

Figure 2 reveals the relative contributions of different mitigation levers by comparing relative changes between 2021 and 2050 for aviation total climate impacts and the magnitude of CDR needed to achieve net-zero emissions. For example, annual emissions nearly triple assuming BAU changes (+175%), driven by surging demand for air transport (blue bar; Fig. 2a), requiring the highest CDR to meet net-zero targets (3.4 $GtCO_2$), a removal that could cost up to a trillion dollars (Supplementary Fig. 7). In contrast, assuming somewhat lower increases in demand, an almost tripling of historical decreases in energy intensity and that two-thirds of fuel are sustainable and net-zero, annual emissions in 2050 could be roughly equivalent of what they were in 2021 (−13%; Fig. 2e), with a need for CDR for 1.1 $GtCO_2$. Finally, the decreases in carbon intensity of aviation energy in net-zero scenarios (green bar; Fig. 2g–i) are heavily dependent on projected changes in aviation demand and energy intensity—the higher demand for air travel and the lower the improvements in energy intensity, the more important the share of SAFs. In turn, greater use of SAFs lowers the need for CDR to reach net-zero radiative forcing.

Sustainable aviation fuels

The quantity of SAFs required to meet net-zero goals is inversely proportional to changes in aviation demand and energy intensity (Fig. 3). Although this demand might also be reduced by using hydrogen or battery electric propulsion systems, the low energy density of such alternatives will probably limit their use to short-haul applications (Supplementary Fig. 6). For example, assuming a 60% fuel fraction (that is, the share of maximum take-off weight allocated to fuel), 90% increases in energy efficiency and 1,500 kWh t^{-1} H_2, larger body aircraft such as a Boeing 777-200 or Airbus 380-800 (whose fuel fraction is ~50%) converted to hydrogen propulsion would not be anywhere near able to cover the distance of common long-haul routes such as New York to London (5,500 km) or Los Angeles to Beijing (10,000 km). Similar estimates show that the range of large battery electric planes would be ~500 km (Supplementary Fig. 6). Nonetheless, our Net-zero scenarios assume that half of short-haul flights might be serviced by hydrogen or battery electric planes (Supplementary Table 4).

Thus, Fig. 3 shows that without extreme reductions in aviation demand and energy intensity (that is, the green 'Ambitious' curves), by 2050, demand for SAFs in all of our scenarios is more than double the quantity of global production of biofuels in 2019 (~4 EJ including ethanol, biodiesel and hydrotreated vegetable oil)[34] and about 1,800 times more than the 0.005 EJ of bio-based jet fuel produced in 2019[35]. Such a biofuel demand could derive in a land expansion as high as 300 million hectares (~19% of global cropland in 2019; Supplementary Fig. 8). It is likely, however, that as electrification of other sectors continues, some of the ~64 EJ of global biomass energy supply[34] are diverted to produce bio-based jet fuels—and it is unlikely that the entirety of SAF demand is met by biofuels. In addition to biofuels, SAFs might ultimately include hydrocarbons produced by Fischer–Tropsch (FT) or methanol synthesis using carbon captured from the atmosphere and hydrogen generated without fossil CO_2 emissions (for example, by electrolysis using renewable or nuclear electricity)[36].

Whether biofuels or synthetic fuels, a major barrier to the penetration of SAFs is cost, which, in turn, depends on the cost of feedstocks and the costs and efficiency of conversion processes. In the case of synthetic fuels, the cost of hydrogen primarily reflects electrolyser and electricity costs, and the cost of captured carbon depends on the technology involved. For example, assuming current costs of electrolytic hydrogen and captured carbon are around US\$4.50 kg^{-1} H_2 (ref. [36]) and US\$0.25 kg^{-1} CO_2 (ref. [37]), respectively, synthetic jet fuel costs are about US\$2.60 l^{-1}, more than three times higher than the global 2022 average cost of fossil jet fuel (as of 31 May 2022)[38] (Fig. 4a). If we incorporated the costs of removing carbon from the atmosphere to compensate for the non-CO_2 impacts embodied in burning one liter of synthetic jet fuel, then this cost would increase to about US\$3.20 l^{-1} (based on a GWP100 and US\$350 t^{-1} CO_2; Fig. 4b). These estimates are broadly consistent with other recent studies that reported costs of synthetic fuel ranging from US\$1.30 to US\$4.70 per liter (refs. [39,40]). Economies of scale and learning-by-doing may substantially reduce electrolyser and carbon capture costs in the future, making synthetic fuels more competitive[36].

Even though there are several conversion pathways for biofuels, FT biofuels and hydro-processed esters and fatty acids (HEFA) are among the few advanced biofuels with 'near commercial' fuel readiness level. Near-commercial readiness means the conversion pathway has been certified and the technology is beyond the research and development stage. On the basis of average feedstock costs of US\$0–1.10 kg^{-1} of biomass and conversion efficiencies between 30–50% (~2–4 kg biomass per kg fuel)[41], current production costs for FT biofuels are between US\$1.00 and US\$2.30 l^{-1} (ref. [35]) or US\$1.68 and US\$2.97 l^{-1}, accounting for the costs of removing the carbon equivalent to the non-CO_2 forcing in that liter of biofuel (Fig. 4c,d). The lower end uses a zero-cost waste feedstock with 67% and 33% of the production cost represented by capital and operating expenditures, respectively; the

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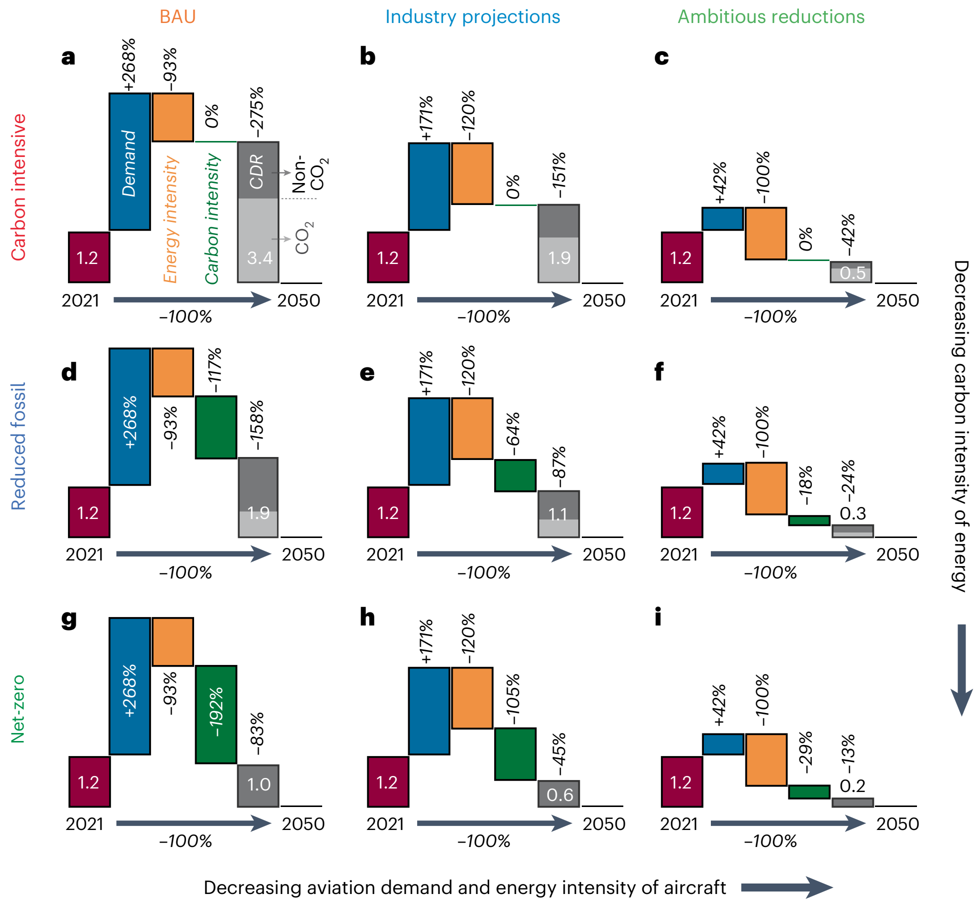

Fig. 2 | Decomposition parameters for changes in emissions in $GtCO_2eq$ from 2021 to 2050. Each column represents a combination of demand and energy intensity (*De*), and each row represents a carbon-intensity trajectory (*f*). Each panel represents a demand and energy-intensity trajectory combined with a specific carbon intensity (*Def*). Colours for the headers represent low- (orange/red), medium- (blue) and high-ambition (green), for example, panel **a** represents the lowest ambition scenario with BAU demand and energy intensity and a carbon intensive fuel mix. Each bar within each panel represents a Kaya parameter: historical emissions in 2021 (maroon), increase in emissions based on projected demand (blue), decrease in emissions based on energy-intensity improvements (orange), potential further reductions due to changes in carbon intensity of energy (green) and carbon dioxide removals (CDR) needed to reach net-zero by 2050 (grey). The CDR grey bar is divided into two, representing the split between CO_2 and non-CO_2 equivalent emissions in each scenario.

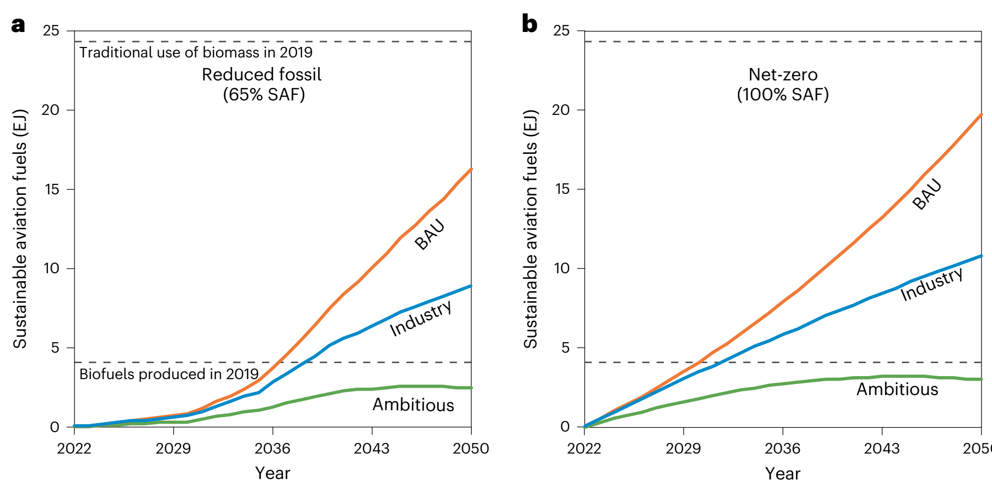

Fig. 3 | Projected demand for SAFs. a,b, SAF demand varies considerably for reduced fossil (**a**) and net-zero (**b**) pathways. Each solid line represents a combination of demand (*D*) and energy intensity (*e*); orange stands for BAU, blue for Industry projections and green for Ambitious pathways. The dashed horizontal grey line in the bottom shows total biofuel production worldwide in 2019[81], whereas the top dashed line shows the total global traditional use of biomass in the same year[34]. For reference, in 2019, total global bioenergy use was almost 64 EJ (ref. [34]), while bio-jet fuel production was only 0.005 EJ (ref. [35]).

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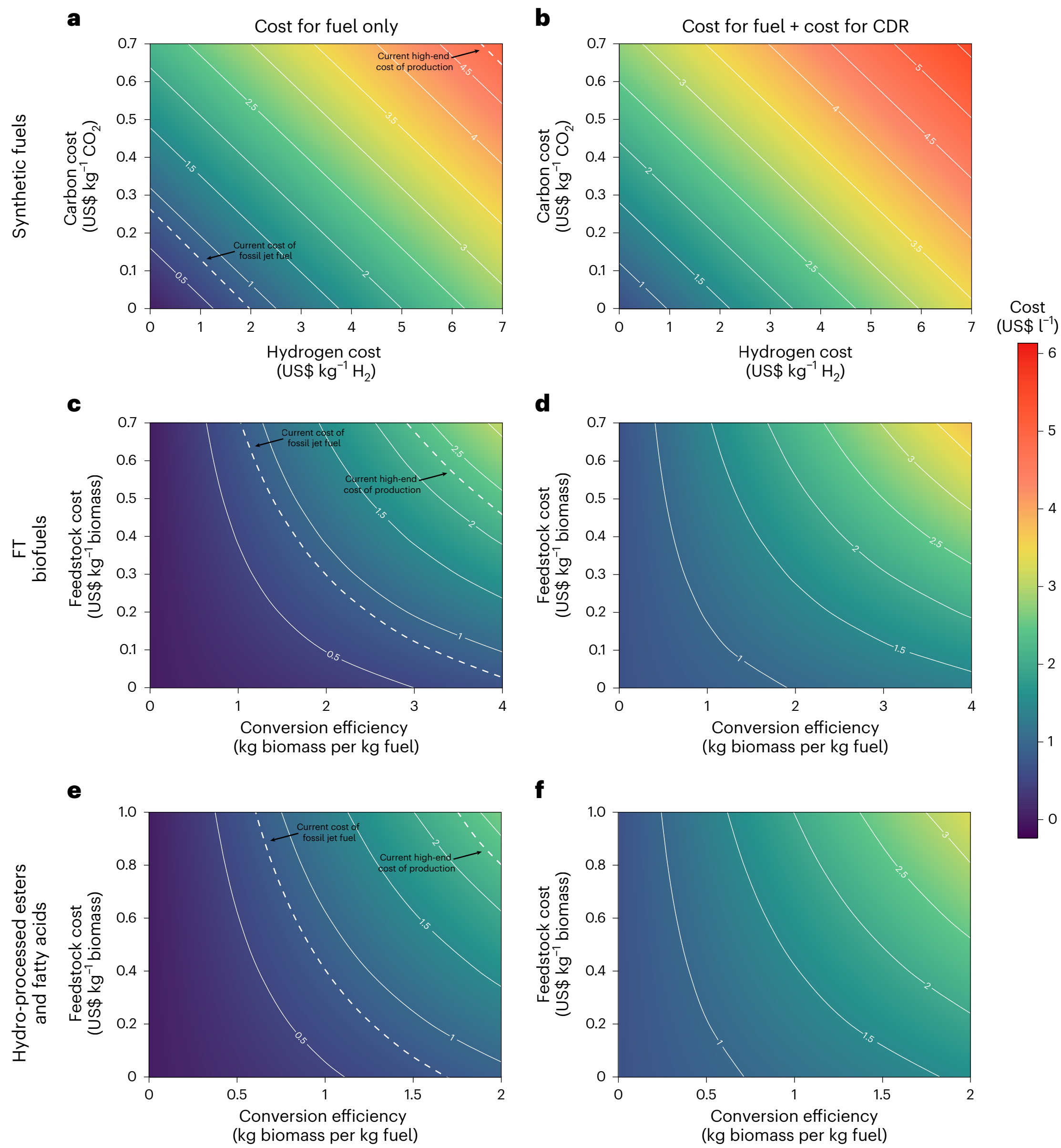

Fig. 4 | Costs of near-commercial sustainable aviation fuels with and without CDR. a–f, Contours show costs of synthetic fuel (**a**,**b**), FT biofuels (**c**,**d**) and hydro-processed esters and fatty acids (**e**,**f**) based on key input costs and conversion efficiencies. The left three panels (**a**,**c**,**e**) include the cost for producing each fuel. The right three panels (**b**,**d**,**f**) represent the same costs as in the right panels plus what it would cost to remove from the atmosphere the carbon equivalent non-CO_2 emissions embedded in a liter of SAF for a GWP100 and an assumed cost of CDR of US\$350 t^{-1} CO_2 (for other assumptions, refer to Supplementary Fig. 7b). For comparison, one of the dashed white lines in each left panel indicates the 2022 average cost of fossil jet fuel as of the end of May (US\$0.80 l^{-1}), according to IATA's Fuel Price Monitor[38]. The other dashed white line represents upper-end costs from the literature[35]. Further details of calculations are in Methods and Supplementary Tables 6–11.

upper end uses a lignocellulose feedstock that is 33% of production cost, with the remainder 45% and 22% represented by capital and operating expenses, respectively[35]. Although the low end of this range approaches the current cost of fossil jet fuel, the additional expense may be limiting uptake in a cost-competitive industry where, at least in the near-term, emissions reductions remain mostly voluntary. Achieving cost parity could thus greatly increase use of FT biofuels and might entail a carbon price of as little as US\$78 t^{-1} CO_2. For HEFA biofuels, costs of feedstocks (for example, from used cooking oil to jatropha oil) are routinely US\$0.70–2.60 kg^{-1} (ref. [35]) and unlikely to decrease much in the future. The HEFA conversion pathway has the highest efficiency compared with other bio-based jet fuel routes at around 76% (ref. [42]) (~1–2 kg biomass per kg fuel), with production cost ranges between US\$0.80 and US\$2.30 l^{-1} (ref. [35]) or US\$1.46 and US\$3.00 l^{-1} if the non-CO_2 forcing was included (Fig. 4e,f). Although the lower-end costs are less than fossil jet fuel, feedstock availability is limited as it represents used cooking oil that is a byproduct of consumption, and 90% of this feedstock is already used for biodiesel production (at least in the European Union)[35].

Discussion

Without ambitious reductions in air transport demand and improvements in aircraft energy efficiency, decarbonizing aviation will require important quantities of 'drop-in' sustainable aviation fuels (SAFs), especially given the number and long lifetime of commercial aircraft (~23,000 and >25 years). As much as 19.8 EJ of SAFs—nearly five times the total quantity of biofuels produced worldwide in 2019[34]—might be necessary to achieve net-zero carbon emissions under business-as-usual changes in demand and energy intensity. Such scale would require the ethanol and biodiesel industries to grow four times faster than they did in the early 2000s[43]. Additionally, in a net-zero world, bio-based jet fuels would compete for feedstocks with other hard-to-decarbonize sectors and with electricity generation from bioenergy with carbon capture and storage (which would provide a source of negative emissions).

Because of aviation's non-CO_2 forcing, achieving a net-zero emissions sector would also rely on CDR ranging from 0.2 to 3.4 $GtCO_2$ in our scenarios. If carbon credits are less expensive than SAFs, airlines may seek to offset rather than reduce their combustion emissions (Supplementary Fig. 7). Indeed, many airlines currently offer their customers offsets, and ICAO's CORSIA establishes mandatory schemes to achieve carbon neutrality, relying mostly on offsets[14]. However, such credits are increasingly facing questions of permanence and additionality[44] that make reliable mitigation through fuel switching and operational shifts, such as contrail avoidance by plane rerouting, vital[45].

Given that airline net profits in 2019 were about US$3.26 per thousand passenger-kilometers (ref. [46]) and fuel represents between 20% and 30% of airlines' operating costs[47], the high current costs of SAFs (2–4 times higher than fossil jet fuel based on recent references; Fig. 4) may not be feasible. These high costs make fuel switching the most difficult in developing regions, where aviation demand is growing the fastest. Projected decreases in the costs of electrolytic hydrogen[36] and captured carbon[48] would make synthetic fuels more affordable, and higher conversion efficiencies and lower feedstock costs would help FT and HEFA biofuels. Such improvements may be induced via specific policy incentives such as cleaner aviation fuel tax credits (as those included in the Inflation Reduction Act in the United States)[49] and low-carbon fuel standards[50], though HEFA feedstock costs have been quite volatile in recent years[51]. Carbon pricing could also change the incentive structure and make SAFs more competitive, potentially hastening deployment and further reducing costs via learning and economies of scale[35].

Several important limitations and caveats apply to our findings. Although it is possible to produce SAFs with net-zero or even net-negative CO_2 emissions to the atmosphere, recent studies have estimated that the life-cycle emissions related to biofuels often entail emissions of 6–108 $gCO_2eq\ MJ^{-1}$ (ref. [3]). ICAO's SAF requirements only demand a 10% emissions reduction[14], though we have assumed SAFs to be net-zero carbon. Ensuring the carbon neutrality of future biofuels will require resolving a host of complex accounting decisions, such as the time allowed between an emission and an uptake, the global warming potential of non-CO_2 and the attribution of emissions from indirect land-use change[52,53]. Moreover, the American Society for Testing Materials certification currently allows blends of up to 50%, mostly because of the low aromatic content of SAFs. Fully deploying SAFs would require allowing 100%, and although manufacturers such as Boeing have goals of achieving this by 2030, it is not yet guaranteed[31,54]. Additionally, the energy density of SAFs is less than that of fossil jet fuel, which could have implications for their value and aircraft range if fully deployed and derive in higher fuel consumption leading to higher non-CO_2 radiative forcing. Compared with 34.7–35.3 $MJ\ l^{-1}$ of fossil jet fuel[55], the energy densities of synthetic methanol, bioethanol, biodiesel and hydrotreated vegetable oil are 15.6 $MJ\ l^{-1}$, 21.4 $MJ\ l^{-1}$, 32.7 $MJ\ l^{-1}$ and 34.4 $MJ\ l^{-1}$, respectively[56,57]. More generally, while we consider non-CO_2 emissions from aviation, much uncertainty remains on accounting for these emissions, particularly in terms of short-lived climate forcers such as contrails[58]. We assume that SAFs have the same non-CO_2 emissions as fossil jet fuels, though some studies have found that cleaner aviation fuels could both increase or decrease contrail formation[59,60].

Despite these considerations, our analysis demonstrates the large-scale increases in SAF production that may be necessary to decarbonize the sector and the extent to which decreases in demand and improvements in energy intensity can reduce future demand for SAFs and the need for CDR. The main challenges to scaling up such sustainable fuel production include technology costs and process efficiencies, both of which are thus key targets for policies and innovation. Additionally, the interactions with food security, local communities and land use are enormous hurdles for such a ramp-up and come with their own increasingly difficult trade-offs. Yet with moderate growth in demand, continued improvements in aircraft energy efficiency and operational and infrastructure improvements, new propulsion systems for short-haul trips, greatly accelerated production of SAFs and the possibility of balancing non-CO_2 radiative forcing with equivalent amounts of CDR, the aviation sector could achieve net-zero emissions by 2050.

Methods

In this paper, we use the Kaya identity to decompose historical emissions from global aviation and to analyse future pathways for the decarbonization of the sector. This approach has been applied in other studies to analyse historical global and regional drivers of CO_2 emissions as a whole[61] and in specific sectors or regions for historical emissions and future trajectories[62,63]. We analyse emissions, energy and air travel demand data from the International Energy Agency (IEA)[7,25,64–67], the Carbon Monitor[68], the World Bank[69–71], ICAO[8,72–74] and IATA[18].

Scenarios

We develop a total of nine scenarios, shown in Supplementary Fig. 3 and Supplementary Fig. 4, based on variations for demand and energy intensity (*De*) and carbon intensity (*f*). The decomposition of the scenarios and sources for the data for each parameter and the future projected assumptions are available in Supplementary Table 1.

Kaya Parameters

Distance. Given the uncertainty regarding the recovery of and future demand of air travel, we develop three demand-based scenarios with different projections. In the Business-as-usual scenario, passenger demand recovers by 2024, consistent with ICAO's central recovery projection[75] (based on IATA, freight aviation has already recovered)[22], and future projection follows historical GDP growth[76] (1980–2019) of 4% between 2024 and 2050. In the Industry projections scenario, demand also recovers by 2024 and then grows yearly at 2.9% and 2.6% for passenger and freight demand, respectively, consistent with ICAO's low post-COVID demand scenario[8]. In the Ambitious reductions scenario, we assume that behavioural change and consumer preferences derive a slight 12% increase in demand by 2050 compared with 2019, similar with the IEA's net-zero scenario for aviation[25], which translates to a 1% yearly increase in total aviation demand from 2022 to 2050 (Supplementary Table 1 provides more details).

Energy intensity. We model three energy-intensity-based scenarios. In the Business-as-usual scenario, we follow a 1% energy-intensity reduction per year, consistent with the 1970–2019 average[26]. For the Industry projections scenario, we assume that ICAO's A40-18 resolution of 2% yearly improvements in fuel efficiency is met both internationally and domestically[72]. For the Ambitious reductions scenario, we assume energy-intensity reductions similar to the IEA's net-zero scenario, with intensities decreasing rapidly between 2022 and 2025 and more modest decreases between 2025 and 2050, with an overall average yearly decrease of 4% from 2022 to 2050[7] (Supplementary Table 1).

Carbon intensity. There are three carbon-intensity scenarios in this study. In the Carbon intensive scenario, we assume that fossil jet fuel continues to be the main energy source for aviation, consistent with historical record, which leads to a carbon intensity of 73.5 $gCO_2\ MJ^{-1}$ (refs. [66,77]) or 124.9 $gCO_2eq\ MJ^{-1}$ (from tank to wake, excluding fuel production emissions) (Supplementary Table 2). We neglect life-cycle, 'well-to-tank' emissions because such emissions are thought to represent a small fraction of the total (for example, 14.3 $gCO_2\ MJ^{-1}$) (ref. [50]) and because these emissions are, in theory, much easier to avoid than the direct emissions from aviation itself[78]. That is, aviation emissions are particularly difficult to abate because the high-energy-density liquid fuels are needed to power large, long-distance flights, but life-cycle emissions of fuels could be avoided by, for example, electrification of mining or drilling equipment and processing facilities. In the Reduced fossil scenario, we follow IATA's net-zero carbon emissions pathway introduced in the 77th Annual General Meeting. On the basis of IATA's proposition, by 2050, 65% of 2050 estimated emissions are mitigated with SAFs, and new technologies (electric planes and/or hydrogen) mitigate 13%, only allowing electric planes to deploy in short-haul flights, starting in 2025 with less than 1%, linearly increasing to 13% by 2050[18]. In our scenario, this derives in a carbon intensity that decreases from 73.5 $gCO_2\ MJ^{-1}$ (or 124.9 $gCO_2eq\ MJ^{-1}$) in 2021 to 23.9 $gCO_2\ MJ^{-1}$ (or 71.7 $gCO_2eq\ MJ^{-1}$) in 2050 (Supplementary Table 3). The Net-zero scenario follows a more aggressive deployment of both SAFs and new propulsion technologies by 2050, and we assume that the entirety of medium- and long-haul planes are powered with SAFs and that for short-haul aviation, the split is 50–50 between SAFs and new propulsion planes. In our scenario, this derives in a carbon intensity that decreases from 73.5 $gCO_2\ MJ^{-1}$ (or 124.9 $gCO_2eq\ MJ^{-1}$) in 2021 to 0 $gCO_2\ MJ^{-1}$ (or 37.6 $gCO_2eq\ MJ^{-1}$) in 2050 (Supplementary Table 4). We assume that biofuels and synthetic fuels are net-zero carbon fuels and that they have the same non-CO_2 emissions as fossil jet fuel, that the electricity to power short-haul planes comes from a renewable grid—and thus also has a net-zero carbon content—and that hydrogen is a product of electrolysis (Supplementary Table 1).

Non-CO_2 emissions

In this study, we calculate CO_2 emissions based on the Kaya identity presented in equation (1), considering the demand for aviation, the energy intensity of aviation and the carbon intensity of the energy used to power aviation. Non-CO_2 emissions are calculated based on multipliers from Lee et al.[6] (Supplementary Table 5). These emissions include contrail cirrus, nitrous oxides, soot emissions, sulfur dioxide and water vapour. We use a global warming potential of 100 years (GWP100) and report GWP of 20 and 50 years and global temperature potentials (GTP) of 20, 50 and 100 years in Supplementary Fig. 9.

For scenarios with a carbon intensity following the Reduced carbon and Net-zero pathways, we assume that SAFs are net-zero in terms of carbon but that they have the same non-CO_2 emissions as fossil jet fuel given the uncertainty around non-CO_2. Therefore, the net-zero carbon-intensity scenarios result in emissions in terms of carbon equivalence even though they are considered net-zero carbon. The carbon intensity for scenarios including non-CO_2 emissions measured in $gCO_2eq\ MJ^{-1}$ was calculated based on estimated total fuel consumption and CO_2eq emissions.

Cost estimates

Synthetic fuels. The cost estimate for synthetic fuels is based on the mass balance, estimated as:

$$CH_2\ \text{cost} = \frac{(\text{Hydrogen unit cost} \times 0.4) + (\text{Carbon unit cost} \times 3.14)}{\text{Conversion efficiency}}$$

We are assuming a conversion efficiency of 80%. We are representing costs in liters, assuming 0.8 kg of synthetic fuel in each liter. Capital and operation costs are not considered in the equation as they represent only a minor portion of the cost compared to the hydrogen and carbon costs[79]. The constants 0.4 and 3.14 are the weight of hydrogen and CO_2 needed to produce 1 ton of CH_2 ($3H_2 + CO_2 \rightarrow CH_2 + 2H_2O$). The values for Fig. 4 are depicted in Supplementary Tables 6 and 7.

FT biofuels. The cost estimate of Fischer–Tropsch (FT) biofuels includes capital expenditure, operational expenditure, feedstock costs and efficiencies. The cost is estimated as:

$$\text{FT cost} = \frac{\left(0.07\frac{\text{USD}}{\text{kg biomass}} + 0.12\frac{\text{USD}}{\text{kg biomass}} + \text{Feedstock cost}\right)}{\text{Conversion efficiency}}$$

We are representing costs in liters, assuming that there are 0.88 kg in each liter for HEFA fuel, based on biodiesel density (1 liter = 0.88 kg). The constants 0.07 and 0.12 represent the capital and operation costs without considering the biomass cost per input[80]. The values for Fig. 4 are depicted in Supplementary Tables 8 and 9.

HEFA biofuel. The cost estimate of hydro-processed esters and fatty acids (HEFA) biofuels includes capital expenditure, operational expenditure, feedstock costs and efficiencies. The cost is estimated as:

$$\text{HEFA cost} = \frac{\left(0.17\frac{\text{USD}}{\text{kg biomass}} + 0.34\frac{\text{USD}}{\text{kg biomass}} + \text{Feedstock cost}\right)}{\text{Conversion efficiency}}$$

We are representing costs in liters, assuming that there are 0.88 kg in each liter for HEFA fuel, based on biodiesel density (1 liter = 0.88 kg). The constants 0.17 and 0.34 represent the capital and operation costs without considering the biomass cost per input[80]. The values for Fig. 4 are depicted in Supplementary Tables 10 and 11.

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

Data were compiled from open sources (except for aviation's energy consumption), and the references are mentioned in Supplementary Table 1. The open-source data are available at https://doi.org/10.5281/zenodo.7187059. The only exception is the IEA proprietary data for aviation's energy consumption[65]. Historical emissions are from IEA[66] and CMP[68], while future emissions are calculated based on equation (1). Historical demand is from ICAO[73,74], while freight demand is from the World Bank[69] and IATA[22]. Future aviation demand follows assumptions with data from the International Monetary Fund[76], ICAO[8] and IEA[25]. Historical energy-intensity values were calculated based on demand data and fuel consumption data from IEA[65]. Future energy-intensity estimates follow assumptions from Zheng et al.[26], ICAO[72] and IEA[7]. Historical carbon intensity is calculated with data from Bosch et al.[50], and carbon equivalent intensity is calculated based on Lee et al.[6]. Future carbon intensities are calculated based on penetration of different SAFs and electric/hydrogen-powered planes.

Code availability

Data processing was done in Excel. The generation of Fig. 4 and Supplementary Fig. 7 of this manuscript were done in R version 4.1.0 and are available at https://github.com/CandeBergero/Code-Fig4-Net-zero-emissions-aviation.git.

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Author contributions

C.B. and S.J.D. conceived the study. C.B. performed the analyses with support from G.G., D.G., S.K., M.B. and S.J.D. The writing of the manuscript was done by C.B. and S.J.D., with inputs and revisions from G.G., D.G., S.K. and M.B.

Competing interests

The authors declare no competing interests.

Additional information

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Reporting Summary

Nature Research wishes to improve the reproducibility of the work that we publish. This form provides structure for consistency and transparency in reporting. For further information on Nature Research policies, see our Editorial Policies and the Editorial Policy Checklist.

Statistics

For all statistical analyses, confirm that the following items are present in the figure legend, table legend, main text, or Methods section.

n/a	Confirmed	
☒	☐	The exact sample size (*n*) for each experimental group/condition, given as a discrete number and unit of measurement
☒	☐	A statement on whether measurements were taken from distinct samples or whether the same sample was measured repeatedly
☒	☐	The statistical test(s) used AND whether they are one- or two-sided *Only common tests should be described solely by name; describe more complex techniques in the Methods section.*
☒	☐	A description of all covariates tested
☒	☐	A description of any assumptions or corrections, such as tests of normality and adjustment for multiple comparisons
☒	☐	A full description of the statistical parameters including central tendency (e.g. means) or other basic estimates (e.g. regression coefficient) AND variation (e.g. standard deviation) or associated estimates of uncertainty (e.g. confidence intervals)
☒	☐	For null hypothesis testing, the test statistic (e.g. F, t, r) with confidence intervals, effect sizes, degrees of freedom and P value noted *Give P values as exact values whenever suitable.*
☒	☐	For Bayesian analysis, information on the choice of priors and Markov chain Monte Carlo settings
☒	☐	For hierarchical and complex designs, identification of the appropriate level for tests and full reporting of outcomes
☒	☐	Estimates of effect sizes (e.g. Cohen's *d*, Pearson's *r*), indicating how they were calculated

Our web collection on statistics for biologists contains articles on many of the points above.

Software and code

Policy information about availability of computer code

Data collection	No software was used for data collection.
Data analysis	Data analysis was performed in Excel using a variation of the Kaya identity, as described in the Methods. For Figure 4 and Supplementary Figure 7 we used R version 4.1.0 (2021-05-18) -- "Camp Pontanezen". The code is available in https://github.com/CandeBergero/Code-Fig4-Net-zero-emissions-aviation

For manuscripts utilizing custom algorithms or software that are central to the research but not yet described in published literature, software must be made available to editors and reviewers. We strongly encourage code deposition in a community repository (e.g. GitHub). See the Nature Research guidelines for submitting code & software for further information.

Data

Policy information about availability of data

All manuscripts must include a data availability statement. This statement should provide the following information, where applicable:

- Accession codes, unique identifiers, or web links for publicly available datasets
- A list of figures that have associated raw data
- A description of any restrictions on data availability

Almost all data (except for aviation's energy consumption) was compiled from open sources, and the references are mentioned in Supplementary Table 1. Historical emissions are from IEA and CMP, while future emissions are calculated based on Equation 1. Historical demand is from ICAO, while freight demand is from the World Bank and IATA. Future aviation demand follows assumptions with data from IMF, ICAO, and IEA. Historical energy intensity values were calculated based on demand data and fuel consumption data from IEA. Future energy intensity estimates follow assumptions from Zheng et al., ICAO, and IEA. Historical carbon intensity is calculated with data from Bosch et al., and carbon equivalent intensity is calculated based on Lee et al. Future carbon intensities are calculated based on penetration of different SAFs and electric/hydrogen powered planes. All sources are in the manuscript. The open-source data is available in https://doi.org/10.5281/zenodo.7187059

Field-specific reporting

Please select the one below that is the best fit for your research. If you are not sure, read the appropriate sections before making your selection.

☐ Life sciences ☐ Behavioural & social sciences ☒ Ecological, evolutionary & environmental sciences

For a reference copy of the document with all sections, see nature.com/documents/nr-reporting-summary-flat.pdf

Ecological, evolutionary & environmental sciences study design

All studies must disclose on these points even when the disclosure is negative.

Study description	We use the parameters of the Kaya identity and create nine scenarios to 2050 to analyze potential emissions of the global aviation sector based on demand for aviation, the energy intensity of the industry and the carbon intensity of the energy used. We use open source data for historical periods, and project into the future based on assumptions described in the Methods.
Research sample	No sample used. We analyze global aviation emissions.
Sampling strategy	NA
Data collection	Data was collected from different sources, as described in Supplementary Table 1 of the manuscript. Greer Gosnell, Steven J. Davis and me, Candelaria Bergero, collected the data.
Timing and spatial scale	Data collection started in 2021 and concluded around May 2022. We analyze the period 1990-2021, and project for 2022-2050.
Data exclusions	NA
Reproducibility	Data analysis was done in Excel, and the calculations behind each scenario are reproducible. Figure 4 and Supplementary Figure 7 were developed in R, and the coded is provided.
Randomization	NA
Blinding	NA

Did the study involve field work? ☐ Yes ☒ No

Reporting for specific materials, systems and methods

We require information from authors about some types of materials, experimental systems and methods used in many studies. Here, indicate whether each material, system or method listed is relevant to your study. If you are not sure if a list item applies to your research, read the appropriate section before selecting a response.

Materials & experimental systems

n/a	Involved in the study
☒	☐ Antibodies
☒	☐ Eukaryotic cell lines
☒	☐ Palaeontology and archaeology
☒	☐ Animals and other organisms
☒	☐ Human research participants
☒	☐ Clinical data
☒	☐ Dual use research of concern

Methods

n/a	Involved in the study
☒	☐ ChIP-seq
☒	☐ Flow cytometry
☒	☐ MRI-based neuroimaging