JUNE 2022

VISION 2050
ALIGNING AVIATION WITH THE PARIS AGREEMENT

Brandon Graver, Ph.D., Xinyi Sola Zheng, Daniel Rutherford, Ph.D.,
Jayant Mukhopadhaya, Ph.D., and Erik Pronk

ACKNOWLEDGMENTS

The authors thank John Holler, Jo Dardenne, Nikita Pavlenko, Yuanrong Zhou, Joshua Miller, Dale Hall, and Gary Gardner for their contributions. This work was conducted with generous support from the Aspen Institute.

Edited by Gary Gardner.

ABOUT THE ICCT

The International Council on Clean Transportation (ICCT) was established in 2001 as an independent source of technical and policy expertise on clean transportation with the core mission of *improving the environmental performance and energy efficiency of road, marine, and air transportation, in order to benefit public health and mitigate climate change*. In the last five years, we have worked successfully with regulators and lawmakers around the world and have played a significant role in 48 distinct regulations and policies, which together are projected to reduce carbon dioxide emissions by billions of tons and prevent thousands of premature deaths over the next decade and beyond.

Today, the ICCT has an annual operating budget of $20 million, a staff of more than 125, and offices in Washington, San Francisco, Berlin, Beijing, and São Paulo, with a new office planned in India. Our core work focuses on key transportation segments—passenger vehicles, heavy-duty vehicles, marine, and aviation—as well as the fuels that power them. Our geographic focus is on the major automotive markets—China, US/Canada/Mexico, Europe, India, and Brazil—as well as other growing markets in the Middle East, Latin America, Southeast Asia, and Africa. In addition, we work at the sub-national level with major provinces, states, and cities. More information can be found on our website at www.theicct.org.

PANEL OF EXPERTS

As part of this work, we established a panel of experts to review our assumptions and inputs related to carbon reductions. We are grateful to the following panelists for their valuable contributions.

Praveen Bains (International Energy Agency)
David Dwek (SkyNRG)
Stefan Grebe, Ph.D. (CE Delft)
Amy Malaki (SkyNRG)
Jarlath Molloy, Ph.D. (NATS)
Lahiru Ranasinghe (EasyJet plc)
Aaron Robinson (United Airlines)
Susan van Dyk, Ph.D. (SVD Consulting)
Brian Yutko, Ph.D. (Boeing)

This work reflects the views of the authors. It does not necessarily reflect those of the panel of experts or their associations.

International Council on Clean Transportation
1500 K Street NW, Suite 650
Washington, DC 20005

communications@theicct.org | www.theicct.org | @TheICCT

© 2022 International Council on Clean Transportation

EXECUTIVE SUMMARY

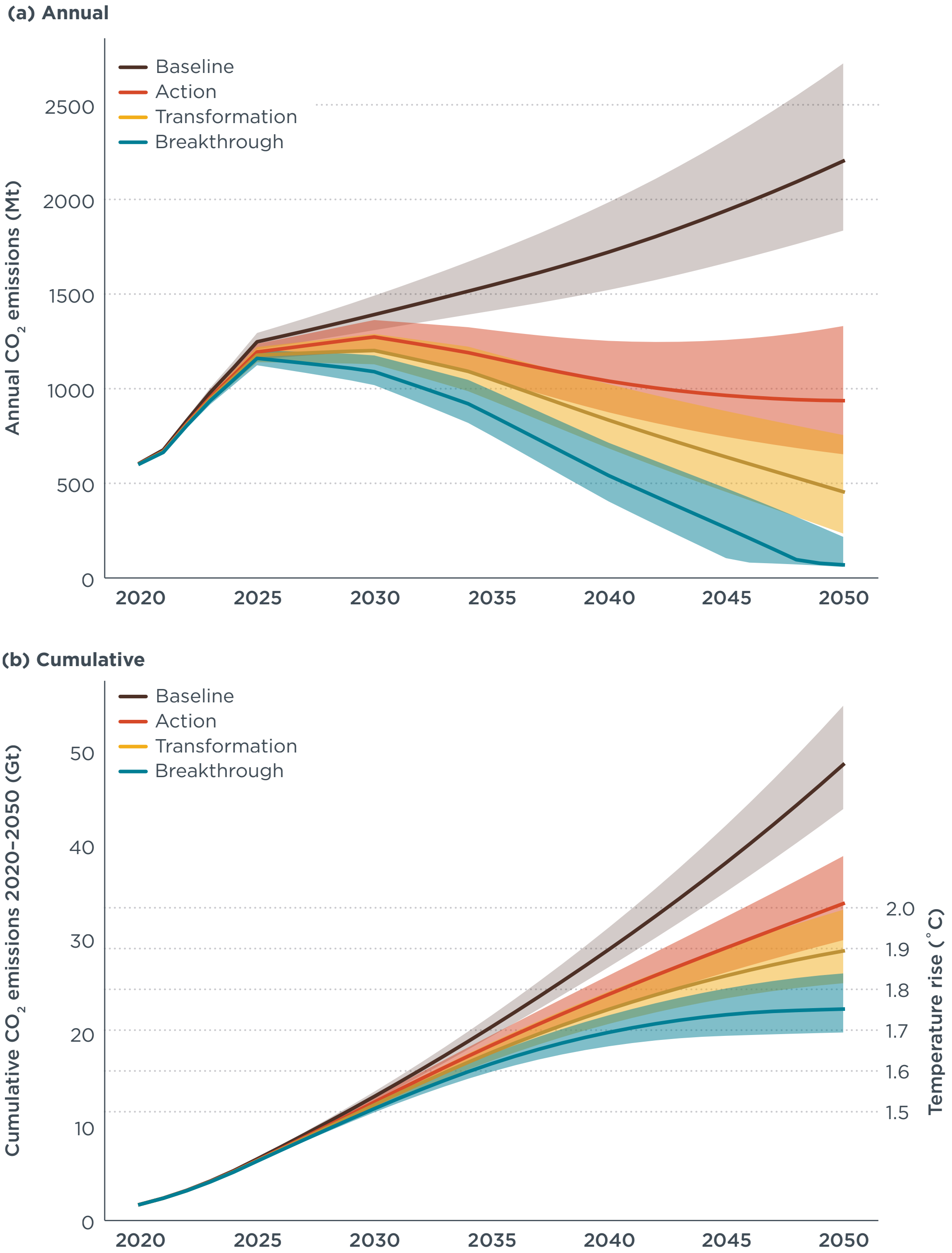
In 2015, policymakers representing 196 countries gathered in Paris, France to ratify an agreement aiming to constrain anthropogenic global warming to well below 2°C, and preferably to 1.5°C, compared with pre-industrial levels. Now, the International Civil Aviation Organization (ICAO), is working to establish, by Fall 2022, a Long-Term Aspirational Goal (LTAG) for limiting emissions from international aviation, consistent with the temperature goals set in Paris in 2015.

Multiple industry groups and governments have developed technology roadmaps analyzing the potential for aviation to decarbonize by mid-century. In this report, we present ICCT's scenarios for aviation technology and operations (defined from ICCT's own research) and evaluate the emission impacts of these scenarios using a new global aviation emissions model. Our goal is *to assess the extent to which measures can reduce cumulative carbon dioxide (CO_2) emissions from global aviation in line with 1.5°C, 1.75°C, and 2°C targets*.

Our roadmap is different from the others in several ways. It is global in scope, but also includes only international operations. It describes the effect of fuel price on traffic demand. It compares cumulative CO_2 emissions from each scenario against global carbon budgets that are tied to the three temperature targets. And it suggests intermediate goals to ensure that the aviation sector makes early investments in new emissions-reduction technology to avoid quickly consuming its share of the global carbon budget.

Three decarbonization scenarios—Action, Transformation, and Breakthrough—are analyzed along with a Baseline scenario, each built around six important parameters: (1) traffic; (2) aircraft technology; (3) operations; (4) zero-emission planes (ZEPs); (5) sustainable aviation fuels (SAFs); and (6) economic incentives. The Baseline scenario represents a continuation of the status quo. In the Action case, coordinated efforts by governments and industry deliver new technologies that cap aviation CO_2 emissions below 2019 levels in 2050. In the Transformation case, concerted efforts by governments and industry shift aviation away from fossil fuels starting in 2035 and nearly halve 2050 aviation CO_2 compared to 2005 levels. In the Breakthrough case, early, aggressive, and sustained government intervention triggers widespread investments in zero-carbon aircraft and fuels, peaking fossil jet fuel use in 2025 and zeroing it out by 2050.

Figure ES-1 shows global aviation's annual (top panel) and cumulative (bottom) well-to-wake (WTW) CO_2 emissions for all four scenarios through 2050. As shown, CO_2 continues unabated through 2050 under the Baseline case, while emissions peak in 2030 (Action and Transformation) and 2025 (Breakthrough). By 2050, CO_2 falls by 9% to 94% below 2019 levels under the three decarbonization scenarios in response to the uptake of SAF, new aircraft and operational efficiency improvements, and the introduction of ZEPs powered predominately by liquid hydrogen. Reductions in air traffic linked to fuel price increases and modal shift to high-speed rail (HSR) in certain markets provide more limited reductions.



The solid line depicts the central traffic forecast, while the shaded area depicts the range between the low and high forecasts.

Figure ES-1. WTW global aviation CO_2 emissions by scenario and traffic forecast, 2020-2050

Figure ES-1b compares cumulative CO_2 emissions by scenario to key temperature thresholds, assuming that aviation maintains its current share (2.9% on a well-to-wake basis) of anthropogenic CO_2 emissions. Under the Action scenario, global aviation exhausts its share of a 2°C carbon budget by 2050. Under the Transformation case, aviation emits carbon in volumes consistent with a 1.9°C budget by mid-century. Both cases assume a 67% chance of meeting the respective temperature targets.

By peaking emissions in 2025 and driving them to near-zero levels by 2050, Breakthrough is consistent with a 1.75°C temperature target. For a 1.5°C pathway to be maintained without increasing aviation's share of a global carbon budget, an additional

50% reduction in cumulative emissions (11 Gt of CO_2) below the Breakthrough case would be required. This is equivalent to achieving net-zero emissions by 2030—two decades sooner than planned in existing net-zero commitments.

While the magnitude of abatement increases by scenario, the relative share by technology remains similar. In all three scenarios, SAF accounts for the largest share of CO_2 reduction potential, varying between 59% and 64%. Improvements in aircraft technical and operational efficiency contribute an additional one-third of CO_2 mitigation, or approximately 16% each. ZEPs powered by hydrogen account for 4% and 5% of emission reductions in the Transformation and Breakthrough scenarios, respectively. Modest reductions in air travel due to increases in fuel cost (2.5% total, or 0.25% compounded annually) and modal shift to HSR are also seen through 2050.

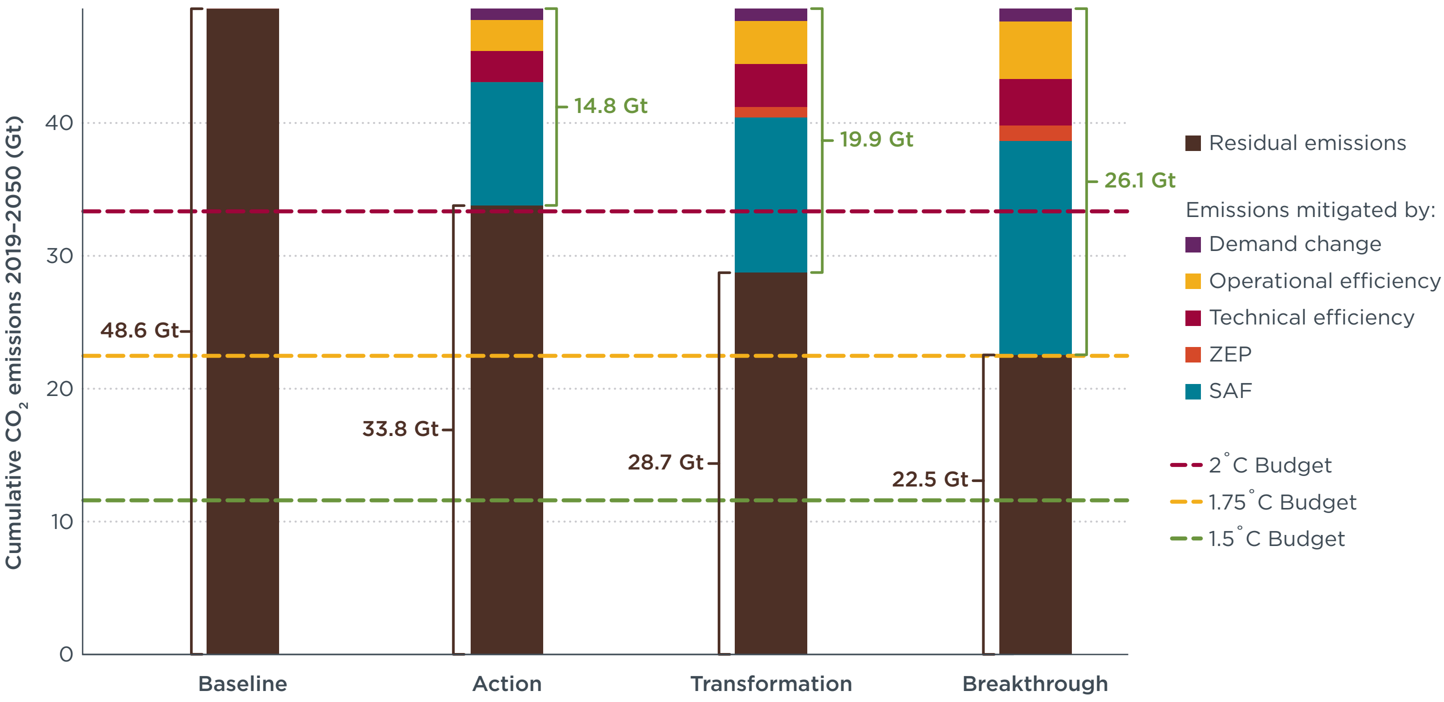


Figure ES-2. Cumulative global aviation CO_2 emissions by scenario and measure, 2019-2050

This work has several implications for policy. First, aligning aviation with the below-2°C aspiration of the Paris Agreement is possible, but will require significant ambition and investment. In the three roadmaps discussed in depth (ICCT, ATAG, and ICAO), the most ambitious scenarios are consistent with a 1.75°C future in which aviation doesn't increase its share of a global carbon budget. But significant investments, driven and rewarded by public policies, will be needed to put aviation on that path. Second, this paper suggests that CO_2 emissions from aircraft need to peak as soon as 2025 to align aviation with the Paris Agreement. Third, we conclude that cumulative targets, rather than an absolute emissions goal for a given year, would provide greater certainty that aviation contributes fairly to the Paris Agreement. Finally, we note that out-of-sector action and/or significant direct curbs to traffic growth would be needed to align aviation with a 1.5°C temperature goal.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

In 2015, policymakers representing 196 countries gathered in Paris, France to ratify an agreement to constrain anthropogenic global warming to well below 2°C, and preferably to 1.5°C, compared to pre-industrial levels. Since that time, international sources of emissions not formally included in the agreement, notably maritime shipping and aviation, have worked to establish goals and measures consistent with that agreement. In 2018, the International Maritime Organization (IMO) agreed to an Initial GHG Strategy with the goal of cutting GHG emissions from international shipping by at least 50% below 2008 levels by 2050 (Rutherford and Comer, 2018). IMO's sister agency for aircraft, the International Civil Aviation Organization (ICAO), is likewise working to establish a Long-Term Aspirational Goal (LTAG) for international aviation later this year (ICAO, 2022a).

We have reached a reckoning. United Nations (UN) Secretary-General António Guterres underscored this in 2021, a year he described as "crucial" in the fight against climate change (UN, 2021).

> The world remains way off target in staying within the 1.5-degree limit of the Paris Agreement. This is why we need more ambition, more ambition on mitigation, ambition on adaptation and ambition on finance.
>
> **—UN Secretary-General António Guterres, 2021**

While 2021 was not a year of notable action—indeed, greenhouse gas (GHG) emissions rebounded after declining due to the COVID-19 pandemic (Jackson et al., 2021)—it was clearly a year of analysis and goal-setting, including in the aviation sector.

February 2021: Europe's aviation sector released Destination 2050, a roadmap for net-zero emissions from all flights within and departing the European Union (EU), United Kingdom (UK), and European Free Trade Area (EFTA). The analysis underpinning the roadmap was conducted by members of the Royal Netherlands Aerospace Centre and SEO Amsterdam Economics (van der Sman et al., 2021). In this roadmap, aircraft technological improvements (including the introduction of hydrogen aircraft) accounted for 37% of CO_2 reductions, followed by sustainable aviation fuels (SAFs) produced from biological or renewable energy feedstocks, at 34%. Most notably, the analysis estimated that decarbonization measures would dampen the 2018–2050 average annual growth in passenger air travel demand within the analysis area, from 2.0% to 1.4%. This correlates to a 15% reduction in CO_2 emissions by 2050 compared to a business-as-usual (BAU) baseline.

The net-zero commitment was made by Airlines for Europe (A4E), Airport Council International Europe (ACI EUROPE), Aerospace and Defence Industries Association of Europe (ASD), Civil Air Navigation Services Organization (CANSO), and European Regions Airline Association (ERA).

March 2021: Airlines for America (A4A), which represents airlines in the United States, committed to net-zero carbon emissions by 2050. A4A's lynchpin is sustainable aviation fuels (SAFs); it set a goal of having 2 billion gallons available for use by 2030, or a 240-fold increase (84% annual average increase) in production from current levels (A4A, 2021a). Five months later, the airlines increased that goal to 3 billion gallons (A4A, 2021b). This goal hinges on securing a proposed fuel blender's tax credit, which has been included in several legislative bills, none of which has been enacted. A4A has not released a detailed technology roadmap in support of its goal.

May 2021: Two research organizations published roadmaps. The German Aerospace Center released Development Pathways for Aviation up to 2050 (DEPA 2050), which projected global CO_2 emissions of approximately 600 million tonnes (Mt) in 2050 under a progressive scenario that includes SAFs (DLR, 2021). SAFs accounted for more than 80% of total fuel consumption in 2050 under this scenario.

The International Energy Agency (IEA) released its net-zero global roadmap pointing to even deeper reductions. That pathway envisions global aviation emissions of 210 Mt in 2050 on a tank-to-wake (TTW) basis, not accounting for upstream fuel production (IEA, 2021). More information on the fuels assumptions used by IEA can be found later in this paper.

October 2021: The leaders of Airports Council International (ACI), Civil Air Navigation Services Organization (CANSO), International Air Transport Association (IATA), International Business Aviation Council (IBAC), International Coordinating Council of Aerospace Industries Associations (ICCAIA), and General Aviation Manufacturers Association (GAMA) committed to net-zero carbon emissions from global civil aviation operations by 2050 (ATAG, 2021a). This updates and strengthens IATA's initial goal of a 50% reduction in aviation CO_2 emissions by 2050 compared to 2005 levels (ATAG, 2021b).

The Air Transport Action Group (ATAG), which represents the industry groups listed above, published a seminal decarbonization roadmap for the aviation sector—Waypoint 2050 (ATAG, 2021c). It outlined how the global industry intends to get to net-zero by mid-century. They include three scenarios with varying levels of technological ambition and SAF deployment. In all scenarios, offsetting maintains carbon neutral growth until 2035, with net emissions decreasing to zero in 2050. Carbon offsets are used to neutralize a residual 6% to 8% of emissions in 2050 compared to BAU.

SAF utilization is the largest driver of CO_2 emissions reduction potential in its analysis, varying between 53% and 71% based on the scenario (ATAG, 2021c). Because of the importance of SAFs in its decarbonization roadmap, a detailed report was commissioned on its production, deployment, and cost (ICF, 2021).

November 2021: Twenty-eight states[1] signed on to the International Aviation Climate Ambition Coalition (UK, 2021) at the 26th meeting of the Conference of the Parties to the UN Framework Convention on Climate Change (COP26). They will work together to advance actions to reduce CO_2 emissions from aviation to levels consistent with limiting the global average temperature increase to 1.5°C. In tandem, the United States Federal Aviation Administration (FAA) released a plan describing a whole-of-government approach to put US airlines on a path toward achieving net-zero emissions by 2050 (FAA, 2021).

November 2021: A task group of technical experts[2] assessed the feasibility of a long-term aspirational goal for international aviation for the ICAO. This was based on an ask by the ICAO Assembly at its 40th Session in 2019 (see text box next page). The analysis identified and evaluated in-sector measures in technology, operations, and fuels for international commercial and business aviation.

ICAO's Committee on Aviation Environmental Protection (CAEP) adopted the results of the analysis in February 2022. The report estimates that 55% of international aviation CO_2 emissions could be reduced by using new and cleaner fuels, a further 21%

1 As of 31 May 2022: Belize, Burkina Faso, Canada, Costa Rica, Denmark, Estonia, Finland, France, Germany, Ireland, Italy, Japan, Kenya, Republic of Korea, Maldives, Malta, Mexico, Morocco, Netherlands, New Zealand, Norway, Rwanda, Slovenia, Spain, Sweden, Turkey, United Kingdom, and United States.

2 Authors Brandon Graver and Daniel Rutherford were experts nominated by the International Coalition for Sustainable Aviation (ICSA).

from new aircraft technology, and an additional 11% from operational improvements (ICAO, 2022a). Residual emissions (203 to 954 Mt, depending on the scenario) would need to be addressed via out-of-sector measures such as direct removals. Additional consultations will be held through high-level meetings of the membership before an emissions reduction goal could be considered at the 41st Assembly meeting in September and October of 2022.

THE INTERNATIONAL CIVIL AVIATION ORGANIZATION

In 2019, the International Civil Aviation Organization (ICAO), the specialized UN agency that governs civil aviation, started the process of determining the feasibility of a long-term aspirational goal for international aviation. Here is language from the authorizing resolution:

Recognizing the global aspirational goals for the international aviation sector of improving fuel efficiency by 2 per cent per annum and keeping the net carbon emissions from 2020 at the same level, as adopted by the ICAO Assembly at its 37th Session in 2010 and reaffirmed at its 38th and 39th Sessions in 2013 and 2016, as well as the work being undertaken to explore a long-term global aspirational goal for international aviation in light of the 2°C and 1.5°C temperature goals of the Paris Agreement

Recognizing that the aspirational goal of 2 per cent annual fuel efficiency improvement is unlikely to deliver the level of reduction necessary to stabilize and then reduce aviation's absolute emissions contribution to climate change, and that goals of more ambition are needed to deliver a sustainable path for aviation

The Assembly [r]equests the Council to continue to explore the feasibility of a long-term global aspirational goal for international aviation, through conducting detailed studies assessing the attainability and impacts of any goals proposed, including the impact on growth as well as costs in all countries, especially developing countries, for the progress of the work to be presented to the 41st Session of the ICAO Assembly. Assessment of long-term goals should include information from Member States on their experiences working towards the medium-term goal

ICAO Resolution A40-18, 2019

In September 2020, the ICCT published Vision 2050, a strategy to decarbonize the global transport sector by mid-century (ICCT, 2020). It addressed the baseline trajectory of global transportation emissions, the magnitude of reductions in 2050 needed to keep global temperature rise below 1.5°C, and ambitious yet feasible policies and technologies. For air transport, the report articulated a set of GHG targets and the steps needed to attain them. The analysis estimated that global aviation CO_2 could be cut to 300 Mt in 2050, about two-thirds below 2019 levels, using aircraft technology improvements and alternative fuels. This report expands on the 2020 evaluation, and addresses the following research question:

To what extent can various measures reduce cumulative CO_2 emissions from global aviation, in line with 1.5°C, 1.75°C, and 2°C targets?

Our roadmap differs from the others mentioned above in several ways. It is global in nature, but also discusses only international operations. This will allow for a comparison to Waypoint 2050 and ICAO's LTAG work. It includes the effect of fuel price on traffic demand, which was included in Destination 2050, but not in Waypoint 2050. It discusses the cumulative total emissions, and compares these totals to global carbon budgets—analysis typically missing from other reports but which helps to ensure that aviation emissions are compatible with a given temperature target. We also identify a peak year of emissions as an input to policy discussions about intermediate goals to ensure that the aviation sector makes early and proactive investments in new technologies and does not consume its share of the global carbon budget too quickly.

The next section outlines the modeling approach and the model's inputs, which vary based on three levels of ambition. We close with modeling results and a discussion of how close emission reductions under each scenario get us to global temperature targets.

MODELING

ICCT's Aviation program and Modeling Center worked together to create a model that projects CO_2 emissions from commercial aviation based on different technological, operational, and economic inputs. This allows for emission reductions to be calculated for future scenarios relative to the Baseline scenario. **Figure 1** portrays a simplified version of the modeling flow. A more in-depth discussion of the Projection of Aviation Carbon Emissions (PACE) model developed for this report can be found in a separate methodology document on the ICCT's GitHub repository.[3]

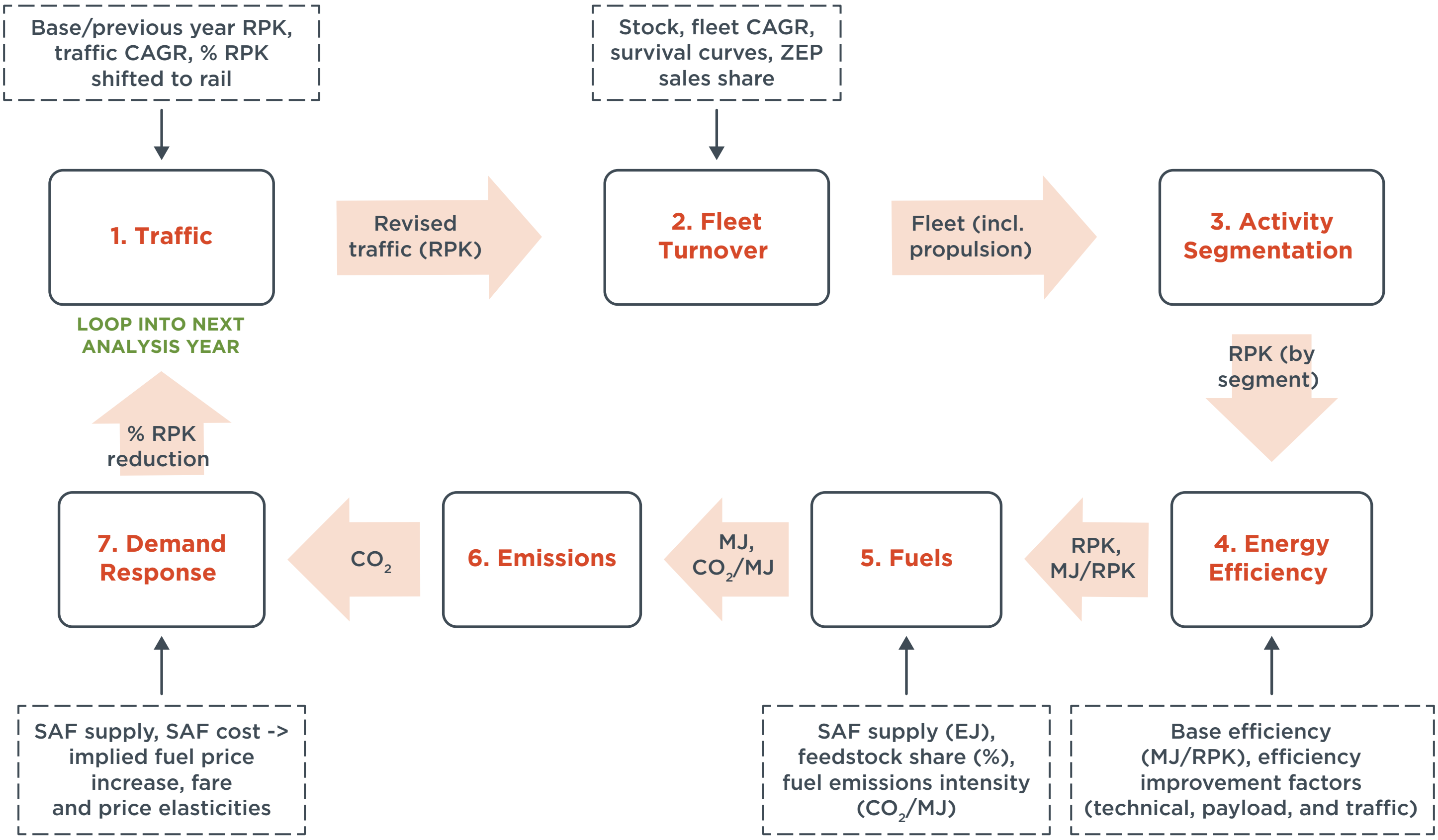


Figure 1. PACE model

The energy and emission rates of passenger transport were given in terms of revenue passenger kilometers (RPKs), while cargo transport uses freight tonne kilometers (FTKs). RPKs were converted to revenue tonne kilometers (RTKs) using 100 kg of mass per passenger, including their baggage (Graver et al., 2020). For cargo transport, freight carried in the belly of passenger aircraft (belly freight) and dedicated freighters is treated separately. The emissions were calculated using expected freight growth rates and expected improvements in freight aircraft and operational efficiencies.

SCENARIOS

We answer the research question posed earlier with scenarios of differing levels of ambition.

Our three modeling scenarios—Action, Transformation, and Breakthrough—are built around the following six important parameters: (1) traffic; (2) aircraft technology; (3) operations; (4) zero-emission planes (ZEPs); (5) sustainable aviation fuels (SAFs); and (6) economic incentives. Each parameter is briefly described in individual subsections below.

3 https://theicct.github.io/PACE-doc/

The ***Baseline*** reference case represents a continuation of the status quo. The traffic forecasts used in the three scenarios are also used in the Baseline. Nominal efficiency improvements (0% to 1.0% per annum, by aircraft class) from aircraft technology were derived from ICCT's Global Aviation Carbon Assessment (GACA) model (Graver et al., 2020), as described by Graver (2022a). SAFs and other alternative fuels, operational improvements, and economic measures to decrease CO_2 emissions were not included in the Baseline.

In the ***Action*** case, coordinated efforts by governments and industry deliver new technologies that cap aviation CO_2 emissions below 2019 levels in 2050. Moderate fuel efficiency standards for new aircraft and investments in modern air traffic control extend fuel efficiency gains through 2050, reducing in-service fuel burn per RPK by more than one-third (-36%) below 2019 levels. Federal incentives and mandates begin to scale up SAFs in 2025, ultimately generating 220 million tonnes (Mt), or about 60% of fuel supply, in 2050. Accordingly, fuel prices rise slightly (+7%) in 2030, increasing to 60% above the 2050 baseline. Higher prices moderate traffic growth slightly, reducing revenue passenger kilometers by 6% in 2050 (2.5% of cumulative traffic) compared to the Baseline case.

In the ***Transformation*** case, concerted efforts by governments and industry shift aviation away from fossil fuels starting in 2035 and nearly halve 2050 aviation CO_2 compared to 2019 levels. Accelerated efficiency standards for new aircraft and domestic and intra-EU fuel taxes reduce fuel burn per RPK of the 2050 in-service fleet by more than 40% below 2019 levels. Industry investments in hydrogen combustion and regional electric aircraft bring viable designs into service in 2035 and 2030, respectively. Aggressive mandates, incentives, and fuel taxes drive widespread SAF uptake and generate 250 Mt of supply in 2050, or almost 70% of total hydrocarbon demand. Fuel prices rise moderately (+17%) in 2030, continue to increase through 2040, then fall through 2050 as economies of scale are reached for synthetic "e-kerosene" produced from renewable electricity.

In the ***Breakthrough*** case, early, aggressive, and sustained government intervention triggers widespread investments in zero-carbon aircraft and fuels, peaking fossil fuel use in 2025 and zeroing it out by 2050. Maximum efficiency standards for new aircraft, a global fuel tax, and breakthroughs in air traffic management reduce 2050 in-service fuel burn per passenger kilometer by almost half (45%) below 2019 levels. Hydrogen-combustion aircraft enter into service in 2035 and account for half of regional and narrowbody aircraft sales in 2050. Global fuel taxes and bans on fossil-fueled aircraft deliver 385 Mt of SAFs by 2050; in support, carbon pricing acting like a cross-subsidy from fossil jet fuel to SAFs peaks in 2037, then falls due to economies of scale. Fuel prices nearly double compared to the Baseline value in 2045 and settle at a level above that found in the Transformation case due to the greater use of direct air capture (DAC) for e-fuel production.

TRAFFIC FORECASTS

Traffic forecasts are vital inputs into any aviation decarbonization roadmap. The COVID-19 pandemic reminds us that unexpected events complicate predictions in any industry, including aviation, especially 10, 20, or 30 years into the future. Still, realistic traffic projections are needed to analyze climate goals and measures to support them. Estimate traffic too high, and industry may be burdened with unrealistic expectations regarding development of advanced concept aircraft and SAF to achieve net-zero emissions. Too low, and decarbonization efforts will fall short of the needed reductions.

We use historical data to project air traffic growth trends out to 2050. Multiple editions of the Boeing Commercial Market Outlook (2005, 2009 & 2021) were employed to get historical passenger traffic data from 1985 to 2019. We then fit second-order polynomial trendlines for data over different periods to obtain low (1985-2010), central (1985-2014), and high (1985-2019) forecasts out to 2050, as shown in **Figure 2**. Passenger traffic for 2020 through 2022 during the COVID-19 dip is based on values reported by IATA (2021). More information on the passenger traffic forecast methodology is provided by Graver (2022b).

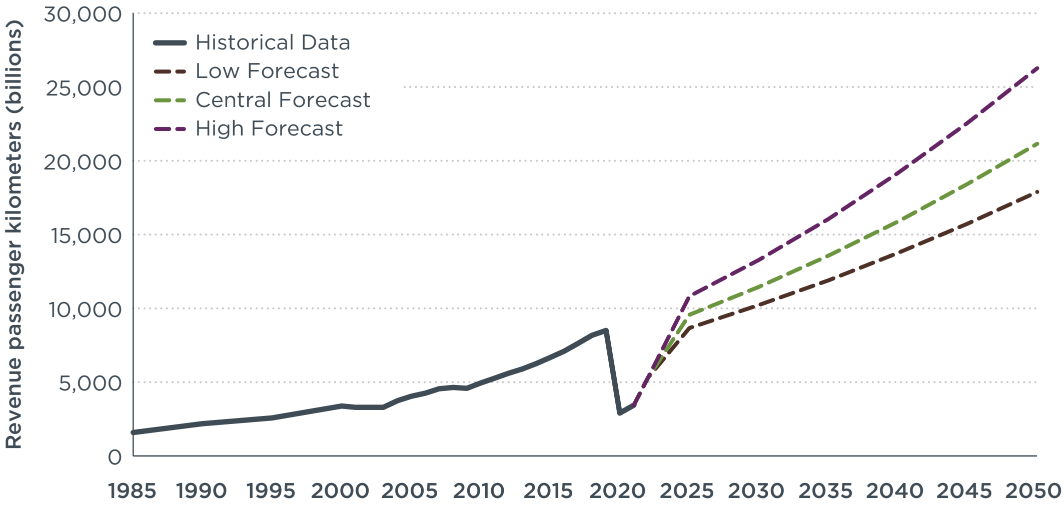


Figure 2. Passenger traffic, in revenue passenger kilometers (RPKs), under three growth scenarios, 1985-2050

Table 1 provides per annum (p.a.) growth in passenger and freight traffic between 2019 and 2050. For comparison, our Central passenger traffic forecast is similar to the central forecast from the Waypoint 2050 report, while our High estimates are similar to ICAO's mid-range forecast (ICAO, 2021a). Due to a lack of expertise in air freight at the ICCT, the ICAO post-COVID freight traffic forecasts (2021a) are utilized in our roadmap. These are modestly higher than our passenger traffic growth rates.

Table 1. Passenger and freight traffic assumptions (all scenarios)

Low	Central	High
Passenger: +2.4% RPK p.a., 2019-2050	**Passenger:** +3.0% RPK p.a., 2019-2050	**Passenger:** +3.7% RPK p.a., 2019-2050
Freight: +2.6% FTK p.a., 2019-2050	**Freight:** +3.5% FTK p.a., 2019-2050	**Freight:** +4.2% FTK p.a., 2019-2050

The PACE model estimates a decrease in passenger traffic growth caused by SAF-driven increases in fuel costs. (This is discussed further in the Economic incentives section.) However, we are unable to model changes in freight traffic from SAF-driven increases in fuel cost due to a lack of freight demand elasticities. The split between cargo carried on passenger aircraft versus dedicated freighters will change if belly freight capacity falls.

AIRCRAFT TECHNICAL EFFICIENCY

Newer aircraft are more efficient, reducing fuel burn per mission (Zheng & Rutherford, 2020). Aircraft manufacturers innovate as fuel costs drive an airline's decision to order new aircraft. **Table 2** presents the fleet-averaged technological efficiency improvements after accounting for fleet turnover. These rates represent a reduction in the energy, in megajoules (MJ), required for each passenger or freight kilometer due to the introduction of newer, more efficient aircraft in the fleet.

Aircraft design and manufacturing are slow processes, with new aircraft types typically providing step-function improvements in fuel efficiency, followed by a decade or more of little change in efficiency as aircraft continue to be produced. Very few new aircraft projects are currently underway, the Boeing 777X being one example. Hence, we assume that no step-change improvement in the technical efficiency of delivered aircraft will be reflected in scenarios until 2035. Anticipated improvements in technical efficiency until 2035 are due to fleet turnover as older, less efficient aircraft are replaced by newer, more efficient ones being delivered or developed today. These are not varied between scenarios because the near-term product mix of manufacturers is primarily set today.

Beginning in 2035, we assume the introduction of new aircraft types with accelerated levels of fuel efficiency by scenario. These new aircraft types are drawn from a comprehensive ICCT assessment of more than 45 discrete technologies to improve aircraft fuel efficiency (Kharina et al., 2016) and associated consulting report (Elliott, 2016) after processing through a fleet turnover model. Each successive scenario assumes that fuel price increases lead to more efficient aircraft being delivered and result in successively larger reductions in energy intensity.

Table 2. Reduction in energy intensity modeled from aircraft technical efficiency improvements

Scenario 1: Action	Scenario 2: Transformation	Scenario 3: Breakthrough
Passenger aircraft: -1.08% MJ/RPK p.a., 2019-2034 -1.15% MJ/RPK p.a., 2035-2050	**Passenger aircraft:** -1.08% MJ/RPK p.a., 2019-2034 -1.83% MJ/RPK p.a., 2035-2050	**Passenger aircraft:** -1.08% MJ/RPK p.a., 2019-2034 -2.16% MJ/RPK p.a., 2035-2050
Dedicated freight aircraft: -1.00% MJ/FTK p.a., 2019-2050	**Dedicated freight aircraft:** -1.25% MJ/FTK p.a., 2019-2050	**Dedicated freight aircraft:** -1.50% MJ/FTK p.a., 2019-2050

Freight fleet turnover is not modeled. Technical efficiency improvements for freighter aircraft are assumed to be constant over 2019-2050 and are slightly lower than the passenger technological efficiency improvements over the 2019-2050 timeframe. This reflects the fact that freighter fuel efficiency tends to lag passenger fuel efficiency because the freighter models typically enter into service later in an aircraft family's production cycle.

Supersonic transport (SST) and hypersonic aircraft are currently under development by several startups but were not modeled in Waypoint 2050 (ATAG, 2021c) or ICAO's analysis (ICAO, 2022b). They are also excluded from this analysis. While emerging SSTs are expected to be anywhere from five (CAEP, 2022; Kharina et al., 2018) to ten (Speth et al., 2021) times more fuel-intensive than subsonic designs, economic and environmental limits are likely to tightly constrain their potential market. Low boom designs and ultralow cost SAFs will be needed before those planes can achieve substantial market share (Rutherford et al. 2022).

PAYLOAD EFFICIENCY

Payload efficiency is one component of operational efficiency, along with traffic efficiency (Graver, 2022a). It reflects how much of the maximum payload is carried on each flight. On an RPK basis, it is more fuel-efficient to fly an aircraft full of people than to fly a plane with half the seats empty. The closer a passenger flight is to full capacity, the better its payload efficiency. Budget airlines are the gold standard for payload efficiency. They achieve very high passenger load factors, which reduces the fuel burned per RPK.

Table 3 describes the reductions in energy intensity resulting from payload efficiency improvements used for the various scenarios. Payload efficiency improvements are applied uniformly across all routes. The Breakthrough scenario represents the case where all airlines achieve the payload efficiency of a prominent budget airline in 2019

(90% of maximum structural payload), one of the highest in the industry by 2050.[4] The Action and Transformation scenarios represent less ambitious cases of 70% and 80% maximum structural payload, respectively. These rates reduce the energy required for each revenue passenger kilometer due to higher passenger load factors.

Table 3. Reduction in energy intensity modeled from payload efficiency improvements

Scenario 1: Action	Scenario 2: Transformation	Scenario 3: Breakthrough
-0.2% MJ/RPK p.a., 2019-2050	-0.35% MJ/RPK p.a., 2019-2050	-0.5% MJ/RPK p.a., 2019-2050

TRAFFIC EFFICIENCY

Several tools can be used to reduce aircraft fuel burn during a mission. A non-exhaustive list includes single-engine taxiing, electric tows to gates, continuous climb and descent, smart air traffic management, reduced fuel loading (EASA, 2022), and formation flying. Some of these measures are already being considered and tested (single-engine taxi, continuous climb and descent), while more ambitious concepts (formation flying) are more distant possibilities.

The overall effect of all these measures is reflected in traffic efficiency improvement. These rates represent a reduction in the energy required for each RPK due to the advancements in airport, airline, and aircraft operations. **Table 4** lists the reductions in energy intensity subsequent to traffic efficiency improvements used for the different scenarios.

Table 4. Reduction in energy intensity modeled from traffic efficiency improvements

<table>
<tr><th>Scenario 1: Action</th><th>Scenario 2: Transformation</th><th>Scenario 3: Breakthrough</th></tr>
<tr><td colspan="3">-0.1% MJ/RPK p.a., 2019-2050</td></tr>
<tr><td colspan="2">No formation flying</td><td>Formation flying:
-0.2% MJ/RPK in 2030
-0.7% MJ/RPK in 2040
-1.9% MJ/RPK in 2050</td></tr>
</table>

Formation flying is the process in which one aircraft follows another to realize savings in fuel burn. This is a similar process to motor vehicles drafting on a highway. Airbus is exploring formation flying through its fello'fly program (Airbus, 2022). Fuel savings and, therefore, CO_2 reductions from formation flying can vary between 2% and 9% per flight based on the airline business model and flight network (Kent & Richards, 2021). Under the Breakthrough scenario, formation flying is applied to 5% of the global passenger flight traffic in 2030 and increases to almost 50% of the global passenger flight traffic in 2050. It was not applied to dedicated freighter aircraft in the model, due to freight's high proportion of unscheduled operations. Therefore, if dedicated freighters were included in formation flying, greater CO_2 reductions could be realized.

ZERO-EMISSION PLANES

Zero-emission planes (ZEPs) are an emerging technology that uses hydrogen and electricity as power sources. Due to the weight of current batteries, electric aircraft will be limited to short-range commuter missions before 2050 (Mukhopadhaya & Graver, 2022). Aircraft fueled by liquid hydrogen (LH_2), on the other hand, could potentially

4 Maximum structural payload (MSP) is the difference between the maximum zero fuel weight (MZFW) and the operating empty weight (OEW) of an aircraft. It measures the maximum payload mass that a plane can legally carry. Because passenger and belly freight load factors are typically below 100%, and aircraft are designed to trade off payload and range on longer flights, 100% MSP is rarely achieved.

service short- to medium-haul flights up to 3,400 km in stage length (Mukhopadhaya & Rutherford, 2022).

The successful development and deployment of these aircraft are not guaranteed, which is why they are excluded from the Action scenario and introduced incrementally in the Transformation and Breakthrough Scenarios. Their introduction is represented by percentages of the new deliveries of the aircraft class they would replace. The percentages used for the various scenarios and timeframes are listed in **Table 5.** For example, in the Transformation scenario in 2035, 12.5% of new narrowbody and regional aircraft deliveries are assumed to be hydrogen-powered. This corresponds to half of the global manufacturers introducing an LH_2 design, accounting for one-quarter of their sales. The profile of hydrogen planes increases to a maximum of 50% of new aircraft deliveries in 2050 under the Breakthrough case.

Table 5. Zero-emission plane modeling assumptions

Scenario 1: Action	Scenario 2: Transformation	Scenario 3: Breakthrough
Electric: None	**Electric:** 2030 entry-into-service 50% of new commuter aircraft, 2030 100% of new commuter aircraft 2050	**Electric:** 2030 entry-into-service 50% of new commuter aircraft, 2030 100% of new commuter aircraft 2050
Hydrogen: None	**Hydrogen:** 2035 entry-into-service 12.5% of new regional and narrowbody aircraft, 2035 25% of new regional and narrowbody aircraft, 2050	**Hydrogen:** 2035 entry-into-service 12.5% of new regional and narrowbody aircraft, 2035 50% of new regional and narrowbody aircraft, 2050
No direct hydrogen use	Hydrogen share (blue/green) 2035: 75% / 25% 2040: 50% / 50% 2050: 0% / 100%	Hydrogen share (blue/green) 2035: 50% / 50% 2040: 33% / 67% 2050: 0% / 100%
Fuel carbon intensity (all scenarios, all years, g CO_2e/MJ)		
hydrogen (blue): 31 hydrogen (green): 0.44 electricity: 0		

The liquid hydrogen-combustion aircraft families presented in Mukhopadhaya & Rutherford (2022) are used in the modeling, with a gravimetric index of 0.275 assumed for the fuel system. WTW emissions for LH_2 are derived from Mukhopadhaya & Rutherford (2022) and assume the availability of additional, zero-carbon renewable electricity and, for blue hydrogen, very high (99%) carbon capture rates. Demand response due to hydrogen fuel cost was not explicitly modeled because LH_2 will likely be cheaper than e-kerosene. This approach may overestimate somewhat the fuel price increase due to SAFs.

Electric aircraft in this analysis are limited to 9- and 19-seat commuter aircraft. The specific energy of batteries at the pack level is set to 300 Wh/kg in 2030, increasing to 500 Wh/kg in 2050. This increases the market coverage of electric commuter aircraft (0.03% of RPKs and 0.16% of CO_2 in 2019) from 30% to 60% in 2030 to 2050. More information on the electric aircraft modeled can be found in Mukhopadhaya & Graver (2022). The emissions impact of battery production was not modeled in this study.

SUSTAINABLE AVIATION FUELS

Sustainable aviation fuels (SAFs) produced from biomass or renewable energy feedstocks are projected to provide the majority of emission reductions under most roadmaps. SAFs are compatible with existing airframes and engines in up to 50% blends, with efforts underway to certify the use of “neat” 100% SAFs. To date, progress has been slow to scale up SAFs (which accounted for ~0.05% of the aviation fuel supply in 2020) but accelerated progress is anticipated under proposed mandates, including ReFuel EU (EC, 2021) and UK's Jet Zero consultation (UK, 2022), and under incentives such as California's Low-Carbon Fuel Standard (LCFS) (CARB, 2022).

Near-term supply will be provided mostly by waste fats, oils, and greases (FOGs) such as used cooking oil and beef tallow. These feedstocks are used in existing, commercialized SAF production pathways. In the medium term, advanced biofuels derived from cellulosic agricultural and forestry wastes are expected to become more common; in the long-term, synthetic fuels (i.e., e-fuels, also known as e-kerosene) are likely to become predominant as the costs of renewable electricity and carbon capture fall.

Consistent with our aim to assess the maximum degree to which different measures can contribute to aviation decarbonization, we exclude food-based biofuels from the analysis due to their sustainability risks. We include SAFs that would reduce emissions by at least 50% over their life cycle, taking into account land use change and displacement emissions, which disqualifies fuels produced from corn, soy, and palm (ICAO 2021b, Pavlenko & Searle, 2021). The aviation industry also excluded feedstocks that "make use of significant quantities of arable land, reserving them for production of food" in their Waypoint 2050 pathways (ATAG, 2021c).

In 2025, 100% of SAF produced is from waste oils; this contribution declines over time (e.g., to 20% in 2030) due to supply constraints as biofuel SAFs are increasingly produced from lignocellulosic residues, particularly agricultural residues. We cap SAF production from waste oils at a maximum of 5 Mt per year, consistent with existing consumption, and we estimate an additional 3 Mt of used cooking oil collection potential in Asian countries (Kristiana, Baldino, & Searle, 2022). Smaller quantities of inedible animal fats may be available beyond this total. Still, these feedstocks often have valuable existing uses, and if diverted to aviation, there may be strong displacement effects that could undermine their climate benefits. In particular, palm fatty acid distillates (PFADs) have a strong likelihood of being substituted by palm oil, with high estimated indirect emissions. Because of this sustainability risk, PFADs are not included in this availability estimate (Malins, 2017).

SAFs and other alternative fuels are not included in the Baseline. SAF volumes from the IEA's Sustainable Development Scenario (SDS) (IEA, 2020) are used in our Action scenario and the Net Zero Emissions (NZE) (IEA, 2021) is used in our Transformation scenario for 2030, 2040, and 2050, with volumes interpolated in five-year intervals. Since IEA's 2030 assumed SAF share for the SDS (7%) and NZE (17%) are notably higher than both current supply and other roadmaps, we halved them in all scenarios.

The Breakthrough case also uses NZE as the basis of SAF volumes, with several adjustments to reflect increasingly ambitious policy drivers, including global fuel taxation and fossil fuel aircraft operation bans after 2030. 2030+ volumes are equal to NZE but accelerated by five years (i.e., 2035 volumes equal to 2040 NZE). An additional 2.9 EJ of e-kerosene, equivalent to the remaining fossil jet fuel supply in the NZE scenario in 2050, is added to the Breakthrough case to reflect potential 2055 SAFs not modelled by IEA. Due to expected supply constraints for sustainable biomass and long-run projected cost reductions for e-kerosene, we cap biofuel supply at 100 million tonnes (~4.3 EJ supply), equivalent to IEA's 2040 biofuel supply under the NZE pathway, and assign all subsequent SAF growth to e-kerosene.

Table 6 summarizes the assumptions used to estimate emission reductions attributable to SAFs; note that the derived fuel costs are subsequently used to reduce traffic growth rates via a demand response. Fuel use and costs are explicitly for carbon fuels and exclude hydrogen.

Table 6. Sustainable aviation fuel assumptions

Scenario 1: Action	Scenario 2: Transformation	Scenario 3: Breakthrough
2030 12 million tonnes biofuels (3% of fuel use) **2050** 100 million tonnes biofuels 120 million tonnes e-fuels (50% of fuel use)	**2030** 23 million tonnes biofuels 2 million tonnes e-fuels (8% of fuel use) **2050** 100 million tonnes biofuels 150 million tonnes e-fuels (80% of fuel use)	**2030** 46 million tonnes biofuels 5 million tonnes e-fuels (17% of fuel use) **2050** 100 million tonnes biofuels 215 million tonnes e-fuels (100% of fuel use)
Average costs (avg. biofuel vs. e-fuel, $/L) 2030: 1.81 / 1.79 2040: 1.98 / 1.59 2050: 2.03 / 1.26	**Average costs** (avg. biofuel vs. e-fuel, $/L) 2030: 1.81 / 2.00 2040: 1.98 / 1.65 2050: 1.40 / 1.36	**Average costs** (avg. biofuel vs. e-fuel, $/L) 2030: 1.81 / 2.00 2040: 1.36 / 1.72 2050: 1.40 / 1.52
e-fuel carbon (point source vs. DAC) 2030: 100% / 0% 2040: 67% / 33% 2050: 67% / 33%	**e-fuel carbon** (point source vs. DAC) 2030: 67% / 33% 2040: 58% / 42% 2050: 50% / 50%	**e-fuel carbon** (point source vs. DAC) 2030: 67% / 33% 2040: 46% / 54% 2050: 25% / 75%
Fuel carbon intensity (all scenarios, all years, g CO_2e/MJ)		
Jet A: 88.5		
Biofuels Used cooking oil HEFA: 14 Agricultural residues gasification-FT: 7.7 Forest residues gasification-FT: 8.3 Municipal solid waste gasification-FT: 39	**Synthetic fuels** e-kerosene (point source capture): 0.44 e-kerosene (DAC): 4.1	

Fuel cost estimates are derived from Pavlenko et al. (2019) and Zhou et al. (2022). Fossil “Jet A” fuel costs are estimated by EIA (2020). Biofuel costs increase over time due to a shift from lower cost, limited supply HEFA fuels made from FOG feedstocks to higher cost, higher supply fuels made from cellulosic residues and wastes. E-kerosene costs, conversely, fall over time due to reductions in the cost of renewable electricity (Zhou et al., 2022). Two sets of biofuel costs are assumed: a base CAPEX cost and a low CAPEX cost (Pavlenko et al., 2019). The base CAPEX cost is used for all years in the Action scenario. Due to early, proactive SAF investments, we assume that the Transformation and Breakthrough cases transition to the low CAPEX cost starting in 2040 and 2030, respectively.

Carbon for e-kerosene is sourced via point source and direct air capture (DAC). E-kerosene costs are derived from Zhou et al. (2022) with additional modeling to capture increased costs of using DAC for carbon sourcing over time, as well as increasing scenario ambition. Point sources provide the majority of carbon in the early years, shifting to predominately DAC over time and with increased use. Point source carbon is capped at two-thirds of the Action scenario’s e-kerosene supply in 2050 (80 MT); additional supply above that level is assumed to require DAC. Point source carbon is assumed to have a stable cost of $40 per tonne CO_2; estimated costs for direct air capture are assumed to decline linearly from $305 per tonne CO_2 in 2020 to $155 per tonne CO_2 in 2050, per estimated costs for solid DAC technologies in IEA (2022). E-kerosene costs are somewhat higher in the Breakthrough Scenario due to higher assumed shares of DAC-derived fuels.

Emissions intensities for various fuels are drawn from ICAO (2021b) and Mukhophadaya & Rutherford (2022). Consistent with the approach taken for hydrogen, e-kerosene is assumed to be produced from 100% additional renewable electricity; residual emissions for e-kerosene are linked to fuel distribution and adsorbents used for carbon capture (DAC). The carbon intensity of SAF made with municipal solid waste (MSW) assumes an 80% bio and 20% non-bio mix, equivalent to an MSW-certified value under California’s LCFS.

ECONOMIC INCENTIVES

Low carbon technologies, notably SAFs and zero-emission planes, will cost more than conventional aircraft operated on fossil jet fuel. Government policies will be needed to raise the price of fossil jet fuel in order to make those technologies competitive.[5] The associated fuel price increase will raise ticket prices and reduce traffic growth rates as fewer people travel. The interdependencies of SAF uptake and aviation demand have been explored in van der Sman et al. (2021), among others.

A variety of policies could potentially close the price gap between alternative and fossil jet fuels, including emission trading systems (ETS), fuel taxes, alternative jet fuel mandates, and Low Carbon Fuel Standards (LCFS). Because SAFs have not yet scaled, their abatement costs remain much higher than carbon prices under ETS; this means that a single, economywide carbon price is unlikely to spur their development. Instead, targeted policies like an LCFS, SAF mandates like that proposed under Europe's "Fit for 55" package, or a fuel carbon levy with revenue recycled for technology deployment are likely needed to jumpstart SAF markets. In time, SAF costs should decline to the point that market-based measures like an ETS could drive their adoption.

Reflecting this, we model the level of fuel price increase needed to promote new technologies through a staged approach, with near-term carbon prices modeled as a fossil fuel levy and cross-subsidy to alternative fuels, and long-term prices assessed as the carbon price equal to the marginal cost of alternative fuels. Specifically, fuel and carbon prices are estimated in each year as the lesser of:

1. A cross-subsidy from fossil jet fuel to SAFs ($ of incremental SAF cost/tonnes of total aviation CO_2)
2. A classic marginal abatement cost ($ of incremental SAF cost/tonne of SAF CO_2 abatement)

The resulting fuel price increase was translated into ticket prices as follows. We purchased 2019 average economy-class fare data from RDC, which covers almost half of the passenger operations in 2019. We extrapolated ticket prices for the rest of the operations based on average $ per km by region. We assume that the real price of airfare does not change significantly over time compared to 2019 levels, apart from fuel cost. A fuel cost pass-through rate of 75% is used, assuming airlines absorb some of the fuel price increases due to competition.

We use price elasticities by region pair (for example, North America—Europe) and by short- vs. long-haul from the InterVISTAS consultant report (2007) commissioned by IATA. While leisure travel is generally more elastic than business travel, we use average elasticities across trip types in this study to match the granularity of our air traffic data. The average elasticity is -0.6, with a range from -0.36 to -0.92. Annual demand change is calculated as a function of the change in carbon price from the previous year, rather than the absolute price in that year. The detailed PACE model methodology document on the ICCT's GitHub repository website has further details.

In addition to a demand response, we expect the fuel price increase to drive an uptake of new fuel-efficient aircraft. That is captured in our technical efficiency assumptions, which are consistent with the fuel price increase modeled according to the base reference in a previous ICCT study (Kharina et al., 2016).

5 The alternative approach, to subsidize low carbon aircraft and fuels, can also be applied. However, due to the substantial cost of the transition—up to $4 trillion US per ICAO (2022)—plus the equity implications of subsidizing air travel (Rutherford, 2019), in this modeling we assume that economic incentives are used to increase fuel costs until low carbon fuels become cost-competitive with fossil jet fuel.

MODAL SHIFT

For short-haul air travel, switching to less carbon-intensive ground transportation can be an effective way to reduce emissions. Among various road transport modes, high-speed rail (HSR) has the most potential to reduce short-haul air travel demand. Consumers are likely to switch when travel time and cost are comparable or less, and when rail service runs frequently and reliably. Past research shows that a new or improved HSR system can compete with air travel over distances up to 1,000 km, and is most competitive for trips under 700 or 800 km (or under 3 hours of travel time) (Zheng, 2022).

Several studies have quantified the magnitude of modal shift from air to rail, with the level of air traffic reduction ranging between 7% and 28%. For instance, Avogadro et al. (2021) estimate that about 7% of intra-European short- and medium-haul traffic can be substituted by rail with no increase in travel time; the ratio goes up to 17% when considering up to a 20% increase in travel time. Meanwhile, a Transport & Environment (2020) model shows that intra-EU air traffic could fall by 25% if HSR were available between all major cities in the region. In China, the introduction of HSR led to a 27-28% air travel demand reduction in the early years (2010-2013) and a 10% decrease in monthly departures in the longer term (2011-2016), according to two studies (Zhang et al., 2017; Zhu et al., 2020).

Table 7 summarizes the modal shift assumptions used in this study. Except in Europe, it is not common for HSR systems to cross borders. We thus limit our modeling to domestic and intra-EU routes. HSR is mostly built between dense cities, so we also impose an annual threshold of 100,000 passengers to narrow down replaceable routes, based on density, to so-called trunk routes.

Table 7. Modal shift assumptions

Scenario 1: Action	Scenario 2: Transformation	Scenario 3: Breakthrough
Domestic and intra-European routes of less than 750 km Number of passengers greater than 100,000 annually 20% traffic shift from air to rail, starting in 2030		

Demand shift will be contingent on infrastructure development and improvement, and we understand that our assumptions may include replacing air routes that do not currently have rail service (e.g., Los Angeles – Las Vegas). However, assuming that only a share (20%) of traffic shifts from air to rail reduces potential emission reductions of these routes, while possibly underestimating the impact of routes where modal shift may achieve higher than modeled air-to-rail shifts.

In Europe, some governments have banned short-haul routes that are replaceable by rail. In these cases, modal shift can happen at a larger scale. Such a policy-driven shift is not modeled in our study.

RESULTS AND DISCUSSION

This section summarizes and discusses our results. It is organized in the following fashion. First, we present key trends identified in the modeling, in the form of changes in fuel mix, fuel carbon intensity, traffic, and energy efficiency across the scenarios. Then, we present emission estimates by scenario, both in absolute and cumulative terms, and relate those to temperature thresholds that are consistent with the Paris Agreement. We also highlight, in general terms, the technologies needed for the most ambitious Breakthrough case to come to fruition, notably renewable energy supply. We close by comparing our results to two prominent existing roadmaps.

KEY TRENDS

SAF costs more to produce than conventional jet fuel. Estimates of how much more vary from 2-3 times (ATAG, 2021c) to 8 times (Bousso, 2021). A large-scale deployment of SAFs will lead to an increase in fuel price. Our model treats SAF supply as an exogenous variable and estimates carbon prices needed to generate that supply. The results are shown in **Figure 3a**. Using the costs outlined in **Table 6** and the estimated fuel volumes derived from the model, the weighted fuel price for each scenario is portrayed in **Figure 3b**.

In 2030, the implied cost of carbon varies between $15 and $80 per tonne, depending on scenario. As more SAF enters the system, the carbon price continues to increase when modelled as a cross-subsidy from fossil jet fuel to SAFs. It peaks at above $330 per tonne in the Breakthrough and Transformation cases, but at different times (2037 and 2042, respectively). The prices then decrease, once it acts as a classic marginal abatement cost, to between $200 and $225 per tonne in 2050, depending on the scenario. In the Action scenario, carbon prices increase more gradually, but continue to grow through 2050, reaching the equivalent of $300 per tonne that year. This is due to the delayed introduction of policies to produce SAF, which also delayed the ability to reach production economies of scale.

Because no SAFs are included in the Baseline scenario, the brown bar in **Figure 3b** represents the cost of Jet A. Under the Action and Transformation scenarios, the average fuel cost in 2050 is 60-65% higher than for conventional jet fuel. Fuel costs in the Breakthrough scenario are 70% higher than in the Baseline, slightly lower than those estimated in Waypoint 2050 once carbon costs are considered (ATAG, 2021c). Fuel prices in Breakthrough are higher than in Action and Transformation due to larger SAF volumes and the greater use of DAC for e-fuel production.

(a) Carbon prices (in US dollars) derived from SAF assumptions

(b) Weighted average fuel price (in US dollars per liter) used to derive carbon pricing

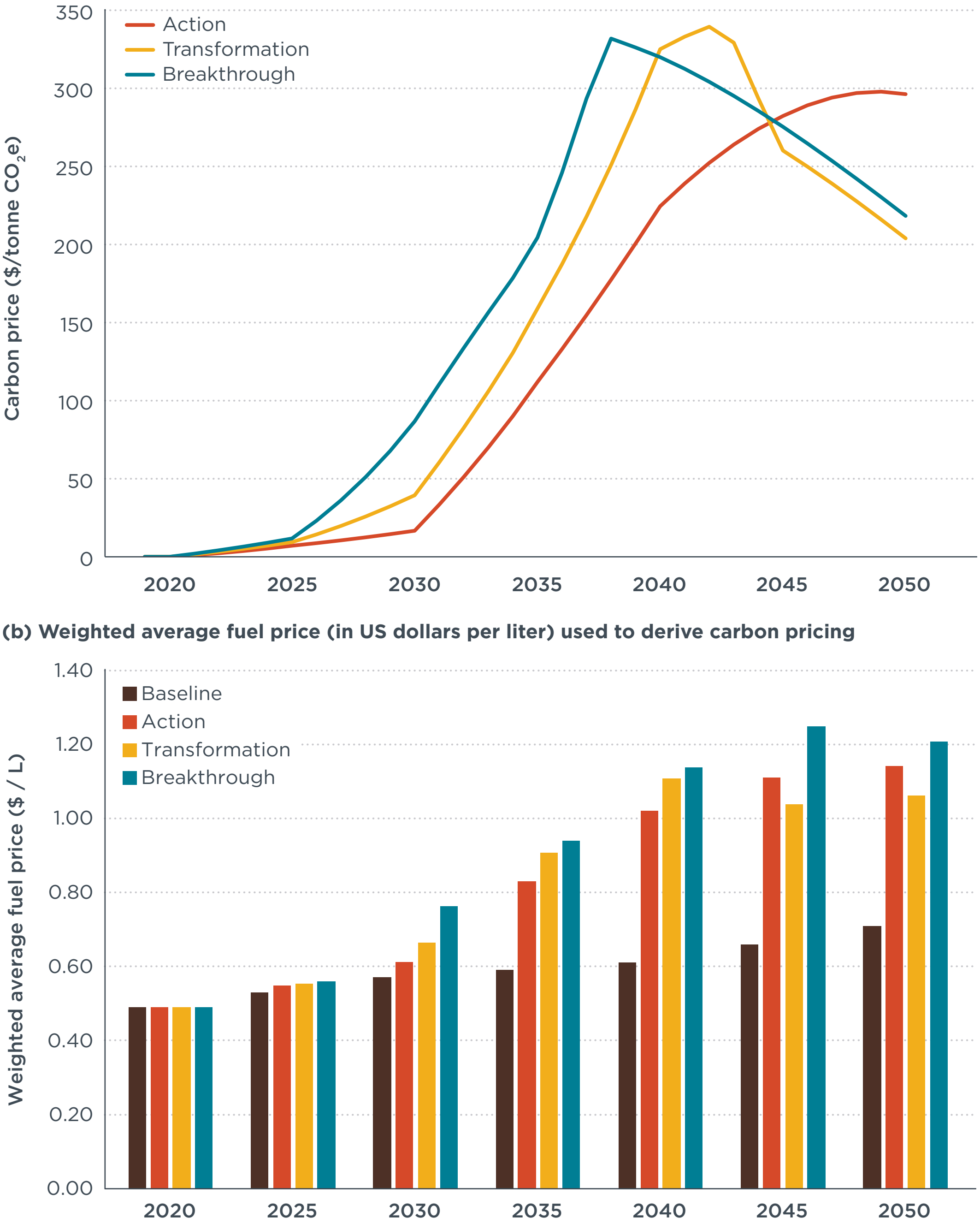


Figure 3. Effects of SAFs on carbon pricing and average fuel price

As mentioned previously, Destination 2050 included demand reduction in its analysis due to the cost of decarbonization measures, including SAFs, hydrogen, and economic measures (van der Sman et al., 2021). We have also included demand change, but only due to the carbon price associated with SAF costs. Based on the price increases due to SAFs (shown in **Figure 3b**) and price elasticities introduced above, traffic demand falls somewhat for all three scenarios analyzed, as shown in **Figure 4**.

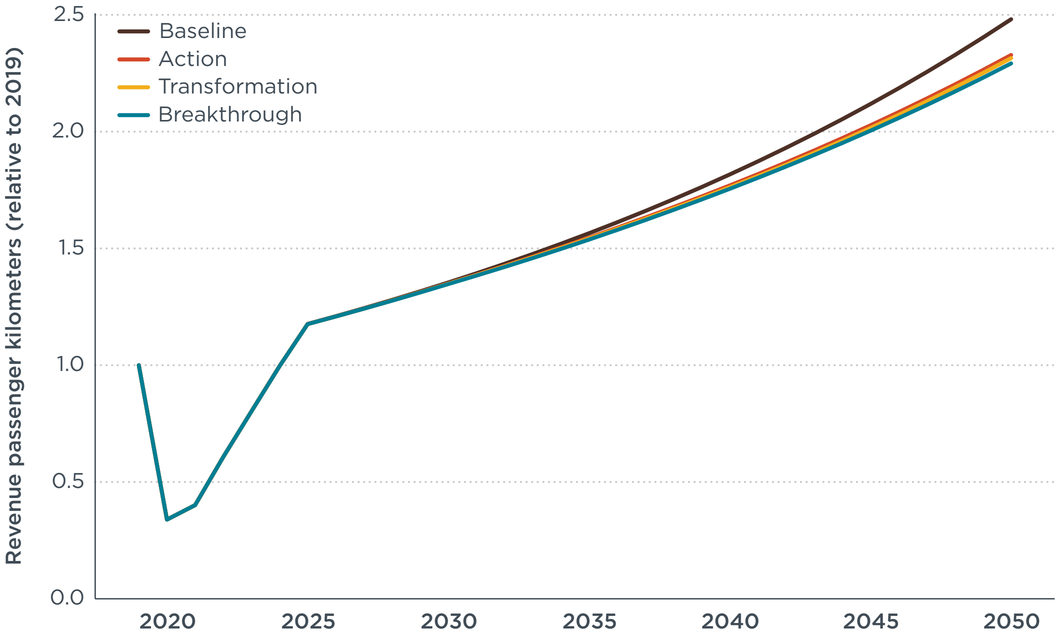


Figure 4. Effect of a carbon price on passenger traffic

Because fuel prices converge in 2050 for all three scenarios, the modeled demand response is likewise similar. In the Breakthrough scenario for 2050, passenger traffic is 4% lower due to a 6% increase in ticket prices off a 70% increase in fuel costs compared to the Baseline case. In terms of the annual growth rate, the effect of more expensive SAFs reduced passenger traffic from 3.0% per annum to 2.76% over thirty years. The total reduction in RPKs between 2019 and 2050 was 2.5%. The demand reduction accounts for 3% of total mitigation, decreasing cumulative CO_2 emissions by 0.8 gigatonnes (Gt) relative to the BAU case.

The assumptions summarized in **Table 2** were used to estimate the energy intensity, in megajoules of energy per RPK (MJ/RPK), for the global aviation fleet by year and scenario (**Figure 5**). Under the Action case, energy per RPK falls by about 20% below the Baseline case in 2050, or more than one-third (-36%) below 2019 levels. Accelerated gains are seen for other cases, with 2050 MJ/RPK falling by more than 40% (Transformation) and by about 45% (Breakthrough) below 2019 levels, respectively. Note that both of the latter scenarios include some increase in energy intensity due to the introduction of evolutionary hydrogen aircraft, which are expected to require more energy per RPK than conventional aircraft (Mukhopadhaya & Rutherford, 2022).

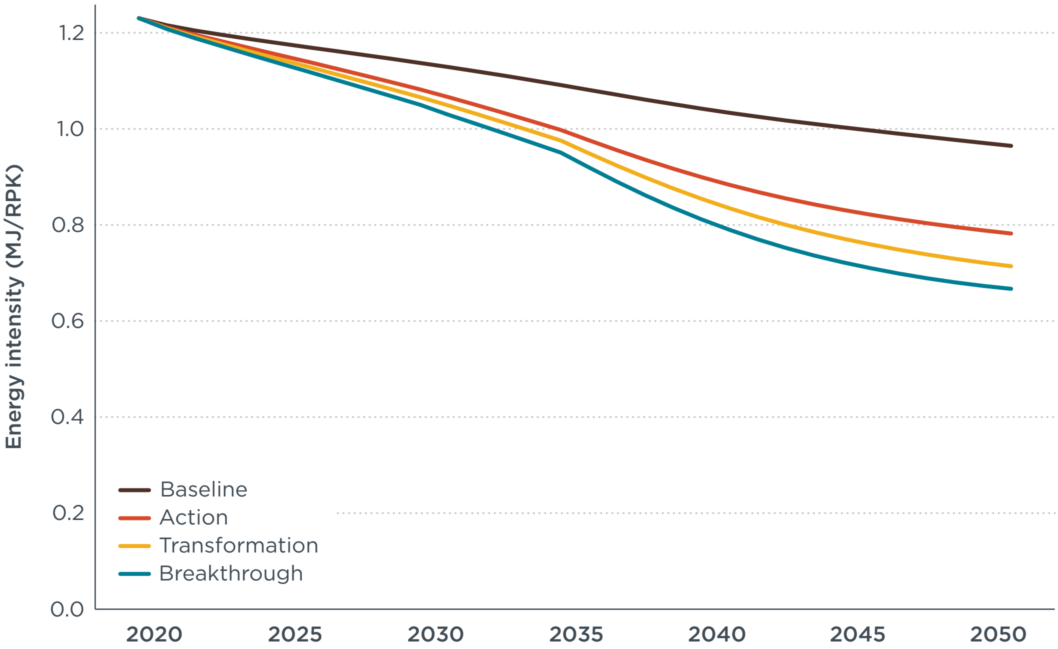


Figure 5. Global aviation energy intensity under baseline and 3 scenarios, 2020-2050

SAFs, in the form of biofuels and synthetic fuels, act as the largest driver of decarbonization in all the roadmaps cited previously. **Figure 6** below shows conventional fuel's share of total energy demand under the three scenarios. Under the Action case, fossil jet fuel's share of aviation energy almost halves by 2050; for Transformation, it drops even further, more than 75%, as synthetic fuels like e-kerosene and hydrogen come to dominate. **Figure 7** depicts fuel volumes in exajoules (EJ) by type through 2050 in the Breakthrough scenario, which has the largest deployment of alternative fuels. Conventional Jet A demand peaks in 2025, then declines precipitously before zeroing out before mid-century.

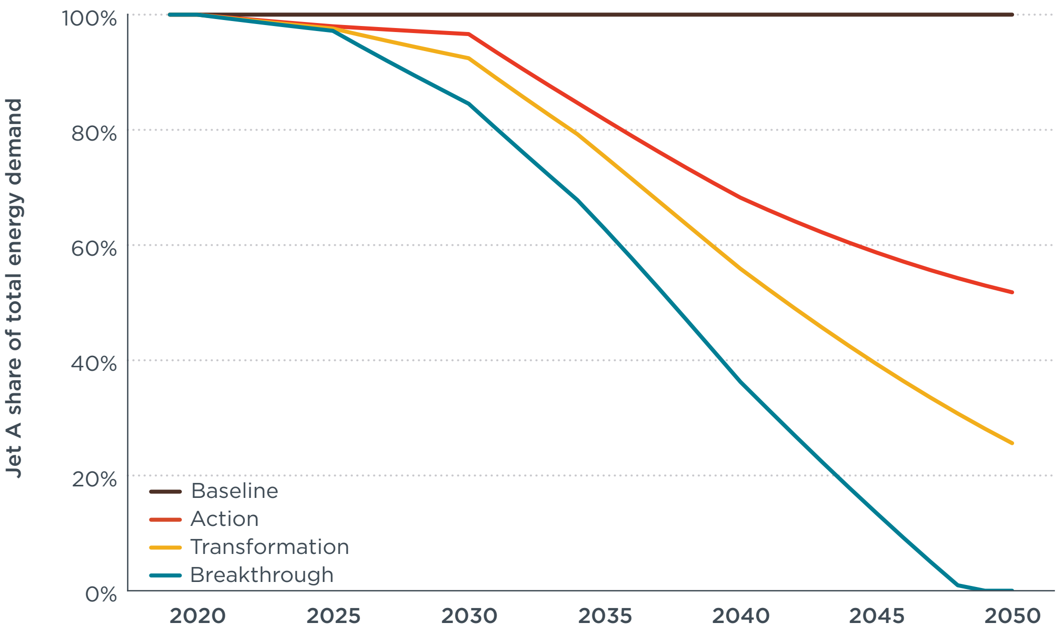


Figure 6. Jet A share of total energy demand in baseline and three scenarios, 2020-2050

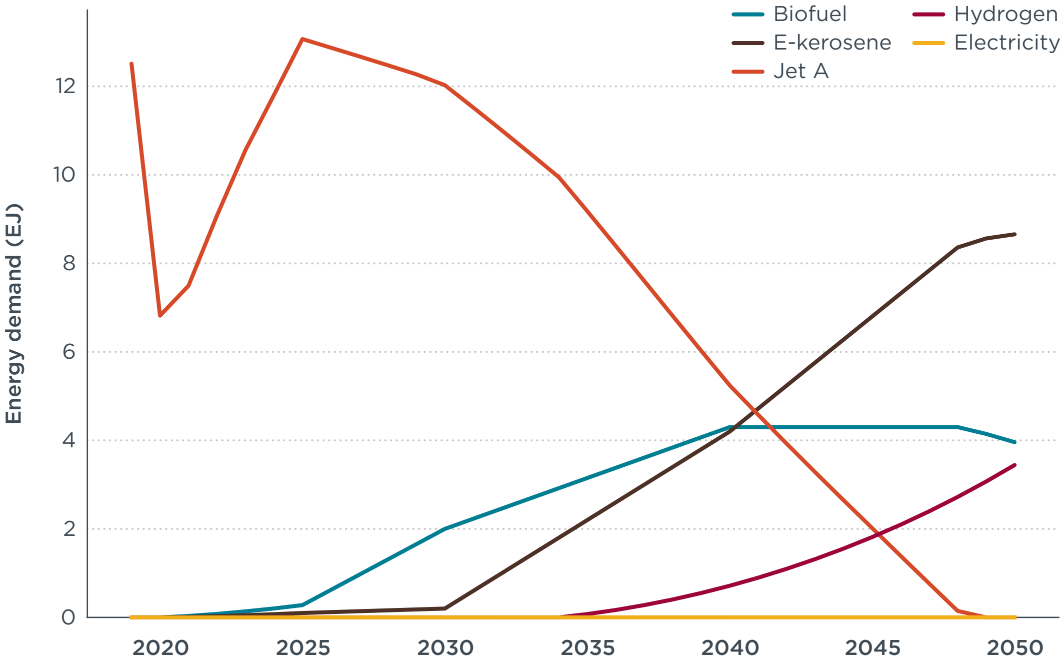


Figure 7. Breakdown of aviation's energy demand by fuel in the Breakthrough scenario

In 2019, almost 12.5 EJ of fuel was consumed, nearly all of it Jet A. The amount of biogenic SAF was too small to be visible in the figure. By 2030, the Breakthrough scenario estimates that 14.25 EJ of fuel will be necessary, 85% of it Jet A. Alternative fuels overtake conventional fuels in 2038. By 2050, 16.3 EJ are estimated to be needed, 54% of which are e-fuels, 24% are biogenic fuels, and 22% are hydrogen. The 78% share of total 2050 fuel demand met by SAFs is akin to the 80% share included in the DEPA 2050 roadmap (DLR, 2021); additional fuel use in that roadmap is the Jet A and LH_2 identified in this study. The share of hydrogen powering commercial aircraft, 20%, is similar to the 2050 estimate cited in Waypoint 2050 (ATAG, 2021c).

In **Figure 7**, electricity used to power electric commuter aircraft is hardly visible. This is because of the small share of total traffic by commuter aircraft on flights of 500 km or less. By 2050, electric aircraft account for 0.01% of total energy demand, which is far less than the 2% calculated in Waypoint 2050 (ATAG, 2021c). The major difference is that this analysis includes only electric commuter aircraft with 19 or fewer seats, while the Waypoint 2050 industry roadmap contains regional electric aircraft with up to 100 seats (which constitutes a larger market share). Mukhopadhaya and Graver (2022) highlight the expected range limitations of those larger aircraft.

With the inclusion of SAFs and hydrogen, we see decreasing carbon intensities in the average fuel mix in the three modeled scenarios, as shown in **Figure 8**. In the Action scenario, which only includes SAFs, the average carbon intensity is 45% lower than Baseline in 2050. Even deeper reductions occur in the Transformation and Breakthrough scenarios (71% and 95% lower than Baseline, respectively, in 2050) due to the addition of hydrogen aircraft.

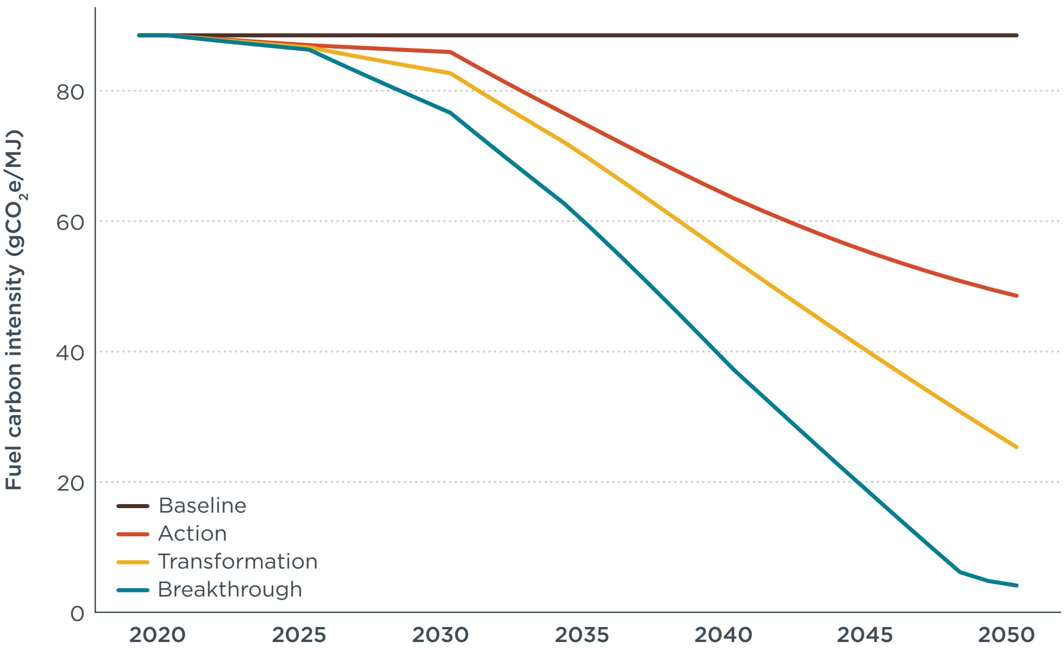


Figure 8. Global aviation fuel carbon intensity under Baseline and 3 scenarios, 2020-2050

EMISSION ESTIMATES

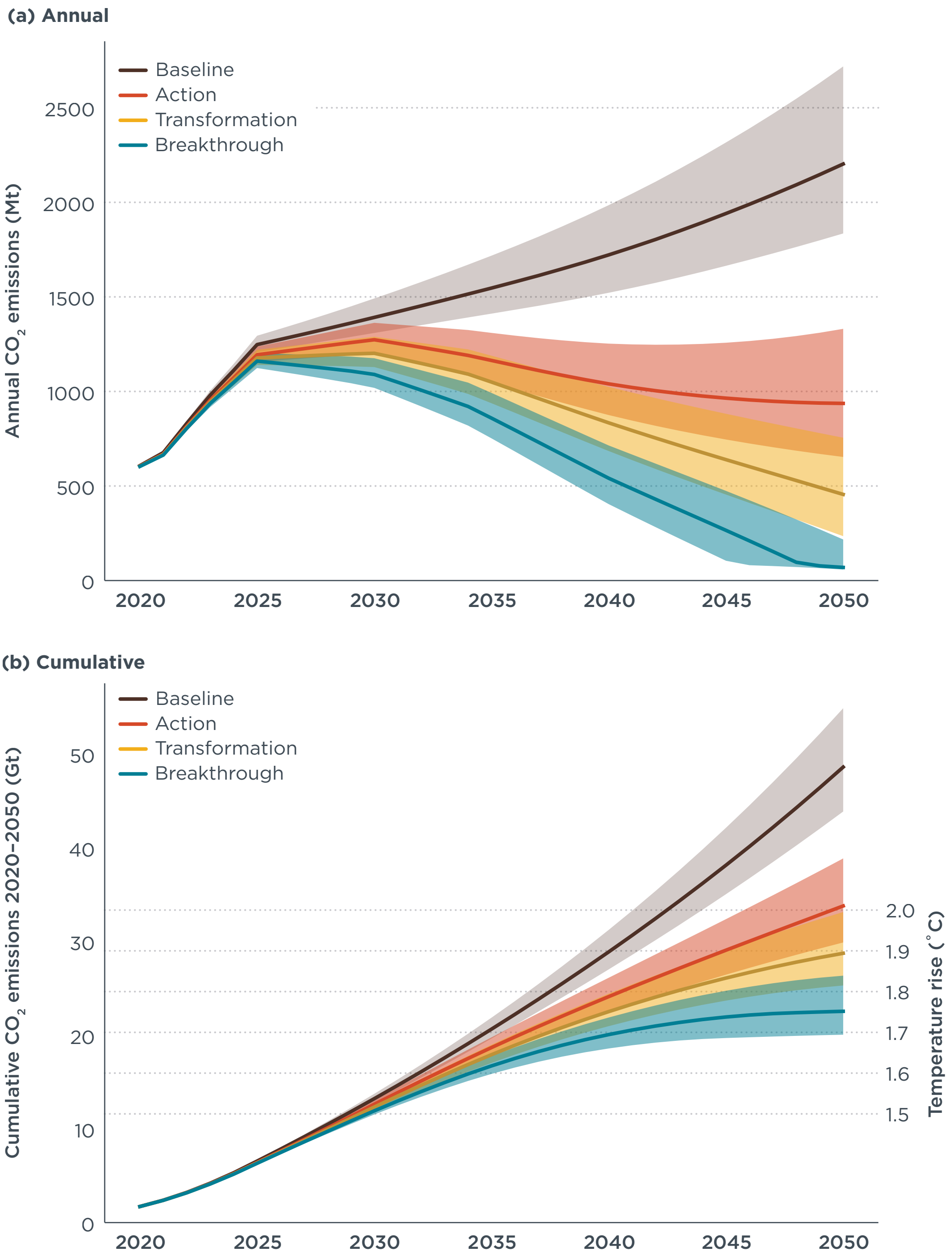
Emissions were calculated on both an annual and cumulative basis for the 2020 through 2050 period. This allows for a comparison of annual emissions to other roadmaps, such as Waypoint 2050, and cumulative emissions to the Intergovernmental Panel on Climate Change's (IPCC's) global carbon budget (IPCC, 2021). We are using the 67% probability of the estimated remaining 2020-2050 budget, which are 400 Gt CO_2 to keep the global surface temperature increase to 1.5°C, 775 Gt CO_2 for 1.75°C, and 1,150 Gt CO_2 for 2°C. In this analysis, we assume that aviation maintains, through 2050, its current share of global CO_2 emissions, 2.9%, consisting of fuel use (2.4%) and upstream fuel production (0.5%) (Graver et al., 2020).

CO_2 emissions are given on a well-to-wake (WTW) basis, which includes the emissions associated with the creation of the fuels used by aircraft (Jet A, biofuels, and synthetic fuels). On average, the WTW emissions are 21% higher than the CO_2 emitted directly from the aircraft engines. In contrast, other roadmaps typically only account for emissions produced from the combustion of fuel (TTW).

Figure 9 depicts the annual and cumulative CO_2 emissions under different scenarios and passenger traffic forecasts. The solid line depicts the central traffic forecast, while the shaded area depicts the range between the low and high forecasts. Cumulative emissions consistent with different temperature thresholds ranging from 1.5 to 2°C are shown, on the right, in **Figure 9(b)**.

Under the Action and Transformation scenarios, CO_2 emissions peak in 2030, with Breakthrough peaking once COVID-19 recovery is projected to be complete in 2025, as shown in **Figure 9a**. In the Baseline case, 2050 annual emissions will be double those in 2019, as shown in **Figure 9a**. In the three scenarios, 2050 annual emissions are less than in 2019. Action provides modest (9%) reductions, with Transformation approximately halving emissions relative to 2019. Under the Breakthrough scenario, aviation achieves "near zero" (70 Mt) emissions in 2050 without the use of out-of-sector measures.

The Baseline case breaches a 2°C carbon budget before 2045. Under the Action scenario, global aviation consumes its share of a 2°C carbon budget by 2050. Under the Transformation case, by the same year aviation exhausts the share available to it under a 1.9°C carbon budget. By peaking emissions in 2025 and reducing them to near-zero levels by 2050, Breakthrough is consistent with a 1.75°C temperature target. For a 1.5°C pathway to be maintained without increasing aviation's share of a global carbon budget, an additional 50% reduction in cumulative emissions (11 Gt of CO_2) beyond the Breakthrough case would be required. This is equivalent to achieving net-zero emissions by 2030—two decades sooner than the aviation industry has planned in its net-zero commitments (ATAG, 2021a).



The solid line depicts the central traffic forecast; the shaded area depicts the range between the low and high forecasts.

Figure 9. Global aviation CO_2 emissions by scenario and traffic forecast, 2020-2050

Figure 10 depicts the 30-year cumulative CO_2 emissions from each scenario, the driver of emission reductions in each case, and thresholds for the three temperature targets (dotted lines).[6] In the Action scenario, emissions fall by 30%, or almost 15 Gt, through 2050 relative to the Baseline scenario, but still exceeds the 2°C target by 2050. The Transformation scenario achieves a 2°C target by 2050 by cutting cumulative CO_2 by 20 Gt (41%) below the Baseline. The Breakthrough scenario cuts CO_2 even deeper by 2050—by 26 Gt, or more than half from the Baseline in 2050—in order to reach the 1.75°C target. Therefore, under all scenarios, additional in-sector and out-of-sector measures would be needed for global aviation to be 1.5°C-compatible. This will be discussed further later in this section.

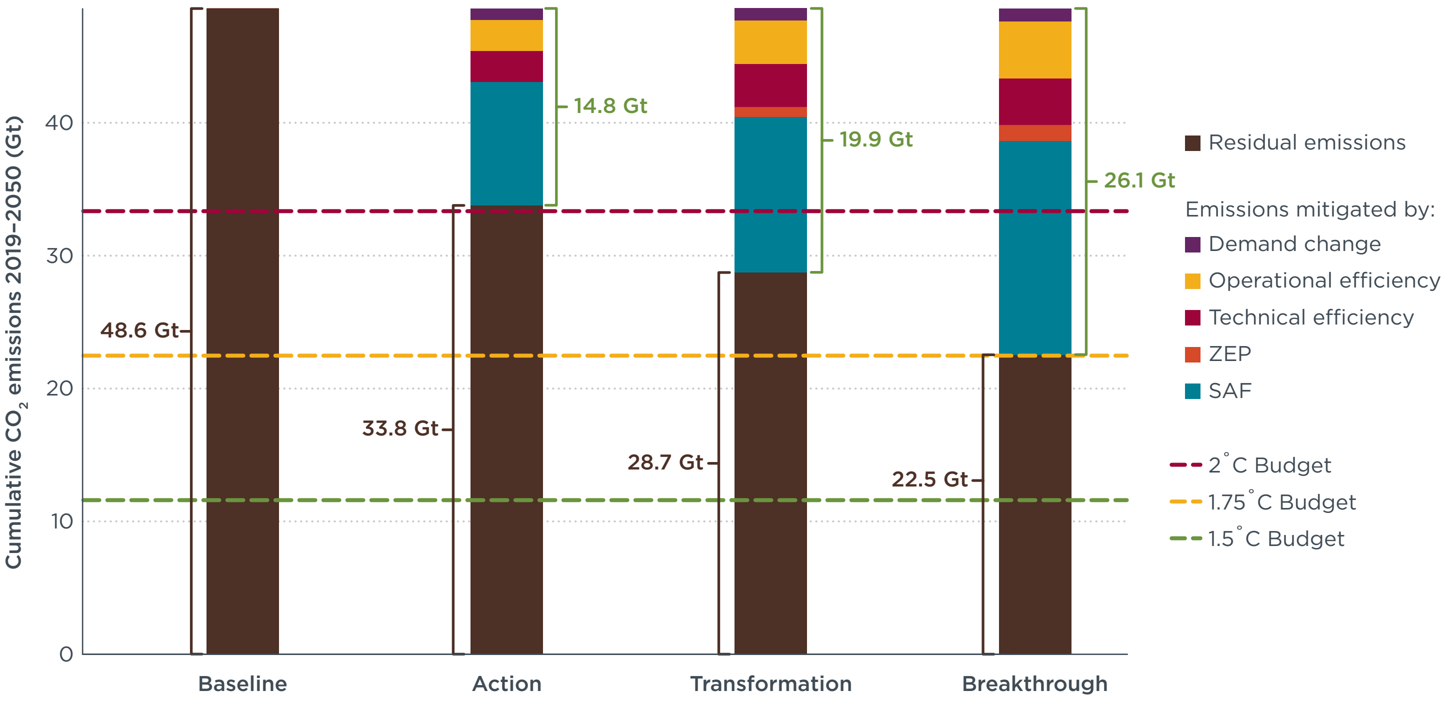


Figure 10. Cumulative global aviation CO_2 emissions by scenario and measure, 2019-2050

In all three scenarios, SAF consumption accounts for the greatest reductions in CO_2 emissions. It is highest in the Action scenario, at 63%, because of the absence of ZEPs and, therefore, the need for more SAFs. In the Transformation and Breakthrough scenarios, SAFs account for 59% and 62% of CO_2 reductions, respectively. These values are similar to the 61% contribution of SAFs to industry's Scenario 1 in Waypoint 2050 (ATAG, 2021c).

Improvements in aircraft technical and operational (combined payload and traffic) fuel efficiency provide about one-third of total mitigation across scenarios, at approximately 16% each. In Breakthrough, technical efficiency improvements account for 13% of mitigation, lower than in other scenarios because of the use of ZEPs, which accounted for less than 5% of mitigation but which increase energy use somewhat. However, operational improvements accounted for 17% of mitigation, higher than in other scenarios due to the inclusion of formation flying. Note that the share of mitigation from ZEPs could rise after 2050 given fuel costs that are lower than for e-kerosene on short and most medium-haul flights, per Mukhopadhaya & Rutherford (2022).

Demand response made a modest contribution to emission reductions, at less than 5% of total mitigation in the Transformation and Breakthrough scenarios. Most of the

6 More information on the attribution of emission reductions to measures can be found in Appendix A of this paper and the detailed methodology document on the ICCT website.

demand response is triggered by fuel price increases; in the Breakthrough scenario, price increases led to 7% less traffic compared to the Baseline in 2050 and 2.5% less traffic over 30 years. The reduction in demand accounts for about 4% of mitigation. The remaining 1% of mitigation comes from a modal shift to HSR. The shift affects a relatively small market: 11% of domestic and intra-EU operations, or 5% of total passenger operations. With the assumed 20% conversion rate, HSR diverted about 1% of passenger RPK from aviation between 2030 and 2050 in total.

TECHNOLOGIES NEEDED

The results summarized above suggest that aviation emissions growth can be constrained via technology and that, for our most aggressive Breakthrough case, aviation can contribute to a 1.75°C climate future. Aggressive technology advancements will be needed to meet these goals. **Table 8** summarizes key advancements needed by scenario. These include the widespread adoption of SAFs, advancements in new aircraft efficiency through new engine and airframe technologies, the development of new technologies for ZEPs, and substantial reductions in the cost of DAC.

Table 8. Advancements needed by scenario

Measure	Metric	Scenario 1: Action	Scenario 2: Transformation	Scenario 3: Breakthrough
Sustainable aviation fuel	2050 supply	220 Mt	250 Mt	315 Mt
	Multiple of 2020 supply[a]	2,800	3,100	3,900
New aircraft	Example technologies[b]	Hybrid laminar flow (empennage) Increased span All composite aircraft Unitized construction Geared turbofan*	Natural laminar flow (wing) Adaptive compliant trailing edge High temperature composites for engine components Improved Geared Turbofan*	Hybrid laminar flow (wing) Active smart wing Adaptive and morphing structures 3D Preforms Open rotor engine*
	Change in average fuel burn compared to 2015 starting in 2035	-28%	-38%	-42%
Traffic efficiency	Technologies needed	Satellite navigation		Advanced air traffic management to support formation flying
Zero emission planes	Technologies needed	—	Liquid hydrogen combustion propulsion Lightweight cryogenic storage tanks Infrastructure for hydrogen production, delivery, storage, and refueling Electric charging infrastructure	Mature manufacturing lines to produce more aircraft Scaling up of hydrogen infrastructure worldwide Higher battery specific energy
	ZEP aircraft fleet share, 2050	—	10%	19%
Direct air capture	CO_2 captured	120 Mt	190 Mt	470 Mt
	Cost reduction relative to 2020[c]	-50%		

[a] 100 million L in 2020, per Mukhopadhaya & Rutherford (2022).
[b] Source: Kharina et al., (2016), for single aisle aircraft. Technologies are cumulative across scenarios except where asterisked.
[c] Source: IEA, 2022.

The Breakthrough case, in particular, envisions a substantial increase in primary energy use and renewable electricity relative to the Baseline. **Figure 11** highlights the total energy use by fuel type, including upstream power needed to generate hydrogen and capture carbon, compared to the fuel energy (black line) and 2019 renewable power production from 2020 to 2050 (dotted line, from IEA, [2021b]). As shown, the estimated electricity used to generate aviation fuels rises from zero in 2020 to 25 EJ in 2050, almost equaling global production of hydro, wind, solar, and geothermal power in 2019. While aviation fuel energy reaches 16 EJ in 2050, an additional 12.5 EJ of energy is needed to generate the hydrogen and carbon for synthetic aviation fuels after accounting for conversion losses.[7]

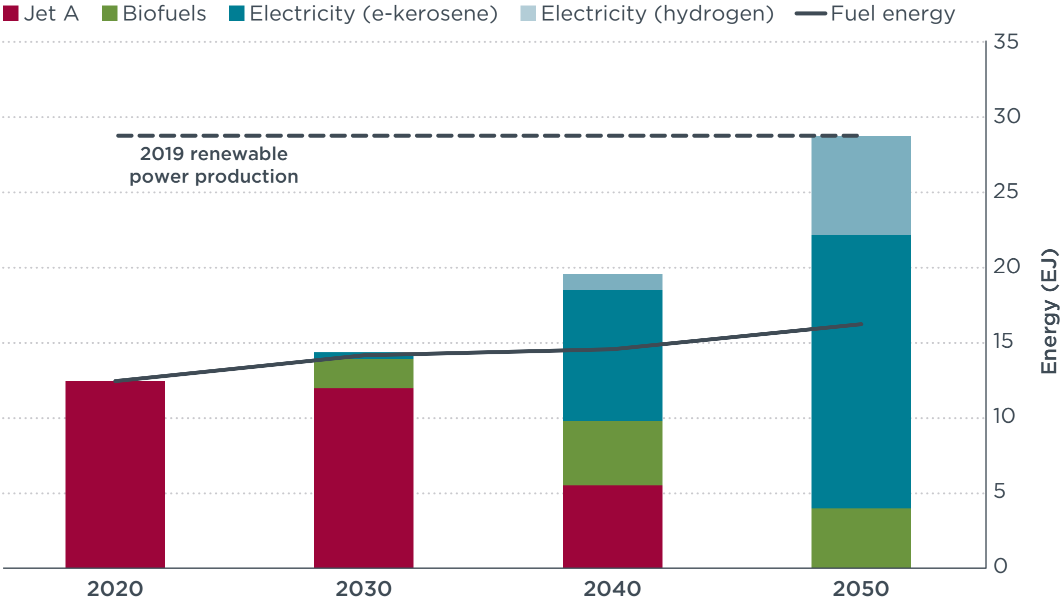


Figure 11. Fuel energy (line) and life-cycle energy (bar) by fuel type under the Breakthrough case vs. 2019 renewable power production, 2020 to 2050

COMPARISONS TO OTHER WORK

The results of our analysis can be compared to other organizations' roadmaps introduced above. Out-of-sector measures were not included in this analysis but would be needed to achieve a 1.5°C temperature target. Under the Breakthrough scenario, 70 Mt of CO_2 emissions would need to be mitigated to reach net-zero in 2050, or a further 3% reduction. This is half of the 6% to 8% reduction identified in Waypoint 2050. **Table 9** gives a high-level summary of the significant outputs of this analysis, and of Waypoint 2050. ICCT results summarized are on a WTW basis, while those for Waypoint 2050 and the ICAO LTAG (Table 10) are based on a modified TTW basis.[8]

The results of the Breakthrough Scenario and Scenario 1 in Waypoint 2050 have many similarities, including shares of emission reductions and alternative energy. When accounting for TTW emissions, but not those associated with upstream fuel production, the cumulative emissions for the 2020-2050 period were less than 1 Gt apart. This puts both analyses on similar global temperature change pathways.

One significant difference is found in annual emissions. Deeper in-sector emission reductions were modeled in the Breakthrough scenario, leading its TTW emissions to be less than half of the industry modeling (without offsets). This is due, in part, to

7 This calculation assumes 56%, 51%, and 46% energy efficiency ratios for liquid hydrogen, point source e-kerosene, and direct air capture e-kerosene, respectively. See Mukhopadhaya & Rutherford (2022). Upstream energy use for Jet A and biofuels is not estimated. Direct electricity use in commuter aircraft is negligible.

8 SAFs, which contain carbon and have a similar energy density to fossil jet fuel, have nearly identical TTW emissions to Jet-A. IATA and ICAO modeling uses a modified TTW approach which integrates the negative upstream emissions of SAFs but not the positive upsteam emissions of fossil jet fuel.

more aggressive assumptions around fuel efficiency, as indicated by the lower total energy consumption (16 EJ vs. 25 EJ) in the Breakthrough Scenario compared to Waypoint 2050's Scenario 1. This comparison shows that no singular pathway exists to decarbonize the aviation industry; different proportions in emission reductions from technology, operations, and fuels can achieve similar results.

Table 9. Comparison of Breakthrough Scenario to Waypoint 2050 Scenario 1

	This analysis: Breakthrough[a]	Waypoint 2050: Scenario 1[b]
2050 annual emissions	70 Mt	With offsets: 0 Mt Without offsets: 140 Mt
2050 energy use	16 EJ	25 EJ
Total reduction from Baseline, 2050 annual emissions	97%	With offsets: 100% Without offsets: 93%
2020-2050 cumulative emissions	21.5 Gt	With offsets: 19.6 Gt
Cumulative emissions temperature pathway	1.75°C	With offsets: 1.78°C (ICCT estimate)
Share of emission reductions, 2050	Technology: 18% Operations: 17% Fuels: 62% Demand change: 4%	Technology: 22% Operations: 10% Fuels: 61% Offsets: 7%
Zero-emission plane energy share, 2050	Hydrogen: 22% Electricity: 0.01%	Hydrogen: 20% Electricity: 2%

[a] WTW basis. [b] Modified TTW basis.

As mentioned previously, 11 Gt of cumulative CO_2 emissions would need to be mitigated beyond the Breakthrough scenario for the 1.5°C goal to be realized, assuming that aviation's share of the global carbon budget remains at 2.9%. Hypothetically, if society were to accept a near-doubling of aviation's share of the carbon budget—so, rising to 5.7%—further economic measures would not be necessary.

The graphics and discussion thus far cover global commercial aviation or a combination of international and domestic operations. ICAO's long-term goal would cover only international aviation; domestic operations would be covered by a country's Nationally Determined Contribution (NDC). **Table 10** compares this study and ICAO's LTAG Integrated Scenario (IS3) analysis (ICAO, 2022b). Our detailed findings for international operations, which typically account for 60% of aviation CO_2 (Graver et al., 2020), are included in Appendix B. Note that hydrogen use is included in the fuels share for the ICCT analysis, and the technology wedge in the ICAO analysis.

The table highlights the similarity in cumulative emissions emerging from the two analyses, but also the stark difference in emissions in 2050. Part of this can be explained by fuel mix, but differing assumptions about achievable efficiency improvements are even more critical. In ICAO's most ambitious scenario, hydrogen does not emerge as a significant fuel source (2% of energy share in 2050) until after mid-century. We model that it could account for up to 18% of international aviation fuel share in 2050. In addition, Jet A is phased out by 2040 in the ICAO analysis, while it remains in the system until 2049 in our Breakthrough scenario. Due to more conservative fuel efficiency assumptions, ICAO's IS3 demands 70% more fuel energy than our Breakthrough case.

Table 10. Comparison of Breakthrough Scenario to ICAO's IS3, international aviation

	This analysis: Breakthrough[a]	ICAO LTAG: IS3[b]
2050 annual emissions	42 Mt	203 Mt
2050 energy use	10 EJ	17 EJ
Total reduction from Baseline, 2050 annual emissions	97%	87%
2021-2050 cumulative emissions	13.6 Gt	12 Gt
Cumulative emissions temperature pathway	1.75°C	1.75°C (ICCT estimate)
Share of emission reductions, 2050	Technology: 15% Operations: 17% Fuels: 65% Demand Change: 3%	Technology: 21% Operations: 11% SAFs: 55%

[a] WTW basis. [b] Modified TTW basis.

As in the other roadmaps and analyses discussed, IS3 of the ICAO assessment is on the 1.75°C temperature target trajectory. Out-of-sector measures, which were not considered in the ICAO analysis, would be needed to reduce emissions further to reach net-zero emissions in 2050 and a 1.5°C temperature goal. ICAO's modeling fails to achieve its current goal of 2% annual fuel efficiency improvement. In the most ambitious case (in which hydrogen is included), per annum energy efficiency improvements are 1.55 to 1.67% through 2050 (ICAO, 2022b). In contrast, our Breakthrough scenario achieves a 2% per annum energy efficiency improvement through 2050.

CONCLUSIONS AND POLICY IMPLICATIONS

One thing is certain: aligning aviation with the below-2°C aspiration of the Paris Agreement is possible but requires significant ambition and investment. Many of the roadmaps explored in this report vary in the level of fuel efficiency improvements assumed, yet offer similar assessments of total emission reductions. This suggests that many pathways to decarbonize the aviation industry are possible: different proportions in emission reductions from technology, operations, and fuels could achieve similar results.

In the three roadmaps discussed in depth (ICCT, ATAG, and ICAO), the most ambitious scenarios are consistent with a 1.75°C future in which aviation doesn't increase its share of a global carbon budget. But aggressive government policies will be needed to support this temperature target. The three decarbonization levers that deserve policymaker attention because they would provide the most significant emission reductions, are SAFs, fuel efficiency, and zero emission planes. Expanding the use of proven efficiency technologies is critical to reducing cumulative emissions from aviation, even if SAFs and ZEPs are what ultimately enable decarbonization. Ensuring that traffic doesn't grow faster than the upper bound explored in this study (3.7% p.a. growth for passengers, 4.2% for cargo) may also be needed.

CO_2 emissions from aircraft need to peak by 2030 at the latest, and as soon as 2025, to align aviation with the Paris Agreement. The Action scenario peaks emissions in 2030 en route to exhausting its share of a 2°C carbon budget by 2050, while the Breakthrough scenario achieves a 1.75°C future after peaking emissions in 2025. Moreover, all scenarios investigated exhaust aviation's proportional share of a 1.5°C carbon budget in 2030. This suggests that near-term, interim targets will be needed to align aviation with the Paris Agreement.

Cumulative targets, rather than an absolute emissions goal for a given year, would provide greater certainty that aviation contributes fairly to the Paris Agreement. Only under the Breakthrough scenario, with maximum deployment of low-carbon aircraft and fuels, does cumulative CO_2 stabilize by reaching near-zero levels by 2050. For other scenarios, airlines continue to emit substantial CO_2 after 2050. Furthermore, aviation could still exhaust its share of a Paris-compatible carbon budget even with deep cuts in CO_2 in 2050 if the development of needed technologies is delayed.

Significant investments, driven and rewarded by public policies, will be needed to put aviation on a path to contribute to the Paris Agreement. However, early action can deliver more considerable reductions at a lower cost in 2050 by unlocking cost reductions for critical technologies. Many proverbial carrot-and-stick approaches are available to pull the three levers mentioned above. For SAFs, blending mandates under Europe's ReFuelEU Aviation proposal (EC, 2021) and California's Low Carbon Fuel Standard could help drive early adoption. Fuel efficiency improvements could be realized by allowing optimized operation of aircraft through air traffic control system enhancements and reviewing and revising the ICAO aircraft CO_2 standards. For ZEPs, funding will be needed to research and develop the aircraft and to develop infrastructure to supply hydrogen and/or electricity (McKinsey, 2020). A short-term priority will be to create a level playing field between SAFs and ZEPs by incorporating the latter into mandates and incentives.

To get to 1.5°C, out-of-sector action and/or significant direct curbs to traffic growth would be needed. While offsets are included in many roadmaps to get to net-zero, serious questions have been raised about offset integrity (Schneider et al., 2019). Existing policies like CORSIA have been periodically weakened over time (Economist, 2020). Economic measures and absolute reductions in traffic would cost airlines, so every technological effort to reduce in-sector emissions should be explored and implemented first.

This report has focused on CO_2 emissions from aviation only. Additional work is recommended to integrate the climate impact of other emissions from aviation, notably water vapor and particulate emissions that contribute to persistent contrail formation. Lee, et al. (2021) conclude that these non-CO_2 effects could be twice as large as CO_2 alone, with some evidence that action to mitigate persistent contrails could reduce warming at minimal cost to industry (Green, 2021). A comprehensive analysis by Klöwer et al. (2021) finds that the short-term effects of non-CO_2 radiative forcers provide an opportunity to halt aviation's contribution to anthropogenic climate change sooner than might be suggested via CO_2-only roadmaps.

Other future work needed includes analyzing the impacts of the Breakthrough scenario at regional and national levels. Some adjustments would be needed to specific modeling inputs; they are global in nature and may not be appropriate at a more geographically granular level (e.g., in the United States or European Union).

REFERENCES

A4A. (2021a) *Major U.S. Airlines Commit to Net-Zero Carbon Emissions by 2050*. Retrieved from Airlines for America https://www.airlines.org/news/major-u-s-airlines-commit-to-net-zero-carbon-emissions-by-2050/

A4A. (2021b) *U.S. Airlines Announce 3-Billion-Gallon Sustainable Aviation Fuel Production Goal*. Retrieved from Airlines for America https://www.airlines.org/news/u-s-airlines-announce-3-billion-gallon-sustainable-aviation-fuel-production-goal/

Airbus (2022) *fello'fly*. Retrieved from Airbus https://www.airbus.com/en/innovation/disruptive-concepts/biomimicry/fellofly

ATAG. (2021a) *Commitment to Fly Net Zero*. Retrieved from the Air Transport Action Group https://aviationbenefits.org/flynetzero

ATAG. (2021b) *Tracking Aviation Efficiency (Fact Sheet #3 / February 2021)*. Retrieved from the Air Transport Action Group https://aviationbenefits.org/media/167475/fact-sheet_3_tracking-aviation-efficiency-v2.pdf

ATAG. (2021c) *Waypoint 2050*. Retrieved from the Air Transport Action Group https://aviationbenefits.org/environmental-efficiency/climate-action/waypoint-2050/

Avogadro, N., Cattaneo, M., Paleari, S., & Redondi, R. (2021) "Replacing short-medium haul intra-European flights with high-speed rail: Impact on CO_2 emissions and regional accessibility," *Transport Policy*. Vol. 114, pp. 25-39. https://doi.org/10.1016/j.tranpol.2021.08.014

Boeing. (2005) *Current Market Outlook 2005*

Boeing. (2009) *Commercial Market Outlook 2009-2028*

Boeing. (2021) *Commercial Market Outlook 2021-2040*. Retrieved from https://boeing.com/commercial/market/commercial-market-outlook/

Bousso, R. (2021) *Oil giant Shell sets sights on sustainable aviation fuel take-off*. Retrieved from Reuters https://www.reuters.com/business/sustainable-business/oil-giant-shell-sets-sights-sustainable-aviation-fuel-take-off-2021-09-19/

CARB. (2022) *Low Carbon Fuel Standard*. Retrieved from the California Air Resources Board https://ww2.arb.ca.gov/our-work/programs/low-carbon-fuel-standard

CAEP. (2022) *Supersonic Exploratory Study Report: Final Report*. International Civil Aviation Organization Committee on Aviation Environmental Protection. CAEP/12-WP/39.

DLR. (2021) *DEPA 2050: Development Pathways for Aviation up to 2050*. Retrieved from the German Aerospace Center https://elib.dlr.de/142185/1/DEPA2050_StudyReport.pdf

EASA. (2022) *EASA publishes new fuel/energy rules with positive environmental impact*. Retrieved from the European Union Aviation Safety Agency https://www.easa.europa.eu/newsroom-and-events/press-releases/easa-publishes-new-fuelenergy-rules-positive-environmental

EC. (2021) *Proposal for a regulation of the European Parliament and of the Council on ensuring a level playing field for sustainable air transport*. Retrieved from the European Commission https://ec.europa.eu/info/sites/default/files/refueleu_aviation_-_sustainable_aviation_fuels.pdf

Economist. (2020). Airlines blame covid-19 for rowing back climate commitments. Retrieved from The Economist https://www.economist.com/business/2020/07/04/airlines-blame-covid-19-for-rowing-back-climate-commitments

EIA. (2020) Annual energy outlook. Retrieved from the Energy Information Agency https://www.eia.gov/ analysis/projection-data.php#annualproj

Elliott, D. (2016) *Aviation fuel efficiency technology assessment (AFETA)*. Tecolote, Research Inc. Retrieved from the International Council on Clean Transportation https://theicct.org/publications/aviation-fuel-efficiency-technology-assessment-afeta

FAA. (2021). United States 2021 Aviation Climate Action Plan. Retrieved from the United States Federal Aviation Administration https://www.faa.gov/sites/faa.gov/files/2021-11/Aviation_Climate_Action_Plan.pdf

Graver, B. (2022a) *Airline fuel efficiency: 'If you can't measure it, you can't improve it*.' Retrieved from the International Council on Clean Transportation https://theicct.org/aviation-fuel-efficiency-jan22/

Graver, B. (2022b) *Polishing my crystal ball: airline traffic in 2050*. Retrieved from the International Council on Clean Transportation https://theicct.org/global-aviation-airline-traffic-jan22

Graver, B., Rutherford, D., & Zheng, S. (2020) *CO_2 emissions from commercial aviation, 2013, 2018, and 2019*. Retrieved from the International Council on Clean Transportation https://theicct.org/publications/co2-emissions-commercial-aviation-2020

Green, J. (2021) *Easy does it for greener skies: summary of 'Mitigating the climate impact of non-CO_2 – Aviation's low-hanging fruit*.' Retrieved from the Royal Aeronautical Society https://www.aerosociety.com/news/easy-does-it-for-greener-skies/

IATA. (2021) *Airline Industry Economic Performance – October 2021 – Report*. Retrieved from the International Air Transport Association https://www.iata.org/en/iata-repository/publications/economic-reports/airline-industry-economic-performance---october-2021---report/

ICAO. (2019) *Resolution A40-18: Consolidated statement of continuing ICAO policies and practices related to environmental protection – Climate change*. Retrieved from International Civil Aviation Organization https://www.icao.int/environmental-protection/Documents/Assembly/Resolution_A40-18_Climate_Change.pdf

ICAO. (2021a) *Post-COVID-19 forecasts scenarios*. Retrieved from International Civil Aviation Organization https://icao.int/sustainability/Pages/Post-Covid-Forecasts-Scenarios.aspx

ICAO. (2021b) *CORSIA Default Life Cycle Emissions Values for CORSIA Eligible Fuels*. Retrieved from the International Civil Aviation Organization https://www.icao.int/environmental-protection/CORSIA/Documents/ICAO%20document%2006%20-%20Default%20Life%20Cycle%20Emissions%20-%20March%202021.pdf

ICAO. (2022a) *Aviation green transition progresses through ICAO CAEP*. Retrieved from the International Civil Aviation Organization https://www.icao.int/Newsroom/Pages/Aviation-green-transition-progresses-through-ICAO-CAEP.aspx

ICAO. (2022b) *Report on the Feasibility of a Long-Term Aspirational Goal (LTAG) for International Civil Aviation CO_2 Emission Reductions*. Retrieved from the International Civil Aviation Organization https://www.icao.int/environmental-protection/LTAG/Pages/LTAGreport.aspx

ICCT. (2020) *Vision 2050: A strategy to decarbonize the global transport sector by mid-century*. Retrieved from the International Council on Clean Transportation https://theicct.org/publications/vision2050

ICF. (2021) *Fueling Net Zero: How the aviation industry can deploy sufficient sustainable aviation fuel to meet climate ambitions*. Retrieved from the Air Transport Action Group https://aviationbenefits.org/media/167495/fueling-net-zero_september-2021.pdf

IEA. (2020) *Energy Technology Perspectives 2020*. Retrieved from the International Energy Agency https://iea.org/reports/energy-technology-perspectives-2020

IEA. (2021a) *Net Zero by 2050*. Retrieved from the International Energy Agency https://iea.org/reports/net-zero-by-2050

IEA. (2021b) *Total primary energy supply by fuel, 1971 and 2019*. Retrieved from the International Energy Agency https://www.iea.org/data-and-statistics/charts/total-primary-energy-supply-by-fuel-1971-and-2019

IEA. (2022) Direct Air Capture: A key technology for net zero. Retrieved from the International Energy Agency https://www.iea.org/reports/direct-air-capture-3

InterVISTAS Consulting Inc. (2007) *Estimating Air Travel Demand Elasticities: Final Report*. Retrieved from the International Air Transport Association https://www.iata.org/en/iata-repository/publications/economic-reports/estimating-air-travel-demand-elasticities---by-intervistas/

IPCC. (2021) *Climate Change 2021: The Physical Science Basis*. Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Retrieved from the Intergovernmental Panel on Climate Change https://www.ipcc.ch/report/ar6/wg1/

Jackson, R.B., Friedlingstein, P., Le Quere, C., Abernethy, S., Andrew, R.M., Canadell, J.G., Ciais, P., Davis, S.J., Deng, Z., Liu, Z., & Peters, G.P. (2021) "Global fossil carbon emissions rebound near pre-COVID-19 levels," *Environmental Research Letters* (pre-print), https://arxiv.org/pdf/2111.02222.pdf

Kent, T.E. & Richards, A.G. (2021) "Potential of Formation Flight for Commercial Aviation: Three Case Studies," *Journal of Aircraft*. Vol. 58, No. 2, pp. 320-333. https://doi.org/10.2514/a.C035954

Kharina, A., Rutherford, D., & Zeinali, M. (2016) *Cost Assessment of Near- and Mid-Term Technologies to Improve New Aircraft Fuel Efficiency.* Retrieved from the International Council on Clean Transportation https://theicct.org/publication/cost-assessment-of-near-and-mid-term-technologies-to-improve-new-aircraft-fuel-efficiency/

Kharina, A., McDonnell, T., & Rutherford, D. (2018) *Environmental Performance of Emerging Supersonic Transport Aircraft.* Retrieved from the International Council on Clean Transportation https://theicct.org/publication/environmental-performance-of-emerging-supersonic-transport-aircraft/

Klöwer, M., Allen, M., Lee, D., Proud, S., Gallagher, L., & Skowron, A. (2021) "Quantifying aviation's contribution to global warming," *Environ. Res. Lett.* **16** (2021) 104027. https://iopscience.iop.org/article/10.1088/1748-9326/ac286e/pdf

Kristiana, T., Baldino, C., & Searle, S. (2022) *An Estimate of Current Collection and Potential Collection of Used Cooking Oil from Major Asian Exporting Countries.* Retrieved from the International Council on Clean Transportation https://theicct.org/publication/asia-fuels-waste-oil-estimates-feb22/

Lee, D.S., Fahey, D.W., Skowron, A., Allen, M.R., Burkhardt, U., Chen, Q., Doherty, S.J., Freeman, S., Forster, P.M., Fuglestvedt, J., Gettelman, A., De León, R.R., Lim, L.L., Lund, M.T., Millar, R.J., Owen, B., Penner, J.E., Pitari, G., Prather, M.J., Sausen, R., & Wilcox, L.J. (2021) "The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018", *Atmospheric Environment*, vol. 244, https://doi.org/10.1016/j.atmosenv.2020.117834

Malins, C. (2017). *Waste not Want Not: Understanding the Greenhouse Gas Implications of Diverting Waste and Residual Materials to Biofuel Production.* Retrieved from the International Council on Clean Transportation https://theicct.org/publication/waste-not-want-not-understanding-the-greenhouse-gas-implications-of-diverting-waste-and-residual-materials-to-biofuel-production/

McKinsey. (2020). *Hydrogen-powered aviation: A fact-based study of hydrogen technology, economics, and climate impact by 2050*. Retrieved from McKinsey & Company https://www.fch.europa.eu/sites/default/files/FCH%20Docs/20200507_Hydrogen%20Powered%20Aviation%20report_FINAL%20web%20%28ID%208706035%29.pdf

Mukhopadhaya, J. & Graver, B. (2022) *Assessing the Climate Benefits of Electric Aircraft*. Retrieved from the International Council on Clean Transportation https://theicct.org/publication/climate-benefits-electric-aircraft-jul22/

Mukhopadhaya, J. & Rutherford, D. (2022) *Performance analysis of evolutionary hydrogen-powered aircraft*. Retrieved from the International Council on Clean Transportation https://theicct.org/publication/aviation-global-evo-hydrogen-aircraft-jan22/

Pavlenko, N., Searle, S., & Christensen, A. (2019). *The Cost of Supporting Alternative Jet Fuels in the European Union*. Retrieved from the International Council on Clean Transportation https://theicct.org/publication/the-cost-of-supporting-alternative-jet-fuels-in-the-european-union/

Rutherford, D. & Comer, B. (2018). *The International Maritime Organization's Initial Greenhouse Gas Strategy.** Retrieved from the International Council on Clean Transportation https://theicct.org/publication/the-international-maritime-organizations-initial-greenhouse-gas-strategy/

Rutherford, D. (2019). *Should you be ashamed of flying? Probably Not.** Retrieved from the International Council on Clean Transportation https://theicct.org/should-you-be-ashamed-of-flying-probably-not

Rutherford, D., Eastham, S., Sanz-Morère, I., Kim J., & Speth, R. (2022) *Environmental Limits on Supersonic Aircraft in 2035*. Retrieved from the International Council on Clean Transportation https://theicct.org/publication/aviation-global-supersonic-safs-feb22/

Schneider, L., Michaelowa, A., Broekhoff, D., Espelage, A., Siemons, A. (2019) *Lessons learned from the first round of applications by carbon-offsetting programs for eligibility under CORSIA.* Retrieved from the Öko-Institut https://www.oeko.de/fileadmin/oekodoc/Lessons-learned-from-CORSIA-applications.pdf

Speth, R. L., Eastham, S. D., Fritz, T. M., Sanz-Morere, I., Agarwal, A., Prashanth, P., Allroggen, F., & Barrett, S. R. H. (2021) *Global Environmental Impact of Supersonic Cruise Aircraft in the Stratosphere (E-19920)*. Retrieved from the National Aeronautical and Space Administration https://ntrs.nasa.gov/citations/20205009400

Transport & Environment. (2020) *Maximising air to rail journeys: Reducing intra-EU aviation emissions through modal shift to rail: limits and opportunities*. Retrieved from Transport & Environment https://www.transportenvironment.org/wp-content/uploads/2021/07/2020_07_Air2Rail_Briefing_paper.pdf

UK. (2021) *COP 26 declaration: International Aviation Climate Ambition Coalition (Updated 21 December 2021)*. Retrieved from the United Kingdom Department for Transport https://www.gov.uk/government/publications/cop-26-declaration-international-aviation-climate-ambition-coalition/cop-26-declaration-international-aviation-climate-ambition-coalition

UK. (2022) *Jet zero: our strategy for net zero aviation (Updated 25 February 2022)*. Retrieved from the United Kingdom Department of Transportation https://www.gov.uk/government/consultations/achieving-net-zero-aviation-by-2050

UN. (2021) *Secretary-General: 2021 a 'crucial year' for climate change*. Retrieved from United Nations https://www.un.org/en/delegate/secretary-general-2021-%E2%80%98crucial-year%E2%80%99-climate-change

van der Sman, E., Peerlings, B., Kos, J., Lieshout, R., & Boonekamp, T. (2021) *Destination 2050: A route to net zero European aviation*. Retrieved from Destination 2050 https://destination2050.eu/wp-content/uploads/2021/03/Destination2050_Report.pdf

Zhang, Q., Yang, H., & Wang, Q. (2017) "Impact of high-speed rail on China's Big Three Airlines," *Transportation Research Part A: Policy and Practice*. Vol. 98, pp. 77-85. https://doi.org/10.1016/j.tra.2017.02.005

Zheng, S. (2022) *The Bullet Train to Lower-Carbon Travel*. Retrieved from the International Council on Clean Transportation https://theicct.org/aviation-rail-shift-lower-carbon-mar22/

Zheng, S. & Rutherford, D. (2020) *Fuel Burn of New Commercial Jet Aircraft: 1960 to 2019.* Retrieved from the International Council on Clean Transportation https://theicct.org/publication/fuel-burn-of-new-commercial-jet-aircraft-1960-to-2019/

Zhou, Y., Searle, S., & Pavlenko, N. (2022). *Current and Future Cost Estimates of E-Kerosene in the United States and Europe.* Retrieved from the International Council on Clean Transportation https://theicct.org/publication/fuels-us-eu-cost-ekerosene-mar22/

Zhu, P., Lin, Y., & Guo, Y. (2020) "How Much Does High-speed Rail Substitute for Air Travel? Implications for Transport, Environmental and Energy Policies," *Research Square.* https://doi.org/10.21203/rs.3.rs-106949/v1

APPENDIX A: ATTRIBUTION OF EMISSION REDUCTIONS TO MEASURES

Emission reductions are attributed to different measures by isolating the effect of each measure and comparing it with the baseline scenario. For example, the impact of the demand change expresses itself in a reduction in passenger RPKs. The emission reduction due to the demand change measure for scenario *s* then becomes:

$$\sum_{Y=2019}^{2050} (RPK_{Y,b} - RPK_{Y,s}) \times CI_{Y,b}, \qquad \textbf{(A1)}$$

where *Y* is the year, *b* represents the baseline case, and *CI* is the average carbon intensity of passenger aviation expressed as g CO_2e / RPK.

Similarly, for the emission reduction due to technical efficiency (η) improvements of aircraft in scenario *s* becomes:

$$\sum_{Y=2019}^{2050} (\eta_{Y,b} - \eta_{Y,s}) \times RPK_{Y,b} \times CI_{Y,b}. \qquad \textbf{(A2)}$$

Similar calculations are carried out for the contributions of operational efficiency improvements, introduction of zero-emission planes, and usage of SAF.

However, these calculations are not zero-residual. The isolation of these individual contributions and their calculation with respect to the baseline case results in the sum of the individual contributions being larger than the total emission reductions of the integrated scenario. For example, in Equation (A2) the change in technical efficiency is multiplied by the baseline RPK and CI, whereas in the integrated scenario modelling the technical efficiency would be multiplied by that scenario's RPK and CI which are likely lower than those in the baseline case. Therefore, adding up the individual contribution calculations results in a higher emission reduction than results from the integrated scenario reduction.

To counter this, the individual contributions are scaled proportionally so that the individual calculations add up to the integrated scenario reduction. Equation (A3) shows this scaling. The scaled mitigation due to demand management M^*_{demand} requires the original contribution calculation, M_{demand}, to be divided by the sum of the individual contributions, $\Sigma_i M_i$, and multiplied by the total CO_2 mitigation for that scenario, M_s. This gives a proportionally accurate attribution of the emission reductions to the individual measures.

$$M^*_{demand} = \frac{M_{demand}}{\Sigma_i M_i} \times M_s \qquad \textbf{(A3)}$$

APPENDIX B: CO_2 EMISSIONS FROM INTERNATIONAL OPERATIONS

While the focus of this analysis is global commercial aviation, special attention is needed for the international segment. In 2019, international operations accounted for approximately 61% of passenger air transport CO_2 emissions (Graver et al., 2020) and falls outside of most country targets under the Paris Agreement.

As noted in the report, the International Civil Aviation Organization (ICAO) conducted a technical assessment on the feasibility of developing a long-term goal for international aviation (ICAO, 2022). The emissions are given on a tank-to-wake basis. Under its most aggressive scenario, the ICAO analysis predicts that 55% of CO_2 emissions could be reduced due to new and cleaner fuels, a further 21% from new aircraft technology, and an additional 11% due to operational improvements. The residual emissions (13% of total) would need to be addressed via out-of-sector measures to achieve net-zero aviation. In our Breakthrough Scenario, 65% of CO_2 emissions could be reduced from fuels including hydrogen, 15% from new aircraft fuel efficiency, and 17% from operational improvements.

Figures B-1 and B-2 depict cumulative and annual emissions for international operations under various modeling scenarios and traffic forecasts. These graphics are similar to the ones for global operations (**Figures 4 and 6**), but are scaled down. No scenario is compatible with a 1.5°C temperature target, but Breakthrough is consistent with 1.75°C.

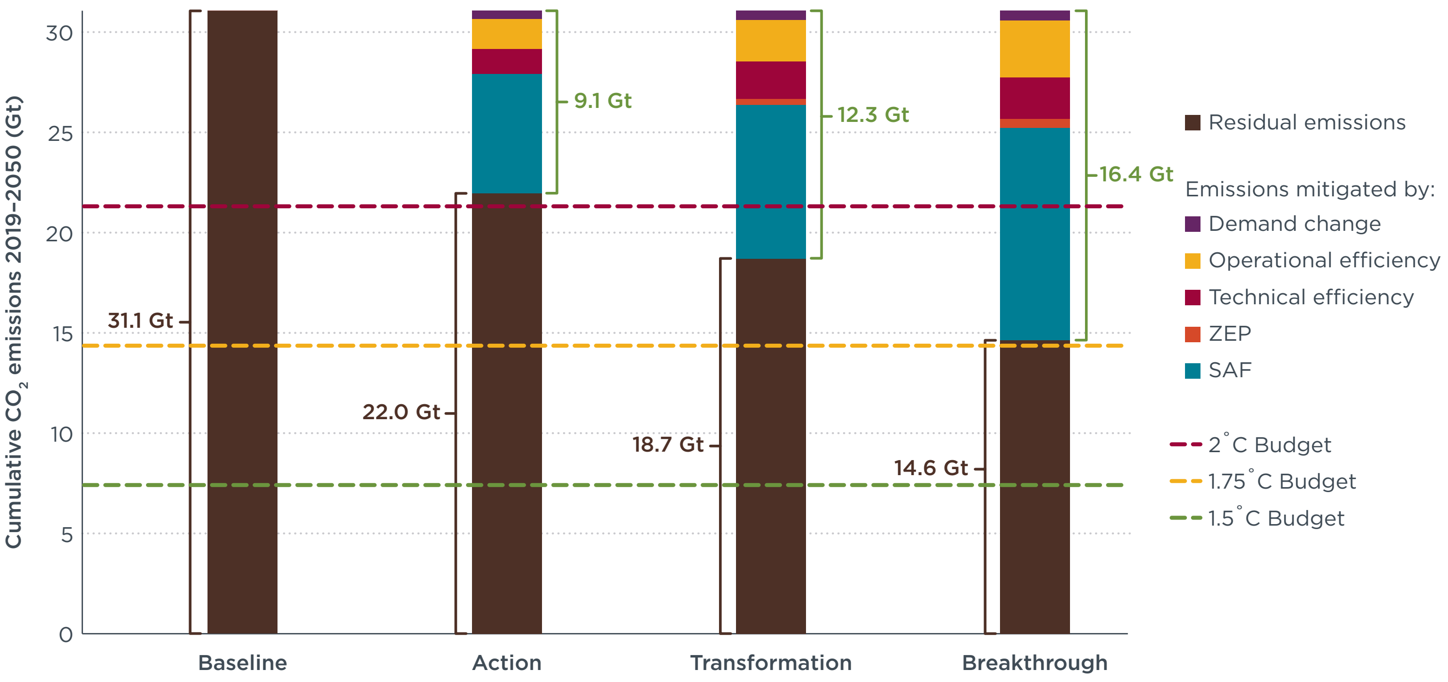
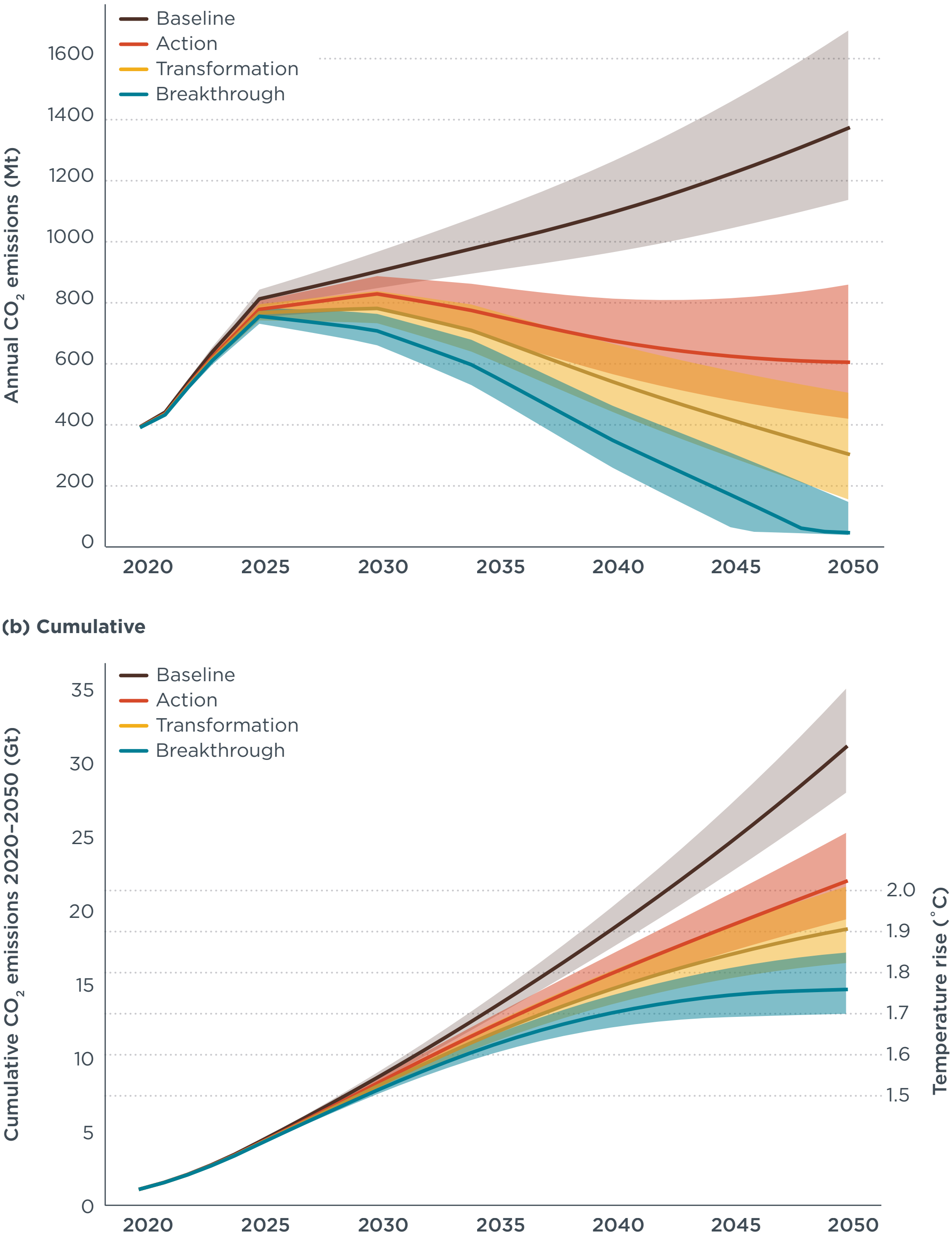


Figure B-1. Cumulative international aviation CO_2 emissions by scenario and measure, 2019-2050

(a) Annual



The solid line depicts the central traffic forecast; the shaded area depicts the range between the low and high forecasts.

Figure B-2. International aviation CO_2 emissions under various traffic forecasts, 2020-2050

www.theicct.org

communications@theicct.org

twitter @theicct

THE INTERNATIONAL COUNCIL ON CLEAN TRANSPORTATION

BEIJING | BERLIN | SAN FRANCISCO | SÃO PAULO | WASHINGTON