WORKING PAPER

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Lifetime emissions from aircraft under a net-zero carbon budget

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SUMMARY

The commercial aviation sector is projected to grow rapidly in the coming decades, with an increase in traffic leading to the doubling of the current fleet size and usage of aircraft. Nonetheless, in 2022, airlines and aircraft manufacturers committed to an international goal of achieving net-zero carbon dioxide (CO_2) emissions by 2050. This goal was codified by the International Civil Aviation Organization (ICAO) at its 41st Assembly.

This study assesses whether current manufacturer delivery projections are consistent with this net-zero target. A net-zero carbon budget of 18.4 billion tonnes was defined for the sector, calculated as an average from four industry decarbonization roadmaps. In this paper, we model lifetime CO_2 emissions from the 2023 global fleet and new aircraft deliveries through 2042 under three decarbonization scenarios, a business-as-usual (Baseline) scenario and scenarios that include the aggressive implementation of two key mitigation measures—sustainable aviation fuels (SAFs; Optimistic SAF) and the use of SAFs and fuel efficiency improvements (Optimistic SAF + Fuel Efficiency). We also consider a sensitivity analysis of more (1.5 °C) and less ambitious (2 °C) climate targets to contextualize the net-zero budget in terms of warming impact.

We find that the 2023 in-service fleet is projected to emit about 9 billion tonnes of CO_2 before being retired, or almost half of a net-zero carbon budget. Lifetime emissions from new aircraft delivered from 2024 to 2042 are projected to exhaust the balance of a net-zero carbon budget between 2032 (Baseline) and 2037 (Optimistic SAF + Fuel Efficiency). This indicates that for airlines to achieve their climate goals, all new aircraft delivered by the mid-2030s will need to emit zero net CO_2 emissions throughout their operational lifetimes. We also estimate there will be a market for at least 10,000 new aircraft powered by hydrogen, electricity, or 100% SAF through 2042.

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BACKGROUND

As commercial aviation confronts the challenge of balancing sectoral growth while progressing toward the International Civil Aviation Organization's (ICAO) 2050 net-zero CO_2 target, measures such as sustainable aviation fuels (SAFs), aircraft efficiency improvements, and zero-emission planes (ZEPs) will be necessary to rapidly reduce emissions (Graver et al., 2022). According to the consensus of net-zero roadmaps (International Air Transport Association, 2024a), SAFs are expected to provide more than half (53%) of all CO_2 mitigation under a net-zero pathway, followed by fuel efficiency at about 30%. Expectations of mitigation from ZEPs powered by hydrogen and electricity vary; in Graver et al. (2022), hydrogen-powered aircraft are responsible for 21% of total aviation energy use in 2050 but only about 5% of cumulative CO_2 mitigation due to the gradual introduction of new aircraft types into the global fleet.

To date, in order to address the climate crisis, manufacturers have been bullish on SAFs (Boeing, 2023c; Airbus, 2024), but have avoided concrete commitments to developing new, significantly more efficient aircraft types or ZEPs. While manufacturers tout the lower fuel burn of new aircraft, which is typically 15% lower than the generation they replace, the steady growth of the global fleet and its emissions indicates that many new aircraft support new traffic, instead of replacing older aircraft (Graver & Rutherford, 2021).[1] Central to all of these measures are the aircraft themselves, with the cycle of production, deliveries, usage, and retirement dictating much of the industry's trajectory toward net-zero emissions.

Each year, aircraft manufacturers release sustainability reports disclosing the emissions associated with their operations. Emissions associated with the complete life cycle of delivered aircraft are captured within Scope 1, 2, and 3 emissions disclosure by manufacturers. Scope 1 emissions are direct emissions from controlled or owned sources, such as manufacturing plants (U.S. Environmental Protection Agency, 2020a). Scope 2 emissions are indirect emissions released from the production of purchased electricity or power used for their operations (U.S. Environmental Protection Agency, 2020b). Scope 3 emissions, or "value-chain emissions," are those released during the lifetime of a product's use by its customers.

In March 2024, the U.S. Securities and Exchange Commission finalized its ruling on corporate emissions disclosure. This ruling requires larger corporations to disclose Scope 1 and Scope 2 emissions, but Scope 3 emissions are not required to be reported at this time (U.S. Securities and Exchange Commission, 2024). Meanwhile, the European Union (EU) has released new rules, called the Corporate Sustainability Reporting Directive, requiring listed EU corporations, as well as foreign entities generating a large amount of revenue in the EU, to report Scope 1, 2, and 3 emissions across their entire supply chain (Directive 2022/24/64). The state of California recently introduced Scope 3 emissions disclosure requirements like those in the EU (Climate Corporate Data Accountability Act, 2023).

Scope 3 emissions account for more than 90% of an aircraft's lifetime emissions (Airbus, 2022). Corporate reporting on these emissions allows companies and their investors to measure progress toward climate goals, identify potential risks, and build climate resilience. Timely action to reduce Scope 3 emissions from aircraft is key to achieving the climate goals set by ICAO and various decarbonization pathways.

1 For example, Graver and Rutherford (2021) found that low-cost carriers, which purchase large numbers of new aircraft, were responsible for almost 90% of aviation CO_2 growth in the United States from 2005 to 2019. Emissions growth from low-cost carriers exceeded that of network carriers because traffic, as measured in revenue passenger kilometers, increased much faster (+119%) than fuel efficiency improved (+34%) compared to legacy carriers (+22% and +20%, respectively). This phenomenon, known as Jevon's Paradox, refers to the scenario where efficiency gains lead to increases, not decreases, in resource use due to falling costs.

The EU has adopted a classification framework (EU Taxonomy) to define whether economic activities are environmentally sustainable and guide investments in clean technology. In 2023, criteria for "green investments" in aircraft manufacturing, aircraft leasing, and commercial passenger air transport were added. For a delivered aircraft to be considered a taxonomy-compliant investment, it must meet fuel efficiency improvement thresholds that are based on ICAO's CO_2 standard and be shown not to increase the global fleet size. Starting in 2028, new aircraft must be compatible with 100% SAF use in order to be compliant with the taxonomy requirements; for airlines, a SAF use condition is added starting in 2030 (European Commission, 2023). These rules have been legally challenged by nongovernmental organizations, which argue they fail to adequately inform investors of the climate impact of aviation (Opportunity Green, 2024).

Aircraft manufacturers have set corporate goals to support these decarbonization pathways. Some, including Airbus, Boeing, and Embraer, have begun to disclose Scope 3 emissions from their annual deliveries. Airbus has a short-term goal to reduce Scope 3 greenhouse gas (GHG) emissions by 46% by 2035 using mitigation strategies like SAF and increased fuel efficiency (Airbus, 2023b). Boeing and Embraer have both committed to supporting the aviation sector's net-zero 2050 target but have not yet set Scope 3 emissions targets. Airbus, Boeing, and Embraer have all set goals to produce aircraft with 100% SAF capability by 2030, with aircraft now in the testing phase (Boeing, 2023b; Airbus, 2023c; Embraer, 2021).

In 2023, there were an estimated 23,689 in-service commercial passenger and freighter aircraft at varying stages of their lifetimes (International Bureau of Aviation, 2024). Each year, this fleet sees retirement of active aircraft at the end of their lifetimes, deliveries for fleet renewal, and additional deliveries to serve traffic growth. Over the next 20 years, manufacturers expect to deliver more than 40,000 new aircraft to support fleet renewal and traffic growth (Insinna, 2023).

Given these aggressive delivery targets and the long operational lifetimes of aircraft, it is key to consider the lifetime emissions from the existing and future fleet when assessing the compatibility of the industry's trajectory with net-zero pathways (Airbus, 2023d). SAFs are understood to be the most important way to reduce aircraft emissions, making up more than 50% of most decarbonization trajectories (Aerospace Technology Institute & Airports Council International, 2022). However, aircraft today cannot use 100% SAFs due to safety and engine compatibility issues and are currently only certified to use SAF blends of up to 50%. As engine and airframe manufacturers continue the testing and production of new aircraft, it is essential for new deliveries to be compatible with alternative fuels, be they 100% SAFs, hydrogen, or electricity, to make meaningful progress toward lowering emissions.

In this paper, we project committed emissions from the existing (2023) fleet and lifetime emissions from new (2024+) aircraft deliveries from Boeing, Airbus, and Embraer to evaluate how original equipment manufacturers (OEMs) can contribute to the net-zero goal. First, we present our modeling framework and assumptions for various mitigation scenarios on opposite ends of the ambition scale. We then present our findings, highlighting when a net-zero carbon budget will be exhausted by new deliveries under each scenario. We also explore the allowable delivery volumes enabled by these technology pathways and the volumes of carbon dioxide removal (CDR) needed for residual emissions. We close with recommendations for OEMs and ideas for future work.

METHODOLOGY

In this analysis, we project the fleet evolution and lifetime emissions of both the in-service fleet and deliveries of conventional aircraft from 2024 to 2042, as derived from manufacturer forecasts. We define conventional aircraft as those that operate on fossil jet fuel or SAF blends (<100% SAF). Each year, Boeing, Airbus, and Embraer release market projections which detail deliveries, demand growth, and fleet dynamics over the coming decades—the Boeing Commercial Market Outlook (CMO), Airbus Global Market Forecast (GMF), and Embraer Market Outlook, respectively (Boeing, 2023a; Airbus, 2023a; Embraer, 2023). The most recent forecasts project expected deliveries by manufacturers through 2042, and those were used in this study to estimate deliveries. Aircraft retirements were estimated using survival and activity curves to age existing fleet and replace aircraft as they go out of service. The aircraft delivered for traffic growth were estimated to be the additional number of aircraft needed to grow the global fleet by 3.2% annually starting from 2023, as projected by the Boeing CMO.[2]

We quantified lifetime emissions from the global fleet in mitigation scenarios of varying ambition and compared those results to aviation carbon budgets based on these forecasted deliveries. In the Baseline Scenario, CO_2 emissions from conventional aircraft deliveries through 2042 were projected assuming limited technological improvement to identify the earliest delivery year by which the aviation carbon budget will be exhausted. The optimistic scenarios use a layered approach to applying decarbonization measures to identify the latest year by which all new deliveries of conventional aircraft will need to be zero-emission to maintain the aviation carbon budget. First, we applied SAF (Optimistic SAF) alone to the in-service fleet and deliveries through 2042 and assess the lifetime emission reductions. Then, we added aggressive fuel efficiency improvements (Optimistic SAF + Fuel Efficiency) to quantify how these two measures contribute to the fleet's emission reductions.

A tank-to-wake (TTW) "net-zero" aviation carbon budget of 18.4 billion tonnes (Gt) was defined for the years 2022–2050 by taking an average of four decarbonization pathways—the Mission Possible Partnership's Optimistic Renewable Electricity and Prudent Scenarios, Waypoint 2050, and the International Council on Clean Transportation's (ICCT) Aviation Vision 2050 Breakthrough scenario converted to TTW (Mission Possible Partnership, 2022; Air Transport Action Group, 2021; Graver et al., 2022). To align this net-zero budget with global temperature targets, 1.5 °C and 2 °C carbon budget scenarios were derived as sensitivity analyses using the Intergovernmental Panel on Climate Change's (IPCC) AR6 pathways (IPCC, 2022). Assuming a constant 2.4% share of the global carbon budget for the sector, TTW carbon budgets of 8.3 Gt and 26.2 Gt were calculated for aviation to remain on the path for these temperature targets.

Committed emissions from the existing fleet were estimated using the 2023 global passenger and freight aircraft breakdown as reported by International Bureau of Aviation (2024), as shown in Table 1.

2 The projected fleet growth rate (3.2%) is slower than the traffic growth rate (3.7%) because the latter incorporates an expected 0.5% annual increase in passengers carried per flight.

Table 1
Breakdown of existing fleet and representative aircraft types, 2023

	Aircraft class			
	Regional jet	**Narrowbody passenger**	**Widebody passenger**	**Freighter**
Number of aircraft	3,207	17,021	3,841	1,559
Average age (years)	15.0	11.5	11.8	19.6
Representative aircraft types	Embraer 175	Boeing 737-800 Airbus A320	Boeing 787-9 Airbus A330-200	Airbus A330-200 Freighter Boeing 777 Freighter

Data source: International Bureau of Aviation (2024)

The following methodology was used to calculate committed emissions from the existing fleet, made up of conventional aircraft. First, representative aircraft types were identified within the fleet for each aircraft class as indicated in Table 1. Then, the average CO_2 emitted per hour was calculated for representative aircraft types within each aircraft class as shown in Equation 1.

$$\text{Aircraft } CO_2 \text{ emissions} \left(\frac{\text{kg}}{\text{hour}}\right) =$$

$$\text{Mission Speed} \left[\frac{\text{km}}{\text{hour}}\right] \times \text{Fuel Burn} \left[\frac{\text{kg}}{\text{km}}\right] \times \text{Fuel Specific Energy} \left[\frac{\text{MJ}}{\text{kg}}\right] \times \text{TTW Fuel Carbon Intensity} \left[\frac{\text{kg } CO_2}{\text{MJ}}\right] \quad (1)$$

Average speed was calculated using flight movement data from the Airline Data Inc's 2022 database and fuel burn per kilometer by representative aircraft type was extracted from the ICCT's GACA 2019 dataset (Graver et al., 2020). Mission speed, which is the average speed over ground during take-off, cruise, approach, and landing, but not including taxi time, was used in this analysis.[3]

A specific energy of 42.8 megajoule per kilogram (MJ/kg) was used for jet fuel and the TTW average fuel carbon intensity of SAFs was extracted from the ICCT's PACE model (Breakthrough Scenario) for the Optimistic SAF Scenario. In the Baseline Scenario, the fuel mix remained 100% Jet A over the lifetime of all delivered aircraft to reflect the fuel carbon intensity with no SAF use.[4] In the Optimistic SAF case, SAFs were introduced into the fuel mix following ReFuelEU SAF mandate volumes, starting at 2% of the blend in 2025 and increasing to 70% by 2050 (Regulation 2023/2405). This scenario assumes a global rollout of the RefuelEU SAF mandate. In reality, SAF use will likely vary across regions, with some countries lagging in policies needed to ensure necessary volumes and low life-cycle GHG emissions.

The global fuel carbon intensity for the Baseline and Optimistic SAF Scenarios through 2050 is shown in Figure 1. On a TTW basis, the average carbon intensity of jet fuel in the Baseline case stays constant at 73.16 gCO_2/MJ, while under the Optimistic SAF case it falls to about 30 gCO_2/MJ in 2050.[5]

3 Average speed for a specific aircraft type was calculated as an average of the total distance flown divided by the total airtime in 2022 from the Airline Data Inc. database. Because aircraft speeds are slower during the landing and take-off (LTO) cycle and approach, mission speeds are, on average, slower than cruise speeds.

4 In 2023, an estimated 99.8% of commercial jet fuel use was derived from fossil fuels; SAFs accounted for only 0.2% (IATA, 2024b). Due to their high cost – typically between two and five times that of fossil jet fuel – uptake of SAF is expected to remain low in the absence of policy support.

5 The well-to-wake (WTW) GHG emissions of the global fuel mix was converted to TTW CO_2 to align with net-zero carbon budgets. On a WTW basis, the global jet fuel mix in our Aggressive case would be 70% SAF in 2050 with a WTW CO_2 of ~36 g CO_2/MJ. Because SAF emissions are greater than zero on a WTW basis, we adjust the TTW GHG savings proportionally to reflect the overlap between system boundaries for Scope 3 emissions. Thus, for a SAF with 90% GHG savings compared to fossil jet fuel, we attribute a 90% emissions reduction in WTT and TTW emissions, respectively, though the TTW emissions would be treated as zero in conventional GHG accounting.

Figure 1

Global aviation fuel carbon intensity scenarios (tank-to-wake)

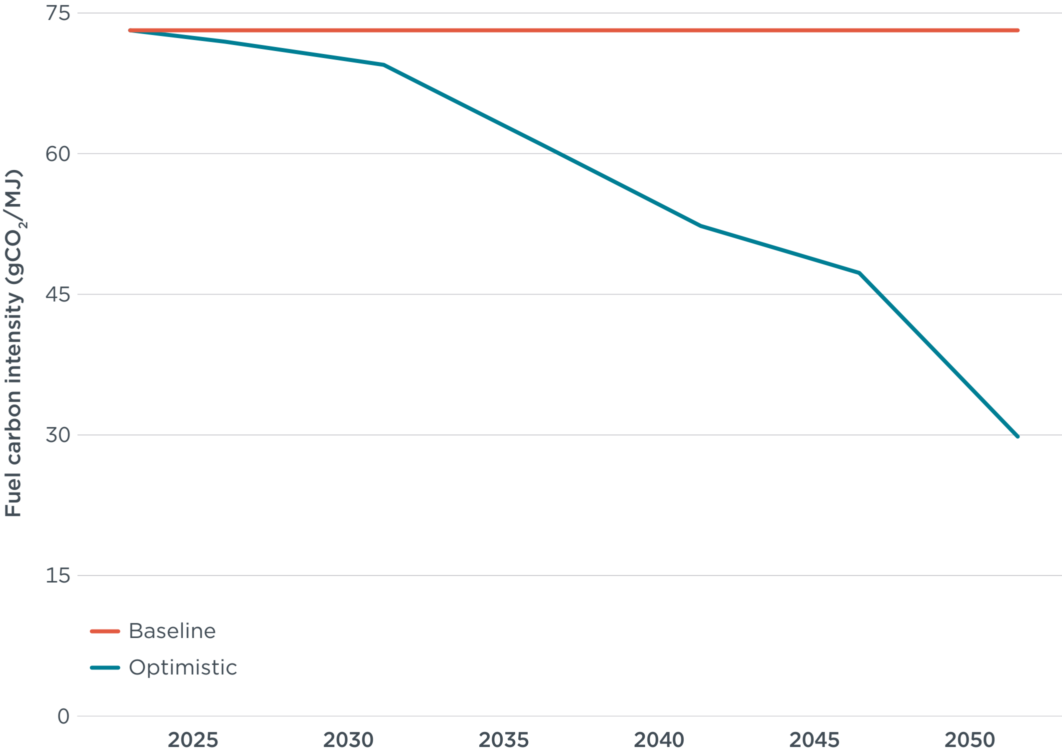

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Table 2 indicates the average mission speed and fuel burn for each of the representative aircraft types in the existing fleet. Mission speeds vary from about 440 km per hour for a regional jet up to more than 700 km per hour for a large widebody aircraft. On average, larger aircraft fly longer missions and, therefore, spend more time in cruise relative to smaller aircraft, thus increasing their average speed. Fuel burn ranges from about 3 kg per kilometer for the Embraer 175 aircraft up to more than 10 kg per kilometer from the Boeing 777 Freighter.

Table 2

Representative aircraft types, average mission speed, and average fuel burn for fleet delivered prior to 2024

Aircraft class	Aircraft type	Mission speed (km/hour)	Average fuel burn (kg/km)
Regional jet	Embraer 175	505	2.92
Narrowbody passenger	Boeing 737-800	566	3.98
	Airbus A320	616	3.98
Widebody passenger	Boeing 787-9	666	6.34
	Airbus A330-200	716	7.27
Freighter passenger	Airbus A330-200	716	8.51
	Boeing 777	724	10.7

Each representative aircraft type's lifetime emissions were then calculated as a product of the CO_2 emitted per hour, activity hours by age, number of aircraft, and survival summed over the course of its useful lifetime (Equation 2). Activity and survival curves were derived from Singh and Rutherford (2011), and are shown in Figures 2 and 3. A steep decline in both survival rates and activity hours can be seen after about 20 years of age across aircraft classes.

Figure 2
Survival curves by aircraft class

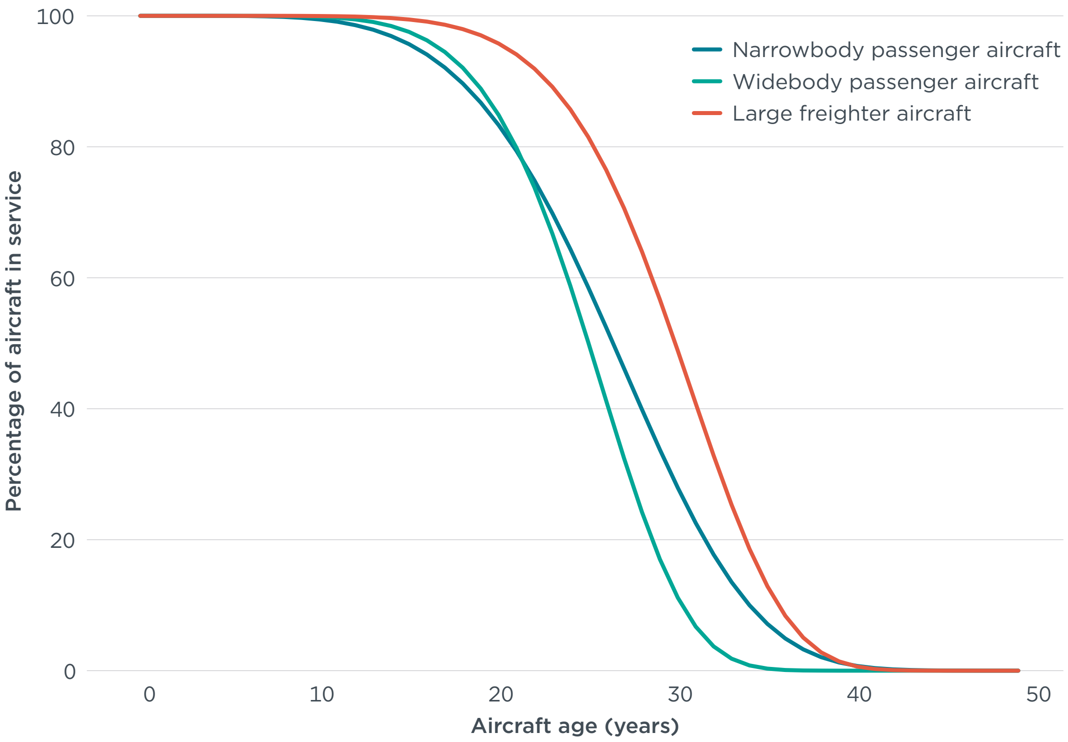

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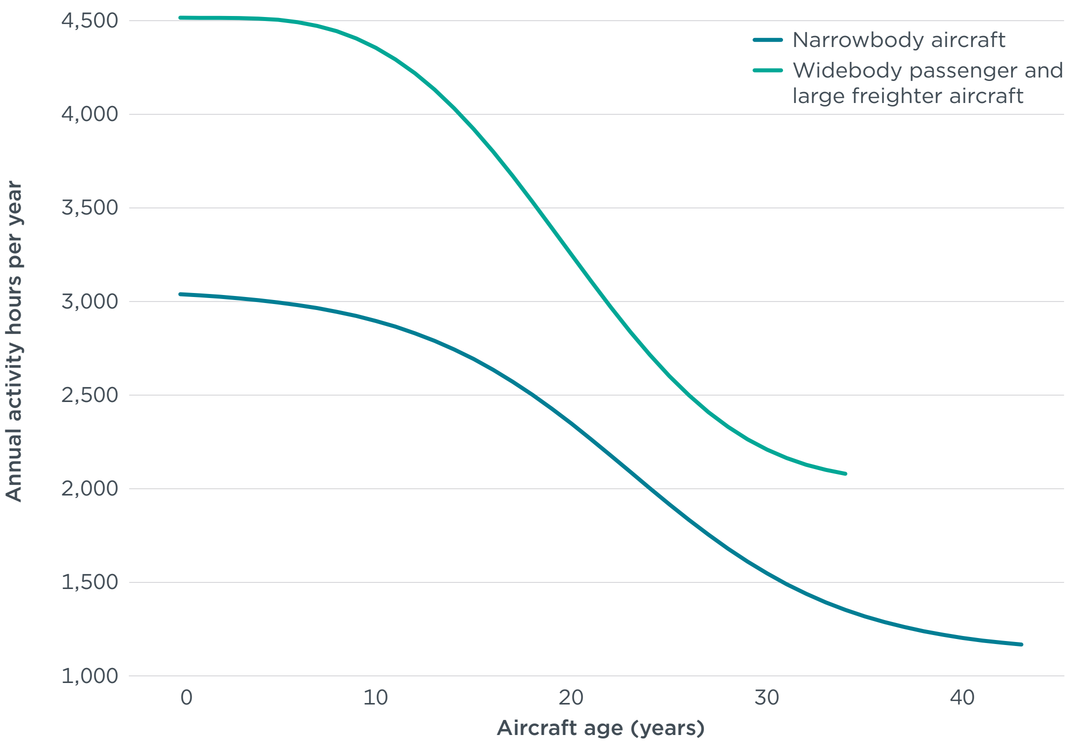
Figure 3
Activity curves by aircraft class



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$$\text{Lifetime } CO_2 = \sum_{1}^{a} n_a \times \frac{CO_2}{\text{hour}} \times \sum_{0}^{t} \frac{\text{hours}}{\text{year}} \times \text{\% of surviving aircraft} \qquad (2)$$

Where:

a is each representative aircraft type

n_a is number of aircraft for each representative aircraft type

t is the year in operation

This calculation for in-service aircraft was repeated to calculate committed CO_2 emissions from 2022 aircraft deliveries from Boeing, Airbus, and Embraer. This allows for our model to be compared against each manufacturer's reported Scope 3 emissions. Starting in 2024, the representative aircraft types used were the most advanced aircraft model in each category to better reflect the fuel burn of new aircraft being delivered today. Table 3 shows the representative aircraft types, average speeds, and average fuel burn rates used for projected deliveries of conventional aircraft from 2024 to 2033 in both scenarios.[6]

Table 3

Representative aircraft types, mission speed, and average fuel burn for 2024-2033 deliveries

Aircraft type	Mission speed (km/hour)	Fuel burn (kg/km)
Embraer 190 E2	513	3.17
Boeing 737-MAX	615	3.36
Airbus A320neo	616	3.29
Boeing 787	665	6.17
Airbus A330-900neo	641	6.65
Airbus A330-300 Freighter	739	7.52
Boeing 777 Freighter	724	10.7

Deliveries were projected by applying a survival curve to each year's in-service fleet to derive retirements, and calculating the additional aircraft needed to support an average fleet growth rate of 3.2% per year from 2024. The most advanced representative aircraft types currently in service (those seen in Table 3) were used until 2033.

Starting in 2034, two different approaches were taken. In the Baseline Scenario, which assumes limited technology uptake, the representative aircraft summarized in Table 3 were used through 2042. In the Optimistic SAF + Fuel Efficiency Scenario, we added a second mitigation technology into our modeling. Starting in 2034, advanced fuel-efficient aircraft were modeled using the "Aggressive" fuel efficiency improvement scenario in Kharina et al. (2016). These new aircraft types were phased into new aircraft deliveries over the course of 6 years beginning in 2034, increasing in the share of deliveries annually by 16.67%. Accordingly, starting in 2039, all new deliveries are assumed to be these "Aggressive" technology aircraft. Since Kharina et al. (2016) does not model freighters, and technological advancements on freighter aircraft are often slower to market, a constant annual 1.04% fuel efficiency improvement was applied to new freighters in the Optimistic SAF + Fuel Efficiency Scenario. Table 4 summarizes

6 Where the average speed for an aircraft type was unavailable, the average speed of a comparable aircraft within the same aircraft family was used.

the speed and fuel burn assumptions used for future deliveries (2034+) of conventional aircraft in the Optimistic SAF + Fuel Efficiency Scenario.

Table 4
Aircraft class, average speed and average fuel burn for the Optimistic SAF + Fuel Efficiency Scenario (2034+)

Aircraft class	Mission speed (km/ hour)	Fuel burn (kg/km)
Regional jet	515	1.94
Passenger narrowbody	616	2.16
Passenger widebody	695	4.49
Freight widebody	724	1.04% p.a. improvement from Baseline

In these scenarios, the lifetime emissions from each year's deliveries were calculated as a product of the fuel burn, fuel CO_2 intensity, activity hours, and survival curves and added to the emissions of the in-service fleet. This total was compared with the aviation carbon budget to identify the delivery year by which the budget is fully consumed.

RESULTS

In this section, we present the key findings from our analysis. First, we compare our modeled committed emissions from 2022 deliveries to those provided by OEMs in their Scope 3 reporting. Next, we present our estimate of committed emissions from the 2023 in-service fleet. We then summarize the potential lifetime emission reductions from new aircraft by delivery year across the Baseline and Optimistic Scenarios. We then compare projected emissions under both scenarios with various (net-zero, 1.5 °C, and 2 °C) carbon budgets to determine when all new aircraft need to become zero emission throughout their operational lifetimes to meet climate targets. We also quantify the amounts of CDR required to address residual emissions in each of these scenarios through 2042. We close by analyzing how mitigation measures enable manufacturers to meet their net-zero goals and delivery targets.

COMPARISON WITH REPORTED 2022 SCOPE 3 EMISSIONS

To validate our modeling framework, we first calculated the committed CO_2 emissions of 2022 deliveries from Airbus, Boeing, and Embraer and compare these with the respective reported Scope 3 GHG emissions. For a consistent comparison, we compared each OEM estimate, which assumes a worst-case "no-SAF" future, with the lifetime emissions from 2022 deliveries calculated in our Baseline case.[7] Table 5 compares these results.

7 Scope 3 emissions from 2023 deliveries have not yet been reported by OEMs, so reported values from 2022 deliveries were used for comparison with our model.

Table 5

Comparison of reported and modeled well-to-wake Scope 3 emissions from 2022 deliveries

Manufacturer	Manufacturer estimate (Mt CO_2e)	ICCT model estimate (Mt CO_2e)	Difference (ICCT versus manufacturer)
Boeing	363	455	+25%
Airbus	494	490	-1%
Embraer	15.6	53	+240%
Total	**873**	**998**	**+14%**

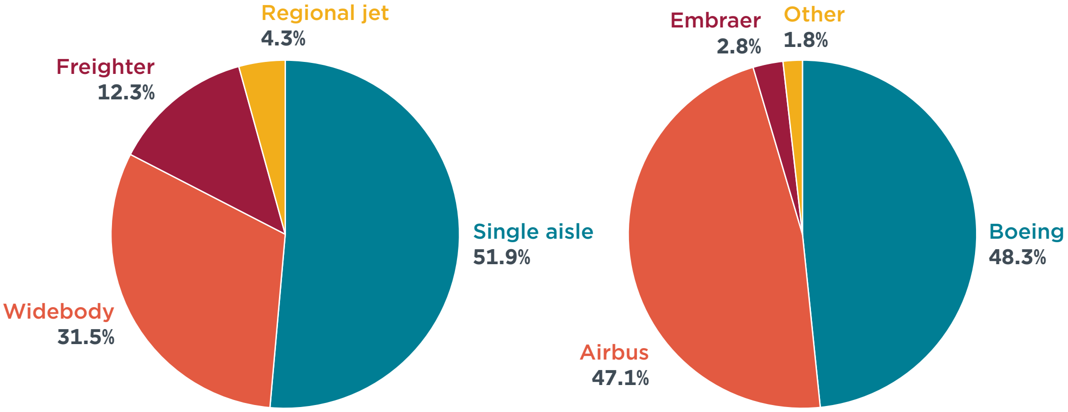
Overall, we found agreement between our modeling of projected emissions for 2022 deliveries with OEM estimates of Scope 3 emissions from Boeing and Airbus, after converting our results to well-to-wake emissions.[8] Our estimate of projected emissions from Airbus deliveries is essentially identical to their estimates, while our estimates for Boeing are about 25% higher. Our emissions estimate for Embraer deliveries is more than triple that provided by Embraer. It is unclear what drives this, but it can likely be attributed to differences in modeling assumptions including aircraft survival, activity hours, and representative aircraft types. These differences highlight the value of developing a standardized methodology for manufacturer calculations of Scope 3 emissions, as variance in methodology makes it difficult to compare emission estimates.

COMMITTED EMISSIONS FROM THE IN-SERVICE FLEET

Using this methodology, both committed emissions from the current in-service fleet and projected emissions from future deliveries could be assessed. The emissions of the in-service fleet (9.1 Gt) are broken down by manufacturer and aircraft class in Figure 4.[9] More than half the committed emissions of the existing fleet come from narrowbody passenger aircraft, followed by widebody passenger aircraft (32%), freighters (12%), and regional jets (4%). This is due to factors such as the volumes, activity curves, and survival curves of the different aircraft types in the fleet.

Figure 4

Committed emissions from the 2023 in-service fleet by aircraft class (left) and manufacturer (right), Baseline Scenario



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8 In this study, emissions were calculated on a TTW basis to align with net-zero trajectories. On a well-to-wake basis, emissions are about 18% higher than TTW emissions due to energy use in upstream fuel production.

9 This breakdown assumes no SAF use, per the Baseline Scenario. However, it would remain almost identical in the Optimistic SAF Scenario given the limited SAF uptake throughout the lifetime of the in-service fleet.

When considering the breakdown by manufacturer, the vast majority of emissions (over 95%) from the fleet can be attributed to Boeing and Airbus aircraft. This is due to the volume of commercial aircraft produced by these two manufacturers; in the current passenger fleet, they make up over 95% of existing narrowbody, widebody, and freighter aircraft.

PROJECTED LIFETIME EMISSIONS FROM FUTURE DELIVERIES

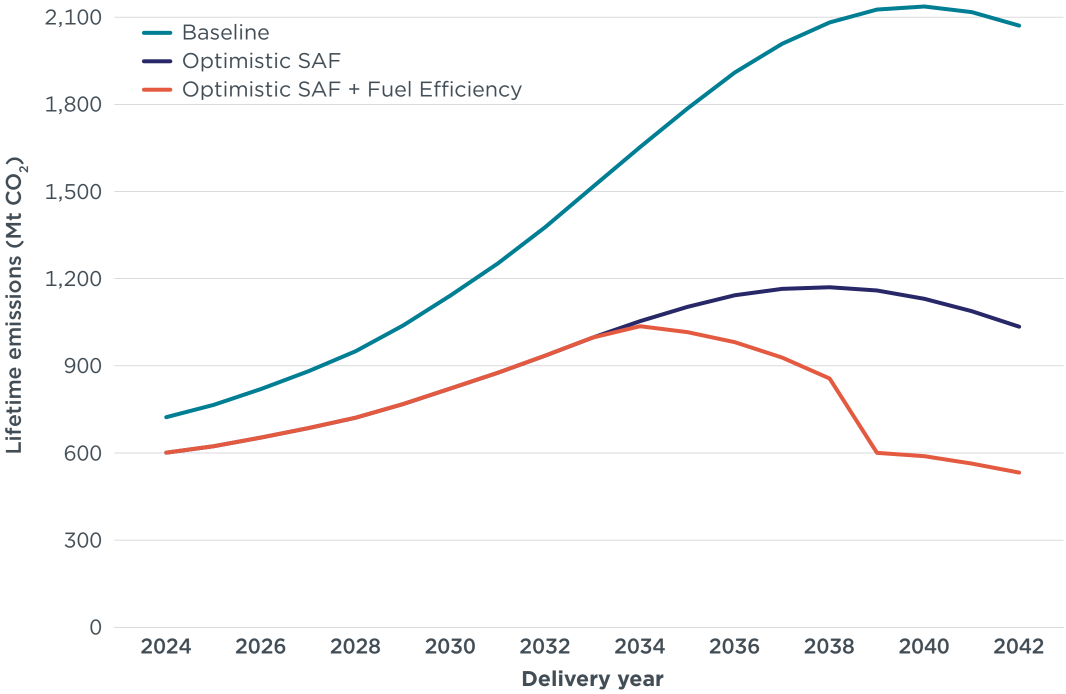
Comparison of the projected lifetime emissions from conventional aircraft by delivery year across the Baseline and Optimistic Scenarios indicate a substantial potential to reduce emissions from SAF use and fuel efficiency improvements (Figure 5). Under the Baseline Scenario, projected emissions from new deliveries increase consistently through 2040. The Optimistic Scenarios still show steady emissions growth over the next decade; however, the lifetime emissions of each year's deliveries are below the Baseline Scenario because aggressive decarbonization measures are in place. The impact of individual mitigation technologies can be seen when comparing the Optimistic SAF and Optimistic SAF + Fuel Efficiency Scenarios, as emissions reduction is maximized with the aggressive use of both SAFs and fuel efficiency improvements.

In 2034, emissions from new deliveries start to fall due to greater amounts of SAF in the fuel mix and the introduction of new aircraft types. By 2039, a gradual drop can be seen in the lifetime emissions of new deliveries because all deliveries are assumed to be new, more efficient aircraft types (as shown in Table 4) operating on over 60% SAF throughout their lifetimes. This result can be viewed as the maximum potential for conventional aircraft given the challenge of introducing both radically more fuel-efficient aircraft types starting in 2034 and the use of ReFuelEU volumes of SAFs globally.

Cumulative CO_2 from new conventional aircraft delivered between 2024 and 2042 would be cut by more than 50%—from 29 Gt to 14 Gt—under the Optimistic SAF + Fuel Efficiency Scenario.

Figure 5

Projected lifetime emissions for new aircraft by delivery year and scenario, 2024–2042



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Our findings highlight the need to scale up SAF use and improve fuel efficiency over the coming decade, as the projected lifetime emissions from each year's deliveries would increase annually (shown in Figure 5) due to anticipated fleet growth.[10] For these deliveries to substantially reduce their projected lifetime emissions and limit emissions growth, the introduction of SAF and other measures is necessary. Even greater ambition will be required for new aircraft delivered in the 2030s.

COMPARISON WITH CARBON BUDGETS

In the conservative Baseline Scenario, the share of fossil jet fuel remains constant at 100% of the fuel mix. As stated, the net-zero aviation carbon budget was assumed to be 18.4 Gt; the 1.5 °C and 2 °C budgets are 8.3 and 26.2 Gt, respectively. The emissions associated with aircraft in service in 2023 consume almost 50% of the net-zero budget, as they make up the largest portion of the fleet and consequently require the most fuel over their lifetime. Added to that, the projected lifetime emissions of conventional aircraft delivered through 2032 would fully deplete the carbon budget (Figure 6). The low (1.5 °C) carbon budget is consumed just by committed emissions from the in-service fleet, while the high (2 °C) carbon budget is consumed by lifetime emissions of deliveries through 2038.

Figure 6

Consumption of aviation carbon budget from cumulative lifetime emissions of projected fleet

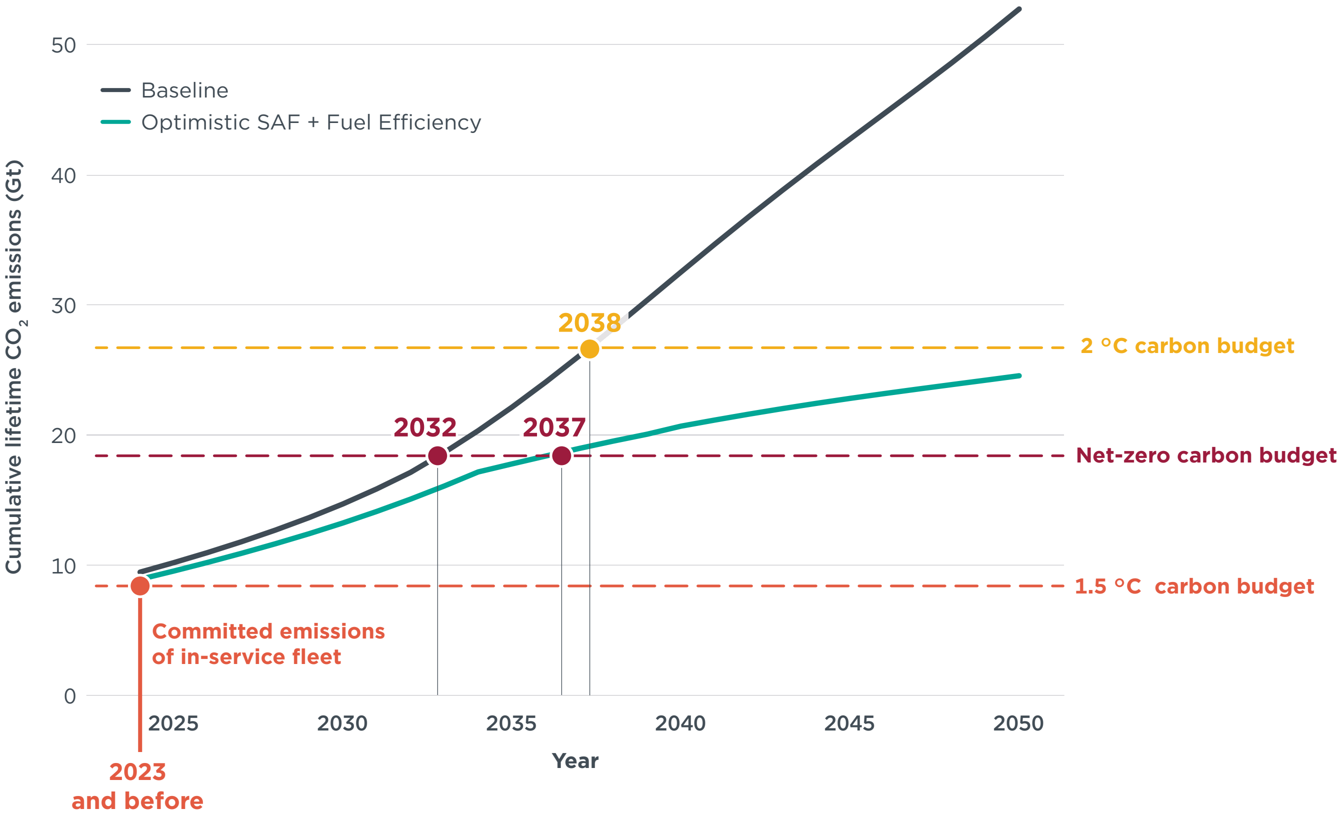

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Figure 6 also shows the cumulative lifetime emissions trajectory for deliveries with the deployment of SAF and aggressive fuel efficiency improvements (Optimistic SAF + Fuel Efficiency). In this case, these measures delay the year by which the net-zero

10 The reported 2022 deliveries from Airbus, Boeing, and Embraer are higher than annual deliveries estimated by our model through 2028. Some real-world variation from the modeled delivery estimates is expected due to uncertainty in order fulfillment, backlog, and usage cycles.

aviation carbon budget is fully consumed by the lifetime emissions of new deliveries from 2032 to 2037. After that time, any emissions from new conventional aircraft that are not removed by CDR would exceed the available carbon budget and, therefore, be incompatible with a net-zero goal.

As with the Baseline Scenario, under both Optimistic Scenarios, the 1.5 °C aviation carbon budget is depleted by the in-service fleet. However, in the Optimistic SAF + Fuel Efficiency Scenario, the 2 °C carbon budget is not depleted by deliveries through 2042. To model a 2 °C carbon budget, we maintained the fleet growth assumptions and technology deployment of the Optimistic SAF + Fuel Efficiency Scenario until the budget was fully consumed, which in this case occurs in 2053. This indicates the need for potentially deploying other measures, such as CDR and non-CO_2 mitigation, to supplement the strategies implemented.

We also calculated the volumes of CDR in the form of direct air capture (DAC) that would be needed to remove CO_2 emissions from projected aircraft deliveries through 2042 after the net-zero carbon budget is exhausted. In the Baseline Scenario, we estimate that about 22 Gt of DAC will be needed to capture the lifetime CO_2 emissions of aircraft delivered through 2042.[11] In the Optimistic SAF + Fuel Efficiency Scenario, we estimate that about 5 Gt of DAC will be needed under the net-zero budget. This is on the order of 2,500 times the global capacity of DAC facilities currently under construction or in advanced stages of development for use by all industries in 2030 (International Energy Agency, 2024).[12]

Collectively, these findings suggest that, between 2032 and 2037, all new aircraft must be net-zero aircraft, defined here as either ZEPs or aircraft operating on 100% low-carbon SAF, over their operational lifetimes for airlines to achieve net-zero emissions in 2050. In other words, manufacturers must go net-zero about 15 years before airlines. After that time, all newly delivered aircraft must be fueled by 100% SAFs, hydrogen, or electricity, all with very low life-cycle emissions, or have their emissions fully removed using widescale CDR, for airlines to meet their climate goals.[13]

This study also explored the potential market for conventional versus net-zero aircraft. Figure 7 shows the breakdown of OEM projected deliveries (far left) through 2042 under a net-zero budget, divided by conventional and net-zero aircraft for our two scenarios. We estimate that OEMs could only deliver about 24,000 conventional aircraft, or about 62% of projected deliveries, under the Baseline Scenario. The remaining 14,500 aircraft would need to be net-zero throughout their lifetimes in order to meet the 2050 net-zero goal. Under the Optimistic SAF + Fuel Efficiency Scenario, an additional 4,500 conventional aircraft could be delivered because the use of SAF blends and aggressive fuel efficiency improvements would economize on the available carbon budget. Even then, manufacturers will need to deliver at least 10,000 net-zero aircraft powered by hydrogen, electricity, or 100% SAF by 2042.[14] All new aircraft delivered after 2042 would also need to be net-zero.

11 Additional removals would be required for deliveries made between 2043 and 2050, which was not modeled in this exercise.

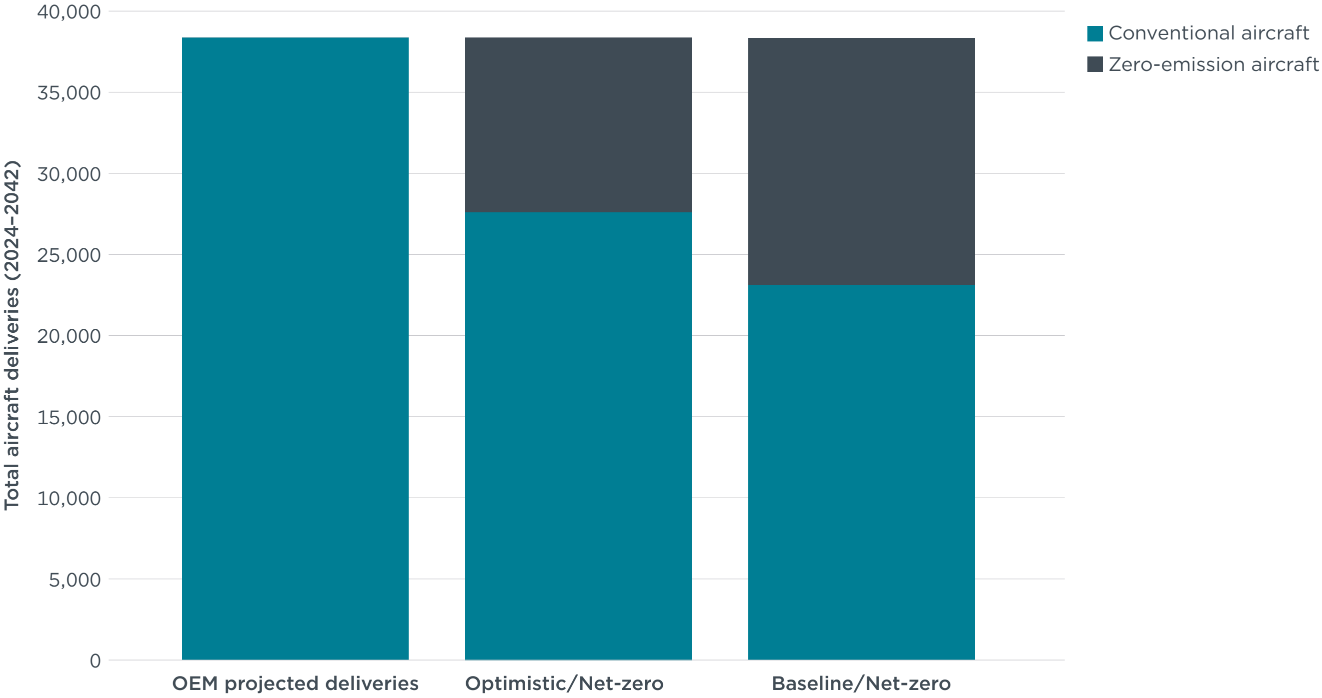
12 The International Energy Agency's projection for global CO_2 capture by direct air capture is about 2.5 million tonnes in 2030 when considering facilities in the construction and advanced development phases.

13 Although in lower volumes than with fossil jet fuel, CO_2 is still emitted from the combustion of 100% SAF. Some CO_2 removal will be required for new deliveries to be zero-emissions and the carbon budget to be maintained.

14 This approach, which does not consider deliveries from 2043–2050, provides a conservative estimate of the impact of the net-zero goal on new aircraft deliveries. This is because aviation's net-zero carbon budget through 2050 is being exhausted by deliveries before 2042.

Figure 7

Projected deliveries and breakdown of allowable deliveries under net-zero budget by scenario, 2024–2042



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CONCLUSIONS

This analysis explored how aircraft production, sales, and usage cycles are linked to airline emissions. We compared two categories of emissions with a net-zero carbon budget of 18.4 Gt: committed emissions from aircraft already in service in 2023, and projected lifetime emissions from new conventional aircraft deliveries through 2042. Today's in-service fleet is expected to emit about 9 Gt of CO_2 over the remainder of their useful lives, or almost 50% of a net-zero carbon budget and the entirety of a 1.5 °C carbon budget. Under a conservative Baseline Scenario with limited technology uptake, aviation emissions are projected to increase linearly, doubling by 2035 due to fleet growth. Projected emissions from new deliveries of conventional aircraft would then fully deplete a net-zero aviation carbon budget in 2032.

Concentrated investments in SAFs and new aircraft fuel efficiency technologies can dramatically cut projected CO_2 emissions from new deliveries of conventional aircraft. Under the Optimistic SAF + Fuel Efficiency Scenario with substantial SAF uptake and aggressive fuel efficiency improvements from new aircraft types, the projected lifetime emissions of total new deliveries would fall more than 50%, from 29 Gt to 14 Gt, by 2042. Still, due to traffic growth, we project a net-zero aviation carbon budget would be depleted by new aircraft deliveries by 2037 under the Optimistic SAF + Fuel Efficiency Scenario. Thus, while SAF blending and efficiency improvements can substantially cut projected emissions from the fleet, additional action will be needed from aircraft manufacturers to transition away from fossil fuels by the mid-2030s.

RECOMMENDATIONS

Aircraft manufacturers could consider dramatically increasing investments in clean aviation technologies to reduce CO_2 emissions, notably ZEPs. Our modeling suggests that there will be a substantial market for aircraft that are net-zero over their lifetimes—between 10,000 and 14,500 units through 2042, depending on SAF and fuel efficiency uptake. Specifically, our conclusions point to three recommendations for manufacturers to consider:

1. Accelerate efforts to develop narrowbody ZEPs, especially those powered by hydrogen, that emit no CO_2 during operation.
2. Ensure that all new aircraft can burn 100% SAF, not just SAF blends, starting in 2030.
3. Establish stringent Scope 3 emission targets requiring that the aircraft delivered will emit less CO_2 emissions over their lifetimes.

First, regarding ZEPs, we recommend that manufacturers accelerate efforts to develop hydrogen and electric aircraft. Since the range and capacity of the latter are expected to be low, priority should be placed on bringing liquid hydrogen combustion narrowbody aircraft into service by 2035 (Mukhopadhaya & Rutherford, 2022; Airbus, 2020). Electric aircraft may play a minor role in specific applications, including commuter aircraft, electric vertical take-off and landing (eVTOL) aircrafts, and for training purposes (Mukhopadhaya & Graver, 2022). Regional hydrogen aircraft powered by fuel cells, either retrofits or clean sheet designs, may enter service faster than liquid hydrogen combustion aircraft and can be used to scale aviation hydrogen infrastructure. However, given that most projected emissions in the coming decades are from narrowbody aircraft, manufacturers should accelerate the development and entry of hydrogen combustion narrowbody aircraft into the fleet.

Second, in the near-term SAF will continue to be used in diffuse blends (0.5% global average) at airports. Still, manufacturers must consider the compatibility of their aircraft deliveries with 100% SAF, as many aircraft delivered today will remain in-service through 2050. Given the ongoing development and gradual introduction of new aircraft types, deliveries are expected to be a mix of new and legacy aircraft, and there is a long road ahead before all new aircraft will be able to use 100% SAF upon delivery. The constraint of jet fuel availability becomes more prevalent as the SAF percentage in the fuel mix increases, so aircraft manufacturers should consider prioritizing the rapid introduction of fully SAF-compliant aircraft and integrating this capability into existing engines with the necessary upgrades, while ensuring safety standards.

Finally, this analysis suggests that for airlines to achieve net-zero CO_2 emissions in 2050, manufacturers will need to achieve net-zero Scope 3 emissions from their deliveries around 2035. This implies that all manufacturers of commercial aircraft and jet engines should set a 100% Scope 3 emission reduction target in 2035. Since all alternative fuels, including hydrogen, electricity, and SAFs, have residual emissions associated with fuel production, a negative emission technology such as CDR will be required to meet these targets.

POTENTIAL FUTURE RESEARCH

This study investigated Scope 3 emissions from new aircraft deliveries in relation to aviation climate targets. It took a global approach focusing on two of the most important technologies for decarbonizing aviation— SAFs and advanced fuel-efficient aircraft. Future expansion of this research can include the impacts of projected fleet evolution on non-CO_2 forcers. Another potential area of study is to consider global fleet renewal and growth from a regional perspective. Committed emissions from the in-service fleet are likely dominated by airlines in developed economies, while rapidly growing airlines in emerging economies may contribute more to projected emissions. The growth of lifetime emissions could then be assessed from an equity lens, as there is significant regional variation in projected aircraft deliveries over the next two decades.

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