CASCADE

THE BOEING CASCADE CLIMATE IMPACT MODEL

FAQs

April 2024

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General

Why did Boeing develop Cascade?

To support the aerospace industry as it maps a path to net zero emissions, Boeing created Cascade, a data modeling and scenario analysis tool that quantifies the potential of decarbonization strategies to cut emissions, including fleet renewal, operational efficiency, renewable energy and future aircraft. The tool allows the industry to visualize, for the first time, the total climate impact of each of our major paths to decarbonize aviation and to inform the most impactful and effective strategies to reach net zero by 2050.

Cascade accounts for the life cycle impact of renewable energy from the production, distribution, and use of alternative energy carriers including electricity, hydrogen, and sustainable aviation fuel (SAF). The tool was developed to collaborate with airline operators, industry partners, and policymakers to inform when, where, and how different fuel sources intersect with new airplane designs.

What data sources and models are you using?

Cascade uses traffic data from Cirium, aircraft performance models and fleet renewal strategies from Boeing, operational efficiency improvements derived from ICAO and IATA analysis, and renewable energy data from ICAO, GREET, NREL, and IEA forecasts.

What are the sources for historical data?

Historic emissions data is derived from a variety of sources for the following range of years - 1960-1989 Sausen & Schumann; 1990-2003 Lee et al.; 2004-2014 $IATA_1$; 2015-2018 $IATA_2$. Historic capacity data from 1960-2018 is from Airlines for America (A4A).

What emissions are included in Cascade?

Cascade accounts for the life cycle emissions of each fuel from “well-to-wake.” This includes the emissions produced or sequestered during the production and distribution of the fuels used to power the aircraft, as well as the emissions produced by the aircraft due to combustion of the fuel. Within the settings, you have the option to select the emissions scope for jet fuel, hydrogen and electricity that you want to apply to your decarbonization scenario. In line with the IATA TrackZero Methodology, SAF is always accounted for with its total life cycle emissions. CO_2-eq is defined by the Intergovernmental Panel on Climate Change (IPCC) based on a 100-year Global Warming Potential (GWP).

What type of capabilities are included in Cascade?

You will find two modes with differing capabilities. The Explore Strategies mode enables a detailed analysis on the decarbonization strategies for a single point in time. The Forecast Scenarios mode projects impacts of selected decarbonization strategies over time and out to 2050.

What is the difference between the Explore Strategies and Forecast Scenario Mode?

The Explore Strategies mode visualizes the potential of each decarbonization strategy to reduce emissions if implemented instantaneously. This mode enables more control over a number of input variables such as market share and carbon intensity of various renewable energy sources, and the performance capability of future aircraft concepts.

The Forecast Scenario mode enables projection of emissions reductions out to 2050. In order to keep the inputs simple, multiple variables related to future aircraft concepts and renewable energy sources are included in each slider and change simultaneously based on a range of pre-defined forecasts. In a recent release, we have created Insights that takes the user through a guided tour to further understand how to customize scenarios based on topics impacting the decarbonization of the aviation industry, such as CORSIA.

How do you know Cascade is accurate?

Cascade is based on industry data and information from leading studies. As a system-level validation exercise, the scenarios from ATAG Waypoint 2050 were used as inputs into the tool. For each of the ATAG scenarios, the resulting net CO2 emissions forecasts for each of the individual strategy levers (e.g., fuels, technology, operations) were within 2% of the Waypoint 2050 results.

Is Cascade biased toward Boeing aircraft?

The energy and fuel burn models provide generic unbiased aircraft performance estimates for a variety of original equipment manufacturers (OEMs). We are using a third party data source with Eurocontrol's Small Emitters Tool (SET) for fuel burn calculations. As part of the fleet renewal methodology, previous-generation aircraft are replaced with new latest-generation aircraft from the same OEM wherever possible.

Scenarios

Do any default scenarios in Forecast Scenario mode reflect Boeing's view of the most likely future evolution of aviation emissions?

The default scenarios shown are starting points from which you can examine how changes in demand, technology, fuels, operations, and the use of offsets could affect net emissions. The power of Cascade lies in the users' ability to vary each strategy based on their own assumptions regarding future technology and investment scenarios.

What do low, moderate, and high scenarios correspond to for each strategy?

Each strategy represents a broad range of strategy impacts from a low investment/aspiration case to a high investment/aspiration case which would require massive broad cross-sector investment and collaboration. For additional information on the range of scenarios provided, see the FAQs for each strategy.

How does Cascade's CO_2 emissions forecast compare to ATAG Waypoint 2050, ICAO LTAG, and the FAA US Climate Action Plan?

While the influential work conducted in these efforts use similar analysis techniques and assumptions, Cascade is a standalone effort. In particular, the default scenario does not represent any specific scenario from recent ATAG, ICAO, or FAA studies. Further, comparisons between the model and any other study can be challenging due to differing assumptions, methodology, and scope of air traffic activity considered.

Emissions

What is the scope of emissions included in Cascade?

Cascade accounts for the life cycle emissions of each fuel from "well-to-wake." This includes the emissions produced or sequestered during the production and distribution of the fuels used to power the aircraft, as well as the emissions produced by the aircraft due to combustion of the fuel. Within the settings, you have the option to select the emissions scope for jet fuel, hydrogen and electricity that you want to apply to your decarbonization scenario. In line with the IATA TrackZero Methodology, SAF is always accounted for with its total life cycle emissions. Life cycle assessment of various fuel pathways is especially important when considering the variety of alternative energy carriers that may be used by aviation in the future, as illustrated in Figure 1. CO_2-eq is defined by the Intergovernmental Panel on Climate Change (IPCC) based on a 100-year Global Warming Potential (GWP).

Aircraft manufacturing accounts for less than 1% of an aircraft's total life cycle GHG emissions based on Boeing's Sustainability Report. As a result, manufacturing emissions are not included.

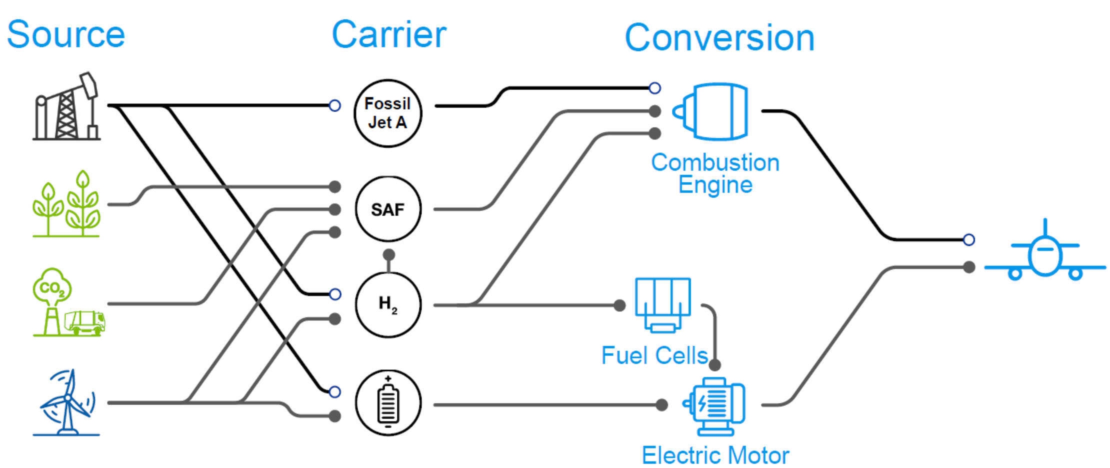

Figure 1 – Simplified schematic showing the energy sources, energy carriers, and aircraft concepts considered from a life cycle perspective within Cascade

What is the difference between well-to-wake and tank-to-wake emissions?

Well-to-wake emissions consider the emissions resulting from production of the fuel, while tank-to-wake emissions result from use of the fuel in an aircraft (these are also referred to as "direct emissions," "combustion emissions," or "tailpipe emissions").

Tank-to-wake emissions from conventional jet fuel make up the majority of airlines' Scope 1 emissions and are the focus of the industry's net-zero goal.

Well-to-wake emissions are important to consider when evaluating alternative fuels such as SAF, electricity, and hydrogen so that aviation does not cause emissions to increase in the energy sector as a result of reducing its own emissions.

What are net emissions?

Net emissions are the remaining emissions for a given scenario after emission reduction strategies are applied. Emission reduction strategies include efficiency improvements that reduce direct emissions such as fleet renewal, future aircraft, and operational efficiency, as well as strategies that reduce life cycle emissions such as sustainable aviation fuels and renewable energy, and strategies that reduce global emissions through the use of high quality out-of-sector carbon offsets or direct carbon removals.

What does CO_2-eq mean?

Carbon dioxide equivalent (CO_2-eq) is a standard measure used to compare emissions from various greenhouse gases by converting into the equivalent amount of CO_2. Cascade uses the definition of CO_2-eq established by the Intergovernmental Panel on Climate Change (IPCC) based on a 100-year Global Warming Potential (GWP). Net CO_2-eq emissions are therefore the net greenhouse gas emissions that have been converted to CO_2 equivalent using the 100-year GWP.

Does Cascade consider non-CO_2 combustion emissions?

Cascade considers all of the greenhouse gas emissions from the production of energy on a life cycle basis. The only emissions from combustion considered are CO2; other emissions that result from the combustion or use of the fuel and potential atmospheric effects are not modeled. Further, it does not currently model aviation-induced cloudiness (AIC – a commonly used term to describe condensation trails and aviation-induced cirrus clouds).

What metrics does Cascade use to measure efficiency?

Fuel efficiency is a measure of the fuel consumption required for a vehicle to transport passengers and/or cargo a given distance. This is similar to familiar metrics for cars like “miles per gallon (mpg)” in the US, or “liters per 100 kilometers (L/100km)” in the EU. In Cascade, the metric is computed by dividing the total fuel consumption by the total number of passengers (Revenue-Passenger-Kilometer, RPK) or tonnes of cargo (Revenue-Tonne-Kilometer, RTK) carried and the distance they were carried across all routes. The inclusion of payload accounts for the fact that aircraft, unlike cars, are designed to carry large numbers of passengers and substantial payloads.

Emissions intensity is a similar measure that considers the amount of CO_2-eq emitted, rather than the quantity of fuel consumed.

How are aircraft fuel burn and emissions calculated?

Cascade estimates fuel and energy consumption from Eurocontrol’s Small Emitters Tool (SET). The fuel consumption in SET is calculated based on aircraft type and flight distance. Cascade does not attempt to account for any airline or region's operating rules, payload capacities, load factors, or other unique and specific factors. For more information, refer to Eurocontrol SET website.

Are you using actual fuel consumption figures from airlines?

No. Cascade does not use actual fuel consumption figures from airline operators, as these are usually commercially sensitive and not generally available to the public.

Fleet Renewal

How are old airplanes replaced with new ones in the fleet renewal strategy?

The fleet renewal strategy provides a quantitative assessment of the decarbonization potential associated with today's technology by replacing previous-generation aircraft (old aircraft no longer in production) with latest-generation aircraft (aircraft that are currently in production or undergoing certification). By using this strategy, previous-generation aircraft are replaced with the nearest like-for-like latest-generation equivalents. For example, a Boeing 737-800 is replaced one-for-one with a 737-8, and an Airbus A320ceo (current engine option) is replaced one-for-one with an A320neo (new engine option). In the Explore Strategies mode, the entire fleet is renewed instantaneously, whereas in the Forecast Scenario mode the rate of fleet renewal can be varied by the user.

How is the rate of fleet renewal determined?

The rate at which new aircraft are introduced into the fleet is determined by two factors: the level of traffic growth and the fleet introduction ratio. The fleet introduction ratio defines the rate at which aircraft are introduced for growth versus for replacement of aging aircraft, where the fleet growth rate is proportional to the traffic growth rate.

In the moderate scenario, an equal number of new aircraft are delivered to replace older aircraft as are used to meet demand for fleet growth. The low and high scenarios vary the fleet introduction ratio by $\pm$30% to accelerate or decelerate fleet renewal within reasonable bounds set by aircraft life limitations and realistic delivery rates.

Future Aircraft

What is the difference between "fleet renewal" and "future aircraft"?

"Fleet renewal" refers to replacing older previous-generation aircraft with new latest-generation aircraft that are currently in development or production. "Future aircraft" refers to aircraft that are not yet commercially available, such as those in the early stages of development or future aircraft concepts. Future aircraft may be advanced conventional aircraft that use jet fuel, electric aircraft that use batteries as their primary power source, or hydrogen-powered aircraft.

What types of future aircraft are included?

There are three types of future aircraft that can be introduced: advanced conventional aircraft that use Jet A/A-1 as the primary energy carrier, battery-electric aircraft, and hydrogen-powered aircraft.

Advanced conventional aircraft may use conventional jet fuel derived from petroleum, as well as drop-in sustainable aviation fuels (SAF).

The electric aircraft model assumes a battery-electric architecture and a range of battery energy densities that reflects potential improvements in battery technology.

The hydrogen aircraft model assumes that the aircraft uses liquid hydrogen, direct combustion, and a fuselage-integrated fuel tank. The performance of hydrogen-powered aircraft is modeled as a delta relative to equivalent conventional aircraft based on Boeing studies that have shown hydrogen-powered aircraft would be less efficient than conventional aircraft on a passenger-km basis.

How is the emissions reduction potential of future aircraft modeled and calculated?

The emissions reduction potential of future aircraft is determined by the performance delta relative to the aircraft being replaced and the share of the market into which the new aircraft are inserted.

For the battery-electric and hydrogen-powered aircraft, the emissions impact associated with the fuel sourcing, production and distribution is also contained in the future aircraft “wedge” in addition to the aircraft performance delta.

In the Explore Strategies mode, the user is able to vary the market share and range capability of the future aircraft directly and see the resulting impact on emissions. In the Forecast Scenario mode, generic values for the Entry Into Service (EIS) and market introduction rate for the three available energy carriers are used that can be varied from low to high and are based on broad assumptions about applicable markets and time-to-market. These generic scenarios are not intended as and should not be interpreted as future product timelines or market projections. The performance deltas, in terms of MJ/pax-km, are also generic and are based on historical improvements for conventional aircraft and high-level estimates for electric and hydrogen-powered aircraft.

What are the performance, EIS, and market share assumptions for future aircraft?

For advanced conventional aircraft the low, moderate and high settings correspond to a 50%, 75%, and 100% replacement of latest-generation aircraft across all markets in 2050 with advanced conventional aircraft that have 25% lower fuel burn per pax-km than best in class today.

For battery-electric aircraft, the low, moderate and high settings correspond to electric aircraft introduction on regional and some single-aisle routes for ranges up to 300 NM, 500 NM, and 700 NM respectively. The operating energy consumption and range limitations are based on a first principles-based analysis of battery energy density that allows for substantial advancements in the state of the art. Future versions of Cascade will refine this approach.

For hydrogen-powered aircraft, the low, moderate, and high settings correspond to aircraft introduction starting in 2050, 2045, and 2040, respectively, across the regional, single-aisle and twin-aisle market at all ranges. Based on previously conducted studies, the hydrogen-powered aircraft have decreased fuel efficiency relative to the aircraft being replaced. Future versions of Cascade will improve the approach being used to model hydrogen-powered aircraft.

How was the default scenario determined for future aircraft in the Forecast Scenario mode?

Each of the future aircraft sliders provides a broad range of future technology deployment scenarios based on a review of external studies and publicly available data. The scenario shown by default corresponds to a case where each technology is developed and deployed equally, without picking a winner, across the three energy-carriers in the relevant aircraft sizes. The default value for all three future aircraft types is set to below the moderate setting in the baseline case because of assumed distributed technology investment and the inability to achieve the cumulative benefit from all three simultaneously.

Operational Efficiency

What is included in the operational efficiency strategy?

The basic operational efficiency strategy introduces a macro-level reduction in fuel burn and emissions as a result of improvements in airplane retrofit and maintenance, fleet and airport operations, and/or flight and traffic management. Improvements can be introduced as a cumulative percentage or individually for each sub-strategy.

The range of low, moderate, and high scenarios represents a range of potential outcomes ranging from no-improvement to ambitious investment in efficiency improvements. The percentage improvements for each category are based on a combination of internal studies and external studies including ATAG Waypoint 2050 and the ICAO LTAG.

Renewable Energy

What are your data sources for carbon intensities of electricity and hydrogen production?

The electricity grid carbon intensity data is based on a compilation of data from the US National Renewable Energy Lab (NREL). Hydrogen carbon intensity data is primarily derived from the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model.

How are the renewable energy forecasts defined?

The renewable energy forecasts represent a range of potential scenarios for the deployment of sustainable aviation fuels (SAF), renewable electricity, and renewable hydrogen that reflect varying levels of ambition and investment across each sector based on published analyses and projections.

The SAF scenarios align with the Waypoint 2050 report published by the Air Transport Action Group (ATAG). The low and moderate scenarios reflect a continuation of current trends, with differing assumptions about the growth trajectory, resulting in SAF reaching 6% and 39% market share in 2050, respectively. In the high scenario, SAF reaches 90% market share in 2050. In each case, SAF reduces life cycle emissions by 75% in 2019, and improves to 100% life cycle emissions reduction in 2050.

The renewable electricity scenarios align with forecasts by the International Energy Agency (IEA). The low scenario represents outcomes from policies that have already been enacted, the medium scenario represents national pledges that do not yet have supporting policies in place, and the high scenario reflects the electricity grid reaching net zero emissions by 2050.

The renewable hydrogen scenarios vary the carbon intensity of hydrogen used for aviation. The low scenario corresponds to grey hydrogen produced by steam methane reforming of natural gas. The high scenario corresponds to green hydrogen produced by electrolysis with net zero emissions electricity.

How was the default renewable energy scenario determined in the Forecast Scenario mode?

The default scenario represents an ambitious but realistic case that is possible with significant cross-sector investment and policy support. While it is difficult to synthesize multiple industry and national forecasts that apply to different energy markets, the default scenario attempts to align with publications from industry groups such as ATAG and IATA, and the stated goals of the US, EU, and ICAO.

Traffic

What flights are included?

The dataset is comprised of scheduled flights and includes 148 commercial aircraft types. General aviation, military, charter, and humanitarian air traffic are currently excluded, as they account for a small percentage of air traffic and are not in scope for industry net-zero targets.

What metrics are used to measure air traffic activity?

Air traffic activity is measured by multiplying the total number of passengers or amount of cargo by the distance flown. Depending on the units selected by the user, this may be indicated as passenger-kilometers (pkm) or tonne-kilometers (tkm).

Market-Based Measures

What is included in the Market-based Measures strategy in Forecast Scenario Mode?

Market-based Measures in Forecast Scenario mode includes a toggle to enable CORSIA, an ICAO program to reduce and offset emissions from international aviation. When CORSIA is activated, Cascade calculates emissions reductions due to the scheme, following the implementation methodology defined by ICAO.

The user can also create a Custom Global Initiative by modifying assumptions and extending the timeframe beyond 2035.

If the user would like to include voluntary carbon offsets or carbon removals, the Voluntary Measures toggle is available to customize.

What is included in the Market-based Measures strategy in Explore Strategies Mode?

In the Market-based Measures in Explore Strategies mode, the user can set a percentage of remaining emissions to be offset in a given scenario by moving the slider to a preferred state.

How does the CORSIA model work?

CORSIA—the Carbon Offsetting and Reduction Scheme for International Aviation—is an ICAO program to limit emissions from international aviation.

The Cascade CORSIA model calculates offsetting requirements and resulting emissions reductions due to the scheme, following the methodology defined by ICAO.

CORSIA is applied only to flights between participating member states, as defined by the official list published by ICAO.

What is the Custom Global Initiative?

Since the adoption of CORSIA, the aviation sector has significantly increased its ambition from enabling carbon-neutral growth from 2020 to achieving net-zero emissions by 2050.

The Custom Global Initiative allows users to explore how a potential carbon removal program could support international aviation in reaching net zero emissions. This is not intended to predict how future agreements may unfold, but rather to model the impacts of a range of potential scenarios.

This strategy is applied to all international flights, includes a customizable 2050 goal, and sets a split between allocation of emissions reduction requirements to individual operators or to the aviation sector as a whole.

Why is there an option to "Apply to all ICAO Member States" in the Market-based Measures strategy in Forecast Scenario mode?

The CORSIA model includes the actual list of participating member states, as published by ICAO. This checkbox allows users to see how much further emissions could be reduced if all ICAO member states opted in to CORSIA, starting in the voluntary phase.

What does the "Growth Split in 2050" mean in Custom Global Initiative in the Market-based Measures strategy?

Offsetting requirements under CORSIA include a "sectoral" component which is the same for all operators, and an "operator" component which depends on the increased emissions of the individual operator. This option allows users to explore how future schemes may weight the share of these two components.

Note that when analyzing the full global traffic network, this option will not have an effect as all results are aggregated across the sector.

Other

Will there be access to the advanced version of Cascade?

At this time, access to the advanced version of Cascade is limited to those within the Cascade User Community.

Will there be more detailed documentation about the models behind Cascade?

We will be releasing a comprehensive description of the Cascade methodology in the coming months. This information will provide an in-depth description of the logic and assumptions associated with the data and models.

What new features can we expect in future versions of Cascade?

Boeing intends to learn and prioritize new feature development alongside our partners in the Cascade User Community. As we do, we will continue to improve the Cascade model with periodic releases of new features. These proposed improvements include the ability to create and customize more detailed scenarios, refinement and improvement to the modeling approaches and customization of assumptions, and expanding the technical documentation. Future updates will be conveyed in release notes within Cascade and at https://cascade.boeing.com

Which views are available in the Forecast Scenario mode?

There are three views available in the Forecast Scenario mode. The Outlook view provides a wedge chart which allows you to forecast impacts of the selected strategies from the year 2019 through 2050. By selecting a specific year in the outlook chart, you can switch to the corresponding Annual view that shows a "cascading" chart visual for that year. The Map view, also known as Aviation Traffic, uses blue lines that represent routes flown by airlines around the world. It is an interactive visualization where you can zoom in, zoom out and pan around the map to explore aviation traffic.

What chart types are available in Cascade?

As a user you have the option to select different chart types to visualize data , which can be accessed through a dropdown menu located near the chart title. These visualizations include the following:

Within the Emissions tab, the Net CO_2-eq Emissions is the default chart type and shows the total net sum of greenhouse gas emissions in terms of carbon dioxide equivalent. You can also switch to the Cumulative CO_2-eq Emissions which utilizes the same data but accumulates it over time. Those are calculated by adding up all emissions for all years before a specific year and the year itself.

Within the Efficiency tab, the Fuel Efficiency displays fuel consumption for a given amount of passengers and/or cargo carried and distance traveled. Please note that if 'US Customary' is selected as the system for the sustainability metrics, the logic of the wedge and waterfall charts is reversed to reflect the efficiency gains via increases in miles per gallon. The Emissions Intensity informs the user about the greenhouse gas emissions for a given amount of passengers and/or cargo carried and distance traveled.

Within the Flights & Traffic tab, the Flights show the total number of flights over time. Additional metrics such as the Available or Revenue Seats are planned for the future.

Within the Energy Consumption tab, the Quantity of Jet Fuel shows the amount of jet fuel required and includes both conventional jet fuel and sustainable aviation fuel (SAF) while the Energy Consumption informs about the total energy consumed measured in jet fuel equivalent. Both can be displayed in absolute or normalized values and found in the Forecast Scenario mode only.

What metrics are shown throughout the application?

There are four metrics – also described as Aviation Metrics – that are visible throughout the application. Flights show the total number of scheduled flights for 148 commercial aircraft types. Fuel Efficiency displays total fuel consumption for a given amount of passengers and/or cargo carried and the distance traveled. Emissions Intensity is similar to fuel efficiency in calculation, however it measures greenhouse gas emissions instead of fuel consumption. Net CO_2-eq Emissions depict the total remaining net sum of greenhouse gas emissions in terms of carbon dioxide equivalent for a given scenario after emissions-reduction strategies are applied.