CASCADE

THE BOEING CASCADE CLIMATE IMPACT MODEL

Expanded FAQ

May 2023

Scenarios

Do any of the Forecast Scenarios ("wedge charts") reflect Boeing's view of the most likely future evolution of aviation emissions?

No. The default scenario shown when entering Cascade is a starting point 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 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.

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

The path to decarbonization is complex and involves a multitude of trade-offs that were distilled into the web-based application. Cascade employs a selection of simple sliders in the Forecast Scenario mode to visualize 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. The intention is to provide insights that are directionally correct to first-order at the global level.

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

Cascade builds on the influential work conducted in these efforts using similar analysis techniques and similar assumptions. However, Cascade is a standalone effort. In particular, Cascade's default scenario does not represent any specific scenario from recent ATAG [1], ICAO [2], or FAA [3] studies. Further, comparisons between Cascade and any other study can be challenging due to differing assumptions, methodology, and scope of air traffic activity considered.

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 to Cascade. 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?

No. The energy and fuel burn models provide generic unbiased aircraft performance estimates for a variety of original equipment manufacturers (OEMs). A future release of Cascade may include the option to select third-party fuel-burn models that were not developed by Boeing. As part of the fleet renewal methodology, previous-generation aircraft are replaced with new latest-generation aircraft from the same OEM wherever possible.

Emissions

What is the scope of emissions included in Cascade?

Cascade accounts for the lifecycle emissions of each fuel from “well-to-wake.” This includes the upstream emissions produced or sequestered during the production and distribution of the fuels used to power the aircraft, as well as the direct emissions produced by the aircraft due to combustion of the fuel. 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.

Aircraft manufacturing accounts for less than 1% of an aircraft's total lifecycle GHG emissions. [4] As a result, manufacturing emissions are not included in Cascade.

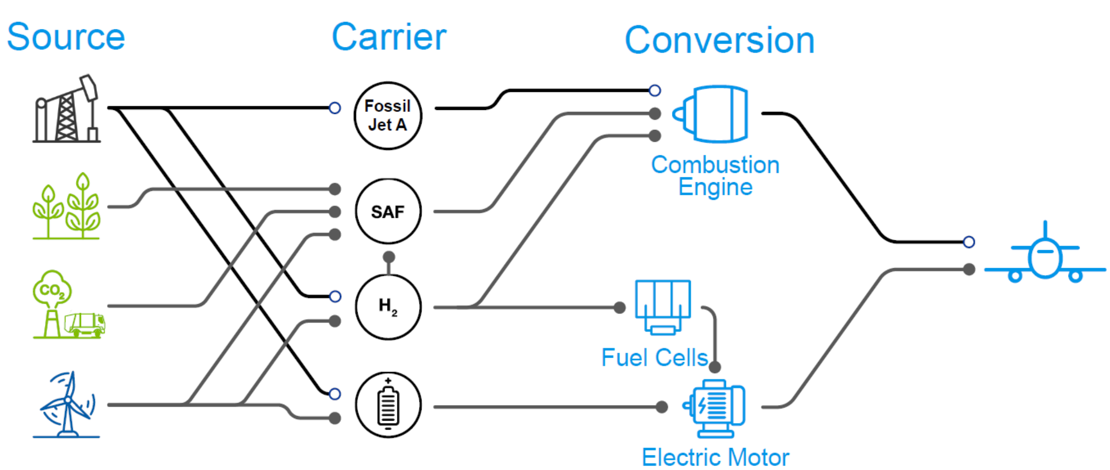

Figure 1 – Simplified schematic showing the energy sources, energy carriers, and aircraft concepts considered from a life cycle perspective within Cascade

What are net emissions?

Net emissions are the remaining emissions for a given scenario after emissions-reduction strategies are applied. Emissions 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 CO2-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 CO_2; other emissions that result from the combustion or use of the fuel and potential atmospheric effects are not modeled. Further, Cascade 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 or tonnes of cargo 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.

Fuel Consumption

How are aircraft fuel burn and emissions calculated?

Cascade estimates fuel and energy consumption based on factors such as aircraft type, flight distance, and estimated payload load factor (i.e., the amount of payload on the aircraft relative to the total payload capacity). The model employs a range of simplifying assumptions in order to enable rapid analysis. For example, Cascade does not attempt to account for any airline or region's operating rules, payload capacities, load factors, or other unique and specific factors. Instead, fuel consumption is calculated based only on a typical flight profile for a given aircraft type.

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).

Using the fleet renewal 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 [1] and the ICAO LTAG [2] [5].

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). [6] Hydrogen carbon intensity data is primarily derived from the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model. [7]

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). [1] 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. [8]

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 [1] and IATA [9], and the stated goals of the US [3], EU [10], and ICAO [2].

Traffic

What flights are included?

The dataset is comprised of commercial and scheduled traffic for 63 of the most commonly used commercial aircraft types. These aircraft types (by ICAO classification) were chosen to ensure the inclusion of more than 99% of global Revenue Tonne Kilometers (RTKs) - the industry standard measure of commercial aviation activity – which provides a measure of payload carried by the aircraft, given in tonnes, and distance flown, given in kilometers. 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), passenger-miles (pmi), or passenger-nautical-miles (pNM).

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 behind Cascade.

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. Sign up to be notified of future updates at https://sustainabilitytogether.aero

References

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