Environmental Trends in Aviation to 2050

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BACKGROUND

At the end of each three-year work cycle, the International Civil Aviation Organization (ICAO) Committee on Aviation Environmental Protection (CAEP) conducts an assessment of future environmental trends in aviation that includes:

- Aircraft engine Greenhouse Gas (GHG) emissions that affect the global climate,
- Aircraft noise, and
- Aircraft engine emissions that affect Local Air Quality (LAQ).

The environmental trends discussed in this section are based on the latest CAEP/11 air travel demand forecast data, using a base year of 2015. Forecast years were 2025, 2035, and 2045, and results were then extrapolated to 2050. The passenger and freighter forecasts were derived from ICAO's Long-Term Traffic Forecast, while the business jet forecast was developed by CAEP. Data presented for years earlier than 2015 are reproduced from prior CAEP trends assessments. Fuel burn and emissions results are for international aviation only, while noise trends include both domestic and international operations. In 2015, approximately 65 per cent of global aviation fuel consumption was from international aviation. This proportion is expected to remain relatively stable out to 2050.

The trends presented here were developed in the context of a longer-term view, and assume that there would be no airport infrastructure or airspace operational constraints. Such trends can be affected substantially by a wide range of factors such as fluctuations in fuel prices, and global economic conditions.

Three environmental models contributed results to the fuel burn and emissions trends assessment: US Federal Aviation Administration's (FAA) Aviation Environmental Design Tool (AEDT), EUROCONTROL's IMPACT, and Manchester Metropolitan University's Future Civil Aviation Scenario Software Tool (FAST). Three models contributed results to the noise trends assessment: US FAA's AEDT, EC / EASA / EUROCONTROL's SysTem for AirPort noise Exposure Studies (STAPES), and UK Civil Aviation Authority's (CAA) Aircraft Noise Contour Model (ANCON).

Key databases utilized in this assessment included: CAEP's Global Operations, Fleet, and Airports Databases.

TRENDS IN EMISSIONS THAT AFFECT GLOBAL CLIMATE

Table 1 below summarizes the aircraft technology and operational scenarios developed for the assessment of trends for fuel burn and aircraft emissions that affect the global climate.

TABLE 1: Fuel Burn and GHG Emissions - Technology and Operational Improvement Scenarios

Scenario	Aircraft Technology: per annum fuel burn improvements for fleet entering after base year	Aircraft Technology: Emissions Improvements against CAEP/7 IE NOx Goal	Additional Fleet-Wide OP Improvements by Route Group from CAEP/9 IE
Fuel 1 - Baseline	NA: use only base-year in-production fleet	NA	NA: maintain baseline meet-demand efficiency
Fuel 2 - Low Aircraft Technology and CAEP/9 IE Operational Improvements	Low: 0.96% to 2015 then 0.57% to 2050	NA	Apply added fleet-wide improvements
Fuel 3 - Moderate Aircraft Technology and CAEP/9 IE Operational Improvements	Moderate: 0.96% to 2050	NA	Apply added fleet-wide improvements
Fuel 4 - Advanced Aircraft Technology and CAEP/9 IE Operational Improvements	Advanced: 1.16% to 2050	NA	Apply added fleet-wide improvements
Fuel 5 - Optimistic Aircraft Technology and CAEP/9 IE Operational Improvements	Optimistic: 1.5% to 2050	NA	Apply added fleet-wide improvements
NOx 1 - Baseline	NA	NA	NA
NOx 2 - Moderate Aircraft Technology, CAEP/9 IE Operational, and 50% CAEP/7 IE Emissions Improvements	Moderate: 0.96% to 2050	50% by 2026 nothing thereafter	Apply added fleet-wide improvements
NOx 3 - Advanced Aircraft Technology, CAEP/9 IE Operational, and 100% CAEP/7 IE Emissions Improvements	Advanced: 1.16% to 2050	100% by 2026 nothing thereafter	Apply added fleet-wide improvements

Trends in Full-Flight Fuel Burn and CO_2 Emissions

Figure 1 shows results for global full-flight (i.e., from departure gate to arrival gate) fuel burn for international aviation from 2005 to 2045, and then extrapolated to 2050. The fuel burn analysis considers the contribution of aircraft technology, improved air traffic management, and infrastructure use (i.e., operational improvements) to reduce fuel consumption. The Figure also illustrates the fuel burn that would be expected if ICAO's 2% annual fuel efficiency aspirational goal were to be achieved.

Even under the most optimistic scenario, the projected long-term fuel efficiency of 1.37% per annum falls short of ICAO's aspirational goal of 2% per annum. The long-term forecast fuel burn from international aviation is lower by about 25% compared with prior CAEP trend projections. This decrease can be attributed to a combination of more fuel efficient aircraft entering the fleet, as well as a reduction in the forecast long-term traffic demand. The computed 1.37% per annum long-term fuel efficiency includes the combined improvements associated with both technology and operations. The individual contributions from technology and operations is .98% and .39%, respectively. The .98% is slightly lower than the 1.3% cited in the latest CAEP/11 Independent Experts (IE) Review for single aisle aircraft.

Figure 2 depicts these contributions in the context of the uncertainties associated with the forecast demand, which is notably larger than the range of potential contributions from technological and operational improvements. Despite these uncertainties, the CAEP/11 forecast traffic trends are broadly consistent with other published aviation forecasts. The forecast commercial market trend, which is for available tonne kilometres (ATK), shows a 20 year (2015-2035) compound average annual growth rate (CAGR) of 4.3%. By way of comparison, using revenue passenger kilometres (RPK) for all traffic as the forecast measurement, forecasts of Boeing, Airbus and Embraer for 2015 have 20-year (2015-2035) CAGRs of 4.8%, 4.5%, and 4.7%, respectively. The CAEP/11 RPK 20-year forecast (2015-2035) has a CAGR of 4.4%.

Figure 3 presents full-flight CO_2 emissions for international aviation from 2005 to 2045, and then extrapolated to 2050. This Figure only considers the CO_2 emissions associated with the combustion of jet fuel, assuming that 1 kg of jet

FIGURE 1: Fuel Burn from International Aviation, 2005 to 2050

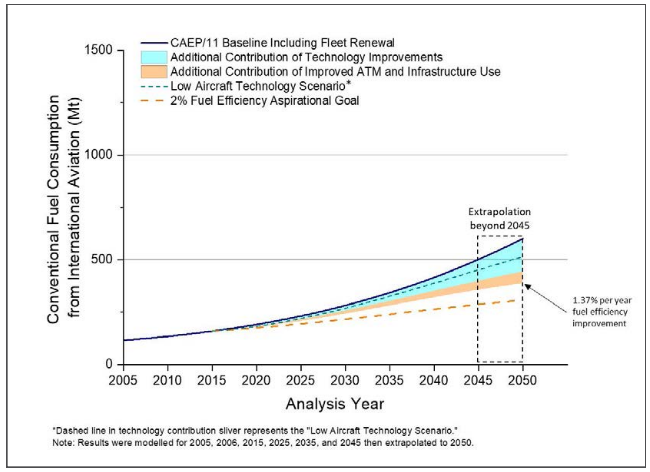


FIGURE 2: Range of Uncertainties Associated with Demand Forecast, 2005 to 2050

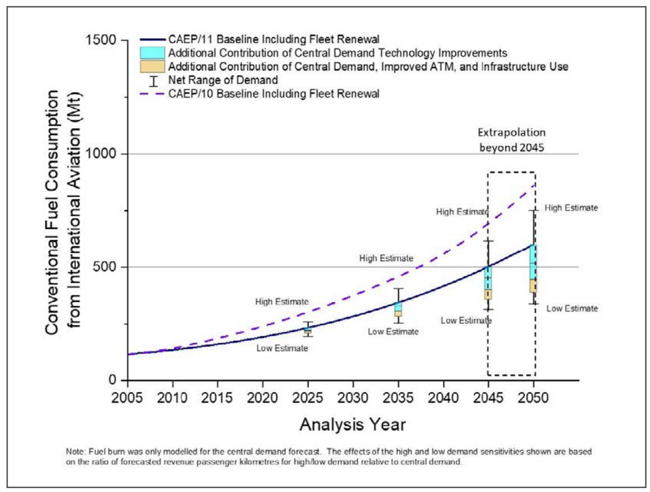
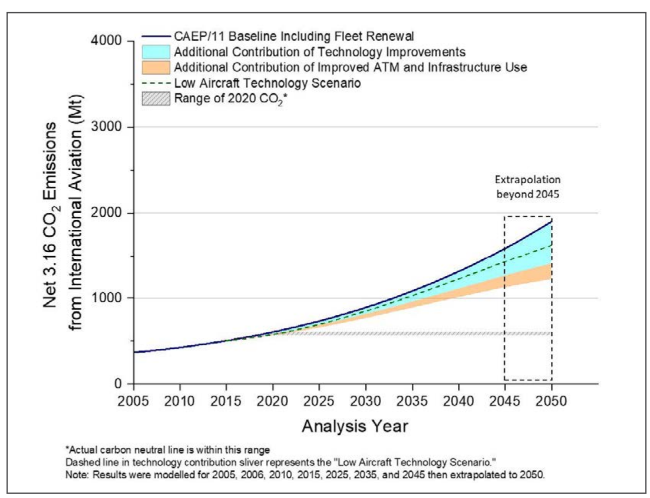


FIGURE 3: CO_2 Emissions from International Aviation, 2005 to 2050



fuel burned generates 3.16 kg of CO_2. As with the previous fuel burn analyses, this analysis considers the contribution of: aircraft technology, improved air traffic management, and infrastructure use (i.e., operational improvements). In addition, the range of possible CO_2 emissions in 2020 is displayed relative to the global aspirational goal of keeping the net CO_2 emissions at this level.

Although not displayed in a separate figure, the demand uncertainty effect on the fuel burn calculations shown in Figure 3 has a similar effect on the CO_2 results. With reference to the fuel consumption scenarios in Table 1; the highest anticipated fuel consumption in 2020 (Scenario 1), and the lowest anticipated fuel consumption in 2045 (Scenario 5), a minimum CO_2 emission gap of 517 million metric tonnes (Mt, 1kg × 10^9) is projected for 2045. Extrapolating Scenario 5 to 2050, results in a minimum gap of 612 Mt.

Contribution of Alternative Fuels to Fuel Consumption and CO_2 Trends

CAEP's Alternative Fuels Task Force (AFTF) was charged with calculating estimates of sustainable aviation fuel (SAF) contributions to fuel replacement and life cycle GHG emissions reductions in conducting its trends assessment out to 2050. Analyses were performed for 2020 and 2050. The short-term scenarios for SAF availability were established from announcements made by fuel producers regarding their production plans from State-sponsored production plans. For the long-term scenarios, CAEP assessed future jet fuel availability in three ways: by estimating the primary bioenergy potential constrained by selected environmental and socio-economic factors, by estimating the proportion of bioenergy potential that could actually be achieved or produced, and by exploring the quantity of SAF that could be produced from the available bioenergy. SAF availability calculations included 9 different groups of feasible feedstocks: starchy crops, sugary crops, lignocellulosic crops, oily crops, agricultural residues, forestry residues, microalgae, municipal solid waste, and waste fats, oils and greases. The final values provided by AFTF to the Modelling and Databases Group (MDG) include potential total global production, and an average Life Cycle Assessment (LCA) value based on the share of different fuel types that contribute to each scenario. The LCA values are not intended to be applied separately to regional forecasts.

For 2020, there were six production estimates and two GHG LCA estimates (low and high), resulting in 12 possible GHG emissions scenarios. The 2020 scenarios result in up to 2.6% petroleum-based fuel replacement and up to 1.2% GHG emissions reductions.

For 2050, CAEP calculated 60 production achievement scenarios and two GHG emissions scenarios, resulting in a total of 120 scenarios. Certain global conditions, economic investments, and policy decisions are assumed as part of each scenario definition, and would be necessary to reach the associated outcome of alternative fuel production and GHG reductions.

The trend assessment figures for international aviation shown below include the range of CAEP results, and an "illustrative" scenario that achieves 19% net CO_2 emissions reduction, assuming significant policy incentives and high biomass availability. Fuel replacement results for international aviation can be found in Figure 4, and Net CO_2 emissions results are shown in Figure 5. The amount of SAF, and the associated CO_2 emission reductions were allocated proportionally between international use and domestic use, based on projected fuel demand (65% and 35% in 2015, respectively).

For 2020 and 2050, total petroleum-based fuel amounts for the different fuel demand scenarios were multiplied by the specific CO_2 combustion emissions factor of 3.16 to get the baseline GHG emissions shown in Figure 5. Calculations of GHG emissions reduction were performed according to the following formula provided by the CAEP Market-Based Measures Task Group:

Total Emissions = 3.16 × (CJF + SAF*(LCA_SAF/LCA_CJF))

Where CJF = conventional jet fuel, SAF = sustainable aviation fuel, and LCA_X = life cycle CO_2 equivalent emissions of fuel X.[1]

1 This calculation provides an "in-flight" equivalent of CO_2 emissions reduction based on the life cycle values of the alternative fuels, which are used because reductions in atmospheric carbon from aviation biofuel use occur from feedstock production and fuel conversion and not from fuel combustion.

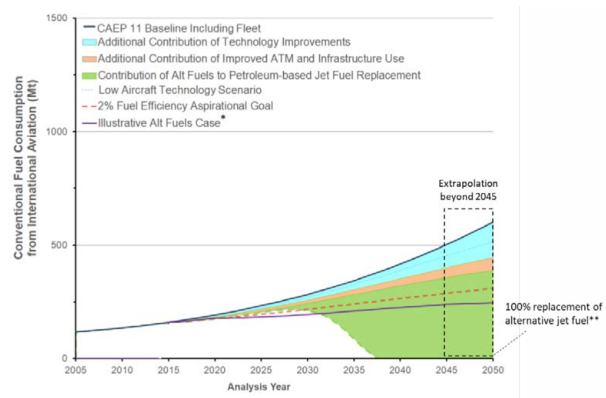
The green GHG reduction "wedge" was created by connecting the least contribution scenario values to each other and the greatest contribution values to each other. The 2020 "medium scenario without green diesel" was connected to the 2050 value for the illustrative scenario. CAEP elected to assume a linear growth for intermediate and high GHG reduction scenarios.[2]

Several of the 2050 scenarios that CAEP evaluated resulted in zero alternative jet fuel production and therefore no contribution to GHG emissions reduction.[3] The zero SAF results are equivalent to the line associated with Scenario 5 for technology and operational improvements as described above. The scenario with the largest contribution to GHG emissions reduction could supply more alternative jet fuel than is anticipated to be used in 2050. For the purposes of this analysis, production for the highest contribution scenario is ramped up to full replacement in 2050, based on Scenario 5.

If the alternative fuel industry growth were to follow an S-shaped curve, the highest growth rates would occur around 2035, in which 328 new large bio-refineries would need to be built each year at an approximate capital cost of US$29 billion to US$115 billion per year. Lower growth rates would be required in years closer to 2020 and 2050. If growth occurred linearly, complete replacement would require approximately 170 new large bio-refineries to be built every year from 2020 to 2050, at an approximate capital cost of US$15 billion to US$60 billion per year.

Achieving the most optimistic net CO_2 emissions scenario would require the highest levels of: agricultural productivity, availability of land for feedstock cultivation, residue removal rates, conversion efficiency improvements, and reductions in the GHG emissions of utilities. It would also require a strong market or policy emphasis on bioenergy in general, and alternative aviation fuel in particular. This implies that a large share of the globally available bioenergy resource would be devoted to producing aviation fuel, as

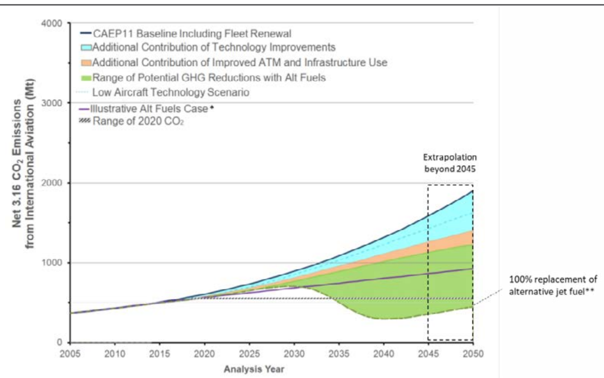
FIGURE 4: Conventional Fuel Consumption from International Aviation, 2005 to 2050, Including Potential Replacement by Alternative Fuels



*Illustrative case would require high availability of bioenergy feedstock, the production of which is significantly affected by price or other policy mechanisms;

**100% replacement of alternative jet fuel would require a complete shift in aviation consumption, from petroleum to biofuel based fuels, and a significant expansion of the agricultural sector, both of which would require substantial policy support.

FIGURE 5: Net CO_2 Emissions from International Aviation, 2005 to 2050, Including Alternative Fuels Life Cycle CO_2 Emissions Reductions (Based on 3.16 kg of CO_2 per 1 kg of fuel burn)



2 CAEP did not specify a function for connecting the 2020 results to the 2050 results in their outputs. However, CAEP did provide information on the range of options for connecting these results. CAEP anticipates that growth of a new industry such as that for SAF will follow an "S-shaped" trajectory, but it is not clear when investment, and therefore, growth of production capacity of the industry, will ramp up. Ramp up to alternative fuel production in 2050 is anticipated to be somewhere between linear and exponential growth (i.e., the lower end of the S-curve). Linear growth for intermediate and high net CO_2 emissions reduction scenarios is shown. No meaningful data exists with which to calibrate the curve. Therefore, values for the intervening years, between 2020 and 2050, for the SAF scenarios should be considered illustrative only.

3 These scenarios reflect a lack of bioenergy availability in general or a prioritization of other bioenergy usages over aviation.

opposed to other uses. It should be noted that all the CO_2 emission scenarios evaluated considered rainfed energy crop production only on land available after satisfying predicted 2050 food and feed demand. Additionally, primary forests and protected areas were not considered for conversion to cultivated energy crop production.

Achievement of carbon neutral growth at 2020 emissions levels out to 2050 would require nearly complete replacement of petroleum-based jet fuel with sustainable alternative jet fuel and the implementation of aggressive technological and operational scenarios. The effort required to reach these SAF production volumes would have to significantly exceed historical precedent for other alternative fuels, such as ethanol and biodiesel for road transportation.

Interpretation

In 2015, international aviation consumed approximately 160 Mt of fuel, resulting in 506 Mt of CO_2 emissions. By 2045, fuel consumption is projected to have increased 2.2, or 3.1 times the 2015 value, while revenue tonne kilometres are expected to increase 3.3 times under the most recent forecasts. Extrapolating to 2050, fuel consumption is projected to increase 2.4 to 3.8 times the 2015 value, while revenue tonne kilometres are expected to increase 3.9 times.

Under the most optimistic Scenario 5, as defined in Table 1, international aviation fuel efficiency, expressed in terms of volume of fuel per RTK, is expected to improve at an average rate of 1.29% per annum to 2045, and at 1.37% per annum, if extrapolated to 2050. This indicates that ICAO's aspirational goal of 2% per annum fuel efficiency improvement is unlikely to be met by 2050. While in the near-term (2015 to 2025), efficiency improvements from technology and improved ATM and infrastructure use are expected to be moderate, they are projected to accelerate in the mid-term (2025 to 2035). During that 2025 to 2035 period, fuel efficiency is expected to improve at an average rate of 1.08% per annum under Scenario 5. This is about as expected, given the 1.5% per annum fuel technology improvement associated with Scenario 5, and the variability of the forecasted RTK.

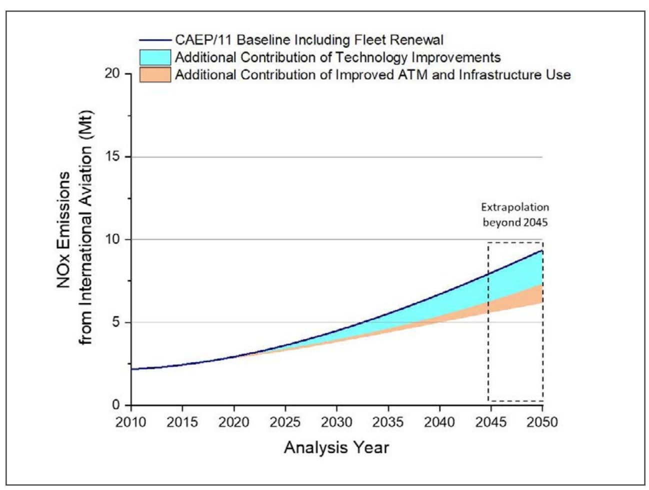
By 2025, it is expected that international aviation will require somewhere between 207 and 226 Mt of fuel, resulting in 655 to 713 Mt of CO_2 emissions. A number of near-term scenarios evaluated by CAEP indicate that up to 2.6% of fuel consumption needs by 2020 could be satisfied by SAF. This analysis also considered the long-term availability of sustainable alternative fuels, finding that it would be physically possible to meet 100% of demand by 2050 with SAF, corresponding to a 63% reduction in emissions. However, this level of fuel production could only be achieved with extremely large capital investments in sustainable alternative fuel production infrastructure, and substantial policy support.

Even under this scenario, achieving carbon neutral growth exclusively from the use of sustainable alternative fuels is unlikely to happen by 2020 or shortly thereafter as an initial ramp-up phase for the production of SAF is required before production can reach the levels mentioned above. Market-based measures are anticipated to help fill the gap to carbon neutral growth, although also later than 2020.

Trends in Full-Flight NOx Emissions

Trends in full-flight nitrogen oxides (NOx) emissions from international aviation are shown in Figure 6. The 2015 baseline NOx emissions were 2.50 Mt. In 2045, forecast NOx emissions range from 5.53 Mt under Scenario 3, to 8.16 Mt under Scenario 1. As with fuel burn, the long-term full-flight NOx from international aviation is lower by about 21% compared with the prior trends projections. This can be attributed to a combination of aircraft with lower NOx engines entering the fleet, as well as a reduction in forecasted long-term traffic demand.

FIGURE 6: Full-Flight NOx Emissions from International Aviation, 2010 to 2050



TRENDS IN AIRCRAFT NOISE

A range of scenarios was developed for the assessment of future noise trends. The noise indicators used are the total contour area and population inside the yearly average day-night level (DNL) 55 dB contours of 315 airports worldwide, representing approximately 80% of the global traffic.

Scenario 1 (CAEP/11 Baseline) assumes no further aircraft technology or operational improvements after 2015. Scenarios 2, 3, and 4 (low, moderate, advanced technology) assume that the noise levels of all new aircraft delivered after 2015 will reduce at a rate of 0.1, 0.2, and 0.3 EPNdB[4] per annum, respectively. For all scenarios, an additional 2% reduction is applied to the population counts inside the noise contours, to reflect a possible improvement of aircraft routing around airports.

Population counts for airports in the US, Europe, and Brazil rely on local census data. For all other airports, the NASA Gridded Population of the World, version 4 (GPW v4) was used.

Figure 7 shows the total 55 dB DNL noise contour area from 2010 to 2050. In 2015, this area was 14,400 square-kilometres, and the population inside that area was approximately 30 million people. By 2045, the area is expected to grow from 1.0 to 2.2 times, compared with 2015, depending on the technology scenario. Of note is that under the advanced aircraft technology scenario (Scenario 4), from about 2030 onwards, the total yearly average DNL contour area may no longer increase with an increase in traffic. The long-term total DNL 55 dB contour area is lower by about 10%, compared with the prior trends projections. This decrease can be attributed to a combination of quieter aircraft entering the fleet, as well as a reduction in the long-term traffic demand.

TRENDS IN EMISSIONS THAT AFFECT LOCAL AIR QUALITY

A range of scenarios have also been developed for the assessment of aircraft emissions that occur below 3,000 feet above ground level (AGL) and affect local air quality; namely NOx and total (volatile and non-volatile) particulate matter (PM). The NOx scenarios are the same as in Table 1. For assessing PM trends, there are two scenarios as follows: Scenario 1 (CAEP/11 Baseline) assumes no further aircraft technology or operational improvement after 2015. Scenario 2, represented by the bottom of the orange sliver, assumes that only operational improvements apply, with no aircraft technology improvements.

Figure 8 provides results for NOx emissions below 3,000 feet AGL from international aviation from 2010 to 2050. The 2015 NOx emissions were 0.18 Mt. In 2045, they are forecast to range from 0.44 Mt under Scenario 3, to 0.80 Mt under Scenario 1. The projections of NOx emissions below 3,000 feet are lower by about 2% compared with the prior

FIGURE 7: Total Aircraft Noise Contour Area Above 55 dB DNL for 315 Airports (km²), 2010 to 2050

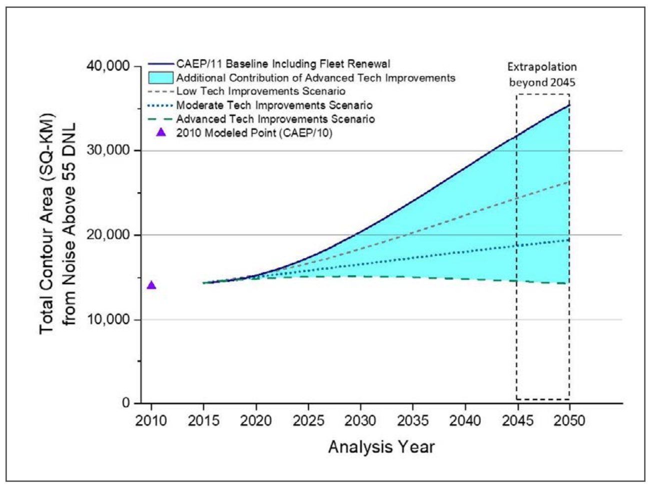
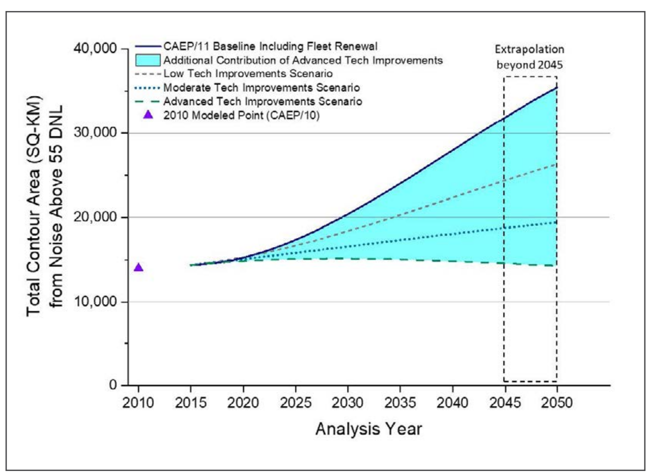


FIGURE 8: NOx Emissions below 3,000 Feet - International Aviation, 2010 to 2050.



4 EPNdB is Effective Perceived Noise Level in Decibels.

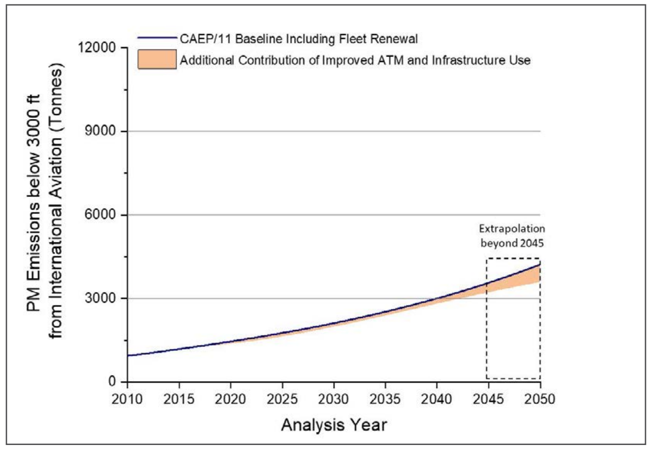
trend projections. This will be due to three main factors: a combination of aircraft with lower NOx engines, a reduction in the long-term traffic demand, and a refinement to the method used for computing emissions below 3,000 feet.

The results for PM emissions from international aviation below 3,000 feet AGL follow similar trends as those for NOx, as shown in Figure 9. The 2015 PM emissions were 1,243 tonnes (t). In 2045, they are projected to range from 3,230 t under Scenario 2, and 3,572 t under Scenario 1.

CONCLUSION

Emissions from international aviation that affect the global climate and local air quality are expected to increase through 2050, by a factor ranging from approximately 2 to 4 times the 2015 levels, depending on the type of emissions (CO_2, NOx or PM), and the analysis Scenario used. Under an advanced aircraft technology scenario, the total area of day-night levels (DNL) noise contours around airports may stabilize after 2030. However, it should be kept in mind that the uncertainty associated with future aviation demand is notably larger than the range of contributions from technology and operational improvements.

FIGURE 9: PM Emissions Below 3,000 feet - International Aviation, 2010 to 2050.



International aviation fuel efficiency is expected to improve through 2050, however ICAO's aspirational goal of 2% per annum fuel efficiency improvement is unlikely to be met by then. The aspirational goal of carbon neutral growth after 2020 is also unlikely to be met. Sustainable alternative fuels have the potential to fill the gap to carbon neutral growth but not in the short term, and data is still lacking to confidently predict their availability over the long term. Market-based measures can help fill that gap as well, but also later than 2020.

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