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INTERNATIONAL CIVIL AVIATION ORGANIZATION

REPORT ON THE FEASIBILITY OF A LONG-TERM ASPIRATIONAL GOAL (LTAG) FOR INTERNATIONAL CIVIL AVIATION CO_2 EMISSION REDUCTIONS

ICAO COMMITTEE ON AVIATION ENVIRONMENTAL PROTECTION

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REPORT ON THE FEASIBILITY OF A LONG-TERM ASPIRATIONAL GOAL (LTAG) FOR INTERNATIONAL CIVIL AVIATION CO_2 EMISSION REDUCTIONS

ICAO COMMITTEE ON AVIATION ENVIRONMENTAL PROTECTION (CAEP)

March 2022

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EXECUTIVE SUMMARY

During the 40th Session of the ICAO Assembly, ICAO Member States requested the Council to continue to explore the feasibility of a long-term global aspirational goal (LTAG) for international civil aviation through conducting detailed studies assessing the attainability and impacts of any goals proposed, including the impact on growth as well as costs in all countries, especially developing countries, for the progress of the work to be presented at the 41st ICAO Assembly.

The CAEP Long-Term Aspirational Goal Task Group (LTAG-TG), in coordination with other CAEP working groups (e.g. Forecasting and Economic Analysis Support Group (FESG), Modelling and Databases Group (MDG)), undertook data gathering from internal and external sources, and the development of three integrated in-sector scenarios based on a subset of scenarios for technology, fuels, and operations each, that represent a range of readiness and attainability levels. Scenarios were analysed to understand the impacts on CO_2 emissions, costs and investments, as well as potential implications on aviation growth, noise, and air quality. The LTAG-TG also documented underlying data for analysing the impact in all countries especially developing countries. Finally, the scenarios were placed within the context of the latest consensus scientific knowledge.

High-level Observations:

While the integrated scenarios show the potential for substantial CO_2 reduction, none of the scenarios reach zero CO_2 emissions using in-sector measures (i.e. technology, operations, and fuels). This is due to the consideration of fuels' life cycle emissions and occurs despite a 100% replacement of conventional jet fuel with novel fuels e.g. Sustainable Aviation Fuel (SAF)-biomass, waste or atmospheric CO_2 based fuels or hydrogen. It is useful to note that as other aspects of economies reduce their emissions, the life cycle value should drop as well. With the scope of the LTAG-TG limited to consider in-sector measures only, 'out of sector' measures were not considered in the LTAG-TG analysis.

The overall traffic growth rate has an important impact on residual CO_2 emissions by 2050 and after.

Drop-in fuels have the largest impact on residual CO_2 emissions driving the overall reductions by 2050. This is, to some extent, independent of the technology and operations scenarios. Hydrogen is not expected to have a significant contribution by 2050 (with only 1.9% of energy share in 2050) but this may increase in the 2050s and 2060s if technically feasible and commercially viable.

Advanced tube and wing aircraft have a clear potential to improve the fuel (energy) efficiency of the international aviation system with some incremental contribution from aircraft with unconventional configurations. Hydrogen powered aircraft would exhibit worse energy efficiency, relative to aircraft operating on liquid fuels, noting that emissions reductions would come from life cycle emissions reductions from the hydrogen.

Analysis shows there are opportunities for operations to reduce CO_2 emissions through improvements in the performance of flights across all phases, including unconventional measures such as formation flying.

The costs and investments associated with the scenarios are largely driven by fuels (e.g. SAF) acknowledging that incremental costs of fuels (i.e. minimum selling price of SAF compared to conventional jet fuels) further motivates fuel (energy) efficiency improvements from aircraft technology and operations. This will also require some investments from governments and industry.

Aircraft technology and associated design decisions will continue to address the global market needs and will not vary by region. Aircraft operators in various regions or States will buy the best aircraft available that meet their needs. Regional variances in implementation of operational measures are also expected. Most significant regional variations are expected in the production and uptake of fuels. This is due to a range of factors such as regional availability of waste and biomass feedstocks, CO_2 and cryogenic hydrogen, renewable energy, market dynamics and infrastructure.

While a limited number of scenarios were constructed by the LTAG-TG to capture increasing aspirations across technology, operations and fuels, there are multiple paths that may result in similar levels of CO_2 emissions. The LTAG-TG analyses show that there is robustness in the LTAG scenarios and analyses, noting that although different pathways can lead to similar levels of CO_2 emissions they may have different implications e.g. in terms of costs (investments) and regional impacts.

This report is the result of nearly two years of intensive work by CAEP. The following sections provide the background, methodologies, results, and interpretations of the LTAG-TG study. A set of supporting appendices also provide modelling approaches, methodologies, models, assumptions, and the depicting of results for the sake of transparency and comprehensiveness.

1. BACKGROUND

1.1 During the 40th Session of the ICAO Assembly (24 September to 4 October 2019), ICAO Member States requested the Council to continue to explore the feasibility of a long-term global aspirational goal (LTAG) for international civil aviation, through conducting detailed studies assessing the attainability and impacts of any goals proposed, including the impact on growth as well as costs in all countries, especially developing countries, for the progress of the work to be presented to the 41st Session of the ICAO Assembly (Assembly Resolution A40-18, operative paragraph 9, refers).

1.2 At the 219th Session of the Council, on 13 March 2020, the Council agreed to the organization of work to assess the feasibility of a LTAG as captured in the Terms of Reference for the CAEP Long-Term Aspirational Goal Task Group (LTAG-TG).

1.3 Upon the agreement by the Council, the CAEP LTAG-TG undertook: (1) data gathering from internal and external sources in a transparent and inclusive manner, (2) development of combined in-sector scenarios from technology, fuels, and operations that represent a range of readiness and attainability based on the data gathering, and (3) conducted final analysis of the scenarios to understand those impacts on CO_2 emissions and cost associated with the scenarios and economic impacts on aviation growth, noise and air quality, in all countries especially developing countries and the results were placed within the context of the latest consensus scientific knowledge.

1.4 The work of the LTAG-TG was performed by dedicated subgroups with experts on aircraft technology (TECH-SG), operational procedure improvements (OPS-SG), fuel production (FUEL-SG), as well as a scenario development subgroup (SD-SG) that coordinated the work across the other SGs and with groups outside of the LTAG-TG such as the MDG and FESG. A Cost Estimation ad hoc group (CEahg) was also formed under the LTAG-TG SDSG to specifically examine cost/investment aspects of the analysis. This final report consolidates cumulative efforts of over 280 experts with more than 200 calls and provides a technical assessment of the feasibility of an LTAG which includes a proposed CAEP recommendation to the Council including options and roadmaps for their realization.

2. SUMMARY OF RESULTS AND SOME HIGH-LEVEL OBSERVATIONS

2.1 Based on the complex and in-depth analyses by CAEP, a few high-level observations were made:

a) While the scenarios show the potential for substantial CO_2 reduction, none of the scenarios reach zero CO_2 emissions through the use of in-sector measures (i.e. technology, operations, and fuels). This is due to the consideration of fuels' life cycle emissions and occurs despite a 100% replacement of conventional jet fuel with novel fuels e.g. Sustainable Aviation Fuel (SAF)-biomass, waste or atmospheric CO_2 based fuels or hydrogen. It is useful to note that as other aspects of economies reduce their emissions, the life cycle value should drop as well. With the scope of the LTAG-TG limited to consider in-sector measures only, 'out-of-sector' measures were not considered in the LTAG-TG analysis.

b) The overall traffic growth rate has an important impact on residual CO_2 emissions by 2050 and after.

c) Drop-in fuels have the largest impact on residual CO_2 emissions driving the overall reductions by 2050. This is, to some extent, independent of the technology and operations scenarios. Onboard hydrogen is not expected to have a significant contribution by 2050 (with only 1.9% of energy share in 2050) but this may increase in the 2050s and 2060s if technically feasible and commercially viable.

d) Advanced tube and wing aircraft have a clear potential to improve the fuel (energy) efficiency of the international aviation system, as do aircraft with unconventional configurations, which will gradually contribute to efficiency. The technology wedge continues to grow after 2050 when these aircraft types penetrate the fleet. However, caution is required with the interpretation of absolute CO_2 emissions levels due to modelling assumptions e.g. aircraft continue to enter the fleet, but their technology is frozen at a 2050 level (no further technology improvements assumed after 2050), which shows CO_2 emissions after 2050 to be higher than would otherwise be expected). Hydrogen powered aircraft would exhibit worse energy in flight relative to aircraft operating on drop-in fuels, noting that its CO_2 emissions reductions depend on the life cycle of the hydrogen used, and drop-in fuels production can exhibit worse energy efficiency than liquid hydrogen production on a lifecycle basis.

e) Analysis shows there are opportunities for operations to reduce CO_2 emissions through improvements in the performance of flights across all phases, including unconventional measures such as formation flying.

f) The costs and investments associated with the scenarios are largely driven by fuels (e.g. SAF) acknowledging that incremental costs of fuels (i.e. minimum selling price of SAF compared to conventional jet fuels) further motivates fuel (energy) efficiency improvements from aircraft technology and operations. This will also require some investments from governments and industry.

g) While a limited number of scenarios were constructed by the LTAG-TG to capture increasing aspirations across technology, operations and fuels, there are multiple paths that may result in similar levels of CO_2 emissions. The LTAG-TG analyses show that there is robustness in the LTAG scenarios and analyses.

3. METHODOLOGY

3.1 **Integrated scenarios:** Three integrated scenarios were developed for LTAG to cover a range of "readiness, attainability, and aspiration".

3.1.1 **Integrated Scenario 1 (IS1)** reflecting "high readiness/attainability and low aspiration". This low or nominal scenario represents the current (c. 2021) expectation of future available technologies, operational efficiencies, and fuel availability. It includes expected policy enablers for technology, operations and fuels and low systemic change, for example no substantial infrastructure changes. Of the three scenarios, it requires the lowest effort for delivery, though this could still be considerable for individual actors.

3.1.2 **Integrated Scenario 2 (IS2)** depicting "middle readiness/attainability and middle aspiration". This increased or further ambition scenario represents an approximate mid-point between the two other scenarios – faster rollout of future technologies, increased operational efficiencies and higher fuel availability. It assumes increased policy enablers for technology, operations and fuels and increased systemic change, for example limited infrastructure changes. Of the three scenarios, it requires medium effort for delivery.

3.1.3 **Integrated Scenario 3 (IS3)** representing "low readiness/attainability and high aspiration". This aggressive or high ambition scenario represents the maximum possible effort in terms of future technology rollout, operational efficiencies, and fuel availability. It assumes maximum policy enablers for technology, operations, and fuels and high, internationally aligned systemic change, for example significant and broad change to airport and energy infrastructure. Of the three scenarios, it requires the highest effort for delivery.

3.1.4 All scenarios are placed in context of an Integrated Scenario 0 (IS0) which represents emission reductions through fleet evolution based on aircraft technology frozen at a 2018 level and with no additional improvements from operations and fuels. This IS0 scenario, which is identical to the CAEP/12 Trends baseline scenario, includes the benefits of fleet renewal whereby airlines make substantial investments towards the acquisition of new aircraft (even if the technology is frozen in 2018 level). CAEP has not modelled a "frozen 2018 fuel efficiency" scenario, in CAEP Trends or the LTAG-TG analysis. Such additional scenario would exhibit fuel burn and CO_2 emissions trends above the IS0 (baseline) scenario, and would capture this incremental contribution from airline fleet renewal. This would not have changed in any way the results of the LTAG-TG study.

3.2 **Modelling framework:** Recognising that the LTAG-TG task is to assess the feasibility of possible future scenarios, the LTAG-TG has taken advantage of tools and methodologies from the Forecasting and Economics Study Group (FESG) and the Modelling and Database Group (MDG) for CAEP Trends. This included leveraging the most recent CAEP/12 trends analysis. For this work, the base year for the LTAG analysis was set to 2018 with the time frame extended to 2070 to be able to observe the impact of new technologies that are introduced into the fleet in 2050. The forecasts have been done by the FESG representing low, medium, and high forecasts of post-COVID international aviation traffic consistent with the Trends.

3.3 **Cost (investment) estimation:** Costs and investments (e.g. non-recurring cost, fuel costs, capital expenditure) associated with LTAG scenarios were quantitatively assessed to develop a total and temporal distribution of costs and investments across different groups of stakeholders. Where potential costs/investments and economic impacts were identified that could not be quantified, they have been described qualitatively.

4. SUMMARY OF RESULTS

4.1 Introduction

4.1.1 This summary of results is structured such that it addresses the following questions.

- How could in-sector measures (i.e. technology, operations, and fuels) help reduce CO_2 emissions from international aviation through 2050 and beyond? (Section 4.2);
- Given CO_2 emissions trends for each scenario, what would be the cumulative emissions from international aviation? How do these cumulative aviation emissions compare to requirements to limit the global temperature increase to 1.5°C and 2°C? (Section 4.3);
- What investments are required to support the implementation of the in-sector measures associated with each scenario? What would be the cost impacts to aviation stakeholders? (Section 4.4);
- What would be the impacts of various future aviation traffic levels? (Section 4.5); and
- How sensitive are the results to scenario assumptions? (Section 4.6).

4.2 International Aviation CO_2 Emissions Trends

4.2.1 Using the modelling framework described in section 3.2, the CAEP assessed CO_2 emissions from international aviation for each scenario IS1, IS2 and IS3. Unless stated otherwise, results are quoted for the mid traffic forecast.

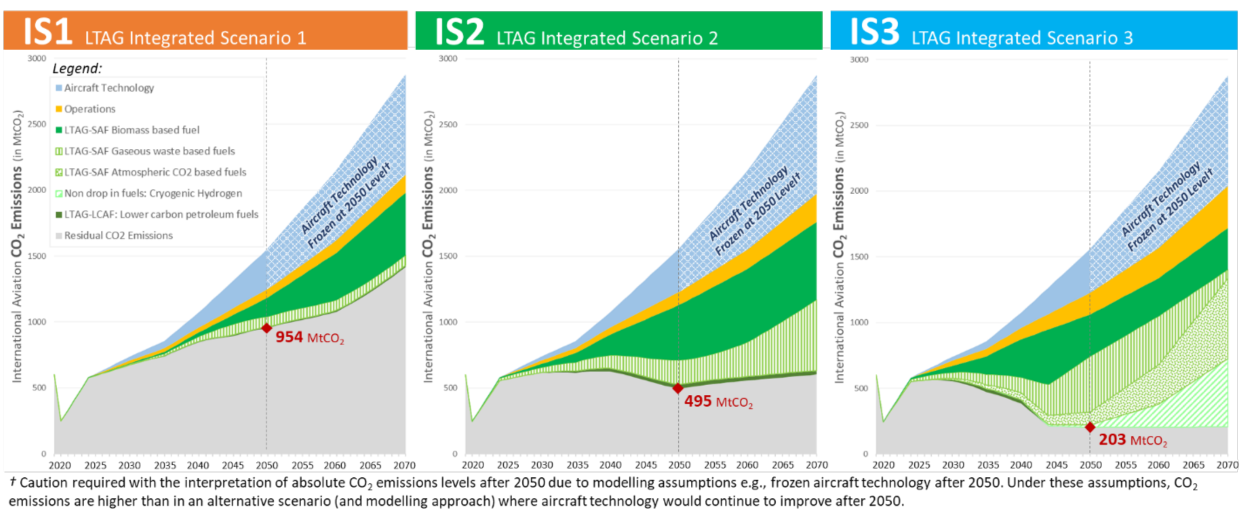


Figure 1. CO_2 emissions from international aviation associated with LTAG Integrated Scenarios

4.2.2 Under an IS1 scenario, CO_2 emissions after reductions from aircraft technology, operations and fuels could reach approximately 950 $MtCO_2$ in 2050 (1.6x from the 2019 CO_2 emissions level) and 1420 $MtCO_2$ in 2070 (2.3x). Under this low/nominal scenario, emissions in 2050 would be reduced by 39% from the baseline scenario (IS0) broken down into 20% from aircraft technologies, 4% from operations and 15% from fuels. By 2070, aircraft technology, operations and fuels could contribute to reductions in emissions of 26%, 5%, and 20% respectively. Under this scenario, residual CO_2 emissions would not stabilize and would continue to grow above a 2019 CO_2 emission levels (as proxy for pre-COVID-19 pandemic 2020 level). Through 2050, global fuel efficiency measured in fuel/RTK would improve by 1.20 to1.31% per annum (vs. the 2% ICAO global fuel efficiency aspirational goal).

4.2.3 In an IS2 scenario, CO_2 emissions could reach ≈500 $MtCO_2$ in 2050 (0.8x from 2019 CO_2 emissions level) and stabilize at roughly 2019 CO_2 emission level. Emissions in 2050 would be reduced by 68% from an IS0 baseline, broken down into 21% from aircraft technologies, 6% from operations, and 41% from fuels. Through 2050, global fuel efficiency measured in fuel/RTK would improve by 1.35 to 1.47% per annum (vs. the 2% ICAO global fuel efficiency aspirational goal).

4.2.4 Shifting to an IS3 scenario, residual CO_2 emissions could reach ≈200 $MtCO_2$ in 2050 (a third of the 2019 CO_2 emissions level) and 210 $MtCO_2$ in 2070. Emissions in 2050 would be reduced by 87% from the baseline scenario (IS0) broken down into 21% from aircraft technologies, 11% from operations and 55% from fuels. Through 2035, global fuel efficiency measured in fuel/RTK would improve by 1.42 to 1.60% per annum. Under this scenario which involves the use of non-drop in fuels such as hydrogen, the 2% ICAO global fuel efficiency aspirational goal becomes obsolete (based on jet fuel/RTK metric) and would need to be adjusted. Through 2050, global fuel energy efficiency measured in MJ/RTK would improve by 1.55 to 1.67% per annum.

4.3 Future International Aviation Emissions in Context

4.3.1 Based on CO_2 emissions trends described in 4.2, CAEP calculated cumulative CO_2 emissions from international aviation through 2050 and 2070 (see Figure 2). The IS1 scenario would result in 23 $GtCO_2$ of cumulative residual emissions from international aviation from 2020 to 2050 and 23 $GtCO_2$ from 2051 to 2070. Shifting to IS2 results in 17 $GtCO_2$ from international aviation from 2020 to 2050 and 11 $GtCO_2$ from 2051 to 2070. IS3 results in 12 $GtCO_2$ from international aviation from 2020 to 2050 and 4 $GtCO_2$ from 2051 to 2070.

4.3.2 CAEP then placed these results in the context of global carbon budgets for limiting global warming to 1.5°C and 2°C, using data from the Intergovernmental Panel on Climate Change (IPCC). The IPCC and CAEP analyses follow different methodologies and embed their own uncertainties, as described in Appendix R3, but the comparison is nonetheless valuable.

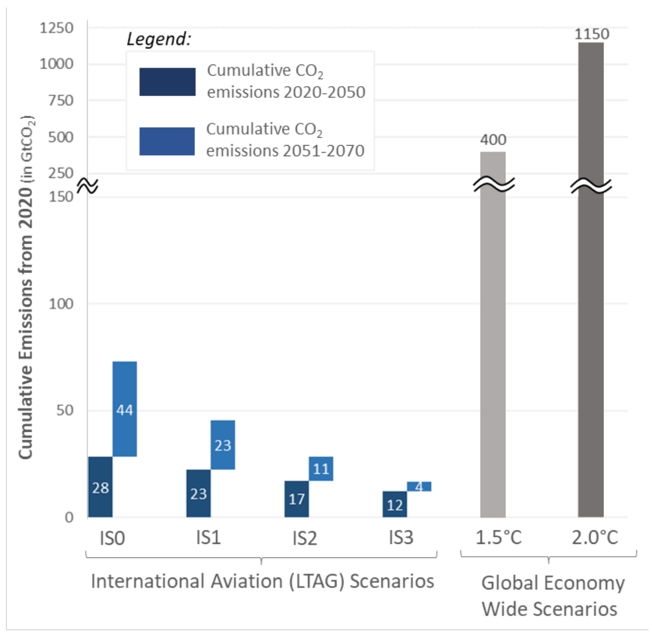


Figure 2. Cumulative CO_2 emissions from international aviation in context of 1.5°C and 2°C

4.3.3 In context, estimated cumulative residual global anthropogenic CO_2 emissions from the start of 2020 to limit global warming to 1.5°C is 400 $GtCO_2$ at 67% probability. Depending on the scenario, international aviation could represent approximately 4.1 to 11.3% of this total. For a warming limit of 2°C, the remaining allowed carbon emissions are estimated to be 1150 $GtCO_2$ at 67% probability. Depending on the scenario, international aviation could represent approximately 1.4 to 3.9% of this total. Comparisons based on a 50% probability of meeting the temperature goals may be found in Appendix R3, Attachment A.

4.4 **Cost and Investments Associated with Integrated Scenarios**

4.4.1 The CAEP has assessed the costs and investments associated with LTAG scenarios (see Figure 3 for a summary and the Appendices for details and temporal distributions, etc). It is important to note that costs and investments associated with a scenario are not meant to be added towards a total cumulative cost. Some investments from upstream stakeholders are passed on downstream in the form of incremental price of products (e.g. investments from fuel suppliers passed on to operators as part of Minimum Selling Price). As such the costs and investments are displayed across a chain of stakeholders.

4.4.2 ***Investments from States (i.e. governments):*** In order to support aircraft technology developments, States may need to invest in research and development. Under an IS1 scenario, investments could range from $15 to $180 billion through 2050. To support advanced aircraft configuration and/or energy systems (i.e. hydrogen powered aircraft) under IS2 and IS3, this could increase to $75 to $870 billion.

4.4.3 ***Investments from aircraft manufacturers:*** To deliver aircraft technology improvements captured in IS1, aircraft manufacturers would need to invest on the order of $180 billion (range $150 to $380 billion) between 2020 and 2050. On an annual basis this represents ≈ $6 billion per year. Developing aircraft with unconventional configurations (IS2) and hydrogen powered aircraft (IS3) would require a substantial increase in investments on the order of $350 billion (range $260 to $1000 billion) between 2020 and 2050.

4.4.4 ***Investments from fuel suppliers:*** To start to scale the production capacity for fuels under IS1, fuels suppliers would need to invest ≈1,300 billion through 2050 broken down into $480 billion for SAF biomass-based fuels by 2050 (to cover 19% of international aviation energy use in 2050), $710 billion for SAF from gaseous waste (8%) and $50 billion towards LTAG-Lower Carbon Aviation Fuel (LCAF) (7%). Scaling the production of fuels under IS2, would require investments of $2,300 billion through 2050. Finally, under IS3 investments would of ≈ 3,200 billion broken down into $950 billion for SAF biomass-based fuels by 2050 (to cover 42% of international aviation energy use in 2050), $1,700 billion for SAF from gaseous waste (46%), $460 billion from SAF from atmospheric CO_2 (10%), $60 billion towards LTAG-LCAF (0%) and $55 billion towards hydrogen (2%). These capital expenditures are for green field fuel production plants and were not reduced by investments that would be made to the conventional fuel sector that would be needed in a baseline (IS0) scenario. In addition, investments captured in the CAEP analyses would lead to local economic development (e.g. refineries that are using renewable or waste feedstocks to produce SAF would spur economic development and opportunities for rural communities).

4.4.5 ***Costs and investments for airports:*** Towards the implementation of operations measures, airports may need to spend or invest from $ 2 to 6 billion across LTAG scenarios. In addition, under an IS3 scenario where hydrogen aircraft may enter service after 2035, airports may need to invest into infrastructure of ≈ $100 to 150 billion by 2050.

4.4.6 ***Costs and investments for Air Navigation System Providers (ANSPs):*** LTAG specific operations measures would require investments and costs by ANSPs from $11 to 20 billion by 2050.

4.4.7 ***Costs and investments for Operators (airlines):*** The entry into the fleet of aircraft with technology improvements would reduce fuel burn and operating fuel costs to airlines of ≈ $710 to 740 billion through 2050. Incremental investments to cover any incremental aircraft prices (after technology improvements) may be required which would reduce the net savings from aircraft technology improvements to airlines. The implementation of operational measures could reduce operators fuel costs by ≈ $210 to 490 billion through 2050 but would require additional costs and investments ranging from $40 to 155 billion. Fuel related costs in the form of incremental costs of fuels (minimum selling price) vs. conventional jet fuel in a baseline scenario would have the largest impact on operators. In an IS1 scenario, acquisition of fuels by airlines could result in incremental costs compared to conventional jet fuel of $ 1100 billion broken down into 300B, $ 770B, and $ 50B for SAF biomass based, SAF waste-based fuels and LCAF respectively. Incremental fuels costs would increase under an IS2 to ≈ $2700 billion. Finally, under and IS3 scenario where 100% of conventional jet fuel is replaced by fuels starting in 2040, the costs to airlines would reach $4000 billion through 2050 (broken down into $1600 billion, $1800 billion, $600B, $60 billion, and $10 billion for SAF biomass based, SAF waste-based fuels, SAF from atmospheric CO_2, LCAF and hydrogen respectively).

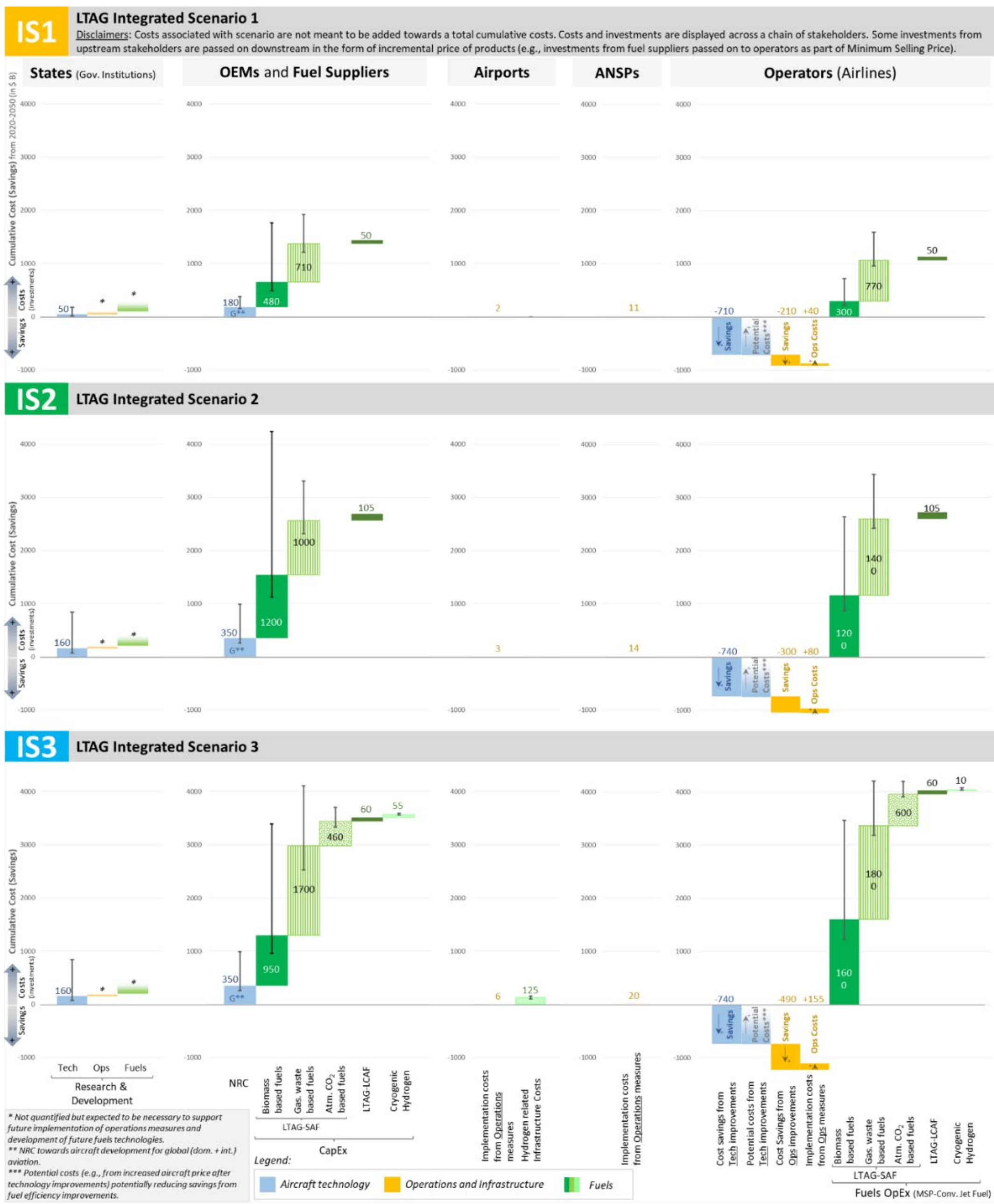
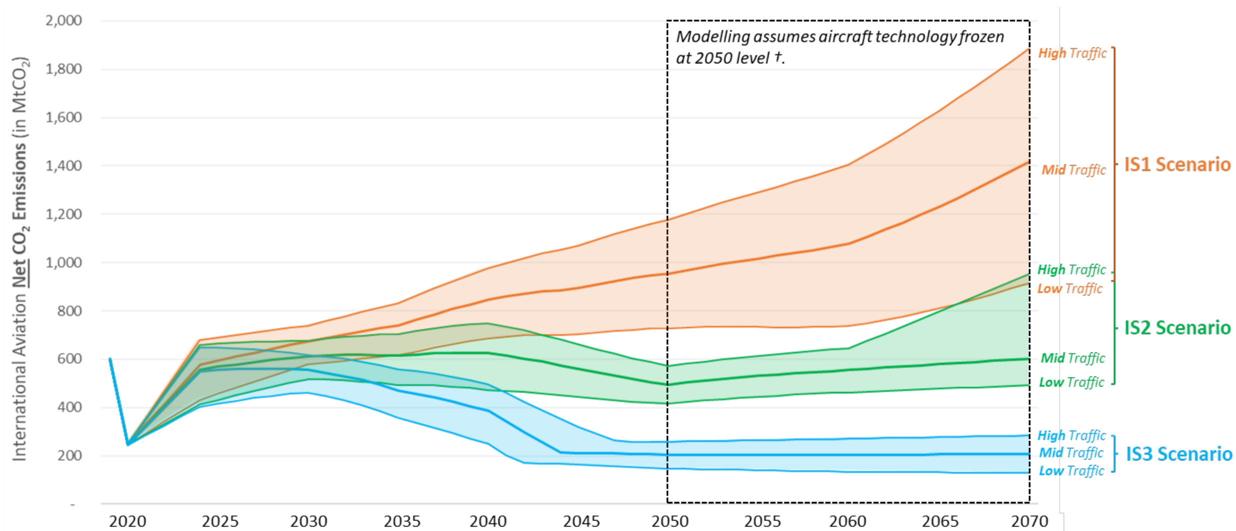


Figure 3. Integrated cost and investments associated with LTAG Integrated Scenarios

4.5 Impact of Aviation Traffic Forecast

4.5.1 The scenarios described above are based on a mid-traffic forecast. The CAEP has also assessed the potential impacts of higher and lower traffic forecasts. Figure 4 shows the residual CO_2 emissions from international aviation (after aircraft technology and operations improvements and emissions reductions from LTAG-SAF, LTAG-LCAF and non-drop in fuels i.e. hydrogen where applicable) across the LTAG scenarios and various traffic forecasts levels.

4.5.2 Under an IS1 scenario, CO_2 emissions in 2050 could range from 730 to 1160 $MtCO_2$ or +/- 23% around the mid traffic scenario and 920 to 1880 $MtCO_2$ (+/- 35% around the mid traffic scenario) in 2070. Under an IS2 scenario, CO_2 emissions in 2050 could range from 420 to 590 $MtCO_2$ (+/-16% around the mid traffic scenario) and 490 to 950 $MtCO_2$ in 2070 (+58% to -18% around a mid traffic scenario) in 2070. Finally, under an IS3 scenario traffic forecasts may influence residual CO_2 emissions levels in 2050 ranging from 150 to 260 $MtCO_2$ (+/- 27% around a mid-traffic scenario) and 130 to 280 $MtCO_2$ in 2070 (+/- 38% around the mid traffic scenario).



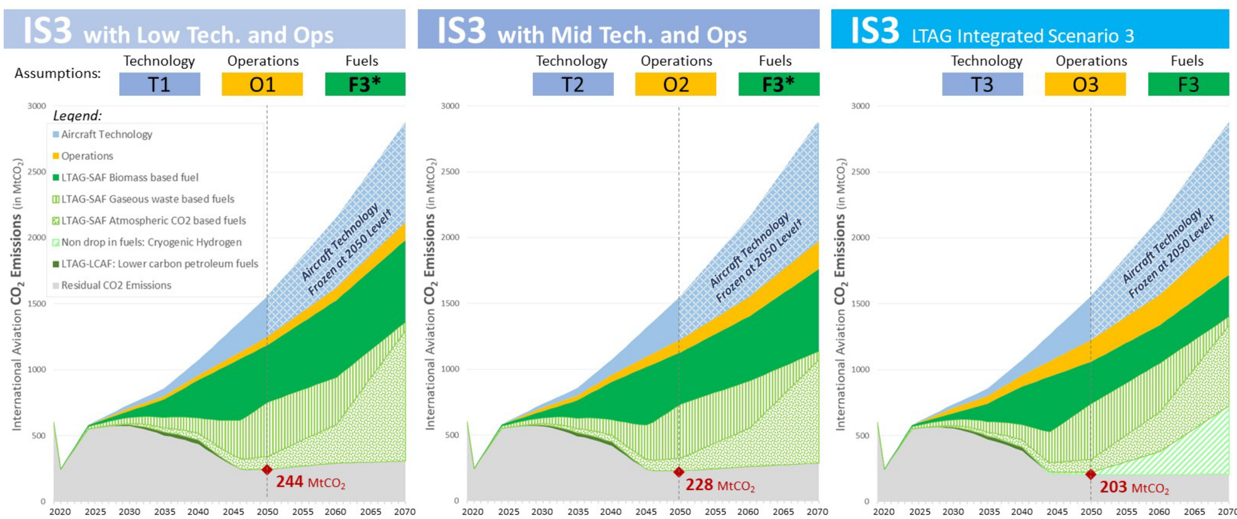
† Caution required with the interpretation of absolute CO_2 emissions levels after 2050 due to modelling assumptions e.g., frozen aircraft technology after 2050. Under these assumptions, CO_2 emissions are higher than in an alternative scenario (and modelling approach) where aircraft technology would continue to improve after 2050.

Figure 4. Effects of traffic scenarios on residual CO_2 emissions across LTAG integrated scenarios

4.6 Sensitivity Analysis of IS3 Scenario to Examine Importance of Fuels

4.6.1 As described in section 3.1 on "integrated scenarios" and illustrated in section 4.2 on "international aviation CO_2 emissions trends", the LTAG-TG developed a set of three integrated scenarios that explore a range of residual CO_2 emissions after technology, operations and fuels. In its deliberations about the development of integrated scenarios, the LTAG-TG recognized that there could be multiple combinations of technology, operations and fuels scenarios to form "alternative integrated scenarios," which are not examined exhaustively unlike the "integrated scenarios." In addition, the subgroups on technology, operations and fuels developed ranges of estimates around measure specific scenarios. For example, the LTAG-TG Technology subgroup developed lower, medium, higher progress estimates for aircraft technology improvements (see Appendix M5 for details). The LTAG-TG Operations subgroup developed low, mid and high estimates of operational improvements. These different combinations of measure specific scenarios and ranges of estimates provided the basis for scenario based and sensitivity analyses.

4.6.2 Figure 5 depict illustrative sensitivity analyses of IS3 scenarios with lower technology and operations improvements. The right-hand side chart is similar to Figure 1. The middle chart illustrates the case of mid-technology and operations where advanced tube and wing and unconventional aircraft use drop-in fuels in line with a Fuels 3 scenario which results in 228 $MtCO_2$ by 2050. Similarly, in a scenario with lower technology and operations improvements and adjusted F3 scenario to ensure internal consistency within the scenario, CO_2 emissions by 2050 may reach 244 $MtCO_2$. These results show that there are multiple paths that may result in similar levels of CO_2 emissions. They also show that there is robustness in the LTAG scenarios and analyses as well as the critical contribution from fuels to decouple the growth in international aviation traffic from its CO_2 emissions.



* Amended Fuel Scenario (F3) to align with Aircraft Technology scenarios associated with IS1 and IS2 (i.e., no ACA-T3 hydrogen powered aircraft included in IS1 and IS2) and adjusted to meet fuel volume constraints. Note. – Under a F3* (IS1 Hybrid) scenario LTAG-SAF Atmospheric CO_2 fuel volumes scaled by 1.68 in 2070 (no changes in 2060). Similarly, under a F3* (IS2 Hybrid) scenario LTAG-SAF Atm. CO_2 fuel volumes scaled by 1.33 in 2070 (no changes in 2060).

† Caution required with the interpretation of absolute CO_2 emissions levels after 2050 due to modelling assumptions e.g., frozen aircraft technology after 2050. Under these assumptions, CO_2 emissions are higher than in an alternative scenario (and modelling approach) where aircraft technology would continue to improve after 2050.

Figure 5. Sensitivity analysis of IS3 scenarios with lower technology and operations improvements

4.6.3 Sensitivity analyses are not shown for technologies as the reduction does not vary substantially among the three technology scenarios. Further, sensitivity analyses are not provided for operations due to their relatively modest emissions reductions relative to the technology and fuel contributions.

5. CONSIDERATIONS REGARDING OPTIONS

5.1 Based on the results of the LTAG-TG feasibility study, some technical options for metrics were identified below, which could support the discussions on the feasibility of a possible long-term aspirational goal. This is not an exhaustive list and other formulations may of course be considered.

a) The **annual level of emissions** potentially achievable by the measures; for example, 950, 500 or 200 MtCO_2 in 2050 (based on the integrated scenarios assessed). Using a reference year earlier than 2050 may not give the long-term certainty expected to be a key benefit of adopting an LTAG. Using a reference year after 2070 would be subject to increased uncertainty given the uncertainties both in the underlying forecast and the propagation of advanced technologies through the global fleet and, based on this analysis, may not necessarily allow for higher in-sector aspiration.

b) **Intermediate waypoints** in milestone years could add a trajectory to the emissions profile in times.

c) The **cumulative total emissions from the international aviation sector during a certain period**, for example 23, 17 or 12 GtCO_2 from 2020 to 2050 (based on the integrated scenarios assessed). The cumulative total emissions from the sector would most closely translate into an atmospheric temperature response and allow for monitoring of progress without the need for intermediate waypoints. Otherwise, similar considerations apply as above.

5.2 With the scope of the LTAG-TG limited to consider in-sector measures only, 'out-of-sector' measures were not considered in the LTAG-TG analysis.

6. OTHER CONSIDERATIONS

6.1 **Impacts on aviation growth:** CAEP considered the potential impacts of the overall costs (and investments) related to measures that would underly LTAG scenarios on aviation growth. While difficult to quantitatively assess these impacts on aviation growth far out in the future, CAEP noted that while an LTAG may increase operating costs, some costs may be passed on to the flying public. Given the relatively lower price elasticity associated with international aviation (and limited travel alternatives for long haul trips), the impact on aviation growth may be limited. Some study reviewed found statistically significant differences between different geographic air travel markets. The main drivers pointed as possibly increasing elasticity are the low level of maturity of the market, the predominance of shorter distances of routes, the arising of low-cost carriers and presence of charter airlines, the emergence of the middle class and the existence of liberal pricing regulation. In addition, it is expected that aviation will continue to deliver benefits to national, regional and the global economies.

6.2 **Regional impacts summary:** Aircraft technology and associated design decisions will continue to address the global market needs and will not vary by region. Aircraft operators in various regions or States will buy the best aircraft available that meet their needs. Regional variances in implementation of operational measures are also expected. Most significant regional variations are expected in the production and uptake of fuels. This is due to a range of factors such as regional availability of waste and biomass feedstocks, CO_2 and cryogenic hydrogen, renewable energy, market dynamics and infrastructure.

6.3 **Impacts on noise and air quality:** In all three scenarios, increased traffic will lead to an increase in total noise and NO_x emissions. However, noise and local air quality will remain priorities, particularly around individual airports, whose local rules and charges will continue to influence some aircraft designs. Advances in aircraft technology typically provide reductions in noise and emissions alongside reductions in fuel burn. Operational efficiencies may have co-benefits for noise but are not expected to impact local air quality. LTAG-SAF and cryogenic hydrogen have lower particulate emissions and produce no sulfate emissions, leading to co-benefits for air quality and contrail formation, while no impact on noise is expected.

6.4 **Comparison with CAEP/12 trends:** CO_2 emissions under the three LTAG-TG scenarios (IS1, IS2 and IS3) were compared with those calculated under the Fuel Scenario 4 of the CAEP/12 environmental trends analysis out to 2050. The baselines (termed IS0 for LTAG-TG) are identical between the two sets of analyses. The residual in-sector emissions under LTAG-TG scenario IS2 are very close to those under the CAEP/12 Trends Fuel Scenario 4. LTAG-TG integrated scenarios IS1 and IS3 give, respectively, higher and lower CO_2 emissions than the CAEP/12 Trends scenario in 2050. Details are provided in Appendix R2.

6.5 **Implementation Roadmap:** The aircraft technologies, operations measures improvements and fuels development and scale-up will require a sequence of enablers and conditions along a timeline through 2050 and beyond. These are noted in Appendix R1 with more detail available in the relevant methodological appendix.

6.6 **Monitoring of progress towards a goal:** A process is anticipated for monitoring progress towards any goal ultimately adopted. It would be preferable not to duplicate existing processes or place reporting expectations on non-state actors. State Action Plans, voluntarily submitted by States under Article 10 of Resolution A40-18, may be a mechanism for States to share progress towards a goal. If and once a goal is adopted, CAEP could conduct future work towards recommendations on metrics, reporting mechanisms, etc. building on expertise from the development of CO_2 emissions reporting mechanisms as contained in Annex 16 Volume IV.

6.7 **Review:** ICAO may need to review any goal ultimately adopted to ensure it remains appropriate, considering information such as: progress towards the goal, technological developments, progress in other sectors, cost and other impacts on States and aviation stakeholders, the latest scientific knowledge. If a triennial review process is considered it could align with CAEP and Assembly meetings to review progress and recommend/decide on any adjustments, in a similar way to the CORSIA Periodic Review.

6.8 **Capacity building:** There could also be potential needs for capacity building and assistance to realise the scenarios, which could include workshops on solutions that States can implement to reach goals, including understanding likely costs, and assistance on monitoring and measuring CO_2 emissions from international aviation, as part of an overarching training programme that could be similar to the successful ACT-CORSIA.

7. APPENDICES TO THE FINAL REPORT

7.1 This summary of the LTAG-TG study is the result of two years of work by CAEP. A set of supporting documents provide modelling approaches, methodologies, models, assumptions and results for transparency and comprehensiveness.

7.2 Summary sheets (Appendix R1) in the final report provide additional information on the results, their interpretations and roadmaps for implementation of the technology, operations and fuels measures. Appendix R2 provides a comparison between the LTAG-TG (CO_2 emissions) trends and the CAEP/12 GHG (CO_2 emissions) trends. Appendix R3 places the results of the LTAG-TG study in context of cumulative emissions to limit temperature increases below 1.5°C and 2°C. Finally, Appendix M1 provides details on the approach for developing the scenarios as well as the costs (investments) estimation approaches, methodologies, and results. Appendices M2, M3, M4 and M5 provides details on the forecast, technology, operations, and fuels scenarios respectively. Appendix S1 on the climate science context which includes the ISG report to LTAG-TG and Appendix B1 with background which describes overall activities and working methods of the LTAG-TG are also attached.

List of appendices:

Appendix R1: Summary Sheets	https://www.icao.int/environmental-protection/LTAG/Documents/ICAO_LTAG_Report_AppendixR1.pdf
Appendix R2: Comparison to Trends	https://www.icao.int/environmental-protection/LTAG/Documents/ICAO_LTAG_Report_AppendixR2.pdf
Appendix R3: Results in Context	https://www.icao.int/environmental-protection/LTAG/Documents/ICAO_LTAG_Report_AppendixR3.pdf

Appendices on Methodology

Appendix M1: Overview of the Modeling Approaches used in the Development of the Results	https://www.icao.int/environmental-protection/LTAG/Documents/ICAO_LTAG_Report_AppendixM1.pdf
Appendix M2: Forecast	https://www.icao.int/environmental-protection/LTAG/Documents/ICAO_LTAG_Report_AppendixM2.pdf
Appendix M3: Technologies	https://www.icao.int/environmental-protection/LTAG/Documents/ICAO_LTAG_Report_AppendixM3.pdf
Appendix M4: Operations	https://www.icao.int/environmental-protection/LTAG/Documents/ICAO_LTAG_Report_AppendixM4.pdf
Appendix M5: Fuels	https://www.icao.int/environmental-protection/LTAG/Documents/ICAO_LTAG_Report_AppendixM5.pdf

Appendix S1: Climate Science Context	https://www.icao.int/environmental-protection/LTAG/Documents/ICAO_LTAG_Report_AppendixS1.pdf
Appendix B1: Background	https://www.icao.int/environmental-protection/LTAG/Documents/ICAO_LTAG_Report_AppendixB1.pdf

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