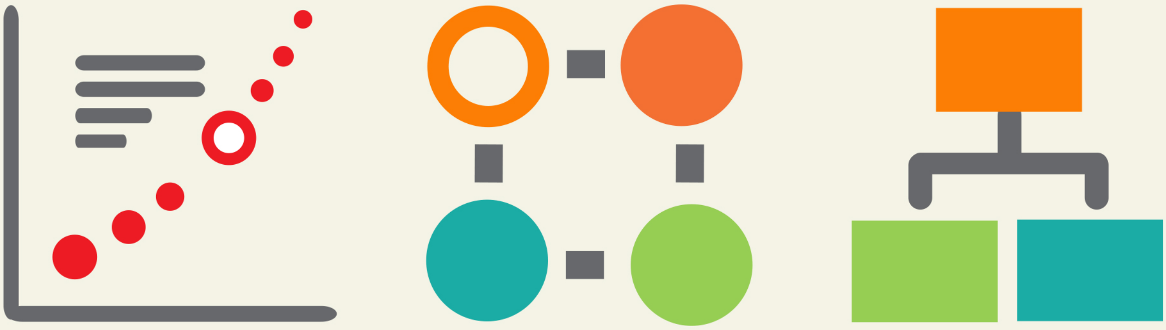
ICAO

INTERNATIONAL CIVIL AVIATION ORGANIZATION

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

Appendix M1 Overview of the modeling approaches



ICAO COMMITTEE ON AVIATION ENVIRONMENTAL PROTECTION
MARCH/2022

APPENDIX M1

OVERVIEW OF THE MODELING APPROACHES USED IN THE DEVELOPMENT OF THE RESULTS

PART A: DEVELOPMENT OF INTEGRATED SCENARIOS

1. BACKGROUND, OBJECTIVES AND PROCESS

1.1 The work of the CAEP Long-Term Aspirational Goal Task Group (LTAG-TG) is broadly divided into three phases: data gathering (Task LTAG.02), scenario development (Task LTAG.03) and final analysis (Task LTAG.04). Following CAEP-SG2020, LTAG-TG formed the Scenario Development Sub-Group (SDSG) to lead the scenario development task and coordinate the final analysis.

1.2 The LTAG-TG Terms of Reference require it to "develop scenarios to create combined in-sector scenarios of technology, fuels, and operations that represent a range of readiness and attainability. The scenarios will utilize findings from the data gathering exercise and include a range of forecasts in future air transport demand. The work should be placed in the context of an analysis of achieving the current ICAO aspirational goals."

1.3 While the SDSG has led this task, it has relied on the expertise of the LTAG-TG Technology (TECH), Operations (OPS) and Fuels (FUEL) Sub-Groups, recognising that these sub-groups have both a depth and breadth of expertise not present in the SDSG. It has also relied extensively on advice from MDG and FESG, particularly in relation to the "range of forecasts in future air transport demand" and the relationship between the LTAG analysis and CAEP Trends.

2. OVERVIEW OF METHODOLOGY FOR INTEGRATED SCENARIO DEVELOPMENT

2.1 **"Readiness and attainability"**: SDSG recognised that "readiness and attainability" could be interpreted in a variety of different ways, and that these terms might apply differently to technology, operations, fuels and to the overall scenarios. Therefore, rather than seeking to exhaustively define these terms in a quantitative way, SDSG has aimed to provide an overarching narrative to guide TECH, OPS and FUEL in the development of their elements of the scenarios. In general terms, the integrated scenarios have been developed to cover a range from high readiness and attainability and low aspiration (Integrated Scenario 1), to low readiness and attainability and high aspiration (Integrated Scenario 3).

2.2 **Integration**: Initial views on the scenario descriptions were sought from TECH, OPS and FUEL in February and more detailed input requested in April. SDSG has reviewed all inputs from the other sub-groups to ensure consistency and integration between these elements. Integration is an iterative process that will continue after LTAG-TG/3 as we proceed with the final analysis.

2.3 The technology element of the scenarios was developed to be consistent with IS1, IS2 and IS3. Within IS1, advanced tube and wing (ATW) with conventional technologies and drop-in fuels are being assessed. Two overlapping advanced concept aircraft (ACA) “baskets” of innovation are considered beyond ATW, with conventional or drop-in fuel: ACA1 (IS2) is representative of alternative architecture airframes and/or propulsion (with conventional or drop-in fuels), and ACA 2 (IS3) is representative of advanced airframes and advanced propulsion characterized by the use of non-drop-in fuels with or without alternative airframe architecture changes. Note that an ATW configuration with non-drop-in fuels would also be considered as an ACA2 alternative in IS3 (see also **Appendix M3**)

2.4 The operations element of the scenarios was developed by adapting the methodology used previously by CAEP WG2 in the context of the CAEP Trends. Three scenarios are proposed - conservative, medium, and aggressive – aligned with IS1, IS2 and IS3. Five categories of measures have been identified following the data gathering phase, as follows: those delivering horizontal flight efficiency (HFE), vertical flight efficiency (VFE), ground flight efficiency (GFE), innovative flight efficiency (IFE) and advanced flight efficiency (AFE). The scenarios are constructed according to different rates at which these measures are assumed to be implemented, and will be aligned with the TECH and FUELS scenarios, for example in relation to the introduction of advanced concept aircraft into the fleet (see also **Appendix M4**).

2.5 The fuels element of the scenarios was developed by first categorizing possible jet fuel types according to the carbon feedstock source. This generated three high-level categories: LTAG sustainable aviation fuels (LTAG-SAF), LTAG lower carbon aviation fuels (LTAG-LCAF) and non-drop in fuels. Non-drop-in fuel types, including electricity and cryogenic hydrogen, require modifications to conventional engine design and fueling systems. Future fuel volume projections and potential GHG emissions reductions associated with these volumes out to 2070 were then developed. These scenarios represent a range from high readiness and attainability and low aspiration to low readiness and attainability with high aspiration (see also **Appendix M5**).

3. OUTLINE OF INTEGRATED SCENARIOS

3.1 Recognising that the LTAG-TG task is to assess the feasibility of possible future scenarios and not to conduct a forecast LTAG-TG has recognised the need to rely on MDG’s tools and methodologies for CAEP Trends in its work. A CAEP Trends-type scenario with emissions reductions from technology, operations and fuels frozen at the base year levels has been adopted as **LTAG Integrated Scenario 0 (IS0)**.

3.2 **LTAG Integrated Scenario 1 (IS1)**: 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.

3.2.1 For technology, this means advanced tube and wing aircraft, characterized by significant incremental improvements in performance or capability of established aircraft architectures and compatible with drop-in fuel, and operational efficiency improvements via aircraft design rather than new tech.

3.2.2 For operations, this means conservative assumptions about the rate and extent of implementation of operational measures, based on reduced/slower investment in ground and airborne systems and technologies. It assumes a low rate of ASBU deployment to optimise HFE, VFE and GFE.

3.2.3 For fuels, this means the use of drop-in fuels from feedstocks from a variety of settings, including waste gases and blue/green hydrogen. It assumes relatively low incentives for LTAGSAF/LTAG-LCAF production, approval of LTAG-SAF blend levels above 50% and that ground transport and aviation have a level playing field with respect to alternative fuel use.

3.3 **LTAG Integrated Scenario 2 (IS2)**: 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.

3.3.1 For technology, this means that Advanced Concept Aircraft, ACAs, characterized by significant step-changes in performance or capability replace currently dominant aircraft architectures, causing significant architectural/configuration changes at the airframe, propulsion, or combination level.

3.3.2 For operations, this means emissions reductions and operational efficiencies in line with the existing "Rules of Thumb" developed by WG2 and new "Rules of Thumb" developed by LTAG OPS for new measures. It assumes a medium rate of ASBU element deployment to optimise HFE, VFE and GFE and a low rate of ops measure deployment to optimise IFE and AFE.

3.3.3 For fuels, this means the widespread use of blue/green hydrogen and waste gases for drop in fuel production, increased feedstock availability, as well as carbon capture, utilization, and storage (CCUS). It assumes increased incentives leading to reduced LTAG-SAF/LTAG-LCAF cost for users, approval of 100% synthesized jet fuel in all aircraft and electrification of ground transport leading to increased LTAG-SAF availability for aviation.

3.4 **LTAG Integrated Scenario 3 (IS3)**: This aggressive or speculative 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.

3.4.1 For technology, this means that Advanced Concept Aircraft, ACAs, characterized by significant step-changes in performance or capability replace currently dominant aircraft architectures and require major systemic changes such as significant infrastructure change at the airport and likely beyond.

3.4.2 For operations, this means aggressive assumptions about the rate and extent of implementation of operational measures, based on higher/accelerated investment in ground and airborne systems and technologies. It assumes a high rate of ASBU element deployment to optimise HFE, VFE and GFE and a medium rate of operational measure deployment to optimise IFE and AFE.

3.4.3 For fuels, this means widespread use of drop-in fuels and non-drop-in fuels. This includes drop-in fuels produced from CCUS and atmospheric CO_2, further increased feedstock availability and sufficient hydrogen availability to allow cryogenic hydrogen use in aircraft. It assumes large incentives and deep, economy-wide decarbonisation lead to widespread use of these fuels, approval of 100% synthesized jet fuel in all aircraft and infrastructure is developed to enable use of non-drop-in fuels worldwide.

3.5 **Fleet evolution**: In all scenarios, the basic fleet evolution modelling approach has been kept consistent with the Trends baseline, with additional technology improvements post-processed.

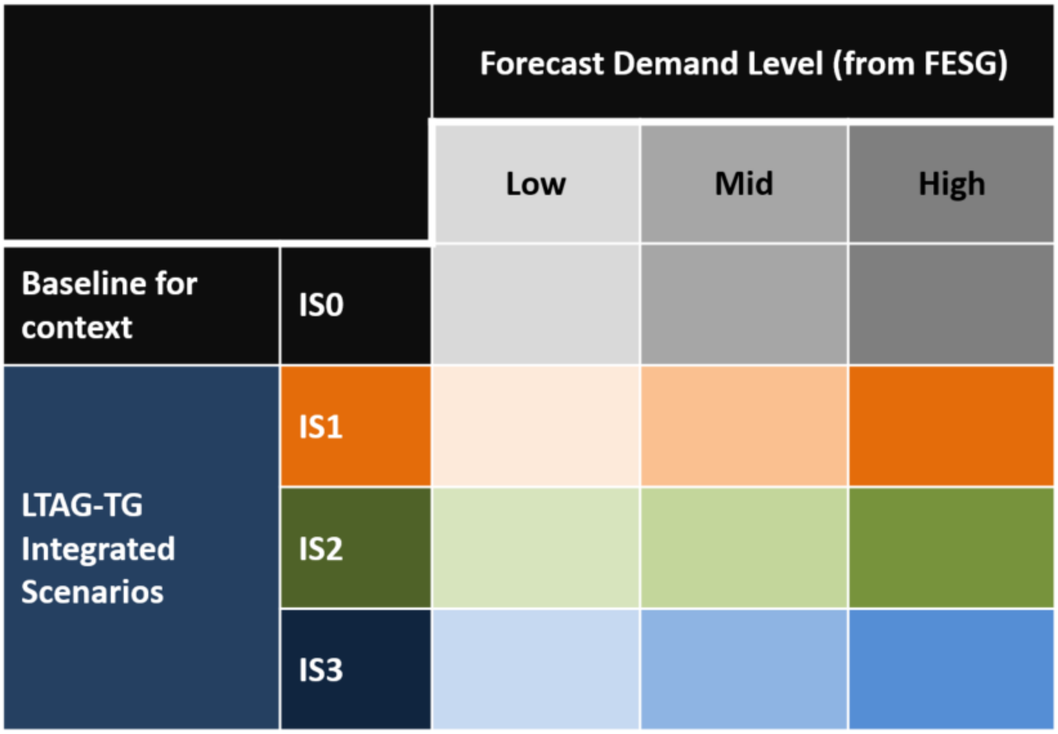
3.6 **Demand forecasts**: These three LTAG integrated scenarios have been overlaid on three demand forecasts from FESG representing low, mid and high forecasts of post-COVID international aviation traffic, again consistent with the CAEP/12 Trends. These forecasts were extrapolated to 2070 to align with the time horizon for the LTAG-TG analysis. This produced three trajectories over time for each integrated scenario – nine in total. While results have been reported for each combination of integrated scenario and demand scenario, time limitations meant that full fleet evolution modelling was only conducted for the mid demand scenario with appropriate scaling factors used to generate results for the other two scenarios. See also **Part B**, below, and **Appendix M2**.

3.7 The following diagrams illustrate the structure and content of the Integrated Scenarios.

3.8 More detail on the technology, operations and fuels elements of the scenarios are found in **Appendices M4, M5 and M6** respectively.

4. SUPPORTING FIGURES

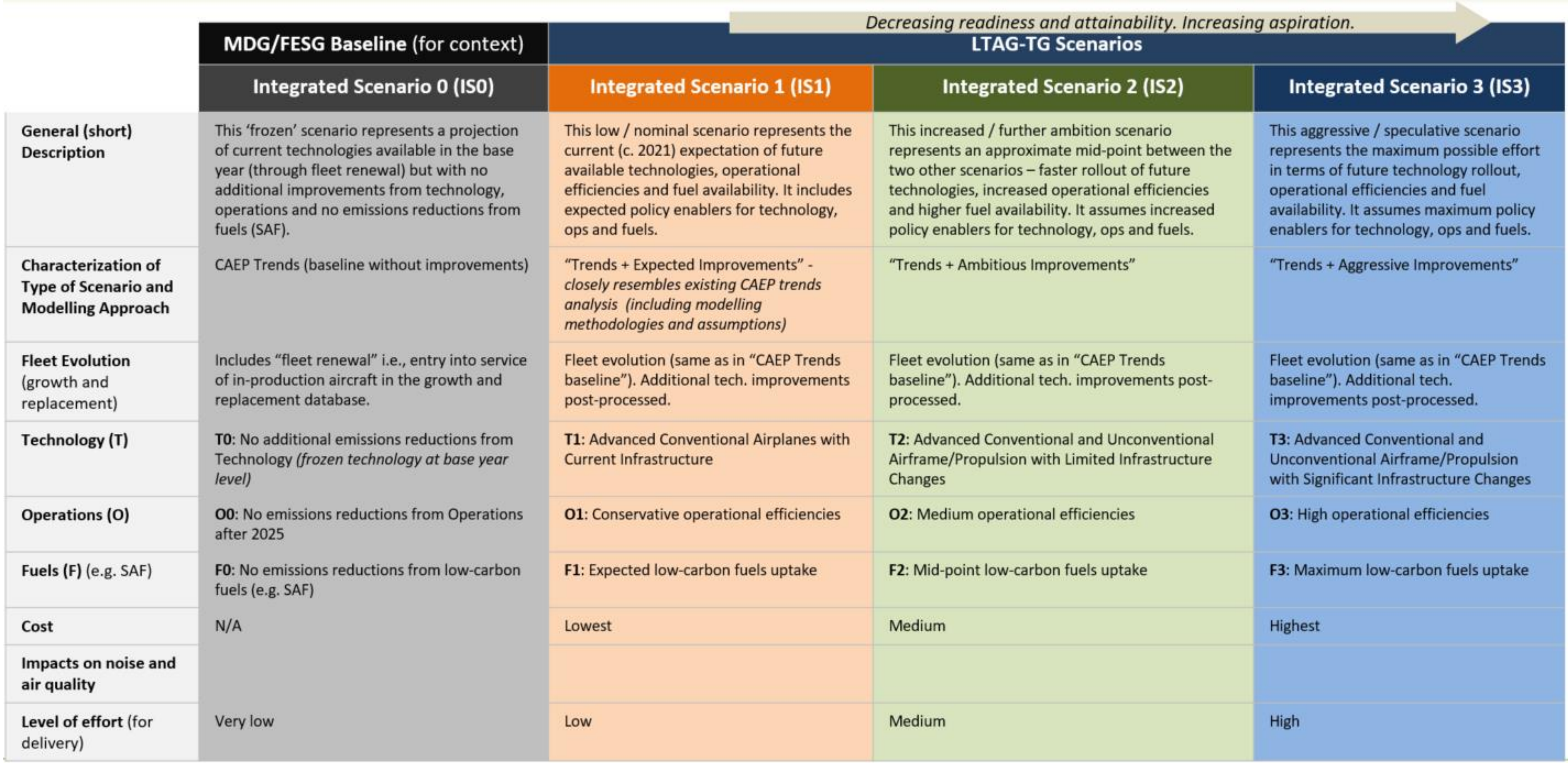
Figure 1 shows how the LTAG integrated scenarios will be combined with the CAEP/12 COVID-impacted demand/traffic forecasts from FESG to produce results. Each cell in the matrix represents a time series that is a combination of a traffic forecast and an LTAG integrated (emissions reduction) scenario over the analysis period.



		Forecast Demand Level (from FESG)		
		Low	Mid	High
Baseline for context	IS0			
LTAG-TG Integrated Scenarios	IS1			
	IS2			
	IS3			

Figure 1. Structure of the LTAG-TG Integrated Scenarios

Figure 2 shows an at-a-glance summary of the modelling approach for each scenario, some of the key input parameters and outputs.

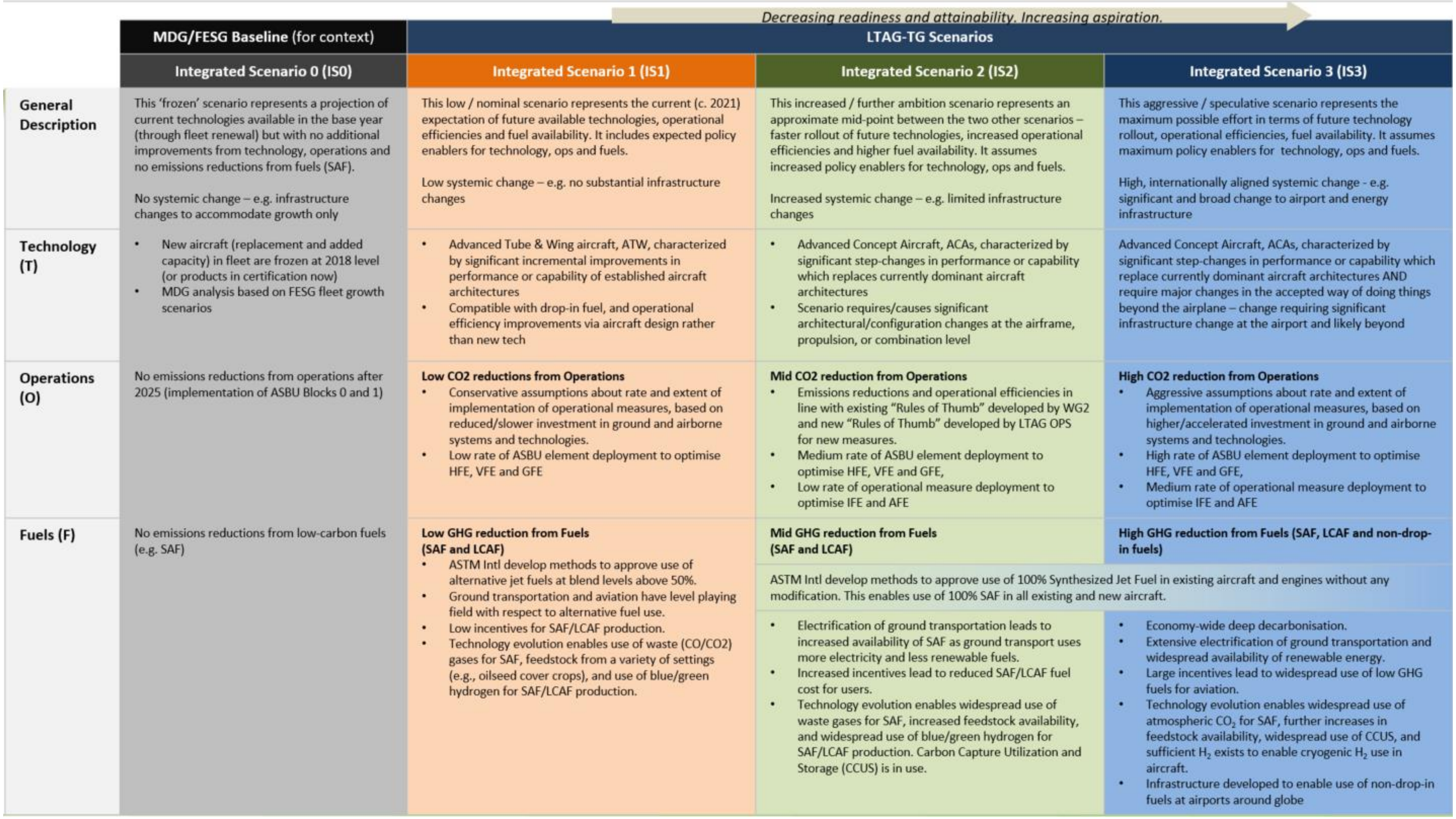


Decreasing readiness and attainability. Increasing aspiration.

	MDG/FESG Baseline (for context)	**LTAG-TG Scenarios**		
	Integrated Scenario 0 (IS0)	**Integrated Scenario 1 (IS1)**	**Integrated Scenario 2 (IS2)**	**Integrated Scenario 3 (IS3)**
General (short) Description	This 'frozen' scenario represents a projection of current technologies available in the base year (through fleet renewal) but with no additional improvements from technology, operations and no emissions reductions from fuels (SAF).	This low / nominal scenario represents the current (c. 2021) expectation of future available technologies, operational efficiencies and fuel availability. It includes expected policy enablers for technology, ops and fuels.	This increased / 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, ops and fuels.	This aggressive / speculative scenario represents the maximum possible effort in terms of future technology rollout, operational efficiencies and fuel availability. It assumes maximum policy enablers for technology, ops and fuels.
Characterization of Type of Scenario and Modelling Approach	CAEP Trends (baseline without improvements)	"Trends + Expected Improvements" - *closely resembles existing CAEP trends analysis (including modelling methodologies and assumptions)*	"Trends + Ambitious Improvements"	"Trends + Aggressive Improvements"
Fleet Evolution (growth and replacement)	Includes "fleet renewal" i.e., entry into service of in-production aircraft in the growth and replacement database.	Fleet evolution (same as in "CAEP Trends baseline"). Additional tech. improvements post-processed.	Fleet evolution (same as in "CAEP Trends baseline"). Additional tech. improvements post-processed.	Fleet evolution (same as in "CAEP Trends baseline"). Additional tech. improvements post-processed.
Technology (T)	**T0**: No additional emissions reductions from Technology *(frozen technology at base year level)*	**T1**: Advanced Conventional Airplanes with Current Infrastructure	**T2**: Advanced Conventional and Unconventional Airframe/Propulsion with Limited Infrastructure Changes	**T3**: Advanced Conventional and Unconventional Airframe/Propulsion with Significant Infrastructure Changes
Operations (O)	**O0**: No emissions reductions from Operations after 2025	**O1**: Conservative operational efficiencies	**O2**: Medium operational efficiencies	**O3**: High operational efficiencies
Fuels (F) (e.g. SAF)	**F0**: No emissions reductions from low-carbon fuels (e.g. SAF)	**F1**: Expected low-carbon fuels uptake	**F2**: Mid-point low-carbon fuels uptake	**F3**: Maximum low-carbon fuels uptake
Cost	N/A	Lowest	Medium	Highest
Impacts on noise and air quality				
Level of effort (for delivery)	Very low	Low	Medium	High

Figure 2. Description of LTAG-TG Integrated Scenarios

Figure 3 shows the narrative descriptions of the LTAG integrated scenarios. It describes the world in each scenario, rather than specific or quantified policies or technical measures.

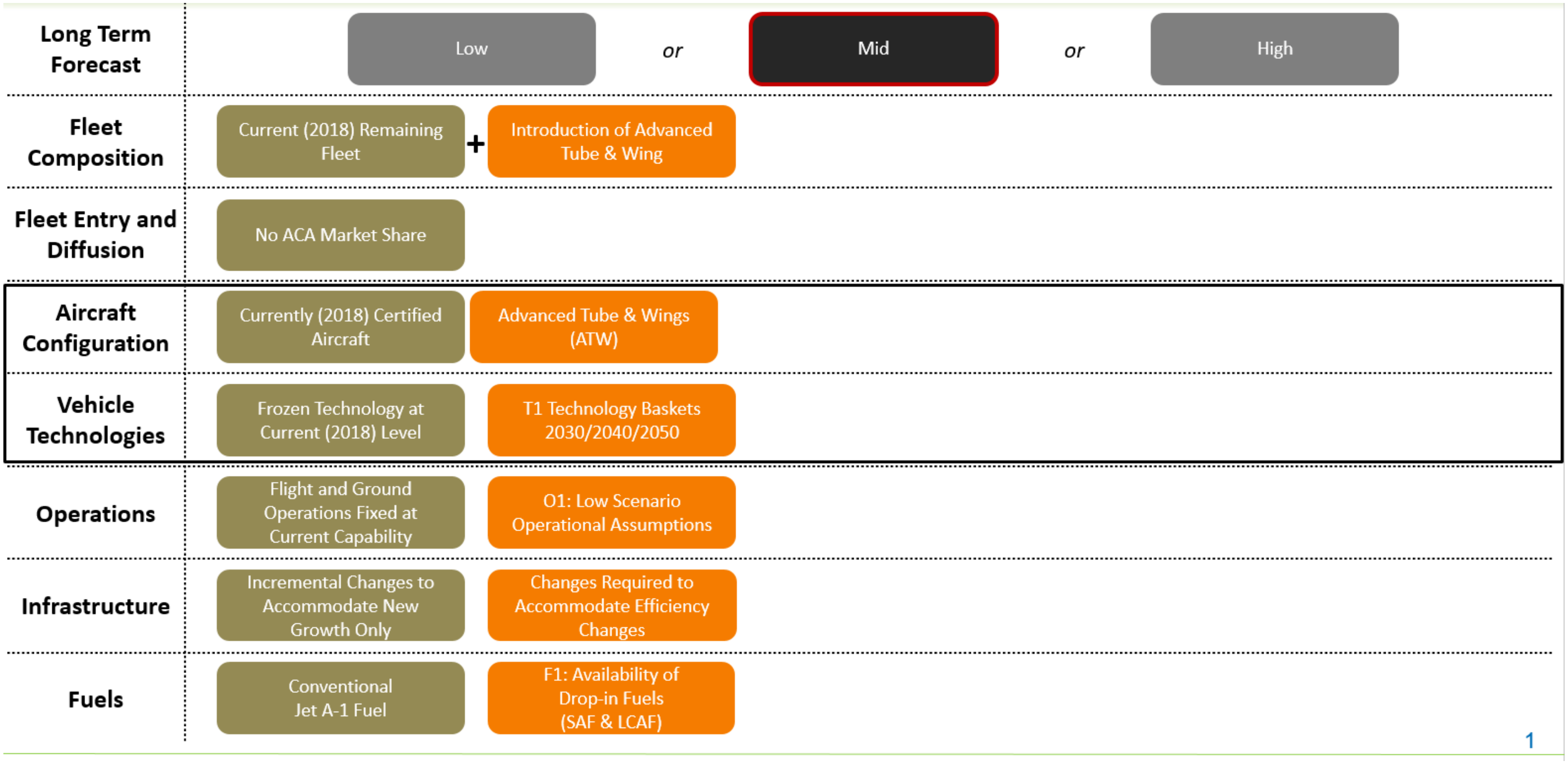


Decreasing readiness and attainability. Increasing aspiration.

	MDG/FESG Baseline (for context)	**LTAG-TG Scenarios**		
	Integrated Scenario 0 (IS0)	**Integrated Scenario 1 (IS1)**	**Integrated Scenario 2 (IS2)**	**Integrated Scenario 3 (IS3)**
General Description	This 'frozen' scenario represents a projection of current technologies available in the base year (through fleet renewal) but with no additional improvements from technology, operations and no emissions reductions from fuels (SAF). No systemic change – e.g. infrastructure changes to accommodate growth only	This low / nominal scenario represents the current (c. 2021) expectation of future available technologies, operational efficiencies and fuel availability. It includes expected policy enablers for technology, ops and fuels. Low systemic change – e.g. no substantial infrastructure changes	This increased / 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, ops and fuels. Increased systemic change – e.g. limited infrastructure changes	This aggressive / speculative scenario represents the maximum possible effort in terms of future technology rollout, operational efficiencies, fuel availability. It assumes maximum policy enablers for technology, ops and fuels. High, internationally aligned systemic change - e.g. significant and broad change to airport and energy infrastructure
Technology (T)	• New aircraft (replacement and added capacity) in fleet are frozen at 2018 level (or products in certification now) • MDG analysis based on FESG fleet growth scenarios	• Advanced Tube & Wing aircraft, ATW, characterized by significant incremental improvements in performance or capability of established aircraft architectures • Compatible with drop-in fuel, and operational efficiency improvements via aircraft design rather than new tech	• Advanced Concept Aircraft, ACAs, characterized by significant step-changes in performance or capability which replaces currently dominant aircraft architectures • Scenario requires/causes significant architectural/configuration changes at the airframe, propulsion, or combination level	Advanced Concept Aircraft, ACAs, characterized by significant step-changes in performance or capability which replace currently dominant aircraft architectures AND require major changes in the accepted way of doing things beyond the airplane – change requiring significant infrastructure change at the airport and likely beyond
Operations (O)	No emissions reductions from operations after 2025 (implementation of ASBU Blocks 0 and 1)	**Low CO2 reductions from Operations** • Conservative assumptions about rate and extent of implementation of operational measures, based on reduced/slower investment in ground and airborne systems and technologies. • Low rate of ASBU element deployment to optimise HFE, VFE and GFE	**Mid CO2 reduction from Operations** • Emissions reductions and operational efficiencies in line with existing "Rules of Thumb" developed by WG2 and new "Rules of Thumb" developed by LTAG OPS for new measures. • Medium rate of ASBU element deployment to optimise HFE, VFE and GFE, • Low rate of operational measure deployment to optimise IFE and AFE	**High CO2 reduction from Operations** • Aggressive assumptions about rate and extent of implementation of operational measures, based on higher/accelerated investment in ground and airborne systems and technologies. • High rate of ASBU element deployment to optimise HFE, VFE and GFE, • Medium rate of operational measure deployment to optimise IFE and AFE
Fuels (F)	No emissions reductions from low-carbon fuels (e.g. SAF)	**Low GHG reduction from Fuels (SAF and LCAF)** • ASTM Intl develop methods to approve use of alternative jet fuels at blend levels above 50%. • Ground transportation and aviation have level playing field with respect to alternative fuel use. • Low incentives for SAF/LCAF production. • Technology evolution enables use of waste (CO/CO2) gases for SAF, feedstock from a variety of settings (e.g., oilseed cover crops), and use of blue/green hydrogen for SAF/LCAF production.	**Mid GHG reduction from Fuels (SAF and LCAF)**	**High GHG reduction from Fuels (SAF, LCAF and non-drop-in fuels)**
			ASTM Intl develop methods to approve use of 100% Synthesized Jet Fuel in existing aircraft and engines without any modification. This enables use of 100% SAF in all existing and new aircraft.	
			• Electrification of ground transportation leads to increased availability of SAF as ground transport uses more electricity and less renewable fuels. • Increased incentives lead to reduced SAF/LCAF fuel cost for users. • Technology evolution enables widespread use of waste gases for SAF, increased feedstock availability, and widespread use of blue/green hydrogen for SAF/LCAF production. Carbon Capture Utilization and Storage (CCUS) is in use.	• Economy-wide deep decarbonisation. • Extensive electrification of ground transportation and widespread availability of renewable energy. • Large incentives lead to widespread use of low GHG fuels for aviation. • Technology evolution enables widespread use of atmospheric CO_2 for SAF, further increases in feedstock availability, widespread use of CCUS, and sufficient H_2 exists to enable cryogenic H_2 use in aircraft. • Infrastructure developed to enable use of non-drop-in fuels at airports around globe

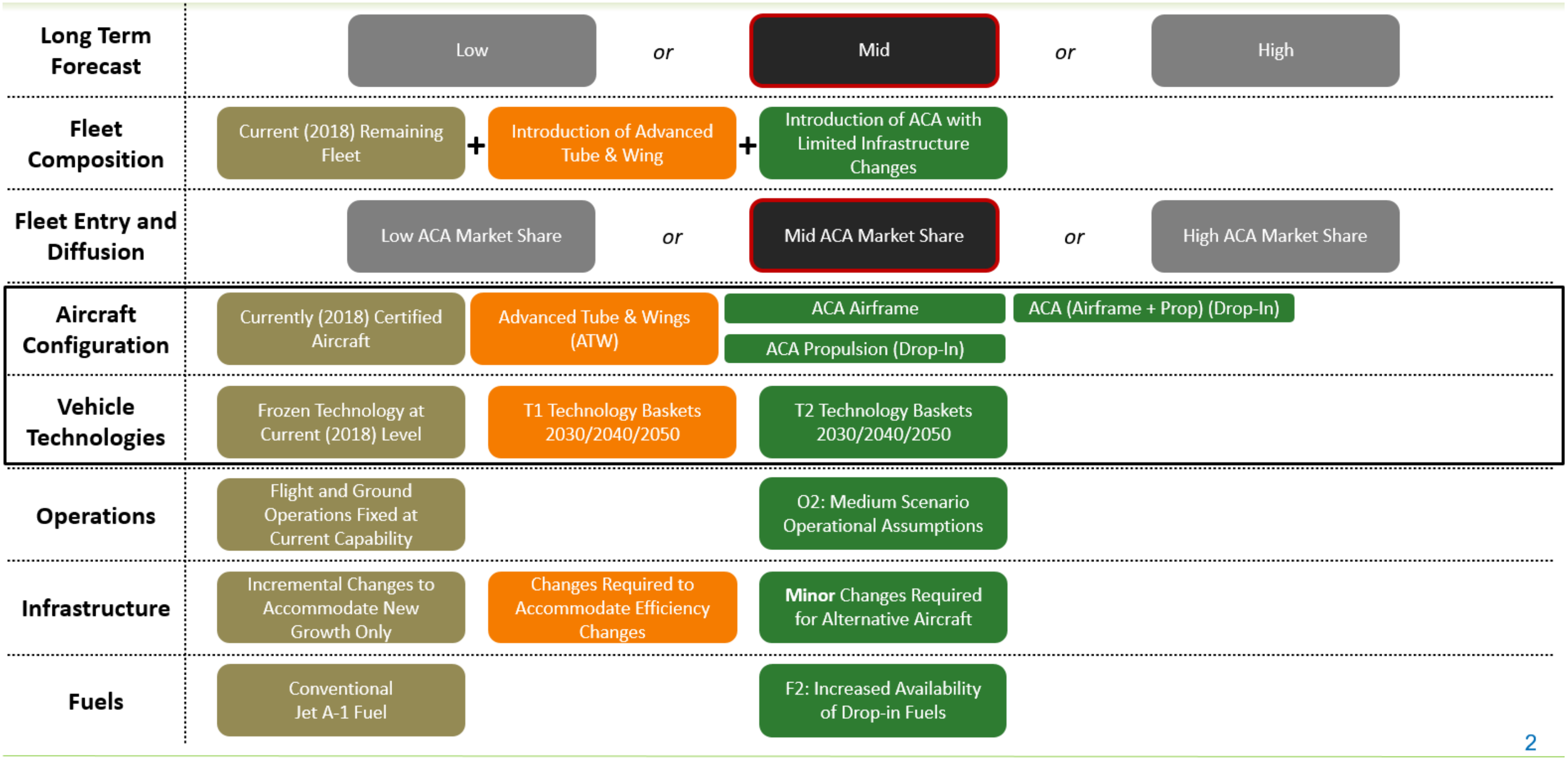
Figure 3. Description of LTAG-TG Integrated Scenarios (continued)

Figures 4, 5 and 6 shows an alternative visualisation of the composition of the LTAG Integrated Scenarios.



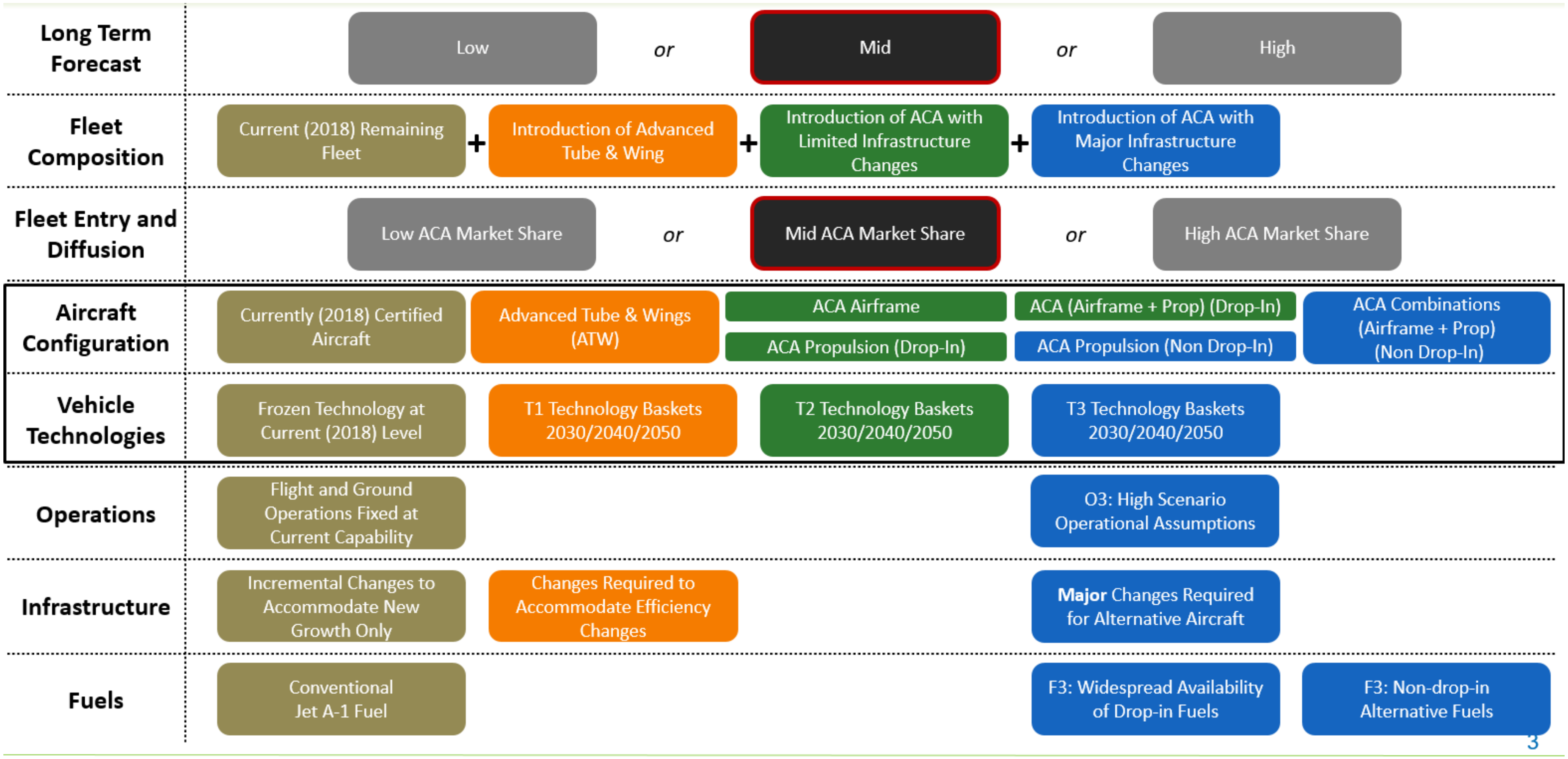
Long Term Forecast	Low	*or*	Mid	*or*	High
Fleet Composition	Current (2018) Remaining Fleet	+	Introduction of Advanced Tube & Wing		
Fleet Entry and Diffusion	No ACA Market Share				
Aircraft Configuration	Currently (2018) Certified Aircraft		Advanced Tube & Wings (ATW)		
Vehicle Technologies	Frozen Technology at Current (2018) Level		T1 Technology Baskets 2030/2040/2050		
Operations	Flight and Ground Operations Fixed at Current Capability		O1: Low Scenario Operational Assumptions		
Infrastructure	Incremental Changes to Accommodate New Growth Only		Changes Required to Accommodate Efficiency Changes		
Fuels	Conventional Jet A-1 Fuel		F1: Availability of Drop-in Fuels (SAF & LCAF)		

Figure 4. IS1: Advanced Tube and Wing Airplanes with <u>No</u> Infrastructure Changes



Long Term Forecast	Low *or*	Mid *or*	High	
Fleet Composition	Current (2018) Remaining Fleet +	Introduction of Advanced Tube & Wing +	Introduction of ACA with Limited Infrastructure Changes	
Fleet Entry and Diffusion	Low ACA Market Share *or*	Mid ACA Market Share *or*	High ACA Market Share	
Aircraft Configuration	Currently (2018) Certified Aircraft	Advanced Tube & Wings (ATW)	ACA Airframe ACA Propulsion (Drop-In)	ACA (Airframe + Prop) (Drop-In)
Vehicle Technologies	Frozen Technology at Current (2018) Level	T1 Technology Baskets 2030/2040/2050	T2 Technology Baskets 2030/2040/2050	
Operations	Flight and Ground Operations Fixed at Current Capability		O2: Medium Scenario Operational Assumptions	
Infrastructure	Incremental Changes to Accommodate New Growth Only	Changes Required to Accommodate Efficiency Changes	**Minor** Changes Required for Alternative Aircraft	
Fuels	Conventional Jet A-1 Fuel		F2: Increased Availability of Drop-in Fuels	

Figure 5. IS2: Advanced Tube & Wing and Unconventional Airframe/Propulsion with Limited Infrastructure Changes



Long Term Forecast	Low	*or*	Mid	*or*	High
Fleet Composition	Current (2018) Remaining Fleet	+ Introduction of Advanced Tube & Wing	+ Introduction of ACA with Limited Infrastructure Changes	+ Introduction of ACA with Major Infrastructure Changes	
Fleet Entry and Diffusion	Low ACA Market Share	*or*	Mid ACA Market Share	*or*	High ACA Market Share
Aircraft Configuration	Currently (2018) Certified Aircraft	Advanced Tube & Wings (ATW)	ACA Airframe ACA Propulsion (Drop-In)	ACA (Airframe + Prop) (Drop-In) ACA Propulsion (Non Drop-In)	ACA Combinations (Airframe + Prop) (Non Drop-In)
Vehicle Technologies	Frozen Technology at Current (2018) Level	T1 Technology Baskets 2030/2040/2050	T2 Technology Baskets 2030/2040/2050	T3 Technology Baskets 2030/2040/2050	
Operations	Flight and Ground Operations Fixed at Current Capability			O3: High Scenario Operational Assumptions	
Infrastructure	Incremental Changes to Accommodate New Growth Only	Changes Required to Accommodate Efficiency Changes		**Major** Changes Required for Alternative Aircraft	
Fuels	Conventional Jet A-1 Fuel			F3: Widespread Availability of Drop-in Fuels	F3: Non-drop-in Alternative Fuels

Figure 6. IS3: Advanced Tube & Wing and Unconventional Airframe/Propulsion with Major Infrastructure Changes

PART B: METHODOLOGY FOR COMBINING SCENARIOS

1. OVERVIEW OF THE MODELING PROCESS

1.1 The LTAG assessment conducted by MDG/FESG evaluates potential contributions of operational and technology improvements, as well as contributions from alternative jet fuels to reducing CO_2 emissions out to 2070. The results are based on the CAEP/12 2018-2050 COVID-19 traffic and fleet forecast as documented in **Appendix M2**. As discussed further in Section 1.8, this forecast was extended to 2070 to specifically support the LTAG Assessment.

1.2 **Supporting Databases:** Prior to understanding the MDG/FESG modelling process there are a number of key global databases that require definition and a broad overview. They include the common operations database (COD), the fleet database, the airports database and the growth and replacement (G&R) database.

1.3 **COD:** The 2018 common operations database is the foundation to all MDG/FESG analyses in the CAEP/12 work cycle. The COD includes radar data from North America, Europe, and Brazil. This portion of the COD, which makes up about 70-75% of global operations in 2018, includes all aircraft operating under instrument flight rules (IFR). The radar data are augmented by two commercial datasets, one from Flight Aware, which is provided through coordination with ICAO/ADAP, and the other from the Official Airlines Guide (OAG). The Flight Aware data provides radar-quality information for Australia and New Zealand and other, smaller regions of the world. The OAG provides rest-of –the-world coverage, and is based on airline schedule information. In total, the 2018 COD contains over 500K origin-destination pairs and includes more than 40M flights.

1.4 **Fleet Database:** The MDG/FESG fleet database is an aggregation of a number of complementary data sources that enhance the global aircraft fleet registry to include the required aircraft parameters needed to compute fuel burn in support of the LTAG analysis. These parameters include those needed for modelling of aircraft full-flight performance and the resultant fuel burn and CO_2.

1.5 **Airports Database:** The MDG/FESG airports database includes geospatial data for over 7900 global airports, which correspond to the airports covered by the 2018 COD. Each airport is mapped to one of seven ICAO regions, which facilitates LTAG results being provided at the regional level.

1.6 **Growth and Replacement Database:** The G&R database defines aircraft that are available to enter the fleet to meet the increase in forecasted demand as well offset the loss of older aircraft that retire from the fleet. The G&R database is made up of in-production aircraft in 2018, apportioned to the passenger, freighter, and business jet markets.

1.7 The fleet and operations dataset from the CAEP/12 Environmental Trends was leveraged for the LTAG assessment. This dataset is considered the baseline scenario for Trends, and for consistency with LTAG terminology is referred to as Integrated Scenario 0 (IS0). As mentioned previously, the Trends Assessment goes to 2050 with an extension to 2070 to support the LTAG assessment. This extension was developed as part of the FESG COVID-19 forecast scenario development process (see below).

1.8 **FESG Covid-19 Forecast Development:** The methodology for developing the COVID-19 forecast required using updated economic forecasts that incorporate the impact of the pandemic and a series of assumptions made by the FESG COVID-19 task group to inform the near-term recovery (see Tables 9, 10 and 11 at the end of this section).

1.8.1 **Passenger Forecast Development:** Developing the passenger long-term traffic forecast (LTF) to account for both the short-term impacts of COVID-19 and eventual long-term recovery required a combination of updated macroeconomic data and recent estimates of the pandemic-driven demand shock (measured in changes to RPKs) to the aviation industry. Updated macroeconomic forecast data accounting for the impact of COVID-19 were sourced from the commercially available source, IHS Markit, while passenger traffic outlooks accounting for the near-term effects of COVID-19 were sourced from IATA. The following steps presented below were taken to combine the updated information and datasets to produce the COVID-19 scenario forecasts.

1.8.2 Incorporating updated macroeconomic data: Country-level economic data forecasts pre- and post-COVID-19 were sourced from IHS Markit to measure the COVID-19-related changes in real GDP and population. These values were aggregated to the route group level and the difference in the growth rates between the pre- and post-COVID-19 outlooks calculated. This rate change (i.e. the difference in percent growth between the two outlooks for each year) was applied to the pre-COVID-19 OECD economic data by forecast scenario (i.e. mid, high, and low economic outlooks). The passenger LTF was then re-processed using the updated economic inputs holding constant the model coefficient values to produce updated forecasts.

1.8.3 COVID-19 RPK adjustment factors: To accurately capture the near-term impact of the COVID-19 downturn on the aviation industry and potential recovery paths, region-based RPK forecasts were sourced from IATA. The RPK forecasts were indexed to 2019 to measure the expected drop in RPK demand in 2020 due to the pandemic, and the subsequent (expected) recovery back to 2019 RPK demand under the mid, high, and low scenario forecasts.

1.8.4 Re-estimation of the Passenger LTF: After the passenger LTF is re-processed using the updated economic inputs, the RPK adjustment factors are applied as a post-estimation process to guide the RPK forecasts during the COVID-19 impact period. Depending on the scenario (mid/high/low), the forecasted growth rates determined by the updated economic data were extended after the defined COVID-19 impact period (e.g. under the high scenario forecast, RPK demand will reach 2019 levels by 2023 and will resume forecasted growth trends based on the updated economic inputs from 2023 onwards). A comparison of the compound annual growth rates (CAGRs) for revenue tonne kilometres between the 2018 LTF and three COVID-19 scenarios is presented in Table 1.

Table 1: FESG COVID-19 Passenger Forecast Scenario Growth Rates

	RPK Compound Annual Growth Rate						
Scenario	**2018-2028**	**2028-2038**	**2038-2050**	**2050-2060**	**2060-2070**	**2018-2050**	**2018-2070**
Low	1.2%	3.6%	3.7%	2.8%	2.6%	2.9%	2.8%
Mid	2.6%	4.0%	3.9%	3.2%	3.0%	3.6%	3.4%
High	3.6%	4.6%	4.4%	3.4%	3.1%	4.2%	3.8%
Pre-COVID-19 Mid	4.2%	4.2%	4.2%	NA	NA	4.2%	NA

1.8.5 Overall, the passenger forecasts are consistent with the COVID-19 assumption matrix, and the methodology and updated results have been agreed to by the COVID-19 Task Group members. Accompanying ASK forecasts were developed through updating the pre-COVID-19 load factor forecasts, using IATA data to inform the 2020 change, then estimating the subsequent recovery and return to long-run trend.

1.8.6 Extending the forecast through 2070 was done by utilizing the income coefficients from the 2018 ICAO LTF and applying a value that represents a potential equilibrium across all the route groups (reflecting the idea that over time growth in developing and mature markets will converge). This value, which was within the range of the estimated LTF income coefficients, was then tapered over the initial 10-year portion of the forecast (based on one standard deviation from the ICAO LTF statistics) to reflect some slowing in the relationship between income growth and travel demand in the outer range of the forecast. The economic forecast trends used for this process were extrapolated from 2050 to 2070.

1.8.7 **Cargo Forecast Development:** The cargo COVID-19 forecast scenario methodology follows a similar logic to the passenger market, beginning with updating the region based economic forecast data to integrate the short and long run impacts to the regional economies. The pre- and post-COVID-19 economic data was sourced from IHS Markit, and the same process described for the passenger update was used to apply the changes in the growth rates to the previous OECD data. The cargo LTF domestic and international models were then re-processed (holding constant the previously estimated coefficients) to produce updated forecast scenarios based on the change in the economic outlooks. Finally, the recovery paths were adjusted during the post-COVID-19 impact period based on the freighter scenario matrix (see Table 2 for freighter tonne kilometre forecast growth rates).

1.8.8 Cargo ATK forecasts were developed through updating the pre-COVID-19 load factors to reflect the 2020 downturn and recovery path back to long-term trends (using IATA data). The extension to 2070 was done through extrapolating economic forecasts to 2070 and then using the coefficients from the ICAO LTF model to forecast FTKs through 2070 by region.

Table 2: FESG COVID-19 Cargo Forecast Scenario Growth Rates

Global	FTK Compound Annual Growth Rate						
Scenario	2018-2028	2028-2038	2038-2050	2050-2060	2060-2070	2018-2050	2018-2070
Low	2.3%	2.7%	2.7%	2.6%	2.4%	2.6%	2.5%
Mid	3.5%	3.4%	3.5%	3.4%	3.0%	3.5%	3.3%
High	4.1%	4.1%	4.3%	4.2%	3.6%	4.2%	4.1%
Pre-Covid-19 Mid	3.5%	3.4%	3.5%	NA	NA	3.5%	NA

1.8.9 **Business Jet Forecast Development:** Development of the business jet COVID-19 forecast utilizes the FESG 2018 base year forecast, the estimated decline in operations in 2020 and economic forecast data from IHS Markit. The initial step involves creating and mapping together indices for operations and real GDP forecasts by region from 2018 through 2050. A correlation coefficient between operations and real GDP is calculated for each business jet region: North America, Europe, Africa, Asia Pacific, China, CIS, Latin America, Middle East, and South Asia.

1.8.10 Using updated 2020 economic data and the correlation coefficients, the economic driven decline in 2020 operations is estimated. From here, the estimated 2020 operations decline is adjusted to match the total historical decline in 2020 operations, providing an approximation of the COVID-19 effect (e.g. lockdown, travel restrictions, etc.) on business jet travel. For example, for North America, the 2020 change in real GDP leads to an estimated 3.6% decline in operations, while historical data suggests a drop of around 20%. This suggests a COVID-19 adjustment at around 16.4%.

1.8.11 The IHS economic forecasts are used to trace out the near-term recovery in operations (mid, high and low), through to the point where they return to 2019 levels (as detailed in the assumptions matrix). During the same period, the COVID-19 adjustment is linearly reduced to reflect increases in vaccination levels and reductions in cases and travel restrictions. Beyond this point, operations are forecast to return to a long-run trend based on the updated COVID-19 economic outlook (see Table 3 for Business Jet operations forecasts).

Table 3: FESG COVID-19 Business Jet Forecast Scenario Growth Rates

Global	Operations Compound Annual Growth Rate						
Scenario	**2018-2028**	**2028-2038**	**2038-2050**	**2050-2060**	**2060-2070**	**2018-2050**	**2018-2070**
Low	2.6%	2.6%	1.8%	1.5%	1.6%	2.3%	2.0%
Mid	3.0%	3.0%	2.1%	1.7%	1.8%	2.7%	2.3%
High	3.3%	3.1%	2.1%	1.8%	1.8%	2.8%	2.4%
Pre-Covid-19 Mid	3.5%	3.1%	2.2%	NA	NA	2.9%	NA

1.8.12 After the operations forecast was finalized, growth in the in-service fleet was calculated using a ratio of in-service fleet per operation to guide this trend over the forecast horizon. The extension through 2070 was done by applying a moving average process to the economic forecast data, maintaining the underlying asymptotic trends in operations from the pre-COVID-19 forecast.

1.8.13 **Fleet Mix:** The COVID-19 task group examined whether current changes in the status of commercial aircraft would suggest making changes to the fleet mix for fleet evolution using the COVID-19 forecast. An examination of commercial fleet information showed a surge in stored aircraft in 2020 due to the sharp decline in demand as a result of the pandemic.

1.8.14 A further investigation of aircraft status indicated that there has been little change in retirement trends in 2020, with most of the change resulting from aircraft moving into storage. As a result, the COVID-19 task group determined there was no clear precedent at this point in time for adjusting the fleet mix for COVID-19 fleet evolution through retirement adjustments, as the stored aircraft are positioned to return to the in-service fleet as demand picks-up.

1.8.15 **Fleet Forecasts and Fleet Evolution:** The COVID-19 fleet forecasts (which are inputs for fleet evolution) were developed using the Airbus and Boeing propriety forecast models. These models extend the traffic demand forecasts to generic fleet forecasts by route group, distance band and competition bin (for the business jet market the fleet forecast is produced by FESG). These are the dimensions required as inputs to the MDG-FESG fleet evolution models. The base year for the COVID-19 forecast is 2018, which is based on the 2018 COD and unchanged from the CAEP/12 pre-COVID-19 traffic demand and fleet forecasts.

1.8.16 The FESG fleet evolution models—FLEET-Builder (FB) and the Aircraft Assignment Tool (AAT) are used to develop the COVID-19 fleet evolution for environmental modelling. Apart from the COVID-19 fleet forecast, there are no other changes associated with inputs or assumptions used in the pre-COVID-19 CAEP/12 fleet evolution models. Figure 7 shows the distribution of passenger available seat kilometres by aircraft and FESG competition bin (CBin) for the mid fleet forecast. As demand increases over the forecast horizon the delivery of ASKs moves towards larger aircraft and in particular to the WB market, which runs from CBin-9 to CBin-11.[1]

---

[1] CBin-2 = 20-85 seats, CBin-3 = 20-85 seats, CBin-4 = 86-100 seats, CBin-5/6/7/8 = 101-210 seats, CBin-9/10/11 = 211 to 401+ seats.

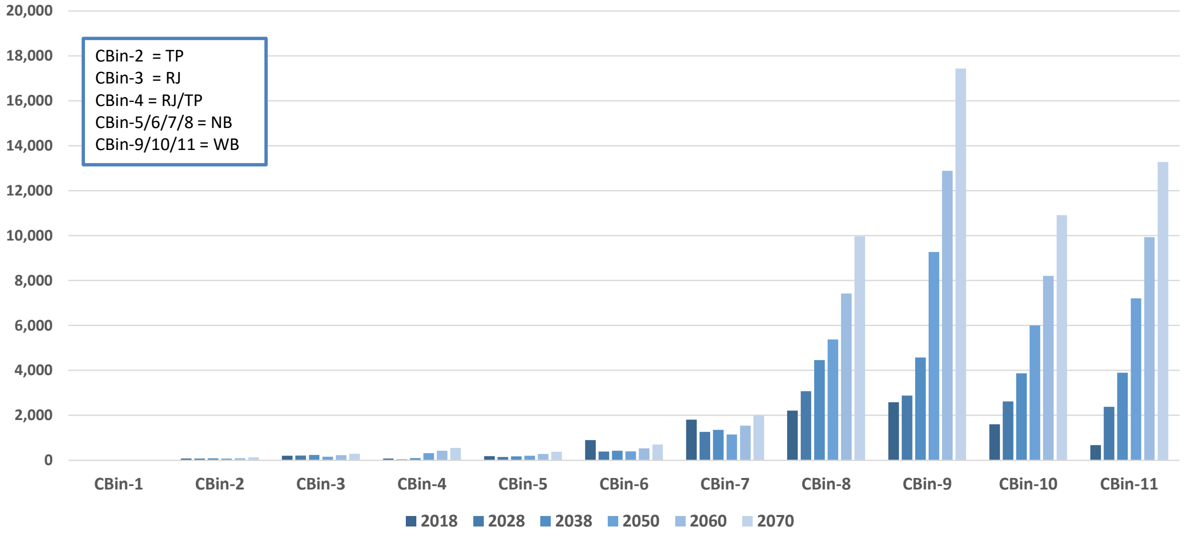


Figure 7: Forecast Passenger ASKs by CBin/Aircraft Market (in billions)

1.8.17 For the LTAG assessment, a post-process fleet evolution approach was developed for introducing the Advanced Concept Aircraft (ACA) into the fleet. Using the COVID-19 mid fleet evolution run and based on specified entry into service years, and delivery market shares provided by LTAG (see Tables 4 & 5 below), the ACA-T2 and ACA-T3 aircraft are introduced into the fleet at the market level (e.g. wide body, narrow body, etc.). While the ACA-T2 and ACA-T3 market shares continue to grow between 2050 and 2070, no additional new types of ACAs are introduced (e.g. ACA-T4, ACA-T5, etc.).

1.8.18 The LTAG fleet evolution process uses the COVID-19 Environmental Trends input assumptions (e.g. growth and replacement database, market share approach, retirement curves). The base fleet evolution for LTAG was run using the mid forecast. High and low outlooks were generated using scalars, which were developed from the high/low FESG forecasts and applied to the mid LTAG fleet evolution run (incorporating the introduction of ACAs by scenario) at the route group level.

1.8.19 The steps for introducing ACAs into each respective market began with translating the aggregate level delivery market share into ASKs shares (and ATK/operations for the cargo and business jet markets respectively) using the base fleet evolution dataset. As an example, at the WB market level this translates to an ACA introduced with 10% delivery market share receiving 10% of the associated ASKs (or ATKs/Ops) for aircraft at a specific entry into service year (EISY), with the remaining 90% of ASKs allocated to the existing ATW aircraft. The same ACA share distribution is also made for operations.

1.8.20 The LTAG fleet evolution ensures ASKs, operations and ATKs are consistent across the base forecast and the integrated scenarios, and maintains the FESG retirement process from the base mid fleet evolution run. Any ACA related range restriction are also accounted for by this process; if an ACA-T3 is range restricted then the ACA-T2 will take the entire ACA market share for new deliveries.

Table 4: LTAG ACA Market Shares for New Deliveries

Market Share for New Deliveries		Turboprop						Regional Jet						Narrow Body					
		2018	2030	2040	2050	2060	2070	2018	2030	2040	2050	2060	2070	2018	2030	2040	2050	2060	2070
IS1	ATW-T1	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
IS2	ATW-T1	100%	100%	75%	40%	10%	0%	100%	100%	65%	40%	10%	0%	100%	100%	70%	40%	10%	0%
	ACA-T2			25%	60%	90%	100%			35%	60%	90%	100%			30%	60%	90%	100%
IS3	ATW-T1	100%	100%	60%	20%	10%	0%	100%	100%	40%	20%	10%	0%	100%	100%	50%	20%	10%	0%
	ACA-T2			20%	40%	45%	50%			30%	40%	45%	50%			25%	40%	45%	50%
	ACA-T3			20%	40%	45%	50%			30%	40%	45%	50%			25%	40%	45%	50%

Table 5: LTAG ACA Market Shares for New Deliveries

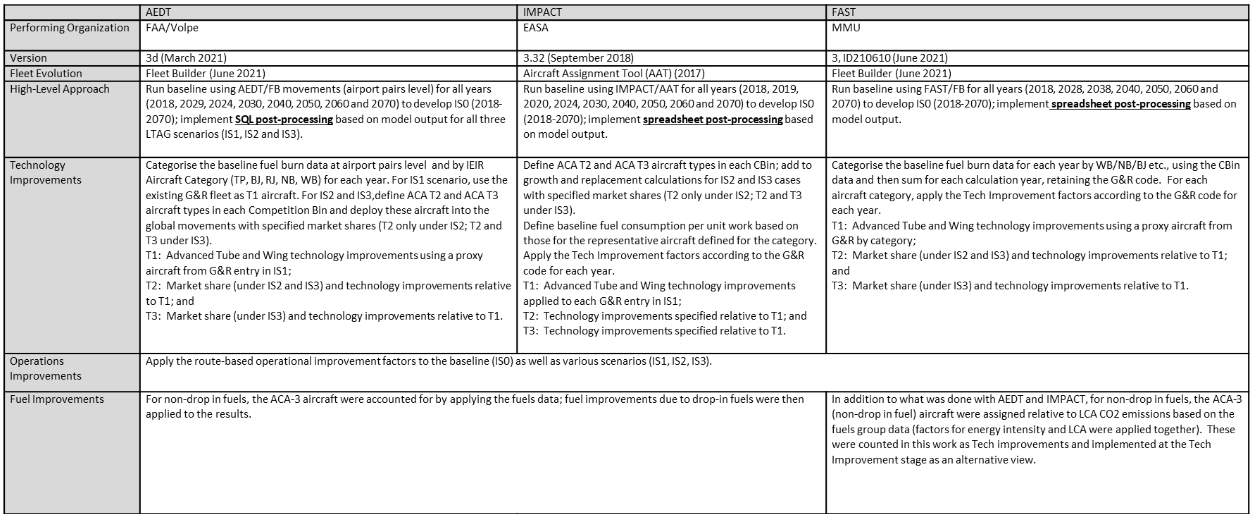
Market Share for New Deliveries		Wide Body						Business Jet					
		2018	2030	2040	2050	2060	2070	2018	2030	2040	2050	2060	2070
IS1	ATW-T1	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
IS2	ATW-T1	100%	100%	95%	50%	25%	0%	100%	100%	65%	40%	10%	0%
	ACA-T2			5%	50%	75%	100%			35%	60%	90%	100%
IS3	ATW-T1	100%	100%	95%	45%	10%	0%	100%	100%	65%	20%	10%	0%
	ACA-T2			5%	50%	50%	50%			30%	40%	45%	50%
	ACA-T3				5%	40%	50%			5%	40%	45%	50%

1.9 **GHG Modelling:** As shown in Figure 8, three fuel burn models contributed results to the LTAG assessment: FAA's Aviation Environmental Design Tool (AEDT); EUROCONTROL's Integrated Aircraft. Noise and Fuel Burn & Emissions Modelling Platform (IMPACT); and Manchester Metropolitan University's Future Civil Aviation Scenario Software Tool (FAST). Also two distinct fleet evolution models were used: FAA's Fleet Builder (FB) and the EC/EASA/EUROCONTROL Aircraft Assignment Tool (AAT). The AEDT and FAST were based on the FB operations, while the IMPACT estimates were based on the AAT operations.

Figures 8: Data and modelling flow supporting LTAG Assessment

1.10 The three complementary modelling approaches are summarized in Table 6. In general, the three approaches were similar. But, it is worth noting a few differences, which likely explain the small variances that will be discussed further in Para 1.12: (1) AEDT and IMPACT use EUROCONTROL's Base of Aircraft Data for computing fuel burn, while FAST uses the commercially available PIANO model; (2) AEDT and FAST use fleet evolution output from Fleet Builder, while IMPACT uses output from the Aircraft Assignment Tool; and (3) FAST generated some complementary graphics to apportion part of the fuels wedge to technology, based on the non-drop-in fuel input.

Table 6: Summary of Modelling Approach



	AEDT	IMPACT	FAST
Performing Organization	FAA/Volpe	EASA	MMU
Version	3d (March 2021)	3.32 (September 2018)	3, ID210610 (June 2021)
Fleet Evolution	Fleet Builder (June 2021)	Aircraft Assignment Tool (AAT) (2017)	Fleet Builder (June 2021)
High-Level Approach	Run baseline using AEDT/FB movements (airport pairs level) for all years (2018, 2029, 2024, 2030, 2040, 2050, 2060 and 2070) to develop IS0 (2018-2070); implement **SQL post-processing** based on model output for all three LTAG scenarios (IS1, IS2 and IS3).	Run baseline using IMPACT/AAT for all years (2018, 2019, 2020, 2024, 2030, 2040, 2050, 2060 and 2070) to develop IS0 (2018-2070); implement **spreadsheet post-processing** based on model output.	Run baseline using FAST/FB for all years (2018, 2028, 2038, 2040, 2050, 2060 and 2070) to develop IS0 (2018-2070); implement **spreadsheet post-processing** based on model output.
Technology Improvements	Categorise the baseline fuel burn data at airport pairs level and by IEIR Aircraft Category (TP, BJ, RJ, NB, WB) for each year. For IS1 scenario, use the existing G&R fleet as T1 aircraft. For IS2 and IS3,define ACA T2 and ACA T3 aircraft types in each Competition Bin and deploy these aircraft into the global movements with specified market shares (T2 only under IS2; T2 and T3 under IS3). T1: Advanced Tube and Wing technology improvements using a proxy aircraft from G&R entry in IS1; T2: Market share (under IS2 and IS3) and technology improvements relative to T1; and T3: Market share (under IS3) and technology improvements relative to T1.	Define ACA T2 and ACA T3 aircraft types in each CBin; add to growth and replacement calculations for IS2 and IS3 cases with specified market shares (T2 only under IS2; T2 and T3 under IS3). Define baseline fuel consumption per unit work based on those for the representative aircraft defined for the category. Apply the Tech Improvement factors according to the G&R code for each year. T1: Advanced Tube and Wing technology improvements applied to each G&R entry in IS1; T2: Technology improvements specified relative to T1; and T3: Technology improvements specified relative to T1.	Categorise the baseline fuel burn data for each year by WB/NB/BJ etc., using the CBin data and then sum for each calculation year, retaining the G&R code. For each aircraft category, apply the Tech Improvement factors according to the G&R code for each year. T1: Advanced Tube and Wing technology improvements using a proxy aircraft from G&R by category; T2: Market share (under IS2 and IS3) and technology improvements relative to T1; and T3: Market share (under IS3) and technology improvements relative to T1.
Operations Improvements	Apply the route-based operational improvement factors to the baseline (IS0) as well as various scenarios (IS1, IS2, IS3).		
Fuel Improvements	For non-drop in fuels, the ACA-3 aircraft were accounted for by applying the fuels data; fuel improvements due to drop-in fuels were then applied to the results.		In addition to what was done with AEDT and IMPACT, for non-drop in fuels, the ACA-3 (non-drop in fuel) aircraft were assigned relative to LCA CO2 emissions based on the fuels group data (factors for energy intensity and LCA were applied together). These were counted in this work as Tech improvements and implemented at the Tech Improvement stage as an alternative view.

1.11 Table 7 shows the 9 priority runs as provided to MDG/FESG by LTAG (see paragraph 1.8.18 for a description of the process used to generate the LTAG high/low forecast scenarios).

Table 7: Priority Runs for LTAG Assessment

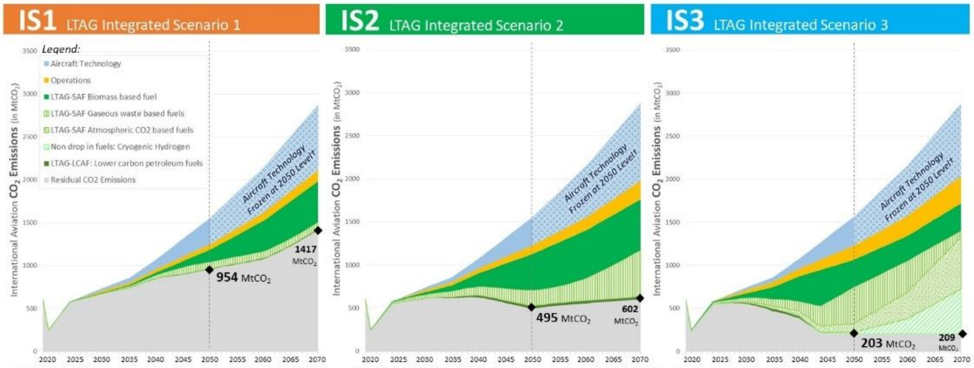
Priority	Integrated scenario	*TECH sub-scenario*	*OPS sub-scenario*	*FUEL sub-scenario*	Traffic forecast
1	**IS2 (medium)**	**IS2 (T2-MED)**	**Medium (O2)**	**Medium (F2)**	**Mid**
2	**IS3 (medium)**	**IS3 (T3-MED)**	**High (O3)**	**High (F3)**	**Mid**
3	**IS1 (medium)**	**IS1 (T1-MED)**	**Low (O1)**	**Low (F1)**	**Mid**
4	**IS2 (medium)**	**IS2 (T2-MED)**	**Medium (O2)**	**Medium (F2)**	**High**
5	**IS2 (medium)**	**IS2 (T2-MED)**	**Medium (O2)**	**Medium (F2)**	**Low**
6	**IS3 (medium)**	**IS3 (T3-MED)**	**High (O3)**	**High (F3)**	**High**
7	**IS3 (medium)**	**IS3 (T3-MED)**	**High (O3)**	**High (F3)**	**Low**
8	**IS1 (medium)**	**IS1 (T1-MED)**	**Low (O1)**	**Low (F1)**	**High**
9	**IS1 (medium)**	**IS1 (T1-MED)**	**Low (O1)**	**Low (F1)**	**Low**

1.12 The three MDG/FESG fuel burn modelers completed the 9 priority runs and the comparative results are shown in Table 8. Table 8 summarizes the percent difference in computed CO_2, after applying technology, operational improvements and fuels for IMPACT and FAST, relative to AEDT, for both 2050 and 2070. Overall, the agreement between the three models is excellent and well within the range of expected differences. These differences are also comparable to what has been observed in current and past environmental Trends assessments. The percent differences primarily ranged between 0 and 3% out to 2050, and are as large as 6 to 7% in 2070.

Table 8: Comparison of LTAG Results from MDG/FESG Models

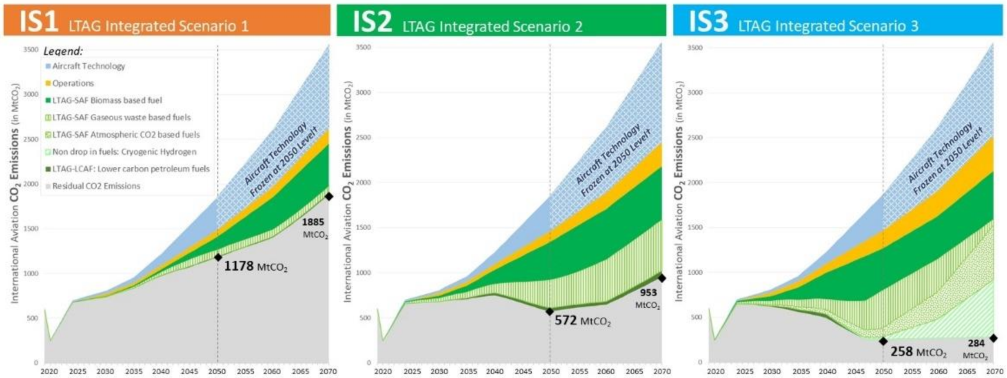
After Tech, Ops and Fuels						
LTAG Scenario	**Analysis Year**	**FB-AEDT Net CO2 (Mt)**	**AAT-IMPACT Net CO2 (Mt)**	**FB-FAST Net CO2 (Mt)**	**PERC_DIFF_AEDT_IMPACT**	**PERC_DIFF_AEDT_FAST**
IS1 Mid Forecast	2050	954	927	954	3%	0%
IS2 Mid Forecast	2050	495	482	488	3%	1%
IS3 Mid Forecast	2050	203	198	202	2%	0%
IS1 Mid Forecast	2070	1417	1,365	1,414	4%	0%
IS2 Mid Forecast	2070	602	578	584	4%	3%
IS3 Mid Forecast	2070	209	197	197	6%	6%
After Tech, Ops and Fuels						
LTAG Scenario	**Analysis Year**	**FB-AEDT Net CO2 (Mt)**	**AAT-IMPACT Net CO2 (Mt)**	**FB-FAST Net CO2 (Mt)**	**PERC_DIFF_AEDT_IMPACT**	**PERC_DIFF_AEDT_FAST**
IS1 High Forecast	2050	1178	1137	1177	3%	0%
IS2 High Forecast	2050	572	553	563	3%	2%
IS3 High Forecast	2050	258	250	250	3%	3%
IS1 High Forecast	2070	1885	1,800	1872	5%	1%
IS2 High Forecast	2070	953	902	923	5%	3%
IS3 High Forecast	2070	284	263	267	7%	6%
After Tech, Ops and Fuels						
LTAG Scenario	**Analysis Year**	**FB-AEDT Net CO2 (Mt)**	**AAT-IMPACT Net CO2 (Mt)**	**FB-FAST Net CO2 (Mt)**	**PERC_DIFF_AEDT_IMPACT**	**PERC_DIFF_AEDT_FAST**
IS1 Low Forecast	2050	728	716	728	2%	0%
IS2 Low Forecast	2050	417	411	410	1%	2%
IS3 Low Forecast	2050	147	146	143	1%	3%
IS1 Low Forecast	2070	916	893	910	3%	1%
IS2 Low Forecast	2070	491	477	477	3%	3%
IS3 Low Forecast	2070	129	124	122	4%	6%

1.13 Figures 9, 10 and 11 present the MDG/FESG results computed by AEDT for the 9 LTAG priority runs. The results presented are for international aviation only and are provided herein as they represent input to the Cost Estimation Ad Hoc Group. More detailed MDG/FESG results are presented in Appendix R, including regional results. For each of the 9 priority runs, wedge graphics are shown which provide the range of contributions from technology and operations, as well as consider the various scenarios provided by the LTAG-Fuels TG. CO_2 emissions results produced by the GHG models are presented for international operations at the global level and by CAEP region. This level of presentation is identical to that computed for Environmental Trends, allowing for a direct comparison between the LTAG and the Trends Assessments. Developing global and regional level results aligns with the MDG/FESG fleet forecast and fleet evolution process which is accomplished at a macro level and is not disaggregated to lower levels.



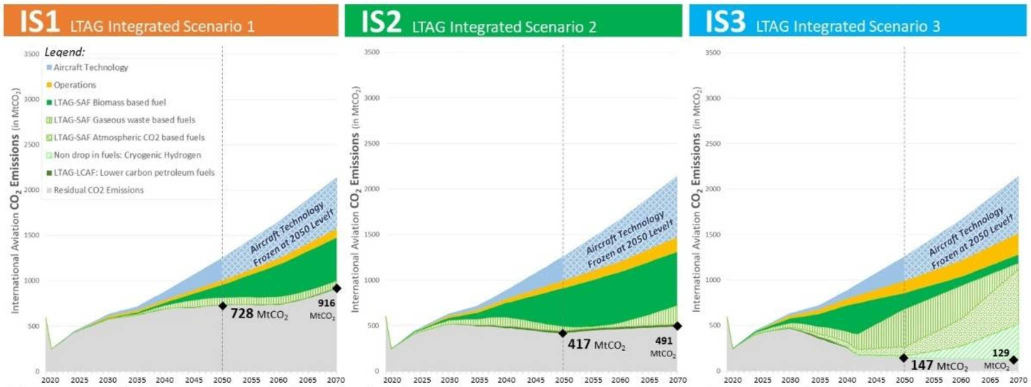
† Caution required with the interpretation of absolute CO_2 emissions levels after 2050 due to modelling assumptions e.g., frozen aircraft technology after 2050. Under these assumptions, CO_2 emissions are higher than in an alternative scenario (and modelling approach) where aircraft technology would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

Figure 9. Residual (in-sector) CO_2 emissions from international aviation associated with LTAG Integrated Scenarios based on <u>Mid</u> Traffic Forecast



† 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 10. Residual (in-sector) CO_2 emissions from international aviation associated with LTAG Integrated Scenarios based on <u>High</u> Traffic Forecast



† 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 11. Residual (in-sector) CO_2 emissions from international aviation associated with LTAG Integrated Scenarios based on <u>Low</u> Traffic Forecast

Table 9: FESG COVID-19 Passenger Forecast Assumption Matrix

Commercial Passenger Market							
Scenario/Assumption	**Vaccine**	**Global Economic Activity**	**Regional Variation**	**Route Variation -- Domestic/International**	**Business Travel Demand**	**Return to 2019 RPKs**	**Return to pre-crisis Trend (levels)**
High	Announced early 2021 Available/widespread use mid/late 2021	V-shaped recovery -- back to 2019 levels in early 2021	--Solid and sustained global recovery --Asia (China) pick-up quickly in 2021 --Recovery in traffic tracks economic growth (NA/EUR follow Asia)	--Domestic traffic responds quickly particularly in U.S./Europe/Asia (China) --International lags somewhat (2022) --solid income growth drives leisure travel	-- Business Travel growth resumes late 2021 --Returns to normal levels in 2022 -- Drives solid recovery in both markets (B2B and conferences)	2023	Yes -- around 2030
Mid	Announced mid-2021 Available/widespread use early/mid 2022	Return to 2019 levels in late 2021/2022 (running behind the optimistic outlook)	-- Recovery lags economic growth (some behavioral changes/lower incomes) -- Resumption in domestic traffic first -- International lags --China/Asia leads the recovery, followed by NA and EUR	--Domestic traffic growth resumes in 2022 U.S./Europe/Asia (China) --International lags (2023) -- Lower incomes reduce leisure travel	--Business Travel growth resumes in late 2022/2023, but never fully returns to normal levels (i.e. some permanent reduction due to substitutes -- Zoom, etc.)	2024	No -- permanent shift due to substitution of online technologies for business and changes in household vacation/travel patterns
Low	Announced early 2022 Available/widespread use late 2022/early 2023	Return to 2019 levels by 2023/2024	--Recovery lags economic growth (more prevalent behavior changes/lower incomes) -- resumption in domestic traffic slow to gain traction --International lags further behind --China/Asia and developing nations lead recovery. NA and EUR lag.	--Domestic traffic resumes growth in 2024 Asia (China) --International lags (2025) -- Lower incomes reduce leisure travel	--Business travel does not fully recover --Permanent and sustained loss in domestic/international travel as a result.	2027	No -- permanent shift due to substitution of online technologies for business and changes in household vacation/travel patterns

Table 10: FESG COVID-19 Cargo Assumption Matrix

Cargo Market					
Scenario/Assumption	**Vaccine**	**Economic Activity**	**Regional Variation**	**Return to 2019 FTKs**	**Return to pre-crisis Trend (levels)**
High	Announced early 2021 Available/widespread use mid/late 2021	V-shaped recovery -- back to 2019 levels in early 2021	Regional variation will depend upon differences in regional economic activity -- Pacific/Asia & Asia/Middle East will lead, followed by North America/Europe	2022	Yes
Mid	Announced mid-2021 Available/widespread use early/mid 2022	Return to 2019 levels in late 2021/2022 (running behind the optimistic outlook)	Regional variation will depend upon differences in regional economic activity -- Pacific/Asia & Asia/Middle East will lead, followed by North America/Europe	2022	Yes
Low	Announced early 2022 Available/widespread use late 2022/early 2023	Return to 2019 levels by 2023/2024	Regional variation will depend upon differences in regional economic activity -- Pacific/Asia & Asia/Middle East will lead, followed by North America/Europe	2022	Dependent upon economic forecast

Table 11: FESG COVID-19 Business Jet Assumption Matrix

Business Jet Market					
Scenario/Assumption	**Vaccine**	**Economic Activity**	**Regional Variation**	**Return to 2019 Ops**	**Return to pre-crisis Trend (levels)**
High	Announced early 2021 Available/widespread use mid/late 2021	V-shaped recovery -- back to 2019 levels in early 2021	Recovery driven by regional economic variation and largest markets -- North America, Europe and China. Variation affected by stock market performance, investment, purchasing managers index, and the US$ exchange rate.	2022	Long-run trend influenced by long-run economic trends
Mid	Announced mid-2021 Available/widespread use early/mid 2022	Return to 2019 levels in late 2021/2022 (running behind the optimistic outlook)	Recovery driven by regional economic variation and largest markets -- North America, Europe and China. Variation affected by stock market performance, investment, purchasing managers index, and US$ exchange rate.	2023	Long-run trend influenced by long-run economic trends
Low	Announced early 2022 Available/widespread use late 2022/early 2023	Return to 2019 levels by 2023/2024	Recovery driven by regional economic variation and largest markets -- North America, Europe and China. Variation affected by stock market performance, investment, purchasing managers index, and the US$ exchange rate.	2024	Long-run trend influenced by long-run economic trends

PART C: METHODOLOGY FOR COST (INVESTMENT) ESTIMATIONS

1. BACKGROUND

1.1 Under task LTAG04 the LTAG-TG remit calls for; "Final Analysis of the scenarios to understand those impacts on CO_2 emissions including relating this to the actual 2020 levels. The **costs associated with the scenarios** and economic impacts on aviation growth, noise and air quality, in all countries especially developing countries…".

1.2 Following the LTAG-TG Plenary meeting in February 2021, the Cost Estimation ad hoc (CEahg) group was established to review and develop an approach and methodologies for estimating cost and investments associated with the LTAG-TG Integrated Scenarios.

1.3 This part of the appendix summarises the methodology followed by the Cost Estimation ad hoc group to produce the cost (investment) estimations summarised in **Appendix R1**.

2. REVIEW OF COST ANALYSES WITHIN CAEP

2.1 The LTAG-TG CEahg started by conducting a background review of cost modelling historically performed by CAEP. The ICAO (CAEP) Trends provide no (or little) cost information. Aircraft technology and operations costs are not quantified. The only considerations of costs i.e. "Cumulative CapEx investment in biorefineries by 2050" were found in sustainable aviation fuels assessments by the Alternative Fuels Task Force (AFTF).

2.2 CAEP analyses on the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) by the Global Market Based Measure-Task Force (GMTF) and now the Working Group 4 on CORSIA have considered costs resulting from offsetting requirements and implementation of Monitoring, Reporting and Verification (MRV) and tracked such cost by type of stakeholders (i.e. operators, States, ICAO) including some regional level analyses that are ongoing. However, market-based measures are outside the scope of the LTAG-TG.

2.3 CAEP stringency analyses in support of standard setting generally consider and quantify the cost resulting from aircraft technology responses (when an aircraft is fixed/improved to meet a standard stringency level). The types of costs considered include Non-Recurring Cost (NRC), Aircraft Value Loss (AVL), other-Direct Operating Costs (i.e. crew, maintenance landing and route costs), capital costs and fuel costs.

3. TYPE OF COST (INVESTMENT) ESTIMATION APPROACH

3.1 Figure 12 shows the summary of the type of cost estimation approach that the LTAG-TG followed for the purpose of the LTAG analysis. Given the length of the analysis timeline (through 2050 extended to 2070) and the definition of integrated scenarios, the approach aimed at producing a first order assessment of costs associated for each LTAG-TG Integrated Scenarios. For each LTAG Integrated Scenario, the costs (or investments) associated with aircraft technology, operations and fuels measures were isolated, and to the extent possible quantified, using a scenario minus baseline approach. For the LTAG analyses, the baseline was defined as Integrated Scenario 0 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.

3.2 The results provide contextual information on the types and order magnitude of costs (investments) required to make a LTAG-TG Integrated Scenario materialize (and to whom these costs or investments would apply). The cost and investment estimations associated with the LTAG analysis is also not a cost analysis that underlies a stringency analysis, as such methodologies and assumptions are deemed fit for purpose only for LTAG purposes. It is also not a cost effectiveness or cost benefit analysis to rank LTAG-TG scenarios.

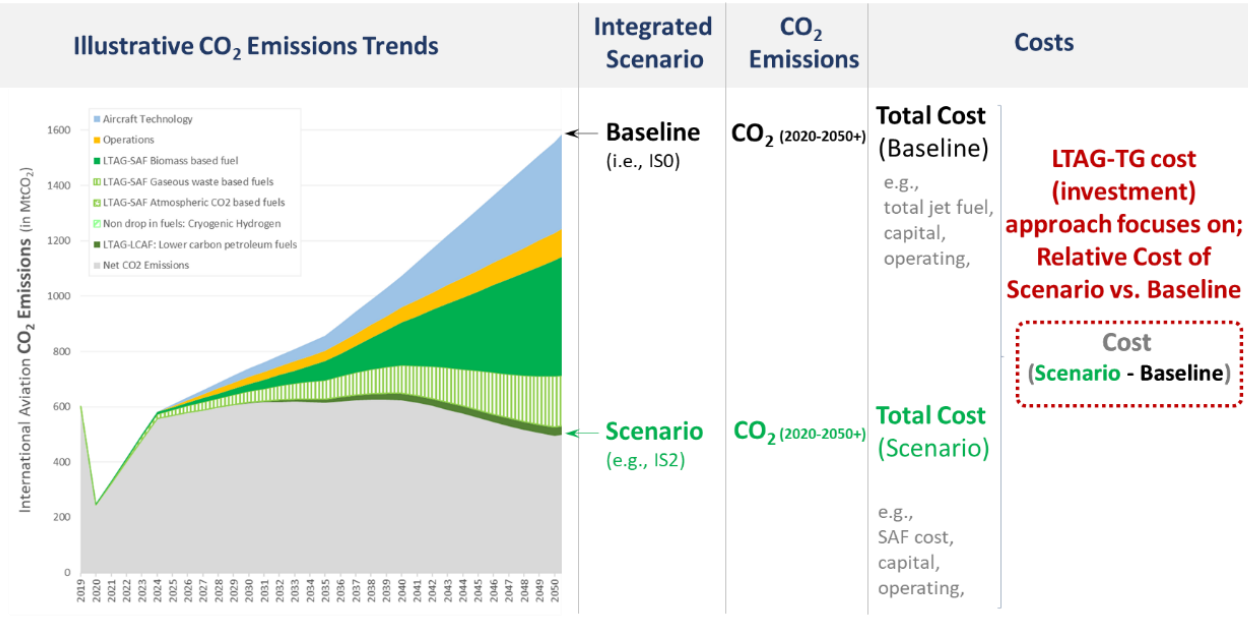


Figure 12: Type of Cost Modelling Approach for LTAG-TG analysis

Note. — The LTAG remit focuses on the "development of in-sector emissions reduction scenarios from technology, operations and fuels". Any estimation of a gap to reach an aspirational goal beyond the contribution from technology, operations and fuels and any associated costs was outside of the LTAG-TG remit.

4. SCOPE OF COST (INVESTMENT) ESTIMATIONS

4.1 The costs associated with LTAG-TG Scenarios span multiple dimensions:

a) ***LTAG-TG Integrated Scenarios***: Costs and investments are driven by the portfolio of measures considered by LTAG-TG subgroups i.e. technology, operations, and fuels. Each LTAG-TG integrated scenario is associated with an estimate of costs;

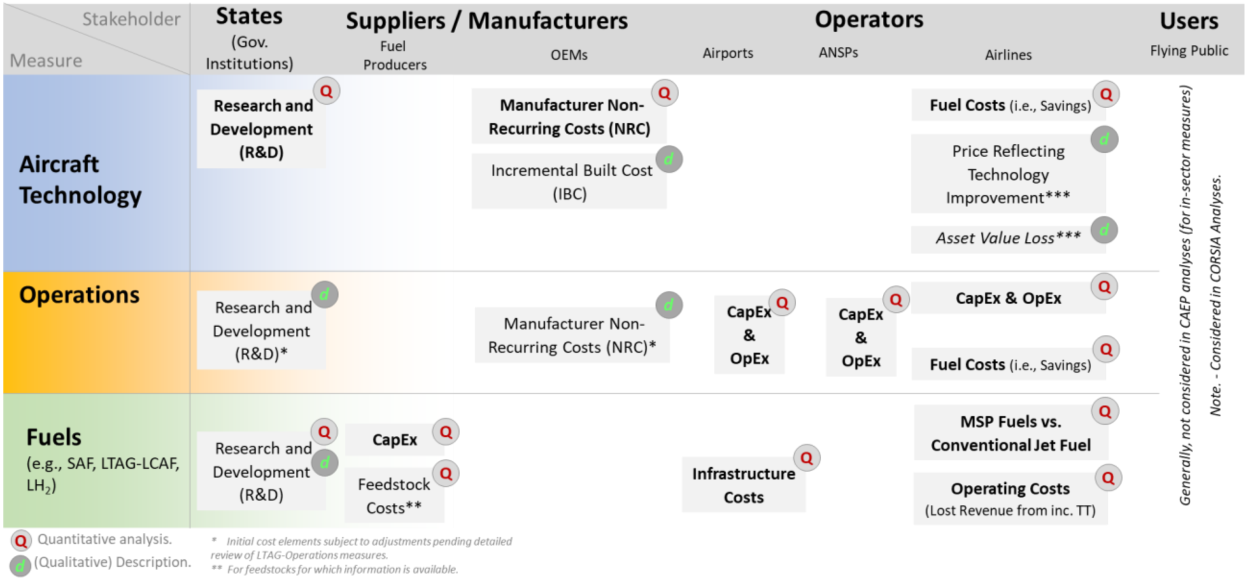
b) ***Aviation Sector Scope*** i.e. International vs. Global: The LTAG-TG cost analysis focuses on international aviation given ICAO's remit[2];

c) ***Temporal dimension (i.e. time):*** The cost estimation analysis captures when costs would need to be incurred (or investments required) to deliver the associated measures;

d) ***Stakeholders (types of stakeholders):*** e.g. suppliers (OEMs, fuel suppliers), operators, States; and

e) ***Geographical distribution:*** e.g. "Costs in all countries, especially developing countries".

4.2 **Figure** shows the scope of the cost elements considered by the LTAG-TG, including the costs (investments) that have been quantified and those that have been acknowledged as potentially relevant and described qualitatively.



Stakeholder / Measure	States	Suppliers / Manufacturers		Operators			Users
	(Gov. Institutions)	Fuel Producers	OEMs	Airports	ANSPs	Airlines	Flying Public
Aircraft Technology	**Research and Development (R&D)** Q		**Manufacturer Non-Recurring Costs (NRC)** Q Incremental Built Cost (IBC) d			**Fuel Costs** (i.e., Savings) Q Price Reflecting Technology Improvement*** d *Asset Value Loss**** d	*Generally, not considered in CAEP analyses (for in-sector measures)* *Note. - Considered in CORSIA Analyses.*
Operations	Research and Development (R&D)* d		Manufacturer Non-Recurring Costs (NRC)* d	**CapEx & OpEx** Q	**CapEx & OpEx** Q	**CapEx & OpEx** Q **Fuel Costs** (i.e., Savings) Q	
Fuels (e.g., SAF, LTAG-LCAF, LH_2)	Research and Development (R&D) Q d	**CapEx** Q Feedstock Costs** Q		**Infrastructure Costs** Q		**MSP Fuels vs. Conventional Jet Fuel** Q **Operating Costs** (Lost Revenue from inc. TT) Q	

Q Quantitative analysis.
d (Qualitative) Description.

** Initial cost elements subject to adjustments pending detailed review of LTAG-Operations measures.*
*** For feedstocks for which information is available.*

Figure 13: Cost Elements Considered by the LTAG-TG

Note. — The CEahg acknowledged that fuel savings from aircraft technology improvements may be reduced by an increase in aircraft acquisition costs driven by Price After Technology Improvement i.e. aircraft technology improvements are not expected to "come for free". Airline acquisition of new aircraft is a multi-attribute decision making process, including aircraft capabilities, operating costs (including fuel efficiency), commonality with other aircraft types in the fleet, etc. The transactions are also not publicly available, and it is challenging to extract/isolate the contribution of aircraft technology improvement to aircraft total price.

---

[2] Note: Some costs such as those related to aircraft technology and operations are difficult and/or inappropriate to break down into international vs. domestic. For example, the investments required to develop future aircraft programs/families that would serve both the international and domestic aviation markets are not split into international aviation alone. If it requires $20 billion to develop a new aircraft and international aviation accounts for 60% of global activity even if an OEM invests $12 billion, this will not result into a certified and viable aircraft i.e. the entire non-recurring costs are required. Such costs are reported as global costs and marked as such in relevant figures of this report.

5. APPROACH FOR GEOGRAPHICAL BREAKDOWN OF COST ESTIMATIONS

5.1 The LTAG-TG CEahg considered its remit along with several factors to devise an approach for addressing the question of geographical breakdown of costs. The group noted that any downstream cost analysis of Integrated Scenarios was subject to the availability of (dis-aggregated) data from MDG/FESG. The LTAG-TG CEahg was established 5 months before SG/3 and 9 months before the CAEP/12 paper deadline. Finally, the group questioned the validity of dis-aggregated forecasts e.g. airline, OEM levels through 2070 that would require a lot of State and aviation stakeholder specific information that either do not exist or are highly confidential such as an aircraft manufacturer's strategic plan to develop future product lines or a SAF producer's planned production volume of SAF in the 2040s, 2050s, etc. The LTAG-TG CEahg therefore devised an approach to (1) quantitatively assess total aggregated costs e.g. NRC, Fuel Costs, Capex, and (2) qualitatively describe potential geographical distribution of costs and trends (with some quantitative assessment of the bases for distribution i.e. current/near-term).

5.2 Despite the absence of disaggregate data to conduct detailed analyses at the regional and/or State level, the LTAG-TG CEahg supported the development of a data package for States to conduct their own analyses if deemed valuable and necessary.

6. CONSIDERATIONS OF IMPACTS ON AVIATION GROWTH

6.1 Background

6.1.1 ***Objective:*** Following discussions during LTAG-TG/3 meeting, the LTAG-TG CEahg (in consultation with the FESG) considered and qualitatively described the potential impacts of the overall costs (and investments) related to measures underlying LTAG-TG scenarios on aviation growth.

6.1.2 ***Approach:*** First, the CEahg reviewed reports, studies, etc. on demand, supply, price of air transport services. The group then considered the impact on aviation growth in the context of the LTAG-TG traffic scenarios (i.e. price elasticity vs. income elasticity). The impacts on aviation growth were also framed in the context of the scope of the LTAG-TG study i.e. price elasticity for international vs. domestic aviation (i.e. inter/supra national flights[3]), and price elasticity for short-haul vs long-haul flights. Finally, a qualitative assessment was developed. Coordination with FESG was also conducted with input and consultation from FESG members also member of LTAG as well as input and feedback from the FESG co-rapporteur.

6.2 Summary

6.2.1 The LTAG-CEahg considered the potential impacts of the overall costs (and investments) related to measures that would underly LTAG scenarios on aviation growth.

6.2.2 While difficult to quantitatively assess these impacts on aviation growth far out in the future, the LTAG-CEahg noted that while an LTAG may result in a net increase in operating costs, some costs may be passed on to the flying public.

6.2.3 Given the relatively lower price elasticity associated with international aviation (and limited travel alternatives for long-haul trips relatively more prevalent in international vs. domestic

---

[3] Supra-national level refers to international flights (beyond an individual country) e.g. flights between countries of the European Union given the use of the term in the IATA study.

aviation), the impact on aviation growth may be limited. In addition, it is expected that aviation will continue to deliver benefits to national, regional and the global economies.

6.3 Dynamics Influencing the Impacts on Aviation Growth in Context of CAEP Modelling

6.3.1 Figure 14 illustrates the dynamics influencing the impacts on aviation growth in context of CAEP modelling. First, economic modelling and traffic forecasts are developed by ICAO/ADAP and the CAEP FESG. These are generally developed in the first half of a CAEP cycle. In the context of the LTAG-TG study, these traffic forecasts were used as input to the fleet evolution based on input from LTAG-TG on aircraft technology scenarios. Downstream modelling of CO_2 emissions based on aircraft technology, operations and fuels scenarios allowed for the estimations of costs and investments associated with each LTAG-TG integrated scenario. Costs to operators are assessed as part of the LTAG-CEahg work. In a closed loop[4] (integrated) model, the cost to operators could be translated into airfare changes (assuming a cost pass through from airlines to aviation customers). Depending on passenger (or aviation system user) choice model/logic (reflecting price elasticity), impacts on demand for aviation may be quantified. However, this feedback loop was not feasible and implemented for this CAEP analysis given CAEP (FESG/MDG/LTAG-TG) modelling process, technical reasons, and time constraints.

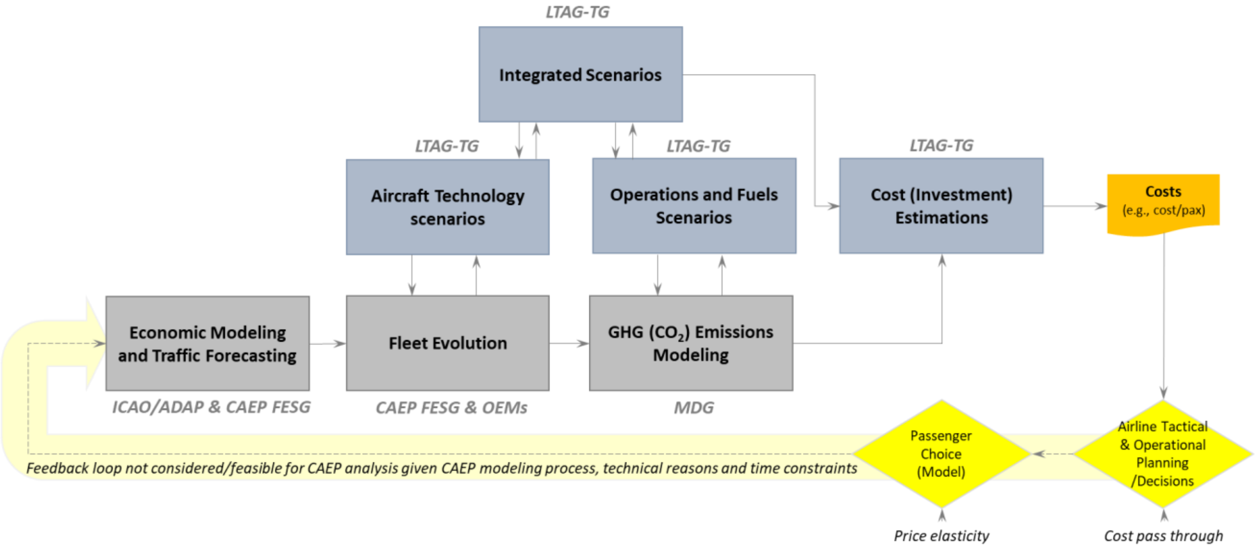


Figure 14: Dynamics Influencing the Impacts on Aviation Growth in Context of CAEP Modelling

6.4 Background/Literature Review

6.4.1 The assumptions and implementation of cost pass through in the aviation sector vary across a range of studies. No consensus has been reached in the literature on aviation: while significant cost pass-through seems likely, the lack of empirical estimates and the abundance of influencing factors make it hard to form reliable estimates.

---

[4] Model in which a feedback loop would be modelled and run iteratively to reach an equilibrium.

6.4.2 Based on a CE Delft study[5], the average cost pass-through rate was assumed to be 60% with a range from 32% as a minimum value and 87% as a maximum value. Literature reviews indicate that many authors simply assume that aircraft operators fully pass through their allowance costs, based on the reasoning that the aviation sector is highly competitive (Frontier Economics, 2006; Anger & Kohler, 2010; Scheelhaase, et al., 2010). Koopmans and Lieshout question this presupposition, as most aviation markets are better described by differentiated oligopolies than by perfect competition (Koopmans & Lieshout, 2016). Under such a market structure, the authors argue that between 50% and 100% of sector-wide cost changes will be passed onto passengers. Although ex-post studies are missing, several modelling efforts have tried estimating cost pass-through rates in the aviation sector. An ex-ante study by Vivid Economics finds that the high degree of market concentration in the European aviation sector likely leads to pass-through rates of 100%. A study by Bloomberg (2011) finds that the pass-through rate may increase over time as aircraft operators adapt to new market conditions, for instance by no longer offering flights between certain city pairs. The authors suggest that a short-term pass-through rate of 30% is likely, while the long run pass-through rate may approach 60% (Bloomberg, 2011).

6.4.3 A study by Gayle, et al. on "Cost Pass-through in Commercial Aviation: Theory and Evidence" investigated the effects of significant worldwide decline in crude oil price beginning in mid-2014 through to 2015 resulted in substantial fuel expense reductions for airlines, but no apparent commensurate reductions in industry average airfares. The paper examined the market mechanisms through which crude oil price may influence airfare, which facilitates identifying the possible market and airline-specific characteristics that influence the extent to which crude oil price changes affect airfare. The analysis revealed that the crude oil-airfare pass-through relationship can be either positive or negative, depending on various market and airline-specific characteristics. Evidence that airline-specific jet fuel hedging strategy and market origin-destination distance contribute significantly to pass-through rates being negative.

6.4.4 An IATA, Air Travel Demand Study (2008) also provides background, statistics, and discussion on cost pass through and demand elasticities. The study defined demand elasticities as the measure of change in the quantity demanded of a particular good or service because of changes to other economic variables, such as its own price, the price of competing or complementary goods and services, income levels and taxes.

6.4.5 The appropriate value of a demand elasticity will vary in accordance with the context in which they are considered. For air transport there are five main levels (for the scope of the market) for which demand elasticities can be estimated: Price Class Level, Airline/Air Carrier Level, Route/Market Level, National Level, Supra-National Level.

6.4.6 In each of the five levels of aggregation, different cross-price elasticities exist, reflecting the availability of substitute options, development of the aviation market and variations in middle-class size. The own price elasticity at one level of aggregation can reflect both the own price and cross price elasticities at other levels of aggregation.

6.4.7 Based on econometric analysis based on over 500 regression models, it was assessed that price elasticity at the route level to be -1.4 for route/market level, -0.8 for national level, and -0.6 for supra-national level.

6.4.8 At the supra-national level (e.g. the European Union) estimates show comparatively low air travel price elasticity of -0.6. This is because as the number of routes covered expands the number of

---

[5] CE Delft, "Additional profits of sectors and firms from the EU ETS" Study evaluated the impacts of EU ETS on firms' profits", May 2021, last retrieved: Oct. 20, 2021, available at: https://cedelft.eu/wp-content/uploads/sites/2/2021/06/CE_Delft_200402_Additional_Profits_EU_ETS_FINAL_3.pdf

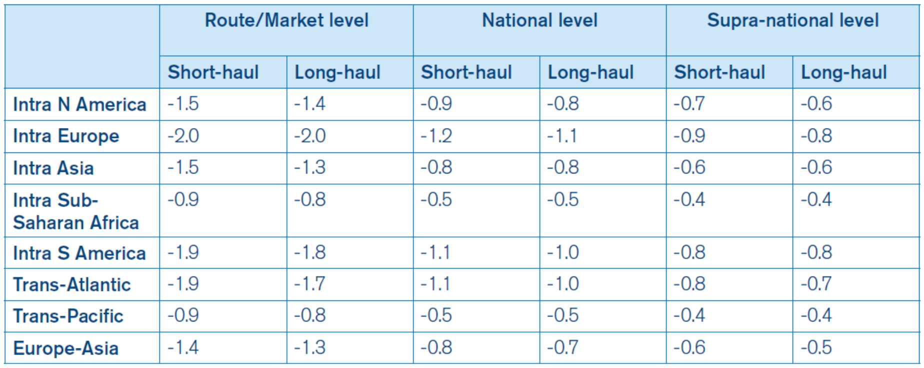
choices for passengers to avoid any travel price increase diminishes. There is less opportunity for traffic to be diverted.

6.4.9 The study also discusses short-haul vs. long-haul aviation which is relevant to considerations within the LTAG-TG study that focuses on international aviation and -by definition- longer flight distance than domestic aviation.

6.4.10 Review of previous research found consistent results showing that air travel price elasticities on short-haul routes were higher than on long-haul routes. This largely reflects the greater opportunity for inter-modal substitution on short haul routes (e.g. travellers can switch to rail or car in response to air travel price increases). Analysis of trans-Atlantic or trans-Pacific markets indicated that entirely long-haul, with virtually no opportunity for modal substitution have lower price elasticity.

6.4.11 There was also 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. These characteristics are more often found in intra Europe, intra South America and North America - Europe markets.

6.4.12 The price elasticity analysis did not consider possible changes with time in the long term, e.g. due to the development of alternative transportation in substitution to aviation or aviation crisis recovery. It is also important to note that some considerations made when the study was developed (2008) may not reflect the present circumstances.



	Route/Market level		National level		Supra-national level	
	Short-haul	Long-haul	Short-haul	Long-haul	Short-haul	Long-haul
Intra N America	-1.5	-1.4	-0.9	-0.8	-0.7	-0.6
Intra Europe	-2.0	-2.0	-1.2	-1.1	-0.9	-0.8
Intra Asia	-1.5	-1.3	-0.8	-0.8	-0.6	-0.6
Intra Sub-Saharan Africa	-0.9	-0.8	-0.5	-0.5	-0.4	-0.4
Intra S America	-1.9	-1.8	-1.1	-1.0	-0.8	-0.8
Trans-Atlantic	-1.9	-1.7	-1.1	-1.0	-0.8	-0.7
Trans-Pacific	-0.9	-0.8	-0.5	-0.5	-0.4	-0.4
Europe-Asia	-1.4	-1.3	-0.8	-0.7	-0.6	-0.5

Figure 15: Estimated price elasticities of passenger demand (IATA, Air Travel Demand (IATA Economics Briefing No9, "measuring the responsiveness of air travel demand to changes in prices and incomes", April 2008)

A Eurocontrol study[6] also found that while passenger numbers increased by 40% between 2009 and 2017, CO_2 emissions only increased by 15%, and noise levels remained stable. There is little evidence that taxing aviation per se leads to lower CO_2 emissions; nor do raising fuel prices or ticket prices reduce CO_2 emissions. Economic output is the main factor influencing demand, and hence higher or lower CO_2 emissions. Factors such as travel restrictions, GDP and the derived air traffic demand have therefore a much stronger influence on the number of flights than any increases in fuel or ticket prices, especially on consolidated markets where prices are more stable. Although more efficient when put against RTK values,

---

[6] Eurocontrol, "Does taxing aviation really reduce emissions?", Oct. 2020, last retrieved: Oct. 20, 2021, available at: https://www.eurocontrol.int/sites/default/files/2020-10/eurocontrol-think-paper-taxing-aviation-oct-2020.pdf

long-distance air traffic dominates aviation emissions, drives their evolution, and hence must be targeted if a reduction in CO_2 emissions is to be achieved.

— — — — — — — —

ATTACHMENT A TO APPENDIX M1

COST (INVESTMENT) ESTIMATIONS: AIRCRAFT TECHNOLOGY

Note. - This Appendix provides a summary of the approaches and methodologies considered by the SDSG Cost Estimation ad hoc group towards the estimation of costs (investments) associated with aircraft technology scenarios.

1. OVERVIEW OF APPROACH AND METHODOLOGIES

1.1 Based on the type of cost modelling approach (described in Appendix M1, Part C, section 3), the expected definition of integrated scenarios, the LTAG-TG CEahg has identified several costs elements associated with aircraft technology that will be either assessed quantitatively or described qualitatively (see Figure 16):

- ***Research and Development (R&D)*** support from States (i.e. governments) to aerospace research institutions towards the development of technologies and commercial aircraft;
- ***Non-Recurring Costs (NRC)*** which captures the fixed costs associated with developing the technology improvements that deliver fuel (CO_2 emissions) reduction benefits. It does not include additional production costs e.g. material, labour, or other recurring costs;
- ***Incremental Built Cost (IBC)*** which captures the variable costs associated with producing aircraft e.g. material, labour, or other recurring costs;
- ***Fuel costs (i.e. savings)*** resulting from the operations of aircraft types exhibiting the technology improvement associated with a given LTAG-TG Integrated (Aircraft Technology) Scenario;
- ***Price after technology improvement*** that reflects the potential pass on of investments (costs) from the manufacturer to deliver an aircraft with technology improvements that deliver fuel (CO_2 emissions) reduction benefits, along with potential incremental built costs; and
- ***Aircraft Value Loss (AVL)*** capturing the impact of the entry into service of aircraft with technology improvement on the in-service fleet.

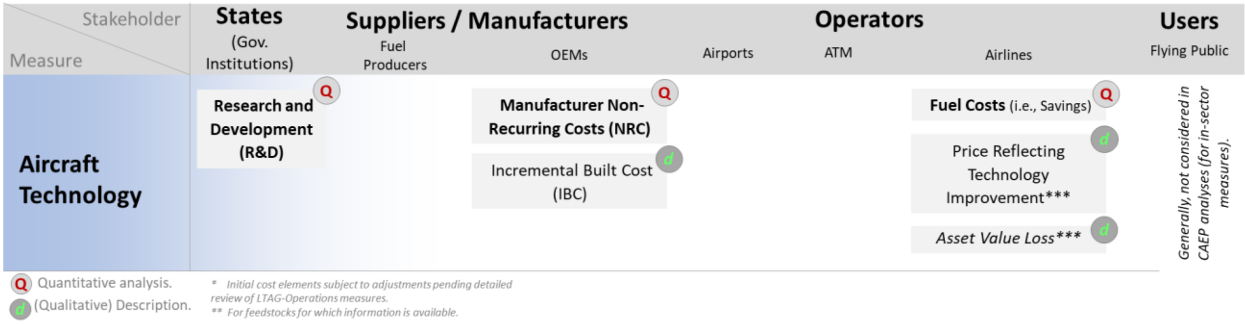


Figure 16: Aircraft technology related cost (investment) elements considered by the LTAG-TG

1.2 The LTAG-TG CEahg acknowledged that fuel savings from aircraft technology improvements may be reduced by an increase in aircraft acquisition costs driven by Price Reflecting Technology Improvement i.e. aircraft technology improvements are not expected to “come for free”. Airline acquisition of new aircraft is a multi-attribute decision making process, including aircraft capabilities, operating costs (including fuel efficiency), commonality with other aircraft types in the fleet, etc. The transactions are also not publicly available, and it is challenging to extract/isolate the contribution of aircraft technology improvement to aircraft total price.

2. MANUFACTURER NON-RECURRING COSTS (NRC)

2.1 Summary of Methodology

2.1.1 ***Description of Cost Element:*** Non-Recurring Costs (NRC) captures the fixed costs associated with developing the technology improvements that deliver fuel (CO_2 emissions) reduction benefits. It does not include additional production costs e.g. material, labour, or other recurring costs.

2.1.2 ***Input:*** As input to the non-recurring cost model, the CEahg uses the LTAG-TG Aircraft EIS and Diffusion scenarios which reflect the aircraft entry into service. The CO_2 metric value improvement are based on the LTAG-TG Technology improvement matrix. Aircraft program/family temporal distributions of NRC (not included in CAEP/10 methodology) were also developed by LTAG-TG CEahg to capture the overall temporal distribution of required investments. The LTAG-CEahg also uses NRC escalation for future generation aircraft and NRC scaling for derivative vs. clean-sheet aircraft. Component NRC from aircraft sub-system developers is also included in the model.

2.1.3 ***Methodology:*** The CEahg leveraged and modified the CAEP/10 methodology and non-recurring cost curve that take as inputs the aeroplane MTOM and a CO_2 metric value improvement. The methodology yields non-recurring costs associated with the technology improvement. The validation of the methodology relied on expert engineering judgment and publicly available aeroplane development cost information based on conventional (i.e. tube and wing) configuration using drop-in fuels. The use of this method in the context of LTAG was applied to technology improvements associated with ATW aircraft (from Tech group). To meet the requirements and specificities of technology scenarios considered by LTAG-TG, the LTAG-TG CEahg had to substantially enhance the CAEP/10 methodology which did not provide a temporal breakdown, nor differentiate all new aircraft vs. derivatives, and advanced concepts aircraft (ACAs).

2.1.4 ***Output:*** The methodology yields non-recurring costs associated with the technology improvement (in billions of dollars). Temporal distribution of NRC based on back propagation from the Entry Into Service (EIS) and representative (average) NRC accrual distribution curves across the development timeline of the aircraft program.

2.2 **Figure 17** shows a summary of methodology, assumptions, and data sources for Non-Recurring Costs (NRC).

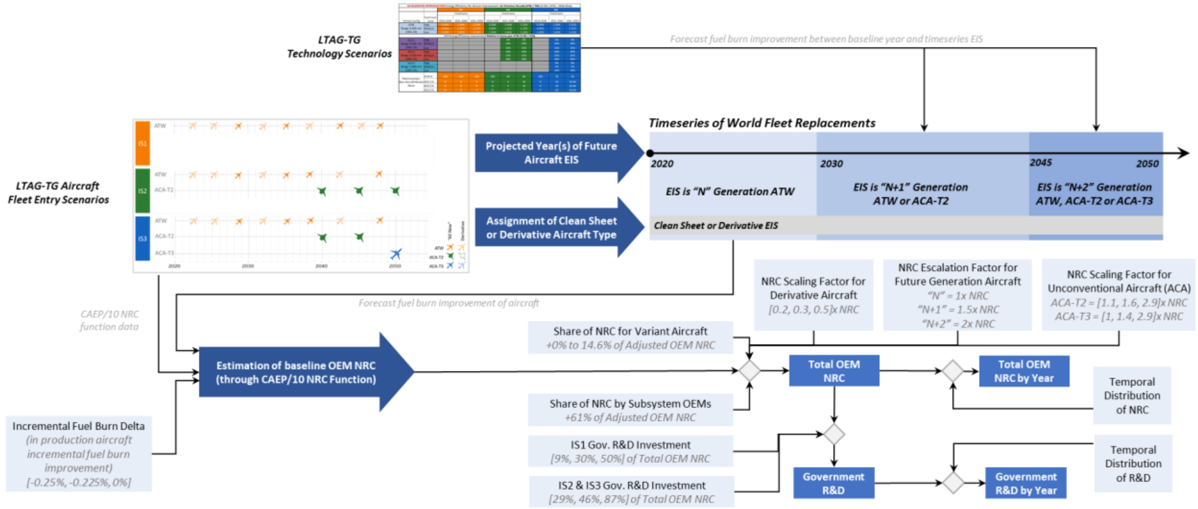
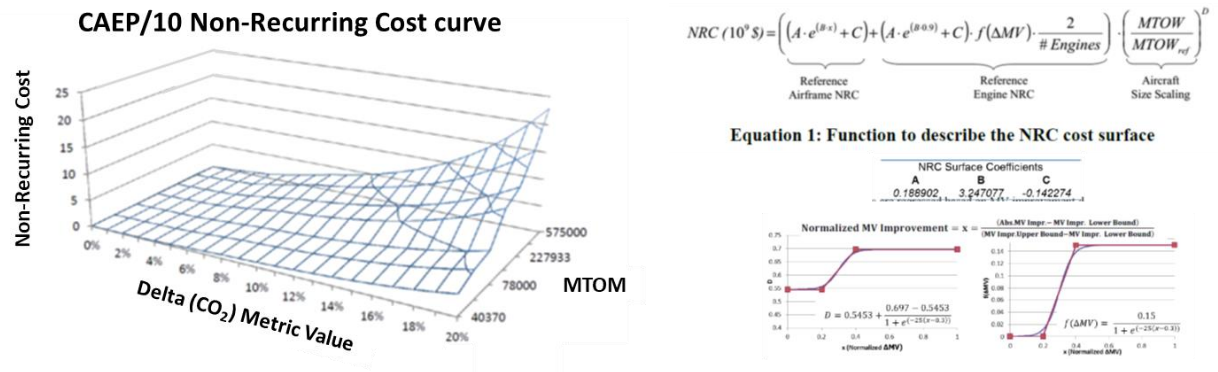


Figure 17: Summary of methodology, assumptions, and data sources for Non-Recurring Costs (NRC)

2.3 Background

2.3.1 The LTAG-TG CEahg reviewed background analyses conducted by CAEP/10 towards the CO_2 Standard. In 2015, CAEP developed and used a methodology to estimate the Non-Recurring Costs associated with a technology response. The methodology uses aeroplane MTOM, number of engines, and CO_2 metric value improvement as inputs and returns non-recurring costs associated with the technology response. This methodology relied on publicly available aeroplane development cost information and expert engineering judgment. The cost-surface was also calibrated to yield NRC estimates across a wide range of aeroplane sizes and metric value improvements. The method consists of a single cost surface that is a function of metric value improvement (up to 20%), number of engines, and aircraft MTOW. For large delta MV improvements, total program costs were used to calibrate the NRC curve.

2.3.2 While LTAG-TG analysis is not a stringency analysis, the CEahg assessed that some elements of the CAEP/10 non-recurring cost curve could be leveraged and enhanced to make it fit for purpose for LTAG-TG analyses.



$$NRC\,(10^9\,\$) = \left(\underbrace{\left(A \cdot e^{(B \cdot x)} + C\right)}_{\text{Reference Airframe NRC}} + \underbrace{\left(A \cdot e^{(B \cdot 0.9)} + C\right) \cdot f(\Delta MV) \cdot \frac{2}{\#\,Engines}}_{\text{Reference Engine NRC}} \right) \cdot \underbrace{\left(\frac{MTOW}{MTOW_{ref}}\right)^{D}}_{\text{Aircraft Size Scaling}}$$

Equation 1: Function to describe the NRC cost surface

NRC Surface Coefficients

A	B	C
0.188902	3.247077	-0.142274

$$D = 0.5453 + \frac{0.697 - 0.5453}{1 + e^{(-25(x-0.3))}}$$

$$f(\Delta MV) = \frac{0.15}{1 + e^{(-25(x-0.3))}}$$

Figure 18: Background: CAEP/10 Non-Recurring Costs (NRC) Function

2.3.3 Figure 19 shows the high-level modelling approach for Non-Recurring Cost (NRC) for conventional Advanced Tube and Wing (ATW) aircraft.

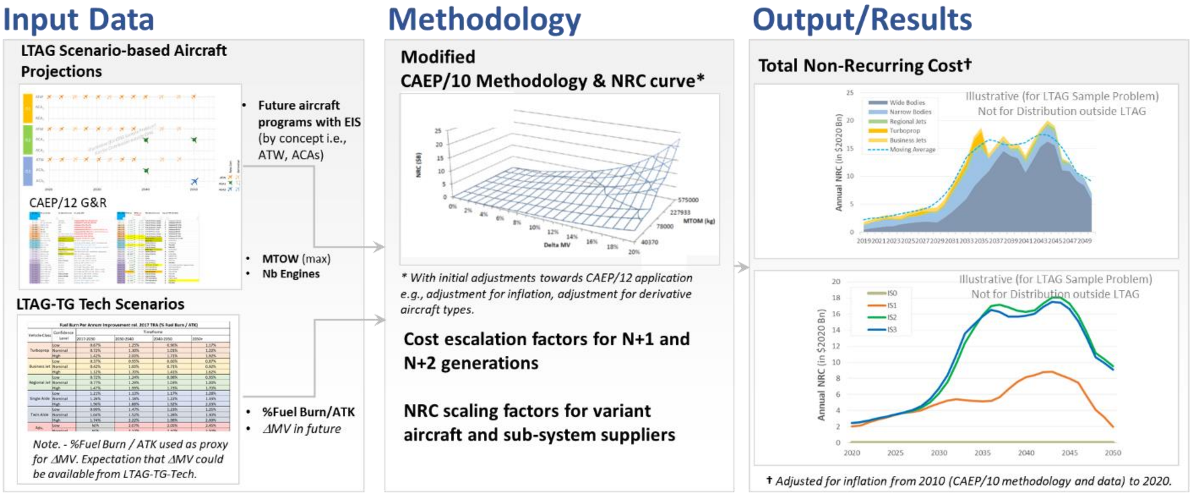


Figure 19: High-level modelling approach for non-recurring cost (NRC) – conventional ATW

2.3.4 The CEahg tested if the CAEP/10 NRC function was representative and fit for purpose for LTAG-TG analysis. The CAEP/10 NRC function cost estimates (adjusted for inflation) were compared to new aircraft programs that entered service between 2010 and 2020. NRC estimates were found generally in-line with new generation aircraft (e.g. A350 & B787). It was also noted that the CAEP/10 NRC function overestimated "derivative" aircraft suggesting that a scaling factor may be necessary to capture NRC for derivative aircraft.

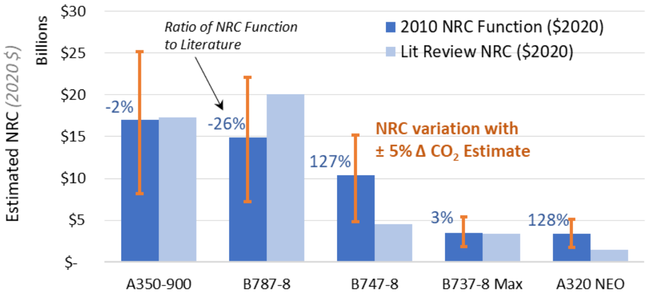


Figure 20: NRC by OEMs – conventional ATW (comparison of historical non-recurring cost data to CAEP/10 NRC function)

2.3.5 The CAEP/10 NRC function was meant to be implemented for a limited scenario of technology response that were assessed to be technically feasible at the time of the study which is not the case with the LTAG analysis. As such the CAEP/10 does not provide the information needed to assess NRC for far-term programs (e.g. 2040 EIS). This created the need to assess and capture cost escalation factors as well as NRC for potential un-conventional aircraft (e.g. ACA-T2s and ACA-T3s).

2.4 Conventional ATW: Variation with level of technology advancement based on historical NRC data

2.4.1 To calibrate the modelling assumptions on cost escalation factors, the CEahg conducted a historical analysis of 19 aircraft programs[7] across 6 generations of aircraft technology going back to the 1930s. All development costs were adjusted to 2020 $. Where NRC estimates were available from multiple sources for an aircraft, an average value used for analysis with error bars to low and high estimates. The CEahg considered two metrics to compare aircraft program NRC; total NRC for program (2020$) and program NRC normalized by aircraft MTOM (2020$/kg).

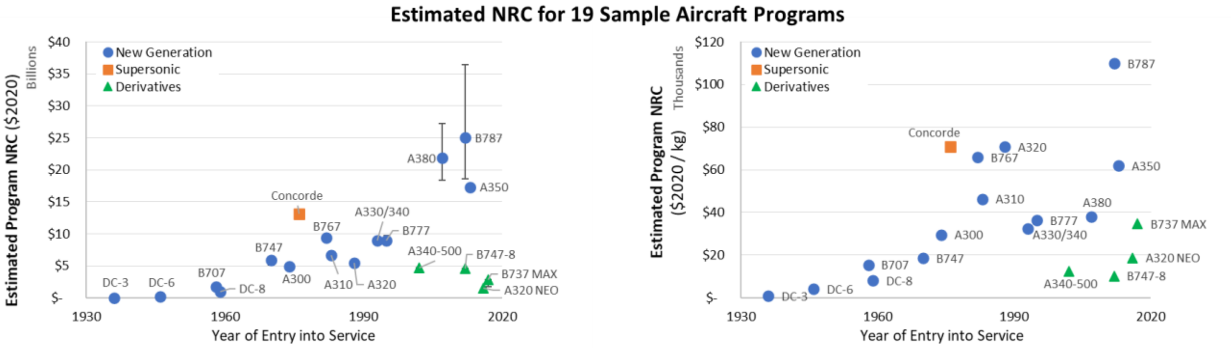


Figure 21: NRC by OEMs (conventional ATW) variation with level of technology advancement based on historical NRC data

2.4.2 The CAEP/10 NRC function estimates NRC for current-day, new-generation aircraft (i.e. gen. “N”). Real-dollar NRC/kg escalation between generations of 1.4 to 5x, understood to be due to increased complexity, new technology, and cost escalation (e.g. materials, labour). An escalation factor was deemed necessary to scale CAEP/10 NRC function estimates for N+1 or N+2 ATW aircraft as well as a scaling factor necessary to account for significant technology step changes (see section on ACA scaling factors for details)[8].

---

[7] Bowen, J. (2010). The Economic Geography of Air Transportation: Space, Time, and the Freedom of the Sky. London: Routledge.
Schwartz, L.A. & Busby, J. (2014). "The 787 Dreamliner: Will it be a dream or nightmare for Boeing Co.?", Journal of Case Research in Business and Economics.
Nolte, P., et al. (2012). "Quantitative Assessment of Technology Impact on Aviation Fuel Efficiency." Air Transport and Operations Symposium.
Mowery, D. C. (1985). “Federal Funding of R&D in Transportation: The Case of Aviation.” National Academies Press. pg. 304.
Stevens, A. & Mullen, J. (2016). "Airbus CEO upbeat on future of A380 after new orders." CNN Business.
Flight Global. (2012). Boeing disputes 737 Max development cost report.
Eberstadt, G. (1991). Competing Economies: America, Europe, and the Pacific Rim. U.S. Government Printing Office.
Gellman Research Associates, Inc. (1990). "An Economics and Financial Review of Airbus Industrie."

[8] Consistent with findings from Aerospace Technology Institute. (2018). The Economics of Aerospace: The Evolving Aerospace R&D Landscape. Consistent with assessment from Gellman Research Associates (1990). An Economics and Financial Review of Airbus Industrie.

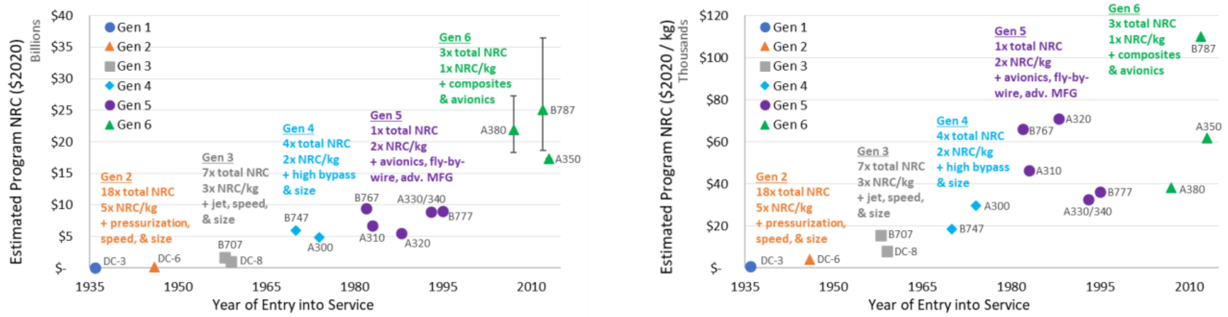
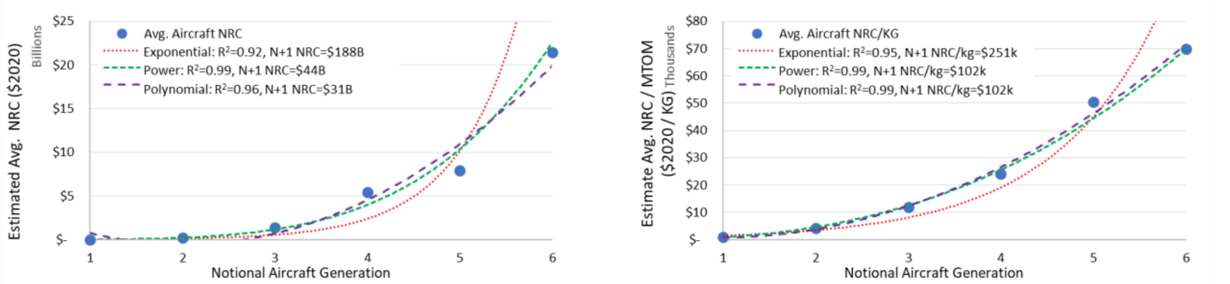


Figure 22: NRC by OEMs (Conventional ATW) Variation with Level of Technology Advancement Based on Historical NRC Data

2.4.3 An escalation factor for future generation aircraft on top of the CAEP/10 function was developed based on statistical analyses of historical data. An average NRC and NRC/kg was estimated for each of the past six generations of aircraft. As shown in Figure 23, power and polynomial trendlines offered higher predictive value for NRC escalation between generations. Escalation factors were estimated from forecast NRC difference between Gen 6 (N), Gen 7 (N+1), & Gen 8 (N+2). The LTAG-CEahg used escalation factors (based on an NRC/kg metric) of 1.5x for N+1 generation aircraft (from 2030-2045) and 2x NRC for N+2 generation aircraft from 2045.



Average NRC by Generation

Forecast Trend	N (Gen 6)	N+1	N+1 (factor)	N+2	N+2 (factor)
Power	$23 B	$43.7B	1.9	$77 B	3.4
Polynomial	$20 B	$31.5B	1.6	$46 B	2.3

Average NRC / MTOM by Generation

Forecast Trend	N (Gen 6)	N+1	N+1 (factor)	N+2	N+2 (factor)
Power	$70 K	$102 K	1.5	$143 K	2.0
Polynomial	$72 K	$102 K	1.4	$139 K	1.9

Figure 23: NRC by OEMs (Conventional ATW) Variation with Level of Technology Advancement Based on Historical NRC Data

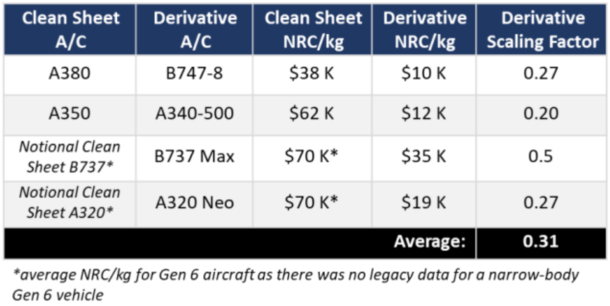
2.5 Non-recurring costs (NRC) for derivative aircraft

2.5.1 NRC for "derivative" aircraft was approximately 20% to 50% of comparable of current generation clean sheet designs[9]. As a result, a scaling factor was used to reduce CAEP/10 NRC function NRC estimates for derivative aircraft only. In its modelling of non-recurring costs associated with LTAG-

---

[9] Consistent with findings from Aerospace Technology Institute. (2018). The Economics of Aerospace: The Evolving Aerospace R&D Landscape. Consistent with assessment from Gellman Research Associates (1990). An Economics and Financial Review of Airbus Industrie.

TG integrated scenarios, the CEahg used an average scaling factor of 0.3 with sensitivity analysis from based on 0.2 to 0.5.



Clean Sheet A/C	Derivative A/C	Clean Sheet NRC/kg	Derivative NRC/kg	Derivative Scaling Factor
A380	B747-8	$38 K	$10 K	0.27
A350	A340-500	$62 K	$12 K	0.20
*Notional Clean Sheet B737**	B737 Max	$70 K*	$35 K	0.5
*Notional Clean Sheet A320**	A320 Neo	$70 K*	$19 K	0.27
			Average:	**0.31**

**average NRC/kg for Gen 6 aircraft as there was no legacy data for a narrow-body Gen 6 vehicle*

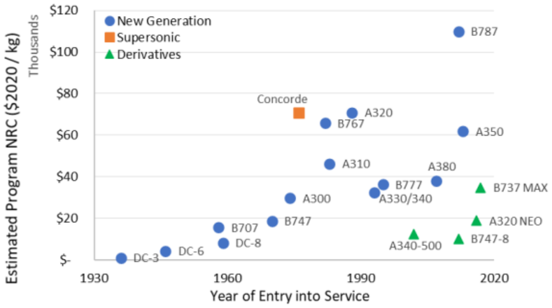


Figure 24: Non-recurring costs (NRC) for derivative aircraft

2.6 Incremental non-recurring costs from aircraft program variants

2.6.1 Variants typically represent additional NRC that may occur after the entry into service (EIS) of the first aircraft in the family (i.e. lead aircraft). EIS timelines were collected and developed for 11 wide-body and 10 narrow-body aircraft programs (i.e. product families). The number and date of variant EIS after lead aircraft was also documented. It was assumed that most variant non-recurring costs were accrued from flight testing and certification. i.e. variant NRC is proportional to lead aircraft CAEP/10 function NRC estimate based upon the ratio of test flight hours. The B787-8 program was used as representative model were 41% of total lead aircraft NRC was accrued during flight testing[10]. For this program there were two variants with about 35% and 20% of the flight hours of the first aircraft type in family, respectively.

2.6.2 The total additional NRC for variants is estimated using the following equation:

$$\mathrm{NRC}_{\mathrm{variant}} = \left(\begin{array}{c}\text{\% of}\\ \text{programs}\\ \text{with variant}\end{array}\right) * \left(\begin{array}{c}\text{\% of lead A/C}\\ \text{flight test hrs}\\ \text{by variant}\end{array}\right) * \left(\begin{array}{c}\text{\% of lead A/C}\\ \text{NRC for flight}\\ \text{testing}\end{array}\right)$$

---

[10] Aerospace Testing International. (2018). “Flight Test Review 2018”. Retrieved 7/16/2021 from https://www.aerospacetestinginternational.com/features/flight-test-review-2018.html
Schwartz, L.A. & Busby, J. (2014). "The 787 Dreamliner”, Journal of Case Research in Business and Economics. Vol. 5. Accessed 3/5/2021 from http://www.aabri.com/manuscripts/141851.pdf

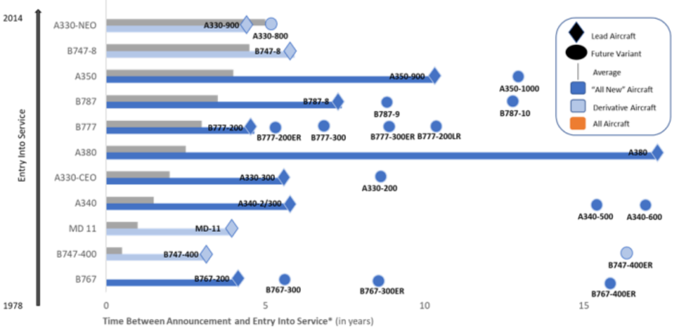
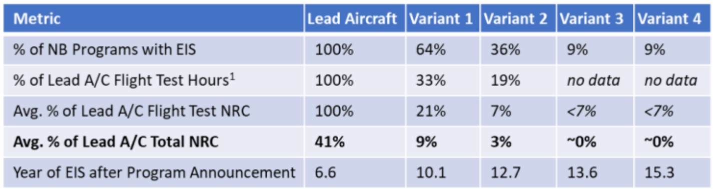


Illustration and Table: Narrow Body Variant NRC Model



Metric	Lead Aircraft	Variant 1	Variant 2	Variant 3	Variant 4
% of NB Programs with EIS	100%	64%	36%	9%	9%
% of Lead A/C Flight Test Hours[1]	100%	33%	19%	*no data*	*no data*
Avg. % of Lead A/C Flight Test NRC	100%	21%	7%	*<7%*	*<7%*
Avg. % of Lead A/C Total NRC	**41%**	**9%**	**3%**	**~0%**	**~0%**
Year of EIS after Program Announcement	6.6	10.1	12.7	13.6	15.3

Figure 25: Entry into service of lead aircraft and variants and probabilistic model of variants for LTAG-TG NRC modelling

2.7 Temporal distribution of Non-Recurring Costs

2.7.1 The non-recurring costs incurred by OEMs are distributed before (and after) aircraft program entry into service (EIS). To develop temporal distribution of NRC (not considered in the CAEP/10 NRC analyses associated with the CO_2 standard), the LTAG-TG CEahg analysed historical time series cost data collected for 5 aircraft programs (i.e. 787 R&D costs from Boeing annual reports[1] and costs for 4 Airbus programs projected from annual government loan reporting[11]). Based on this information, the CEahg developed a temporal distribution profile for the accrual of NRC across the aircraft program development cycle. An additional "long-tail" of the NRC distribution was added to represent average NRC accrued variant development. A triangle function, based on historical data across families of aircraft considered, was used as a model of variant NRC. It should be noted that variants were not modelled for regional jets, business jets, and turboprops which are expected to have limited impacts on the overall LTAG-TG results given the relative (limited) contributions of NRC from variants, the small number of variants for these aircraft categories, and the relatively smaller contribution from these aircraft categories to total NRC.

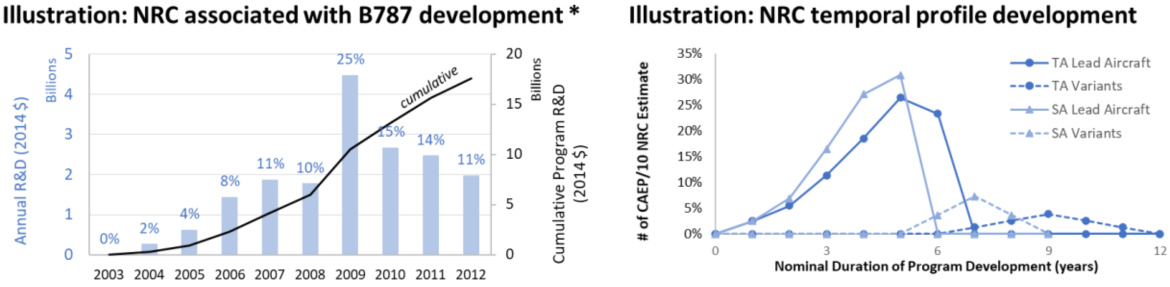


Illustration: NRC associated with B787 development *

Illustration: NRC temporal profile development

Figure 26: Non-Recurring Costs by OEMs: Temporal Distribution of NRC

---

[11] Gellman Research Associates, Inc. (1990). "An Economics and Financial Review of Airbus Industrie."

2.8 Sub-System OEM NRC modelling

2.8.1 The CAEP/10 NRC function was understood to not include sub-system supplier NRC function developed from reported airframer self-funded NRC. To reflect the potential investments requirements from sub-system OEMs under each LTAG-TG scenarios, the CEahg developed estimates of sub-system OEMs NRC. The 2016 NRC by the ten largest global aerospace companies indicates that as much as 38% of total industrial NRC originates from sub-system suppliers[12]. Sub-system OEM NRC was accounted for in the integrated model by scaling the calculated and adjusted CAEP/10 NRC function estimate (which does not account for subsystems OEM non-recurring costs) where the sub-system OEM NRC scaling factor is (33%+5%)/62% = +61%. As subsystems are often not airframe specific (e.g. common engine on multiple aircraft), subsystem NRC is allocated on a 5-year forward looking total aggregate NRC from airframers.

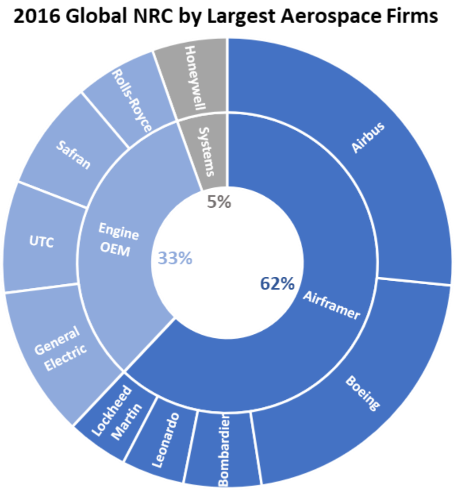


Figure 27: Sub-system OEM NRC modelling approach. Estimation of additional industry NRC from key airframer suppliers.

2.9 Adjustment factors for un-conventional (ACA-T2) and non-drop in fuel powered (ACA-T3) aircraft

2.9.1 Major technology advancements (i.e. step changes) may increase an aircraft NRC. The new generation "escalation factor" for ATW aircraft inherently captured OEM-borne costs associated with some unconventional technology improvements e.g. piston to turbine aircraft, low bypass to high bypass jets, metals to composites.

2.9.2 New aircraft configurations (e.g. ACA-T2 and ACA-T3) or energy sources (e.g. hydrogen) may require NRC beyond the scope of the modelled/anticipated changes for ATW.

2.9.3 The LTAG-CEahg conducted comparative analyses of historical development costs between what may have been considered "unconventional" aircraft types (or capabilities) e.g. supersonics

---

[12] Aerospace Technology Institute. "The economics of aerospace: the evolving aerospace R&D landscape." Accessed 7/23/2021 from https://www.ati.org.uk/media/5fqj5bne/insight_10-the-evolving-aerospace-rd-landscape.pdf

on Concorde, and conventional aircraft of the time. Historical program NRC provides perspective on potential ACA technology scaling *and/or* inter-generational cost Escalation.

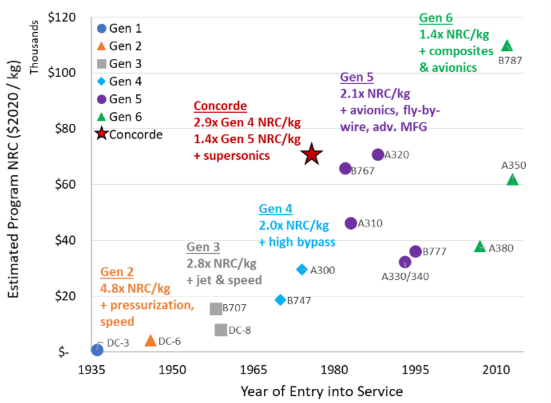
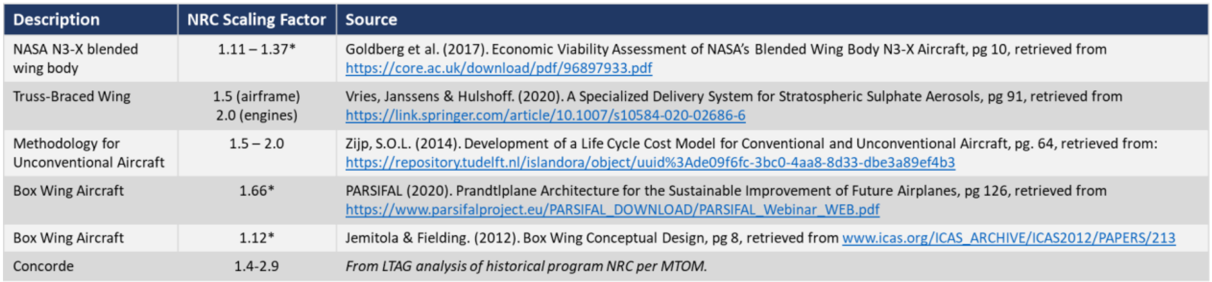


Figure 28: Historic aircraft NRC by aircraft generation

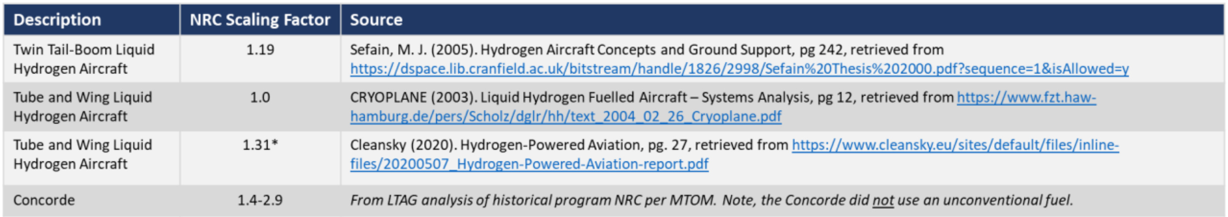
2.9.4 To reflect the potentially higher NRC associated with the development of step-change technologies and unconventional configurations (i.e. ACA-T2 aircraft), scaling cost multipliers were derived from reviewed literature. As shown in Figure 29, the potential ACA-T2 NRC scaling factor range based upon literature is: Low: 1.1x, Mid: 1.6x and High: 2.9x.



Description	NRC Scaling Factor	Source
NASA N3-X blended wing body	1.11 – 1.37*	Goldberg et al. (2017). Economic Viability Assessment of NASA's Blended Wing Body N3-X Aircraft, pg 10, retrieved from https://core.ac.uk/download/pdf/96897933.pdf
Truss-Braced Wing	1.5 (airframe) 2.0 (engines)	Vries, Janssens & Hulshoff. (2020). A Specialized Delivery System for Stratospheric Sulphate Aerosols, pg 91, retrieved from https://link.springer.com/article/10.1007/s10584-020-02686-6
Methodology for Unconventional Aircraft	1.5 – 2.0	Zijp, S.O.L. (2014). Development of a Life Cycle Cost Model for Conventional and Unconventional Aircraft, pg. 64, retrieved from: https://repository.tudelft.nl/islandora/object/uuid%3Ade09f6fc-3bc0-4aa8-8d33-dbe3a89ef4b3
Box Wing Aircraft	1.66*	PARSIFAL (2020). Prandtlplane Architecture for the Sustainable Improvement of Future Airplanes, pg 126, retrieved from https://www.parsifalproject.eu/PARSIFAL_DOWNLOAD/PARSIFAL_Webinar_WEB.pdf
Box Wing Aircraft	1.12*	Jemitola & Fielding. (2012). Box Wing Conceptual Design, pg 8, retrieved from www.icas.org/ICAS_ARCHIVE/ICAS2012/PAPERS/213
Concorde	1.4-2.9	*From LTAG analysis of historical program NRC per MTOM.*

Figure 29: Un-conventional ACA-T2s – background research and literature review

2.9.5 Additional NRC and/or new aircraft acquisition cost multipliers were reviewed in literature to assess potential NRC impacts of step-change technologies and unconventional fuel systems in ACA-T3s. Few studies/data available with NRC estimates due to novelty of new fuel systems. The LTAG-CEahg used the following ACA-T3 NRC scaling factor range based upon available literature: Low: 1.0x, Mid: 1.4x and High: 2.9x.



Description	NRC Scaling Factor	Source
Twin Tail-Boom Liquid Hydrogen Aircraft	1.19	Sefain, M. J. (2005). Hydrogen Aircraft Concepts and Ground Support, pg 242, retrieved from https://dspace.lib.cranfield.ac.uk/bitstream/handle/1826/2998/Sefain%20Thesis%202000.pdf?sequence=1&isAllowed=y
Tube and Wing Liquid Hydrogen Aircraft	1.0	CRYOPLANE (2003). Liquid Hydrogen Fuelled Aircraft – Systems Analysis, pg 12, retrieved from https://www.fzt.haw-hamburg.de/pers/Scholz/dglr/hh/text_2004_02_26_Cryoplane.pdf
Tube and Wing Liquid Hydrogen Aircraft	1.31*	Cleansky (2020). Hydrogen-Powered Aviation, pg. 27, retrieved from https://www.cleansky.eu/sites/default/files/inline-files/20200507_Hydrogen-Powered-Aviation-report.pdf
Concorde	1.4-2.9	*From LTAG analysis of historical program NRC per MTOM. Note, the Concorde did not use an unconventional fuel.*

Figure 30: Un-conventional fuel systems ACA-T3s – background research and literature review

2.10 Validation of LTAG-TG non-recurring cost (NRC): U.S. case study estimation methodology

2.10.1 Due to the specificities and requirements of the LTAG study (and substantial enhancement of the CAEP/10 non-recurring costs methodology), the LTAG-TG CEahg conducted a validation of the LTAG-TG NRC estimation methodology using actual historic data from 1952 to 1982 for United States based on aeronautics NRC by OEMs and non-military aeronautics R&D by governments[13].

2.10.2 The NRC estimation methodology was applied to the period of 1960 to 1982 focusing on the entry into service of twin aisle and single aisle aircraft programs from U.S. OEMs. First, based on the list of aircraft program/families with entry into service in the time window of analysis, each aircraft program/family was assigned a derivative or clean sheet designation. Second, the LTAG-TG CEahg calculated de-escalation cost factors from CAEP/10 NRC function to prior generation aircraft.

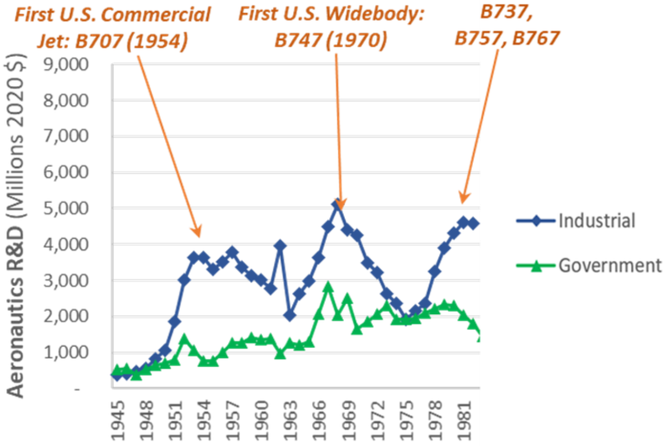
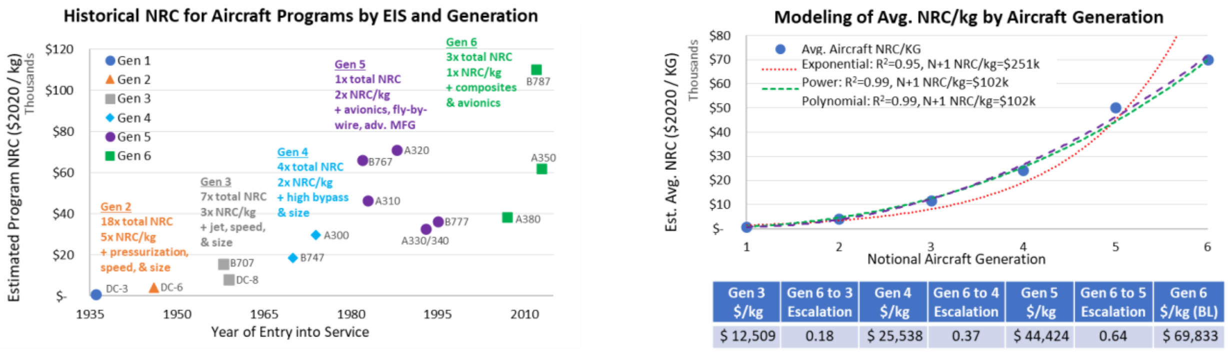


Figure 31: Historical U.S. industry NRC and government R&D investments

2.10.3 The CAEP/10 NRC function estimates NRC for current-day, new-generation aircraft and was adjusted to estimate historic aircraft program costs. An NRC scaling factor for "derivative" aircraft assumed to be 30% clean sheet designs and NRC escalation factors calculated between current generation aircraft and prior generations as shown in **Figure** 32.

---

[13] Mowery, D. C. (1985). "Federal Funding of R&D in Transportation: The Case of Aviation." National Academies Press. pg. 304.



Gen 3 $/kg	Gen 6 to 3 Escalation	Gen 4 $/kg	Gen 6 to 4 Escalation	Gen 5 $/kg	Gen 6 to 5 Escalation	Gen 6 $/kg (BL)
$ 12,509	0.18	$ 25,538	0.37	$ 44,424	0.64	$ 69,833

Figure 32: Validation of LTAG-TG Non-Recurring Cost (NRC): U.S. Case Study Inputs to NRC estimation model

2.10.4 Entry into service dates were estimated as the delivery date for U.S. OEM single aisle and twin aisle aircraft. The range of EIS dates considered 1958 to 1986 (additional programs considered after the final NRC data dated 1982 to account for temporal distribution of NRC from aircraft with EIS after 1982). Each aircraft program/family was designated as a clean sheet or a derivative. In addition, there were no aircraft considered as advanced concepts aircraft (i.e. unconventional configuration or energy system) since all aircraft were based on tube and wing configurations using jet fuel.

Generation	Approx. Coverage	Type	Single Aisles	Twin Aisles
Generation 2	1946 (DC3) to 1951 (Comet)	Clean Sheet	N/A	N/A
		Derivative	N/A	N/A
Generation 3	1952 (Comet) to 1969 (B747)	Clean Sheet	6	N/A
		Derivative	1	N/A
Generation 4	1970 (B747) to – 1981 (B767)	Clean Sheet	0	3
		Derivative	1	0
Generation 5	1982 (B767) and later years	Clean Sheet	1	1
		Derivative	1	0

Figure 33: Summary of U.S. OEM Aircraft EIS by Type from 1958 to 1986

Aircraft	Type	Vehicle Class	OEM	Delivery
B707	Clean Sheet	Single Aisle	Boeing	10/26/1958
DC-8	Clean Sheet	Single Aisle	Douglas	9/18/1959
Convair 880	Clean Sheet	Single Aisle	Convair/General Dynamics	5/1/1960
B727	Clean Sheet	Single Aisle	Boeing	2/1/1964
DC-9	Clean Sheet	Single Aisle	McDonnell Douglas	12/8/1965
DC-8-61	Derivative	Single Aisle	Douglas	2/1/1967
B737 Orig	Clean Sheet	Single Aisle	Boeing	2/10/1968
B747-100	Clean Sheet	Twin Aisle	Boeing	1/22/1970
DC-10	Clean Sheet	Twin Aisle	McDonnell Douglas	8/5/1971
L-1011 TriStar	Clean Sheet	Twin Aisle	Lockheed	4/26/1972
MD-80	Derivative	Single Aisle	McDonnell Douglas	10/10/1980
B767	Clean Sheet	Twin Aisle	Boeing	9/8/1982
B757	Clean Sheet	Single Aisle	Boeing	1/1/1983
B737 Classic	Derivative	Single Aisle	Boeing	12/15/1984

Figure 34: Historical U.S. OEM Aircraft from 1958 to 1986

2.10.5 The NRC model was applied to four aircraft for which aircraft program level historical data was available. The NRC estimates were generally close to the documented actual NRC and supported the validation of the LTAG-TG NRC model to estimate program-level cost.

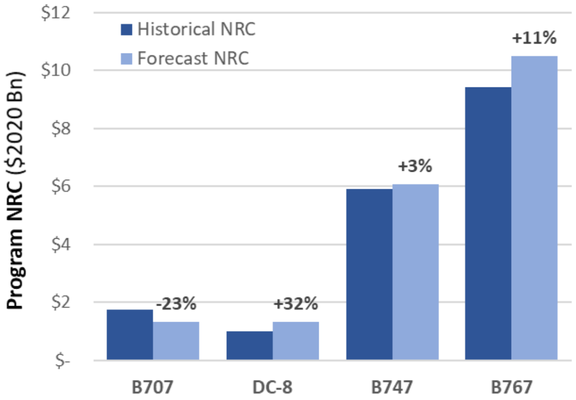


Figure 35: Aircraft Program-Level NRC Estimates

2.10.6 As shown in Figure 36, the predicted NRC (from the LTAG-TG NRC model) generally replicated the temporal distribution of historic timeseries. The predicted NRC was within 13% of actual historical NRC (with total historical NRC of $78 B and predicted NRC of $68 B). The largest underestimates occurred early in the timeseries and in the period in between new aircraft releases.

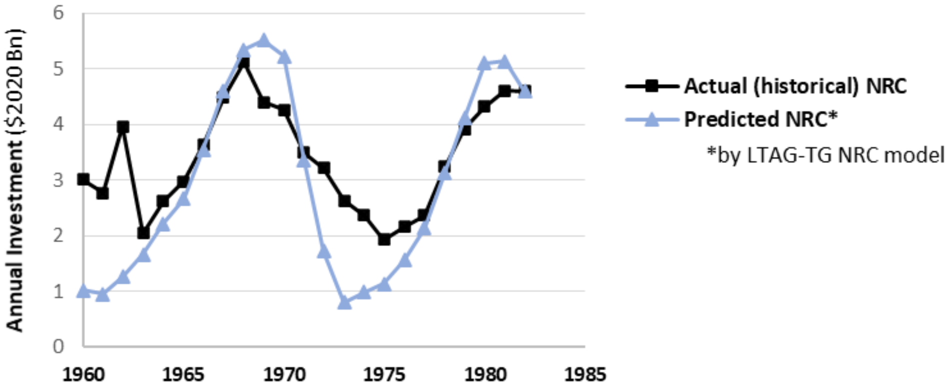


Figure 36: U.S. Industry-Level NRC Estimates

3. RESEARCH AND DEVELOPMENT (R&D)

3.1 The LTAG-TG CEahg developed a methodology, assumptions and data sources for research and development (R&D) support from States (i.e. governments) to aerospace research institutions towards the development of technologies and commercial aircraft.

3.1.1 ***Description of Cost Element:*** Research and Development (R&D) support from States (i.e. governments) to aerospace research institutions towards the development of technologies and commercial aircraft.

3.1.2 ***Input:*** Historical trends in industry and state (government institution) R&D. Case studies of aircraft programs (e.g. unconventional aircraft) including investigations of funding splits between industry and governments. Time series of Non-Recurring Costs (NRC) by manufacturers based on bottom-up build specific to each LTAG-TG scenario.

3.1.3 ***Methodology:*** Literature review of historical trends in R&D government funding per annum at global level. Derive potential (ratio) of government R&D to industry NRC. Estimate government R&D costs (investments) as fraction of future industry NRC trends. *Note. – Assumptions are specific to individual LTAG-TG scenarios.*

3.1.4 ***Output:*** The methodology results in Research and Development (R&D) costs (investments) from States (i.e. governments) to aerospace research institutions towards commercial aircraft development (in billions of dollars per year).

3.2 Figure 37 shows the high-level modelling approach for research and development (R&D) from States (i.e. government institutions).

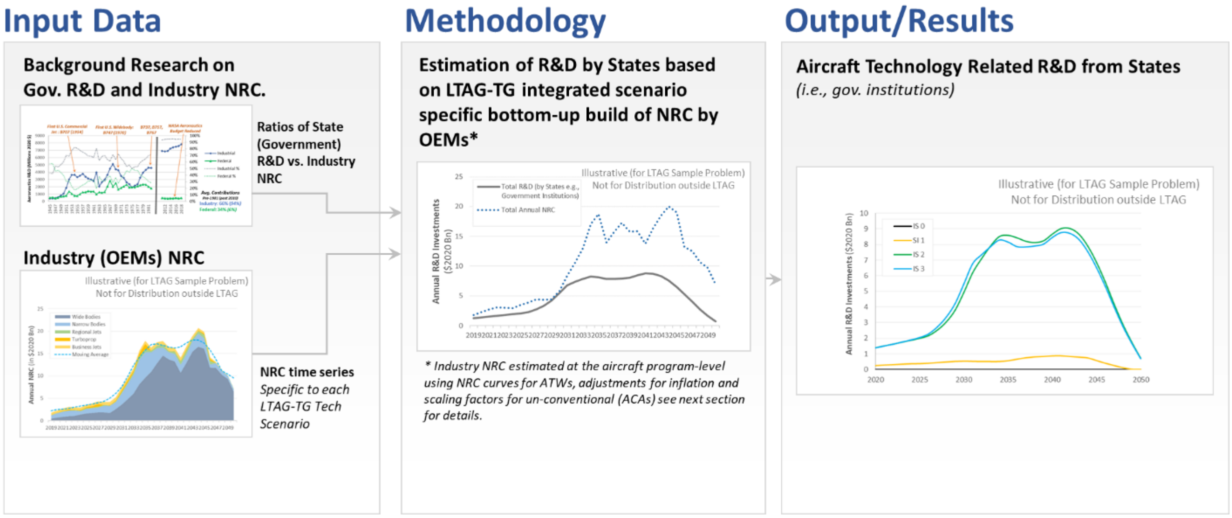


Figure 37: High-level modelling approach for research and development (R&D) from States (i.e. Governments)

3.3 The LTAG-CEahg conducted background research on historical government Aeronautics R&D to inform the magnitude of future potential public investments. Globally, governments invest in aeronautics R&D to directly or indirectly benefit industry based on federal research, personnel, and facilities (e.g. NASA, ONERA, JAXA, RAE, DLR, militaries) for civil or military sponsored research. Historically, aerospace technology step- changes were preceded by large public R&D e.g. 67% of U.S. turbofan engine R&D up to 1970[14], 100% of Concorde and US SST (Boeing 2707)[15] [16] and, ~100% of Japanese FJR-710 engine R&D[17].

3.4 From 1945 to 1982, non-military U.S. government aeronautics R&D averaged ~50% of industry NRC[18] and government and industry investments fluctuated with technology step-changes and EIS dates. Military aeronautics R&D was ~3x industrial NRC and other federal R&D during this period but is not within the scope of this analysis. Estimated data post-2010 suggests non-military U.S. government aeronautics R&D has declined to ~9% of industry NRC[19]. NASA is in a regime of incremental improvement R&D rather than breakthrough research. U.K. government non-military aeronautics R&D from 2010-2016 was ~12% of industry NRC[20]. EU government aeronautics R&D investment is stated as ~50% of industry NRC[21].

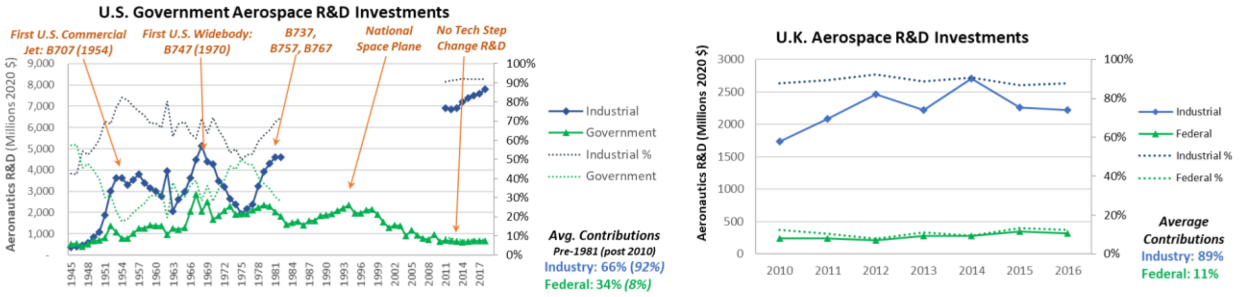


Figure 38: Background research on historical government aeronautics R&D informing magnitude of future potential public investments

3.5 Based on literature reviews and given the expected structure and definition of the LTAG-TG Integrated Scenarios, the LTAG-CEahg implemented an approach where the Research and Development (R&D) from States (i.e. Gov.) is specific to an LTAG Integrated Scenario.

3.6 ***Incremental Development Regime:*** where government maintains a baseline R&D funding level to preserve capabilities (personnel & facilities) and supports less aggressive programs e.g. similar to historical/recent trends. Example includes NASA aeronautics funding since 2005. In this regime, the

---

[14] Arnold & Porter. (1991). *U.S. Government Support of the U.S. Commercial Aircraft Industry*

[15] Johnman, L. & Lynch, F. M. B. (2002). "The Road to Concorde: Franco-British Relations and the Supersonic Project."

[16] IDA Science & Technology Policy Institute. (2019). "Commercial Development of Civilian Supersonic Aircraft".

[17] Eberstadt, G. (1991). "Government Support of the Large Commercial Aircraft Industries of Japan, Europe and the U.S."

[18] Mowery, D. C. (1985). "Federal Funding of R&D in Transportation: The case of Aviation." *The National Academies Press.*

[19] Aerospace Industries Association (2019). *Facts and Figures U.S. Aerospace & Defense*.

[20] Aerospace Technology Institute. (2018). The Economics of Aerospace: The Evolving Aerospace R&D Landscape.

[21] European Commission. *Aeronautics Industries Industry Profile*. Accessed 8/2021. https://ec.europa.eu/defence-industry-space/eu-aeronautics-industry_en

AeroSpace and Defense Industries Association of Europe. (2017). 2017 Facts and Figures. Retrieved 10/2021 from https://www.asd-europe.org/facts-figures

LTAG-TG aircraft technology cost (investment) model assumes government R&D as 9%, 30%, and 50% of industry NRC (low, mid, and high respectively).

3.7 ***Radical Innovation Regime***: where government takes a greater investment stake in high-risk, step change capabilities reflective of historical precedents e.g. turbofans, supersonics, fly-by-wire, new OEM start-up. Under this assumption, government R&D would represent a higher percentage of total R&D+NRC in addition to incremental development government R&D. In this step change innovation regime, governments take a more substantial share of R&D stake in high-risk, step change capabilities. This regime would be reflective of expected regime under an LTAG-TG IS2 and IS3 scenarios. In this case, the estimates for government R&D are 29%, 46%, and 87% of industry NRC (low, mid, and high respectively).

3.8 Government R&D historically preceded industry NRC (i.e. early stage, low TRL research). A separate temporal profile was developed to distribute estimated government R&D. This temporal profile assigned government R&D based on a 5-year, forward looking rolling average of total industry NRC across all aircraft program types.

3.9 The near-term estimates for government R&D may be put in context of current allocations and commitments. In 2020, France Covid19 support increased CORAC funding to €1.5 Bn (over 3 years) for low carbon aircraft R&D[22] e.g. hydrogen powered aircraft[23]. The EU Clean Sky 2 Joint Undertaking provided €1.75 Bn from EU Commission (over 7 years) to support aviation and environment R&D (2017)[24]. Military aeronautics R&D expenditures outpace industrial contributions, however, military R&D is not within the scope of this study.

3.10 Validation of the LTAG-TG Non-Recurring Cost (NRC): U.S. case study

3.11 The validation of the LTAG-TG non-recurring cost methodology through the U.S. case study also allowed for a validation of the States' (government) research and development based on historical non-military government R&D which was around $43 billion during the validation period from 1960 through 1982. The three levels of step-change government research and development (low = 29%, mid = 46%, high = 87% of industry NRC investment by government R&D) are shown in Figure compared to the historical data. Estimates from the LTAG-TG NRC model of government R&D during this period ranged from a low of $20 B to a high of $60 B.

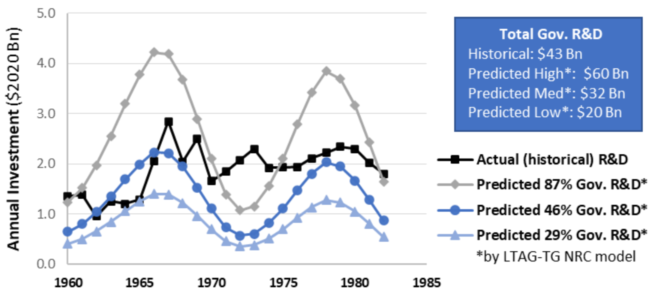


Figure 39: U.S. Government R&D Estimates (5-year forward looking average)

---

[22] French Government (June 9, 2020). "Aerospace Support Plan: for a Green and Competitive Industry." Retrieved from https://www.defense-aerospace.com/articles-view/feature/5/211799/france-unveils-%E2%82%AC15-bn-aerospace-support-plan.html

[23] Reuters (June 9, 2020). "France bets on green plane in package to 'save' aerospace sector." Retrieved from https://www.reuters.com/article/us-health-coronavirus-france-aerospace/france-bets-on-green-plane-in-package-to-save-aerospace-sector-idUSKBN23G0TB

[24] CleanSky. ttps://www.cleansky.eu/sites/default/files/inline-files/CS-GB-Writ%20proc%202020-12%20Updated%20CS2DP_published.pdf

4. IMPLEMENTATION OF THE NRC AND R&D MODEL

4.1 Figure 40 shows a summary of global aviation R&D and NRC estimation methodology for industry and government.

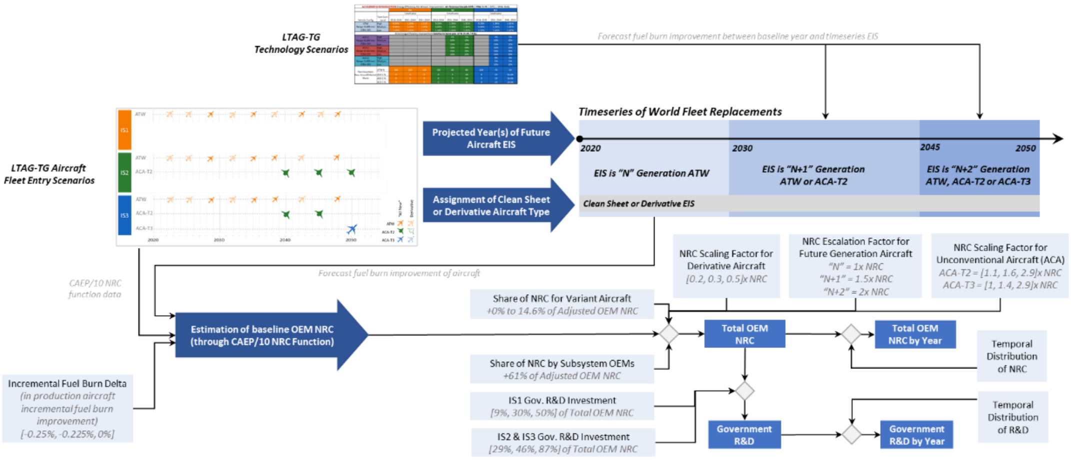


Figure 40: Summary of methodology, assumptions, and data sources for non-recurring costs

4.2 As key input to the implementation of the R&D and NRC estimation methodology for the LTAG Integrated Scenarios 2 and 3, scenarios for future entry into service and diffusion of aircraft program/family (ACA-T2s and ACA-T3s) were developed. Figure 41 shows the approach that was used for developing the LTAG-TG aircraft fleet diffusion scenarios for ACAs.

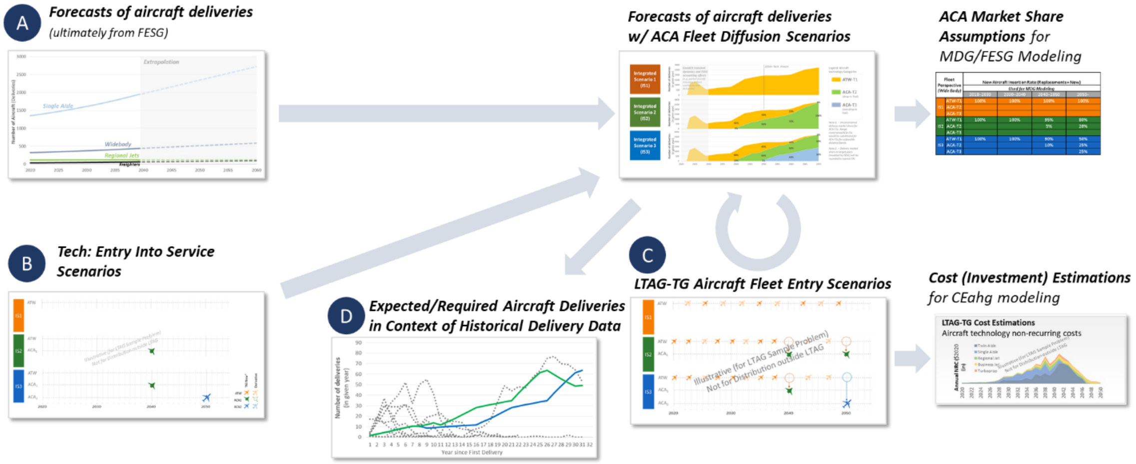
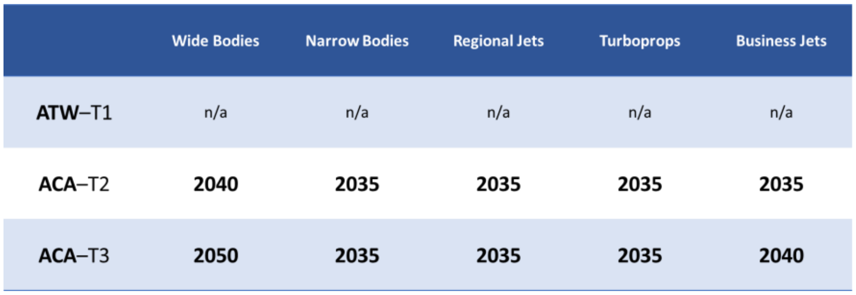


Figure 41: Approach for Developing LTAG-TG Aircraft Fleet Diffusion Scenarios (for ACAs)

4.3 The LTAG-TG aircraft fleet diffusion scenarios for ACA-T2s and ACA-T3s are based in part on the entry into service aircraft types from the LTAG-TG Technology subgroup.



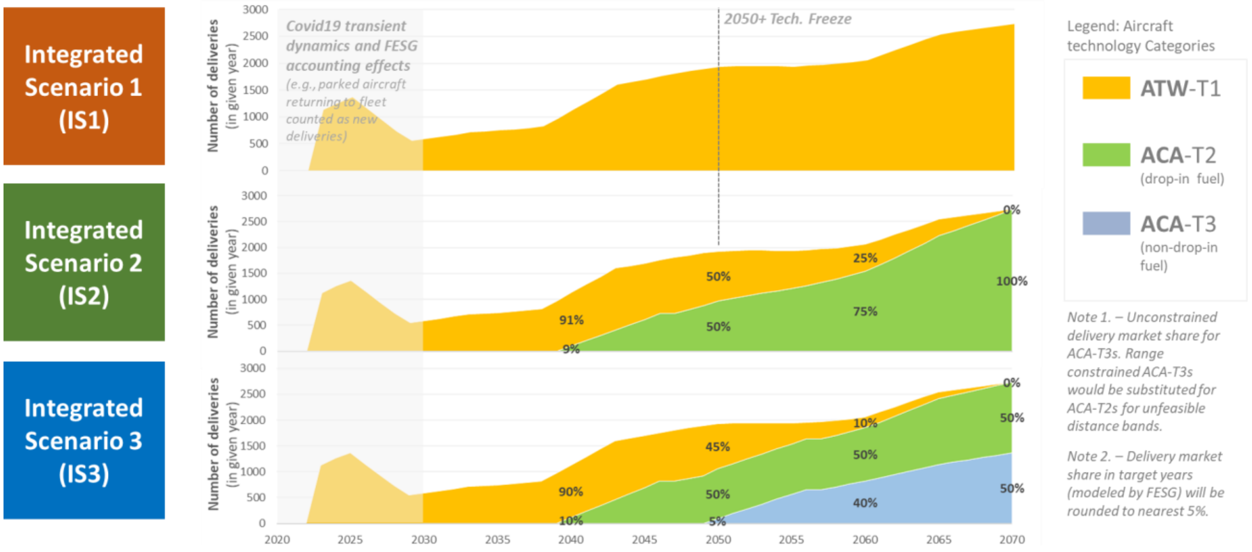
	Wide Bodies	Narrow Bodies	Regional Jets	Turboprops	Business Jets
ATW–T1	n/a	n/a	n/a	n/a	n/a
ACA–T2	**2040**	**2035**	**2035**	**2035**	**2035**
ACA–T3	**2050**	**2035**	**2035**	**2035**	**2040**

Figure 42: Entry Into Service (EIS) input from LTAG-TG technology subgroup

4.4 ***Observation on differences in forecast number of deliveries of wide body vs. narrow body aircraft:*** The LTAG-TG CEahg has noted that the FESG forecasts reflect a large number of wide body aircraft to be delivered in the later decades of the fleet forecast compared to narrow body aircraft. This observation was coordinated with the FESG who reviewed the fleet forecast assumptions. This unexpected relative distribution of forecast deliveries between wide body and narrow body aircraft is due to (1) up-gauging assumptions made in the fleet forecast, and (2) the threshold that was set to define the split between narrow vs. wide bodies which was set by FESG at 211 seats. Given the recent increasing size (i.e. in number of seats) of narrow bodies where under some configuration already exceed this 210-seat threshold, it was acknowledged that CAEP (FESG) would need to review the seating boundary split between narrow body and wide body aircraft as a potential assumption needing a revision in the next CAEP cycle.

4.5 As traffic continues to grow in the outer years of the forecast, the assumption of 211 seats as the split between narrow body and wide body aircraft, causes the traffic for some route flows in the later decades to move up into the wide body aircraft seating categories resulting in aircraft deliveries in the outer years that seems to present an imbalance in the number of wide body aircraft as compared to narrow body aircraft. This imbalance in share of narrow body and wide body may have an impact on the estimated NRC and emissions results in the later decades.

4.6 Figure 43 depicts the entry into service and diffusion scenarios for wide body aircraft.



Note 1. – Unconstrained delivery market share for ACA-T3s. Range constrained ACA-T3s would be substituted for ACA-T2s for unfeasible distance bands.

Note 2. – Delivery market share in target years (modeled by FESG) will be rounded to nearest 5%.

Figure 43: LTAG-TG fleet entry and diffusion scenarios – Wide Bodies

4.7 The LTAG-TG entry into service and diffusion scenarios were translated into potential future aircraft program/families used as input to the NRC costs model. Figure 44 shows an illustrative scenario for wide body aircraft for IS1 with only ATW entering the fleet, IS2 that sees the introduction of ACA-T2 aircraft and IS3 with the introduction of ACA-T3 aircraft.

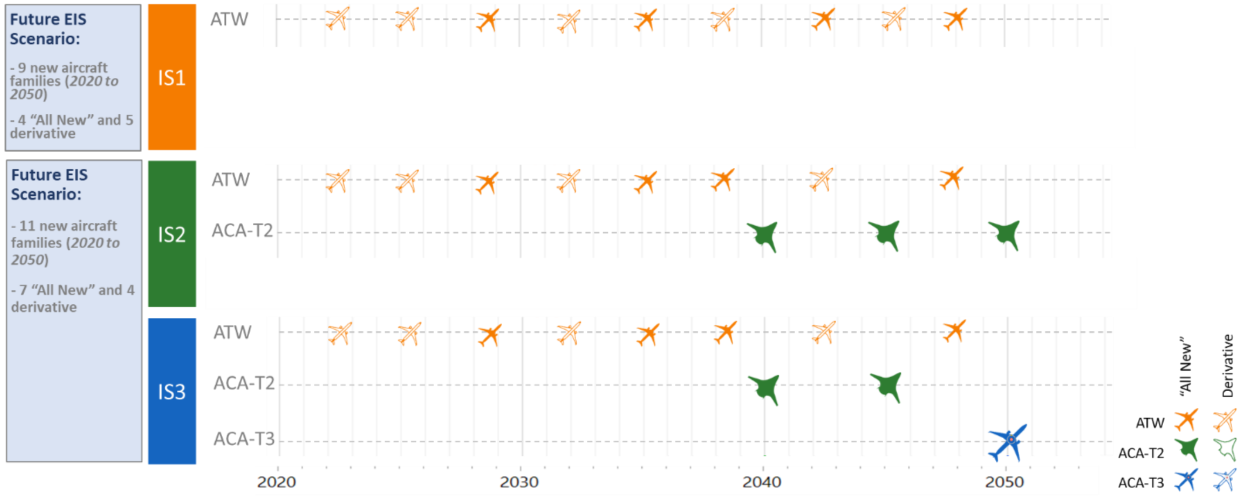
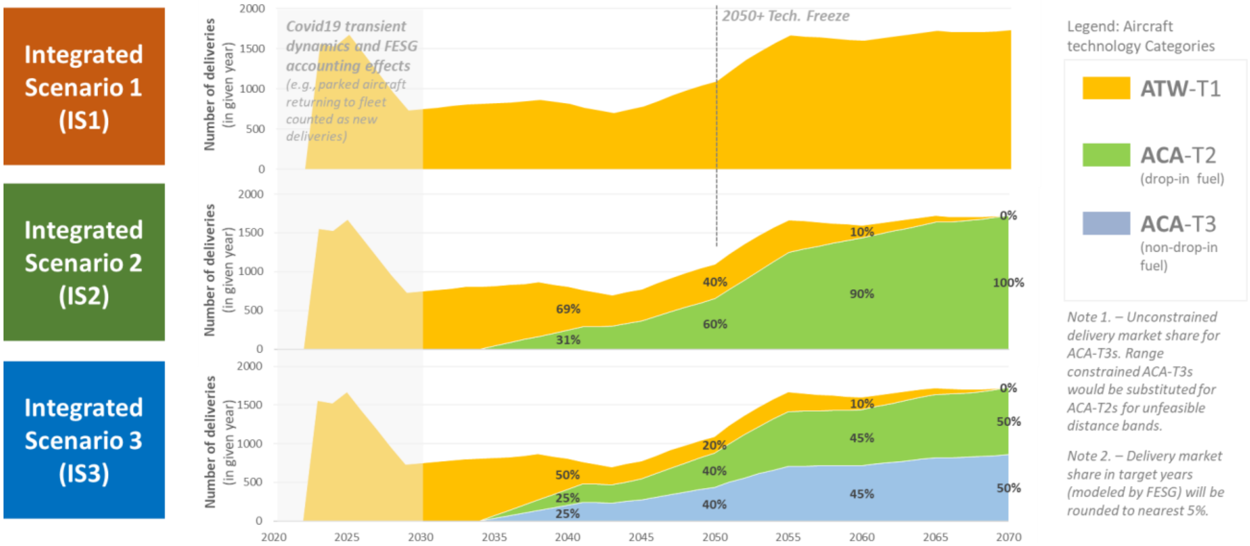


Figure 44: LTAG-TG aircraft fleet entry scenarios used as input to NRC cost model – Wide Bodies

4.8 Figure 45 depicts the entry into service and diffusion scenarios for narrow body aircraft.



Covid19 transient dynamics and FESG accounting effects (e.g., parked aircraft returning to fleet counted as new deliveries)

Note 1. – Unconstrained delivery market share for ACA-T3s. Range constrained ACA-T3s would be substituted for ACA-T2s for unfeasible distance bands.

Note 2. – Delivery market share in target years (modeled by FESG) will be rounded to nearest 5%.

Figure 45: LTAG-TG fleet entry and diffusion scenarios – Narrow Bodies

4.9 Figure 46 shows an illustrative scenario for narrow body aircraft for IS1 with only ATW entering the fleet, IS2 that sees the introduction of ACA-T2 aircraft and IS3 with the introduction of ACA-T3 aircraft.

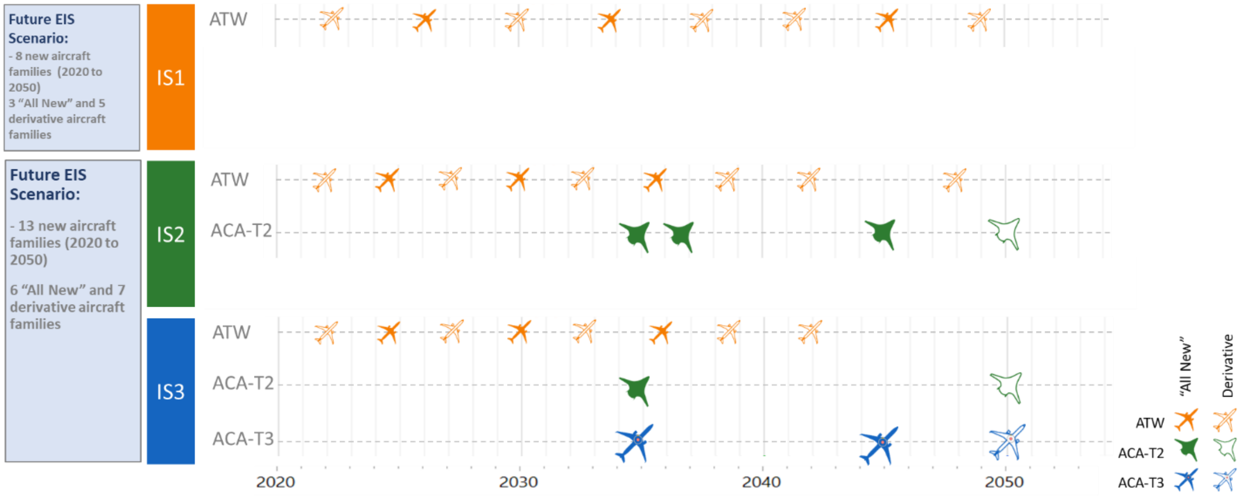
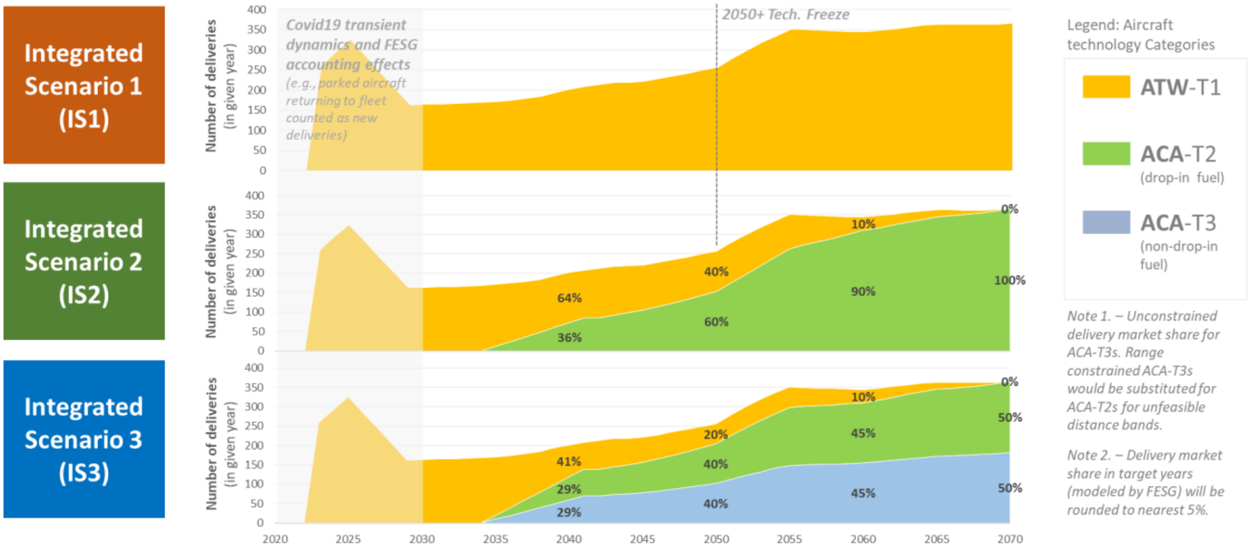


Figure 46: LTAG-TG aircraft fleet entry scenarios used as input to NRC cost model – Narrow Bodies

4.10 Figure 47 depicts the entry into service and diffusion scenarios for regional jets.



Note 1. – Unconstrained delivery market share for ACA-T3s. Range constrained ACA-T3s would be substituted for ACA-T2s for unfeasible distance bands.

Note 2. – Delivery market share in target years (modeled by FESG) will be rounded to nearest 5%.

Figure 47: LTAG-TG fleet entry and diffusion scenarios – Regional Jets

4.11 Figure 48 shows an illustrative scenario for regional jets for IS1 with only ATW entering the fleet, IS2 that sees the introduction of ACA-T2 aircraft and IS3 with the introduction of ACA-T3 aircraft.

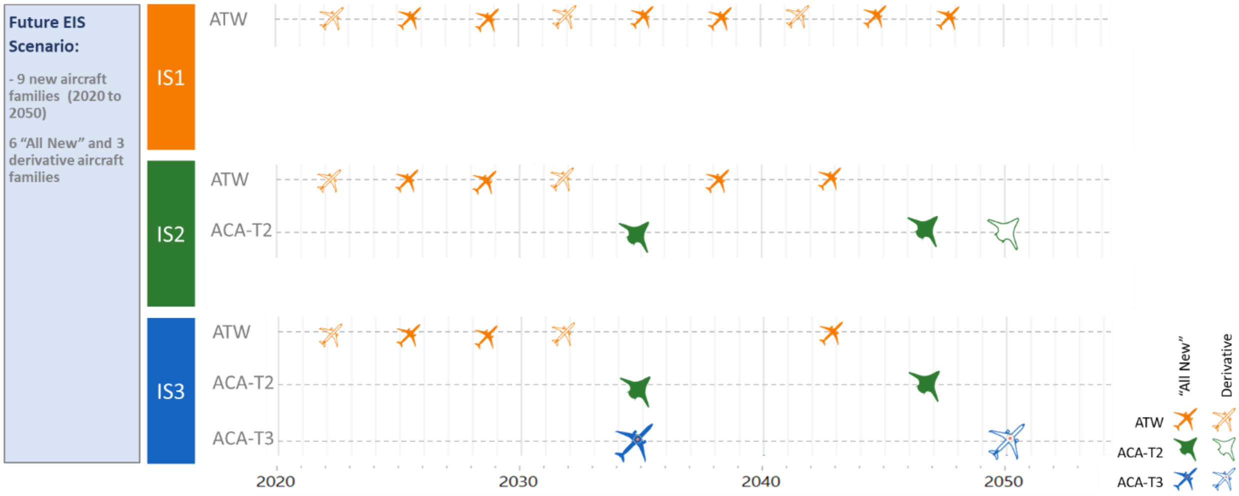


Figure 48: LTAG aircraft fleet entry scenarios used as input to NRC cost model – Regional Jets

4.12 Figure 49 depicts the entry into service and diffusion scenarios for turboprops.

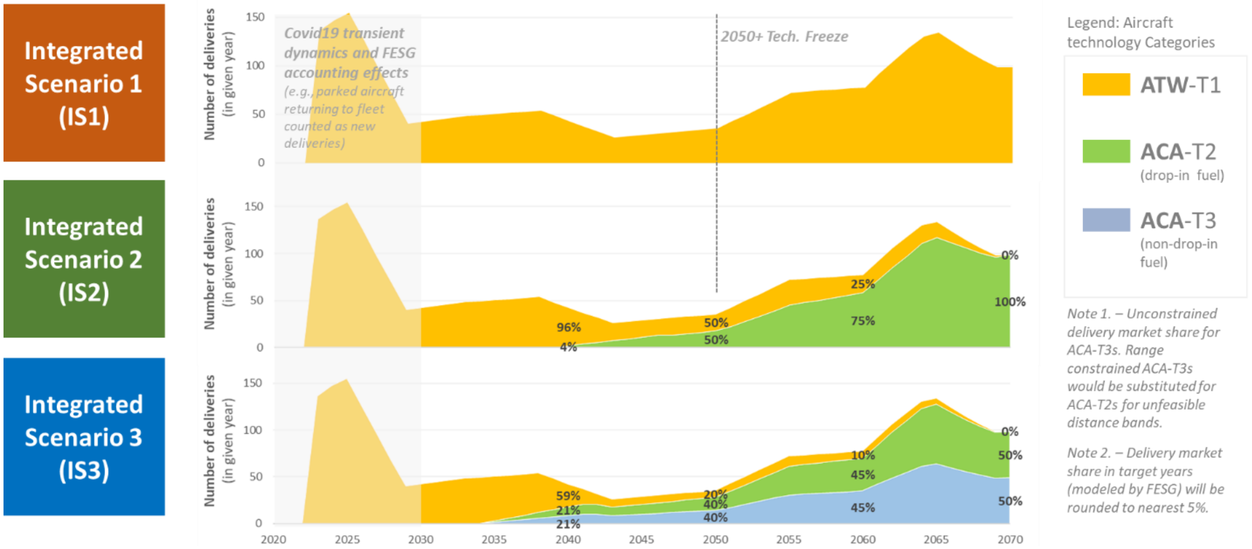


Figure 49: LTAG-TG fleet entry and diffusion scenarios – Turboprops

4.13 Figure 50 shows an illustrative scenario for turboprops for IS1 with only ATW entering the fleet, IS2 that sees the introduction of ACA-T2 aircraft and IS3 with the introduction of ACA-T3 aircraft.

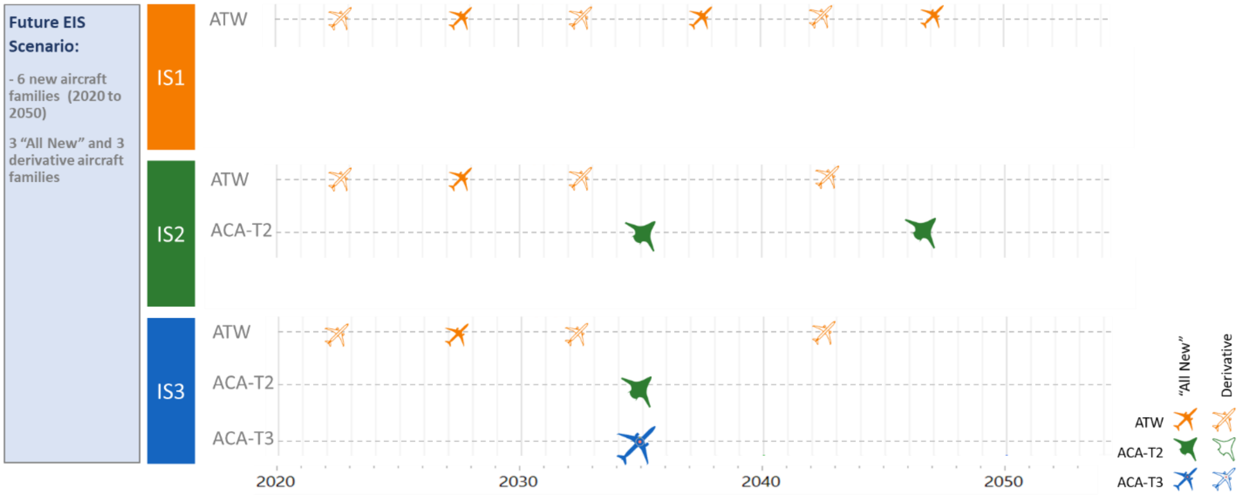


Figure 50: LTAG-TG aircraft fleet entry scenarios used as input to NRC cost model – Turboprops

4.14 Figure 51 depicts the entry into service and diffusion scenarios for business jets.

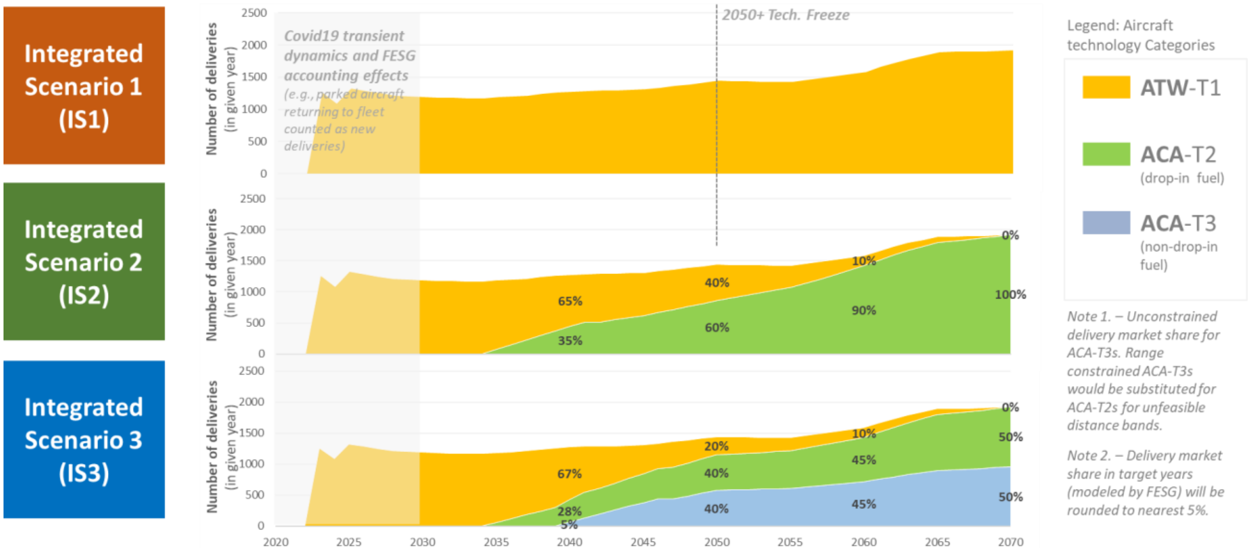


Figure 51: LTAG-TG fleet entry and diffusion scenarios – Business Jets

4.15 Figure 52 shows an illustrative scenario for business jets for IS1 with only ATW entering the fleet, IS2 that sees the introduction of ACA-T2 aircraft and IS3 with the introduction of ACA-T3 aircraft.

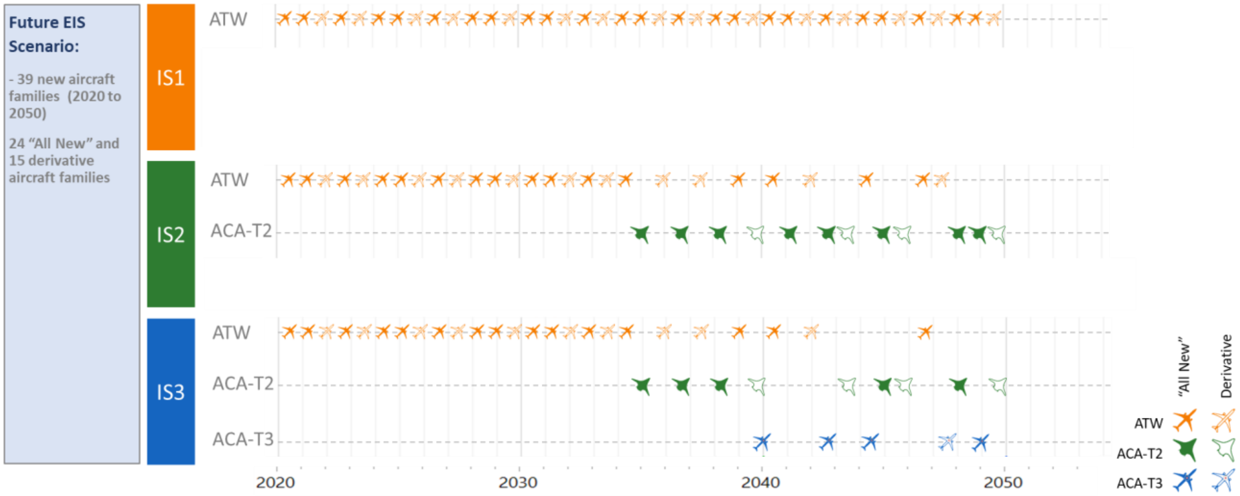


Figure 52: LTAG-TG aircraft fleet entry scenarios used as input to NRC cost model – Business Jets

4.16 Aircraft Non-Recurring Costs (NRC) Temporal Distribution Illustration for one aircraft program (family)

4.17 Using the LTAG-TG Aircraft Technology NRC costs (investment) model, the LTAG-TG CEahg translated the aircraft fleet entry and diffusion scenario to develop a bottom-up build-up of non-recurring costs for each LTAG-TG integrated scenario. Figure 53 shows an illustrative example of one potential aircraft program/family for which the first family variant would enter service in 2040. From the announcement of the program, non-recurring costs would ramp up over several years to reach a peak during flight tests, and certification which occur a few years before entry into service. Additional non-recurring costs (investments) may be required after the entry into service of the first aircraft type in the family towards the development, flight testing and certification of potential subsequent variants.

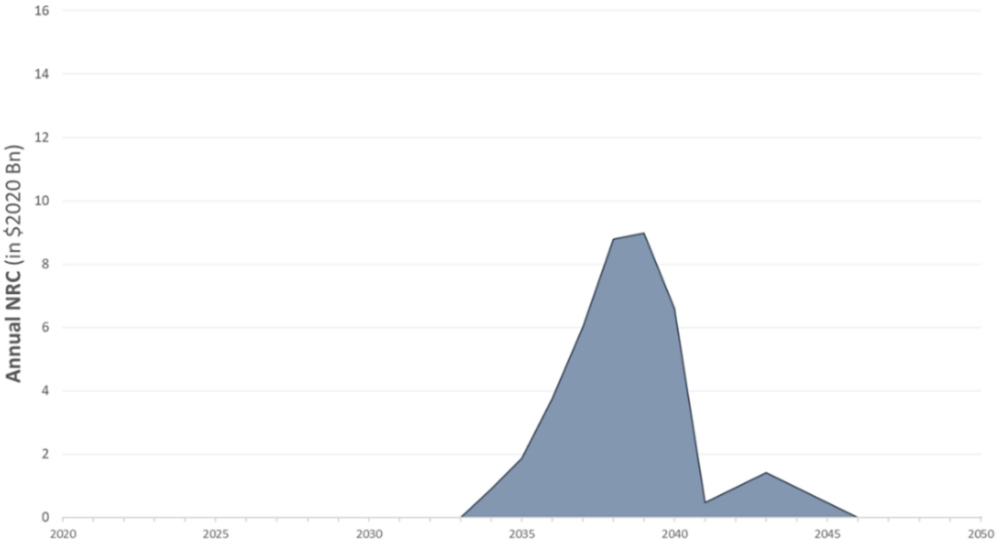


Figure 53: Temporal Distribution of Aircraft Non-Recurring Costs (NRC) for Illustrative Aircraft Program (Family) with potential EIS in 2040

4.18 The LTAG-TG CEahg developed a bottom-up build-up of non-recurring costs for each aircraft program/family depicted in the LTAG-TG aircraft fleet entry and diffusion scenario depicted in the previous figures. Figure 54 shows the temporal distribution of the aggregated set of non-recurring costs across all potential future aircraft programs considered in LTAG-TG integrated scenario 3.

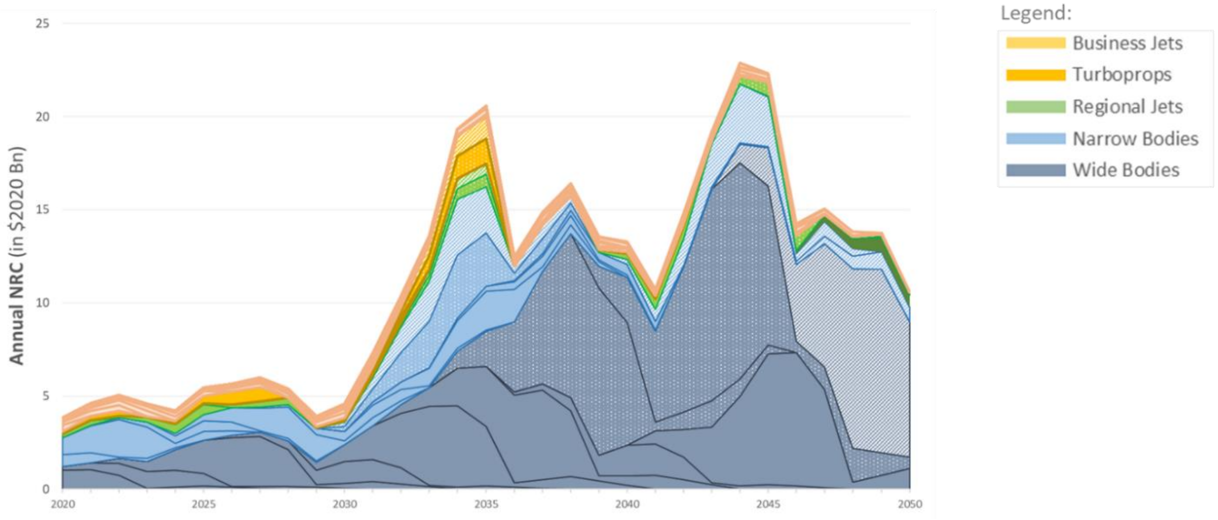


Figure 54: Temporal distribution of aircraft non-recurring costs for aircraft programs (families) considered in illustrative IS3 scenario (including ATWs, ACA-T2s and ACA-T3s)

4.19 Summary of results for other scenarios are presented in Figure 55 as well as described and discussed in Appendix R1.

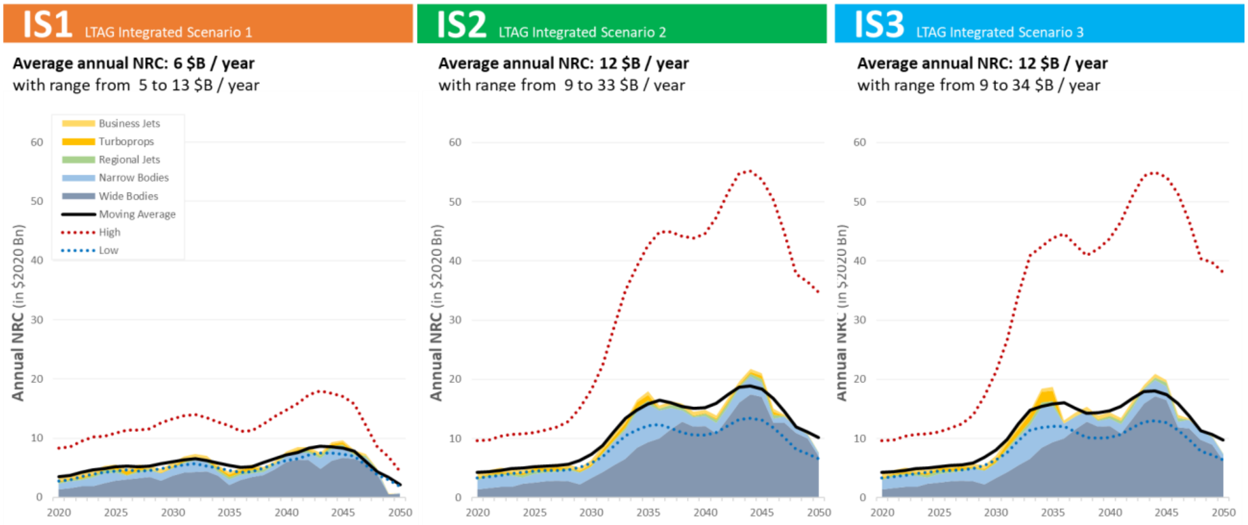


Figure 55: Aircraft non-recurring costs (NRC) across LTAG integrated scenarios 1, 2 and 3

5. FUEL COSTS (I.E. SAVINGS)

5.1 Fuel costs (i.e. savings) result from the operations of aircraft types that exhibit technology improvement associated with a given LTAG-TG Integrated (Aircraft Technology) Scenario.

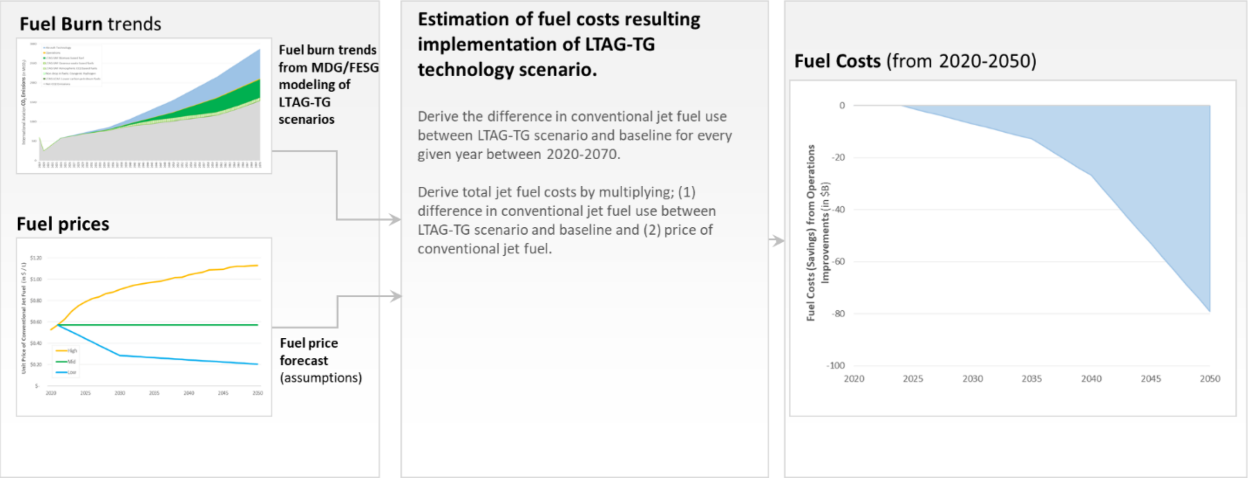
5.2 ***Description of Cost Element:*** Fuel costs (i.e. savings) resulting from the operations of aircraft types exhibiting the technology improvement associated with a given LTAG-TG Integrated (Tech) Scenario. This methodology is applicable to conventional jet fuel use.

5.3 ***Input:*** Inputs include conventional jet fuel burn for each LTAG-TG scenarios from 2020-2070 based on LTAG trends developed by MDG as well as forecast of price of conventional jet fuel.

5.4 ***Methodology:*** Derive the difference in conventional jet fuel use between LTAG-TG scenario and baseline for every given year between 2020-2070. Derive total jet fuel costs by multiplying; (1) difference in conventional jet fuel use between LTAG-TG scenario and baseline and (2) price of conventional jet fuel.

5.5 ***Output:*** The methodology yields fuel cost resulting from the operations of aircraft types exhibiting the technology improvement associated with a given LTAG-TG Integrated (Tech) Scenario (in billion dollars). Temporal distribution of fuel costs (expected based on time series of conventional jet fuel burn from MDG Trends+ and conventional jet fuel price projections).

5.6 **Figure** 56 shows the high-level modelling approach for estimating fuel costs (savings) related to aircraft technology.

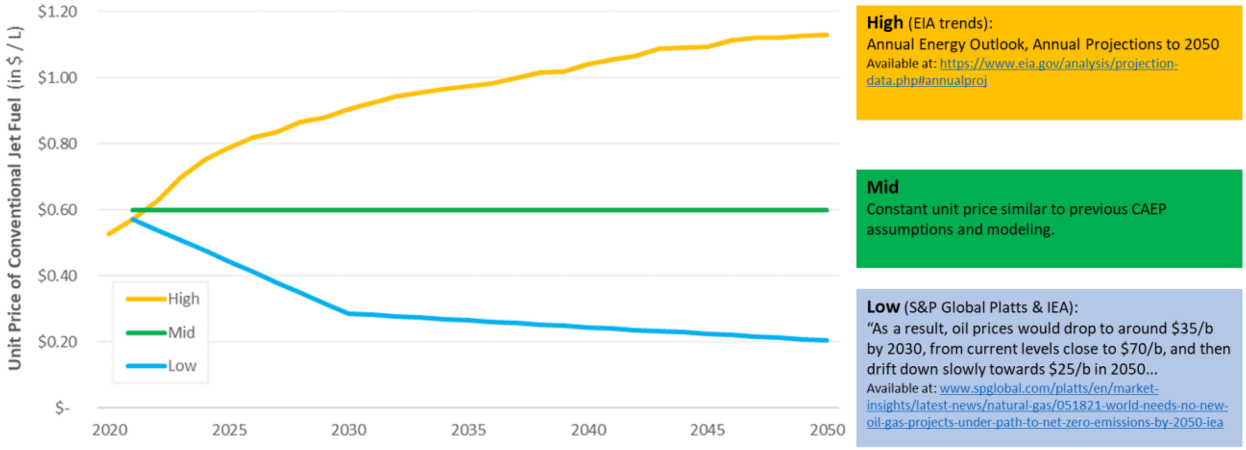


Derive the difference in conventional jet fuel use between LTAG-TG scenario and baseline for every given year between 2020-2070.

Derive total jet fuel costs by multiplying; (1) difference in conventional jet fuel use between LTAG-TG scenario and baseline and (2) price of conventional jet fuel.

Figure 56: High-level modelling approach for fuel costs (savings) related to aircraft technology

5.7 The LTAG-CEahg reviewed assumptions for conventional jet fuel prices used in prior CAEP analyses (non-exhaustive). For CO_2 Standard Main analysis (in 2014/2015), "research showed the price of fuel in 2010 was around $2.23 per U.S. gallon; though, FESG subsequently agreed on $3.00 per U.S. gallon for the CO_2 main analysis, which was also the assumption for the CAEP/9 noise stringency analysis". "The FESG agreed fuel price for the analysis is $3.00 per US gallon (2010$)". A sensitivity analysis was conducted using $2.00 and $4.00 per U.S. gallon fuel prices.



High (EIA trends):
Annual Energy Outlook, Annual Projections to 2050
Available at: https://www.eia.gov/analysis/projection-data.php#annualproj

Mid
Constant unit price similar to previous CAEP assumptions and modeling.

Low (S&P Global Platts & IEA):
“As a result, oil prices would drop to around $35/b by 2030, from current levels close to $70/b, and then drift down slowly towards $25/b in 2050...
Available at: www.spglobal.com/platts/en/market-insights/latest-news/natural-gas/051821-world-needs-no-new-oil-gas-projects-under-path-to-net-zero-emissions-by-2050-iea

Figure 57: Potential scenarios for sensitivity analyses of unit fuel costs assumptions

5.8 For the purpose of the base case analyses, the LTAG-TG CEahg used the mid unit fuel cost scenario of $0.60 per litre.

6. INCREMENTAL BUILT COST (IBC)

6.1 Incremental Built Cost (IBC) captures the variable costs associated with producing aircraft e.g. material, labour, or other recurring costs. Historically, CAEP has developed and used IBC for stringencies analyses, but it was not applied to fuel burn (CO_2) stringency analysis. The CO_2 standard included a sensitivity analysis based on “Price After Technology Response”. However, there were no agreement by CAEP on the implementation of the methodology. This analysis was considered as a sensitivity analysis.

6.2 The CEahg did not conduct a quantitative analysis of recurring costs or incremental built costs (IBC) but it is qualitatively described.

7. PRICE REFLECTING TECHNOLOGY IMPROVEMENT

7.1 This cost focuses on price after technology improvement that reflects the potential pass on of investments (costs) from the manufacturer to deliver an aircraft with technology improvements that deliver fuel (CO_2 emissions) reduction benefits.

7.2 The CEahg reviewed how price after technology improvement estimations were considered in CAEP analyses historically. The CO_2 standard analyses assumed that recurring cost of manufacturing aircraft remains unchanged after they have been modified to meet a stringency option, whereas the additional technology contained in a technology response may be expected to cost more to manufacture (i.e. material, labour, and other recurring costs). A sensitivity analysis of total costs was conducted, using as a proxy the Price After Technology Response (PATR) based methodology.

7.3 Following discussions on the need and feasibility to assess price reflecting technology improvements (to operators), the CEahg acknowledged that: *“Fuel savings from aircraft technology* *improvements may be reduced by an increase in aircraft acquisition costs driven by Price After Technology Improvement i.e. aircraft technology improvements are not expected to "come for free". Airline acquisition of new aircraft is a multi-attribute decision making process, including aircraft capabilities, operating costs (including fuel efficiency), commonality with other aircraft types in the fleet, etc. The transactions are also not publicly available, and it is challenging to extract/isolate the contribution of aircraft technology improvement to aircraft total price."*

7.4 Potential incremental cost to operators, that could counter (some) fuel savings, were captured graphically on summary LTAG-CEahg slides.

8. ASSET VALUE LOSS

8.1 Aircraft Value Loss (AVL) captures the impact of the entry into service of aircraft with technology improvement on the in-service fleet. AVL was assessed in very specific case of CO_2 standard (i.e. timing between announcement of stringency and applicability). The LTAG-TG is not conducting and replicating of CO_2 standard stringency analysis. As such, the LTAG-TG CEahg did not conduct a quantitative analysis of aircraft asset value loss but will qualitatively describe this cost.

9. CONSIDERATIONS ON REGIONAL DISTRIBUTIONS OF AIRCRAFT TECHNOLOGY RELATED COSTS AND INVESTMENTS

9.1 The LTAG-CEahg analysis of costs and investments focused on (1) the research, development, certification of aircraft by OEMs, supported by governments through research and development support and (2) the use of aircraft with technology improvements by airlines.

9.2 Non-recurring costs and research/development support towards aircraft technology development

9.2.1 Current and future regional distributions of cost and investments associated with aircraft development are and will be driver by the location of research, development and production centres by OEM and their suppliers.

9.2.2 ***Current landscape of aircraft technology development:*** **Figure** 58 shows the current landscape of airframe development (by ICAO Member state attribution of certificating authority) based on the CAEP Growth and Replacement database. The database includes in-production aircraft (in 2020) along with the identification of the manufacturers (OEM). ICAO Members States (and groups of States) by decreasing number of aircraft/engine models include the United Sates, the European Union, Canada, the Russian Federation, Brazil, China, Ukraine, Switzerland and Japan. The aerospace supply network extends beyond these States through second and third tier suppliers.

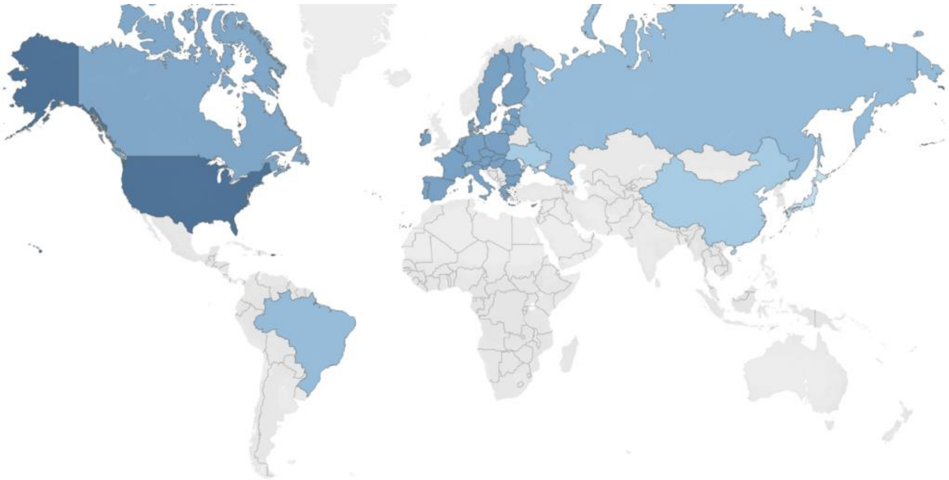


Figure 58: Current (2020) landscape of airframe development (by ICAO Member state attribution of certificating authority)

9.2.3 **Figure** 59 shows which countries export or import more of fixed wing aircraft (with MTOM greater than 15,000 kg)[25]. Each country is coloured based on the difference in exports and imports of fixed wing aircraft during 2019. In 2019, the countries that had a largest trade value in exports than in imports of were France ($34.8B), United States ($24.7B), Germany ($21.6B), Kuwait ($2.04B), and Brazil ($1.61B). In 2019, the countries that had a largest trade value in imports than in exports were China ($15B), India ($6.71B), Ireland ($6.11B), Japan ($3.66B), and Turkey ($3.52B).

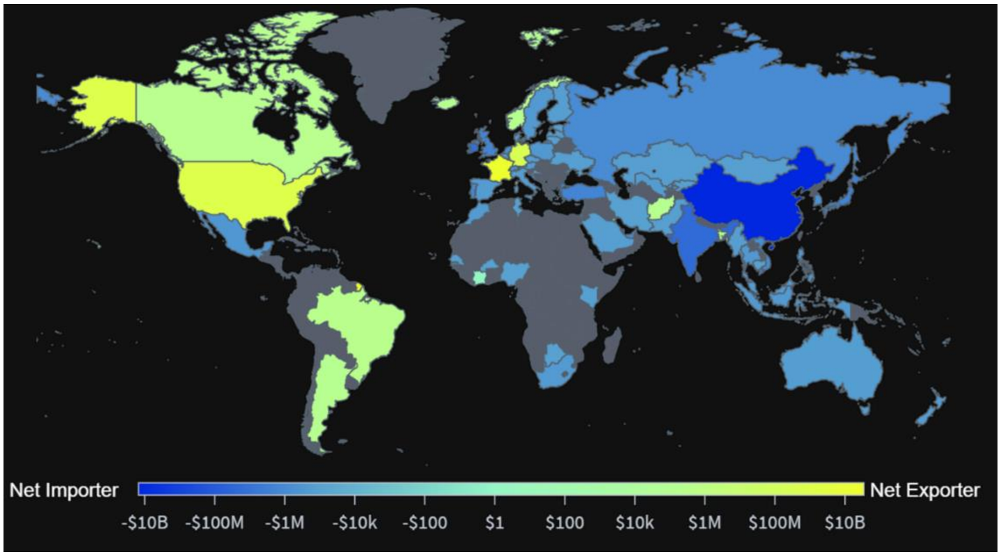


Figure 59: Current (2019) net trade of fixed wing aircraft (MTOM greater than 15,000 kg) [Source: OEC, 2021]

---

[25] OEC, 2019, "Fixed wing aircraft, unladen weight > 15,000kb”, last retrieved October 24, 2021, available at: https://oec.world/en/profile/hs92/fixed-wing-aircraft-unladen-weight-15000-kg

9.3 ***Potential future evolution of aircraft technology development:*** While CAEP did not (and could not) have access to strategic plans by aerospace companies and/or States because those don't exist through 2050 and/or are confidential, some observations were made based on publicly available information:

a) Potential development of Advanced Tube and Wing (ATWs) and Advanced Concept Aircraft (ACA-T2s):

- In its vision for 2050, the U.S. Aerospace Industry Association[26] notes that while "it is impossible to perfectly predict how technologies and their uses will develop over 30 years, but these experts have painted a remarkable picture of the potential uses of these technologies; the scientific and technical advancements, regulations and cultural factors that enable them; and the extent to which they are likely to be a part of our everyday lives by 2050". This includes new materials and manufacturing processes will allow faster and more responsive production of vehicles, making them affordable and bringing them to market faster. The U.S. National Aeronautics and Space Administration (NASA)[27] is researching and supporting the development of technologies that will build from the foundation laid during previous NASA projects such as the Environmentally Responsible Aviation project and studies on future aircraft designs that we called N+3, including small core gas turbine, transonic truss-braced wing, high-rate composites.

- In Europe, CleanSky through ACARE and Flightpath 2050[28] is providing design guidelines that could be commonly accepted across Europe's aviation sector as a basis for moving the industry towards greener standards. This includes advancing the research and technologies that will enable industry (such as airframe manufacturers and engine builders) to take those novel technologies developed to TRL 5/6 through Clean Sky and to develop them to the next stages of development, certification, implementation, and deployment into the aircraft that will carry tomorrow's passengers and cargo.

b) Potential development of non-drop in fuel powered Advanced Concept Aircraft (ACA-T3s):

- In its vision for 2050, the U.S. Aerospace Industry Association also notes that while the path to 2050 will include cleaner and quieter electric propulsion, although it may be more focused on small aircraft (e.g. UAVs and UAMs not predominantly used by international aviation).

- Several research, assessment and/or initiatives are also under towards the use of hydrogen as fuel, either used in fuel cell or towards combustion. In 2020, Airbus[29] "has revealed three concepts for the world's first zero-emission commercial aircraft which could enter service by 2035. These concepts each represent a different approach to achieving zero-emission flight, exploring various technology pathways and aerodynamic configurations to support the company's ambition of leading the way in the decarbonisation of the entire aviation industry. All these concepts rely on hydrogen as a primary power source – an option which Airbus believes holds exceptional promise as a clean aviation fuel and is

---

[26] Aerospace Industry Association, March 2019, "What's Next for Aerospace and Defense: A Vision for 2050", last retrieved Oct. 24, 2021, available at: https://www.aia-aerospace.org/wp-content/uploads/2019/04/Whats-Next-for-Aerospace-and-Defense.pdf

[27] NASA, April 16, 2020, "NextGen Aircraft Design is Key to Aviation Sustainability", last retrieved Oct. 24, 2021, available at: https://www.nasa.gov/aero/nextgen-aircraft-design-is-key-to-aviation-sustainability.

[28] CleaSky, "Aviation", last retrieved Oct. 24, 2021, available at: https://www.cleansky.eu/aviation-0

[29] Airbus, September 21, 2020, "Airbus reveals new zero-emission concept aircraft", last retrieved Oct. 24, 2021, available at: https://www.airbus.com/newsroom/press-releases/en/2020/09/airbus-reveals-new-zeroemission-concept-aircraft.html

likely to be a solution for aerospace and many other industries to meet their climate-neutral targets. In the turbofan configuration, two hybrid hydrogen turbofan engines provide thrust. The liquid hydrogen storage and distribution system is located behind the rear pressure bulkhead. A turbofan design (120-200 passengers) with a range of 2,000+ nautical miles, capable of operating trans continentally and powered by a modified gas-turbine engine running on hydrogen, rather than jet fuel, through combustion. The liquid hydrogen will be stored and distributed via tanks located behind the rear pressure bulkhead. In the turboprop configuration, two hybrid hydrogen turboprop engines provide thrust. The liquid hydrogen storage and distribution system is located behind the rear pressure bulkhead".

- Other countries (and associated aerospace corporations) have also expressed interests in exploring and developing hybrid-electric aircraft where "with Canadian government support, Pratt & Whitney Canada is moving forward with a project to equip a De Havilland Canada Dash 8-100 turboprop with a hybrid-electric propulsion system, with demonstrator flights scheduled to begin in 2024"[30].

9.4 This potential future evolution of aircraft technology developments will drive the future investments (e.g. non-recurring costs and research and development support) and their resulting regional and national distributions to 2050 and beyond.

9.5 Costs (savings) resulting from fuel efficiency improvements

9.5.1 Regional distributions of savings from the entry into the fleet of aircraft with fuel efficiency improvements (i.e. ATWs, ACA-T2s and ACA-T3s) will be driven by fleet evolution to meet demand for new deliveries to meet (1) replacement of aircraft that retired and (2) growth in traffic given a traffic forecast. Figure 60 show the regional distribution of fuel savings resulting from aircraft technology related fuel efficiency improvements.

---

[30] Flight Global, "Pratt & Whitney Canada again commits to develop hybrid-electric propulsion system for regional airliners", July 15, 2021, last retrieved Oct. 24, 2021, available at: https://www.flightglobal.com/engines/pratt-and-whitney-canada-again-commits-to-develop-hybrid-electric-propulsion-system-for-regional-airliners/144615.article

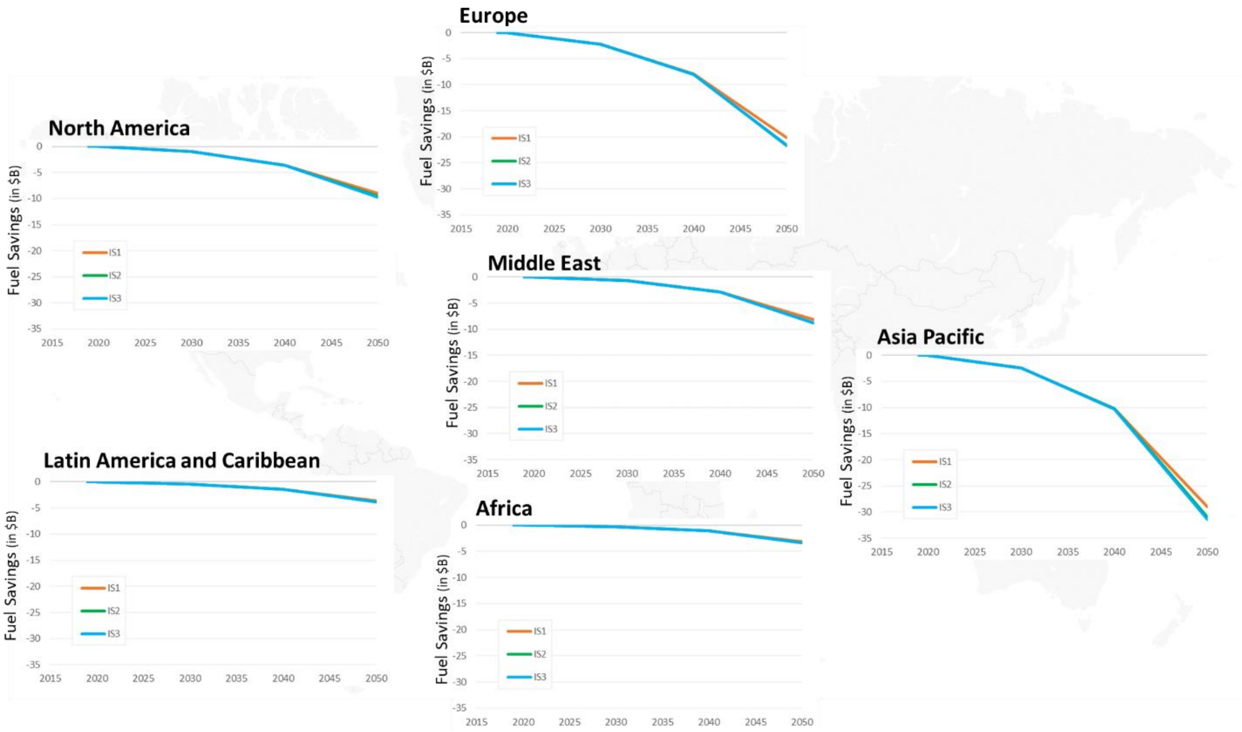


Figure 60: Regional distribution of fuel savings resulting from aircraft technology related fuel efficiency improvements.

ATTACHMENT B TO APPENDIX M1

COST (INVESTMENT) ESTIMATIONS: OPERATIONS

Note. — This Attachment provides a summary of the approaches and methodologies considered by the SDSG Cost Estimation ad hoc group towards the estimation of costs (investments) associated with operations scenarios.

1. APPROACH FOR COST (INVESTMENT) ESTIMATIONS FROM OPERATIONS IMPROVEMENTS

1.1 The CEahg coordinated with LTAG-TG Operations subgroup on the scope of costs potentially considered by the group. **Figure** 61 shows the operations related cost (investment) elements considered by the LTAG-TG.

Figure 61: Operations related cost (investment) elements considered by the LTAG-TG

2. OVERVIEW OF APPROACH FOR SCREENING PORTFOLIO OF MEASURES AND IDENTIFYING COSTS (INVESTMENTS) TO BE QUANTIFIED

2.1 During their coordination, the CEahg and the LTAG-TG Operations subgroup noted that most if not all elements of ATM modernization programs may be motivated primarily for reasons such as capacity increase, congestion reductions, safety, airspace integration, etc.

2.2 Environmental performance (i.e. CO_2 emissions reductions) may not be the primary driver. As such, it may be difficult to (1) isolate the cost (investments) associated with CO_2 emissions reductions and (2) attribute the costs (investments) to an LTAG-TG integrated scenario. One could also argue that in the absence of an LTAG, some ATM Modernization programs would still be implemented.

2.3 On the other hand, certain operational improvements may be more directly motivated by fuel burn reductions and CO_2 emissions reductions.

2.4 The LTAG-TG Operations and LTAG SDSG CEahg considered reflecting these observations in the approach for estimating costs (investments) associated with LTAG-TG Integrated Scenarios. **Figure** 62 shows the high-level approach for cost (investment) associated with operational measures.

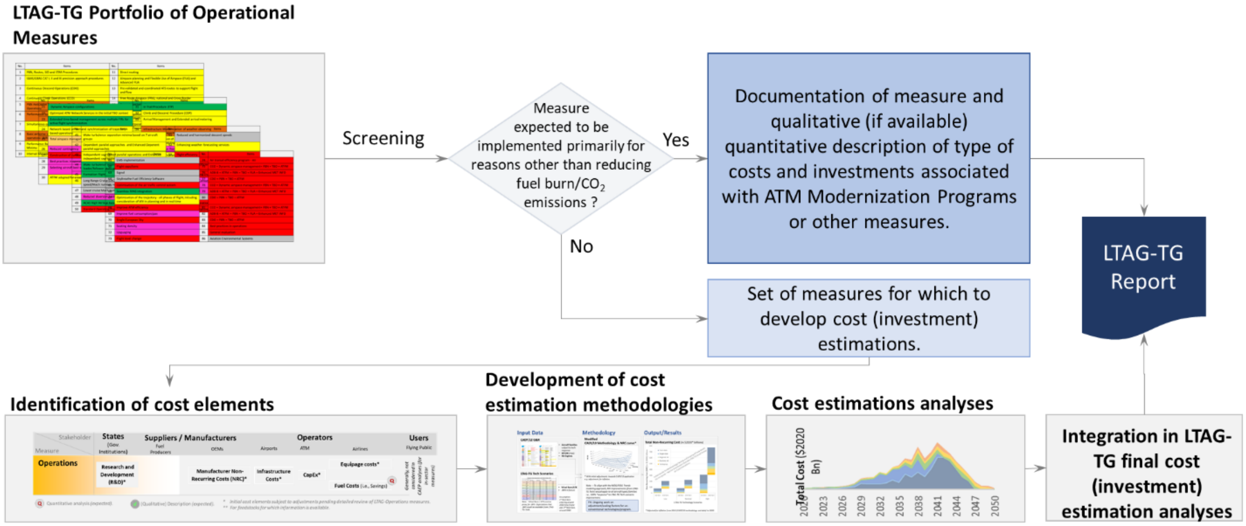
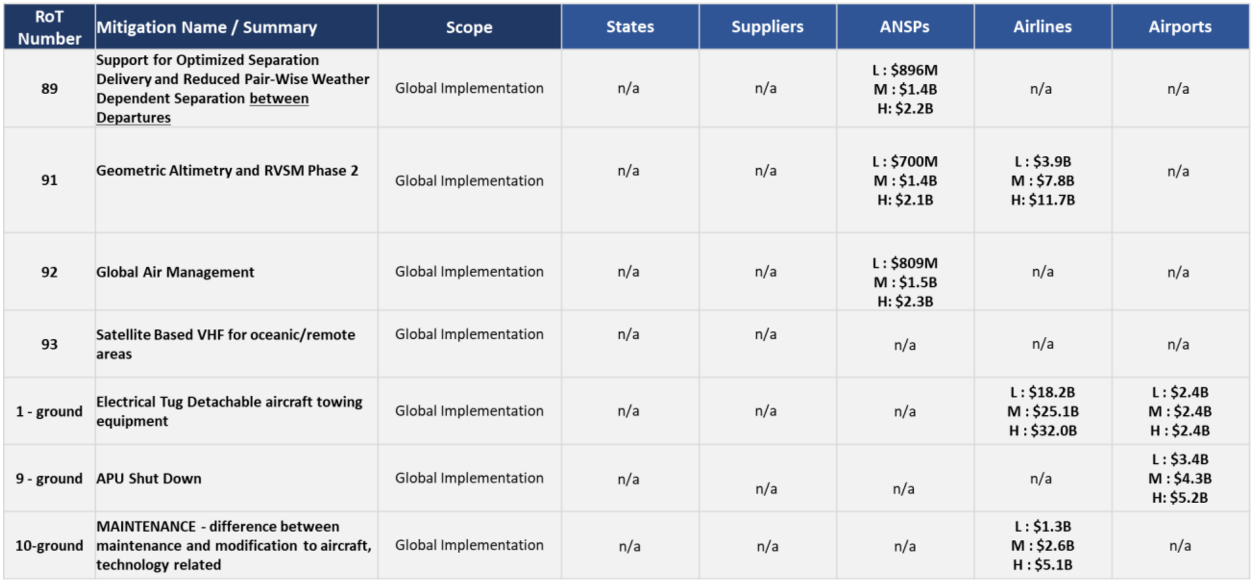


Figure 62: High-level approach for cost (investment) associated with operational measures

2.5 **Figure** 63 and **Figure** 64 shows the summary of operational measures and costs and investments across stakeholders.

RoT Number	Mitigation Name / Summary	Scope	States	Suppliers	ANSPs	Airlines	Airports
15	Dynamic sectorization	Global Implementation	n/a	n/a	L : $3.4B M : $10.7B H : $20.1B	n/a	n/a
26	Reduced Extra Fuel Onboard *This measure is covered by RoT 63.	Global Fleetwide Implementation	n/a	n/a	n/a	n/a	n/a
28	Best practices in operations-Minimizing weight	Global Fleetwide Implementation	n/a	L : $0.1B M : $0.7B H : $1.2B	n/a	L : $15.4B M : $39.5B H: $74B	n/a
31	In-Trail Procedure (ITP)	Oceanic FIR Implementation	n/a	n/a	L : $8M M : $42M H : $76M	L : $0.82T M : $1.0T H : $1.2T	n/a
45	Formation Flight	Global Implementation	n/a	n/a	L : $1.0B M : $2.4B H: $4.7B	L : $21B M : $27B H: $34B	n/a
57	No fuel tankering *This measure is covered by RoT 63.	Global Fleetwide Implementation	n/a	n/a	n/a	n/a	n/a
63	Airline Fuel Management System	Global Fleetwide Implementation	n/a	n/a	n/a	L : $2.5B M : $4.5B L : $7.4B	n/a
88	Optimized Runway Delivery Support tool and Reduced Pair-Wise Weather Dependent Separation between Arrivals	Global Implementation	n/a	n/a	L : $896M M : $1.4B H: $2.2B	n/a	n/a

Figure 63: Summary of operational measures and associated costs (investments) across stakeholders



RoT Number	Mitigation Name / Summary	Scope	States	Suppliers	ANSPs	Airlines	Airports
89	Support for Optimized Separation Delivery and Reduced Pair-Wise Weather Dependent Separation between Departures	Global Implementation	n/a	n/a	L : $896M M : $1.4B H: $2.2B	n/a	n/a
91	Geometric Altimetry and RVSM Phase 2	Global Implementation	n/a	n/a	L : $700M M : $1.4B H: $2.1B	L : $3.9B M : $7.8B H: $11.7B	n/a
92	Global Air Management	Global Implementation	n/a	n/a	L : $809M M : $1.5B H: $2.3B	n/a	n/a
93	Satellite Based VHF for oceanic/remote areas	Global Implementation	n/a	n/a	n/a	n/a	n/a
1 - ground	Electrical Tug Detachable aircraft towing equipment	Global Implementation	n/a	n/a	n/a	L : $18.2B M : $25.1B H : $32.0B	L : $2.4B M : $2.4B H : $2.4B
9 - ground	APU Shut Down	Global Implementation	n/a	n/a	n/a	n/a	L : $3.4B M : $4.3B H: $5.2B
10-ground	MAINTENANCE - difference between maintenance and modification to aircraft, technology related	Global Implementation	n/a	n/a	n/a	L : $1.3B M : $2.6B H : $5.1B	n/a

Figure 64: Summary of operational measures and associated costs (investments) across stakeholders (cont.)

2.6 The following sections provide the description of each operational measure along with a description of the type of costs and investments expected to be required for each measure. A basis for the estimates is also provided. It should be noted that that the purpose of this exercise is to provide a first order (back of the envelope) estimate of potential costs or investments associated with operations measures. It is not meant to be a budgeting exercise for actual implementation of the measures. In addition, the magnitude of the overall costs and investments associated with operations measure should be put in context of other costs (investments) associated with aircraft technology and fuels – along with levels of uncertainty associated with projections through 2050.

2.7 **Rule of Thumb (RoT)**[31] **15: Dynamic Sectorization** *Supporting Information & Summary of Analyses and Results*.

2.7.1 ***General description of approach:*** Dynamic sectorization is expected to be implemented by ANSPs through ATM capabilities infrastructure upgrades and additional/incremental training of controllers (assumed as variable costs function of rate of implementation).

2.7.2 ***Basis for estimates:***

a) *ATM capabilities infrastructure upgrades:* Programs such as STARS and ERAM in the United States were used as basis for first order estimate. The implementation costs of STARS[32] is $2.7B

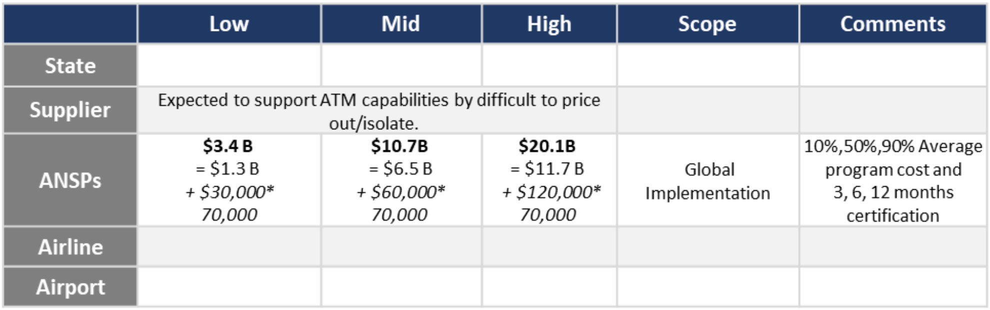
---

[31] Rule of Thumb (ROT) used by the LTAG-TG Operations subgroup to develop benefits (i.e. CO_2 emissions reductions) and costs (investments) from LTAG specific operational measures.

[32] AINonline, "ATC Program Costs, Schedules Unreliable, GAO Says", Feb. 23, 2012, available at: https://www.ainonline.com/aviation-news/air-transport/2012-02-23/atc-program-costs-schedules-unreliable-gao-says

and ERAM cost is $2.58B[33]. A worldwide implementation could cost on the order $13B (extrapolation based on operation counts in 2019). The project cost would be variable costs function of rate of implementation.

b) *Training of air traffic controllers:* The total number of ATC operators was estimated to be 70,000 globally (based on 14,000 ATC operators in the US scaled based on global operations in 2019). The average ATC salary is $120,000/year[34] and the average certification takes 2 to 4 years[35]. The certification would be a variable cost that increases with the deployment of the program. For dynamic sectorization, a complete certification of 2 to 4 years will not be needed for ATC operators (they already went through this certification process). The assumption is that ATC operators will be in training for 3 months (low estimate) to 1 years (high estimate).



	Low	Mid	High	Scope	Comments
State					
Supplier	Expected to support ATM capabilities by difficult to price out/isolate.				
ANSPs	**$3.4 B** = $1.3 B *+ $30,000* 70,000*	**$10.7B** = $6.5 B *+ $60,000* 70,000*	**$20.1B** = $11.7 B *+ $120,000* 70,000*	Global Implementation	10%,50%,90% Average program cost and 3, 6, 12 months certification
Airline					
Airport					

Figure 65: Summary of costs (investments) by stakeholders

Year	Low	Mid	High	Readiness (% of all flights)
2020	**$ 0**	**$ 0**	**$ 0**	0
2030	**$ 0.85 B** = $3.4B * 0.25	**$ 2.7 B** = $10.7B * 0.25	**$ 5.0 B** = $20.1B * 0.25	25
2040	**$ 0.34 B** = $3.4B * 0.1	**$ 1.1 B** = $10.7B * 0.1	**$ 2.0 B** = $20.1B * 0.1	35
2050	**$ 0.34 B** = $3.4B * 0.1	**$ 1.1 B** = $10.7B * 0.1	**$ 2.0 B** = $20.1B * 0.1	45

Figure 66: Temporal distributions of costs for ANSPs (investments)

---

[33] GAO, "Next Generation Air Transportation System: Information on Expenditures, Schedule, and Cost Estimates, Fiscal Years 2004 — 2030" Nov. 17, 2016, available at: https://www.gao.gov/assets/gao-17-241r.pdf

[34] Forbes, "Here's How Much Money Air Traffic Controllers Make In Every State", Nov. 21 2019, available at: https://www.forbes.com/sites/andrewdepietro/2019/11/21/air-traffic-controller-salary-state/?sh=38f2912659ff

[35] DegreeQuery, "WHAT DEGREE DO I NEED TO BECOME AN AIR TRAFFIC CONTROLLER?", available at : https://www.degreequery.com/degree-need-become-air-traffic-controller/

2.8 **RoT 26: Reduced Extra Fuel Onboard** *Supporting Information & Summary of Analyses and Results*.

2.8.1 ***General description of approach:*** The reduction of extra fuel onboard may reduce fuel and CO_2 emissions related costs. However, carrying less extra fuel could result in more disruptions and diversions which will generate additional operational costs to the airlines.

2.8.2 ***Basis for estimates:***

a) Operations costs resulting from flight disruption: The average cost of a flight disruption for an airline is $166 per passenger[36]. In 2019, 0.3% of US flights were diverted[37] (1.4 million flights worldwide, extrapolation on Global Passenger Counts in 2019). The airline cost would cover passenger expenses after a disruption (e.g. lodging, meals…) and would cover the fees related to airport change (e.g. parking, refuelling). The airline would also have to cover cost related to aircraft repositioning towards subsequent flights. This measure may result in impacts to airports such as disruption of airport/gate usage.

2.9 **RoT 28: Best Practices in Operations-Minimizing Weight** *Supporting Information & Summary of Analyses and Results*.

2.9.1 ***General description of approach:*** The best practices in operations-minimizing weight are expected to be implemented by airlines through retrofits of cabins. The new cabins would use lighter materials, especially on the new seats. The cost would be composed of an initial investment based on the price of a complete cabin retrofit (fixed price) and variable costs (e.g. new seats) subject to a deployment of the measure. The acceptable amount of suppliers' investment for developing lighter seats are equals to the benefit that the new seats will bring to the airlines by reducing the amount of fuel burn.

2.9.2 ***Basis for estimates:***

a) *Airliners Cabin Retrofit:* There are currently about 25,000 airliners in activity[38] with an average of 138 seats each. A complete cabin retrofit for an A340 costs $2M[39]. A 10% of that cost for each aircraft is assumed to be the initial investment (fixed cost). Price of seats are between $3k & $20k. The initial cost of 10% (i.e. $200,000 per aircraft) is a fixed cost at the beginning of the program (2020). The variable cost (seats cost) is dependent of deployment in the worldwide fleet.

b) *Suppliers' investment:* The average annual fuel burn reduction of 15KL (11.8K kg) through weight reduction of 195kg per fleet by introducing new seats (ANA Website). This means that 60kg fuel saving per 1kg weight annually. The cost for 60kg fuel is $39 and service life of seat is assumed 10 years and then $39*10=$390 would be an acceptable amount of suppliers' investment for per

---

[36] WNS, "An Automated Path to Managing Flight Disruptions", available at: https://www.wns.com/insights/articles/articledetail/271/an-automated-path-to-managing-flight-disruptions.

[37] BTS, "On-Time Performance - Reporting Operating Carrier Flight Delays at a Glance", available at: https://www.transtats.bts.gov/HomeDrillChart.asp

[38] Oliver Wyman, "GLOBAL COMMERCIAL AIRCRAFT FLEET TO GROW TO MORE THAN 35,000", 2017, available at: https://www.oliverwyman.com/our-expertise/insights/2017/jun/paris-air-show/global-commercial-aircraft-fleet-to-grow-to-more-than-35000.html

[39] Travel Update, "HOW MUCH DOES IT COST TO RECONFIGURE AN AIRCRAFT CABIN?", Sept. 20 2019, available at: https://travelupdate.com/reconfigure-aircraft-cabin-cost/

1kg reduction of a new seats. Since the average seats each is 138, the total cost for 25,000 fleets by reducing 1kg per seat for 10 years will be $390*138seats*25,000fleets=$1.3B.

	Low	Mid	High	Scope	Comments
State					
Supplier	**$0.1B**=$390*138*25,000*10%	**$0.7B**=$390*138*25,000*50%	**$1.2B**=$390*138*25,000*90%		10%,50%,90% Average program cost
ANSPs					
Airline	**$15.4B** = $200,000 * 25,000 + _$3,000*138*25,000_	**$39.5B** = $200,000 * 25,000 + _$10,000*138*25,000_	**$74B** = $200,000 * 25,000 + _$20,000*138*25,000_	Global Implementation	10% initial investment per aircraft + $3k/$10k/$20k seat price
Airport					

Figure 67: Summary of costs (investments) by stakeholders

Year	Low	Mid	High	Readiness (% of all flights)
2020	$5B	$5B	$5B	0
2030	_$2.6B_	_$8.6B_	_$17.3B_	25
2040	_$1.0B_	_$3.5B_	_$6.9B_	35
2050	_$1.0B_	_$3.5B_	_$6.9B_	45

Figure 68: Temporal distributions of costs for Airlines (investments)

Year	Low	Mid	High	Readiness (% of all flights)
2020	$0	$0	$0	0
2030	_$25M_	_$175M_	_$302M_	25
2040	_$10M_	_$67M_	_$121M_	35
2050	_$10M_	_$67M_	_$121M_	45

Figure 69: Temporal distributions of costs for Suppliers (investments)

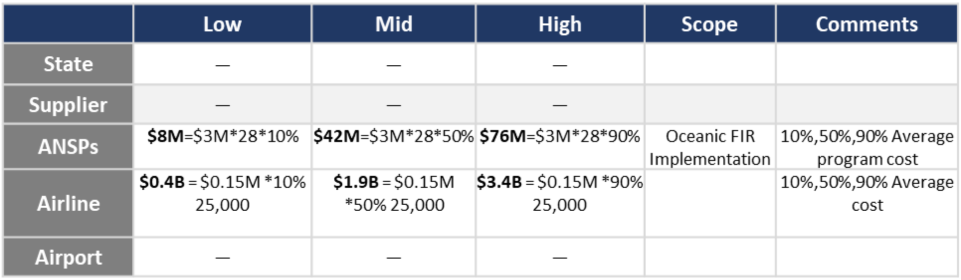
2.10 **RoT31-In-Trail Procedure (ITP)** *Supporting Information & Summary of Analyses and Results*.

2.10.1 ***General description of approach***: There is little need to build a large-scale new ATM system only for ITP operation, and it is possible to realize In Trail Procedure (ITP) by improving the performance of the existing oceanic ATM system (software support).

2.10.2 ***Basis for estimates:***

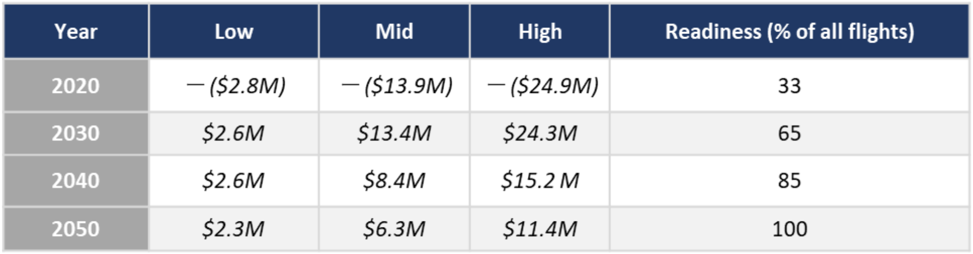
a) <u>ATM system development cost</u>: The ATM systems required for ITP have already been developed in North America, EU, and Japan. The oceanic ATM system required for ITP in Japan spent 3M USD for one oceanic FIR. The global cost should be estimated for oceanic ATM systems in the southern Atlantic Ocean, Southeast Asia Ocean, and the Indian Ocean (total 28 oceanic FIR). The progress of ATM system development and installed ADS-B in into aircraft (Readiness) does not always match, so it is assumed that all ATM system development in all regions will be completed by 2040.

b) <u>Airline avionics installation cost</u>: It is necessary to pay for installing or activating ADS-B in, and it is estimated to be about $ 0.15 million per aircraft according to the airline hearing around 2014 in Japan.



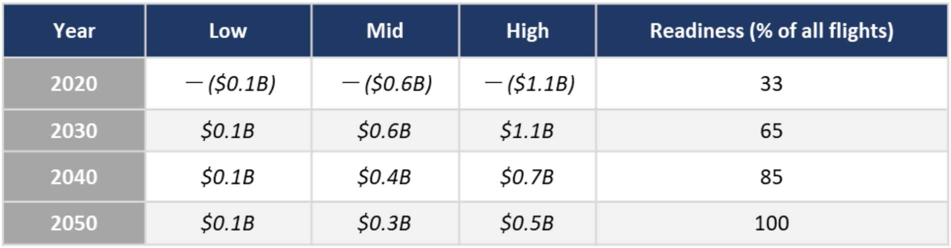
	Low	Mid	High	Scope	Comments
State	—	—	—		
Supplier	—	—	—		
ANSPs	**$8M**=$3M*28*10%	**$42M**=$3M*28*50%	**$76M**=$3M*28*90%	Oceanic FIR Implementation	10%,50%,90% Average program cost
Airline	**$0.4B** = $0.15M *10% 25,000	**$1.9B** = $0.15M *50% 25,000	**$3.4B** = $0.15M *90% 25,000		10%,50%,90% Average cost
Airport	—	—	—		

Figure 70: Summary of costs (investments) by stakeholders



Year	Low	Mid	High	Readiness (% of all flights)
2020	*— ($2.8M)*	*— ($13.9M)*	*— ($24.9M)*	33
2030	*$2.6M*	*$13.4M*	*$24.3M*	65
2040	*$2.6M*	*$8.4M*	*$15.2 M*	85
2050	*$2.3M*	*$6.3M*	*$11.4M*	100

Figure 71: Temporal distributions of costs for ANSPs (investments)



Year	Low	Mid	High	Readiness (% of all flights)
2020	*— ($0.1B)*	*— ($0.6B)*	*— ($1.1B)*	33
2030	*$0.1B*	*$0.6B*	*$1.1B*	65
2040	*$0.1B*	*$0.4B*	*$0.7B*	85
2050	*$0.1B*	*$0.3B*	*$0.5B*	100

Figure 72: Temporal distributions of costs (investments) for Airlines

2.10.3 Japan decided to introduce ITP in the CARATS Project in 2014, and developed the related oceanic ATM system, that improving performance by software update from 2017 to 2018. Since separation is shortened for each type of RNP operation, performance improvements have been made to make it possible to determine the combination of multiple aircraft and determine the control separation for ATC. After development system, verification for ATM system and revision of necessary regulations, ITP operation within Fukuoka FIR is scheduled to start from later this year.

2.10.4 Suppliers: $ 0 The ADS-B IN required for ITP has already been commercialized, and there are some areas where ITP operation is being implemented. Therefore, it is considered unnecessary for Avionics suppliers to make large initial investments for commercialization in the future. Therefore, it is appropriate to record the Cost of this item as zero.

2.10.5 ATM : ＄3 million / 1 Oceanic ATM Center: There is little need to build a large-scale new ATM system only for ITP operation, and it is possible to realize ITP by improving the performance of the existing oceanic ATM system (software support). In Japan, both CDP and ITP are planned to be introduced at the same time, so the costs required for ITP are not separately recorded. The ITP maintenance cost is calculated by considering the difference between common system and the other unique system for ITP.

2.10.6 Airline ＄0.15 million per aircraft. It is necessary to pay for installing or activating ADS-B in, and it is estimated to be about $ 0.15 million per aircraft according to the airline hearing around 2014 in Japan.

2.10.7 According to the ICAO PANS ATM (Doc.4444) and related documents, training is required for ATC and aircraft operators. However, these costs are not considered to be significant because they are additionally added to existing training related to operations utilizing other technologies such as ADS-B out. Therefore, it is not recorded this time.

2.10.8 Cost in the world for ITP: ITP is beneficial for application on heavy traffic enroute in oceanic FIRs, so it is not necessary to introduce ITP to all oceanic FIR in the world. Therefore, it is assumed that the Pacific Ocean, Atlantic Ocean, and Indian Ocean will be needed.

2019 WORLDWIDE AIR TRAFFIC FLOW （SOURCE: ICAO）

North American, Central American and Caribbean (NACC） Region
Oakland oceanic FIR
New York oceanic FIR
Miami oceanic FIR
MAZATLAN oceanic FIR

Figure 73: RoT31-In-Trail Procedure (ITP) potential implementation across regions

2.10.9 **Discussion:** The ATM systems required for ITP have already been developed in North America, EU, and Japan, so the global cost should be estimated for oceanic ATM systems in the southern Atlantic Ocean, Southeast Asia Ocean, and the Indian Ocean. The progress of ATM system development and installed ADS-B in into aircraft (Readiness) does not always match, so it is assumed that all ATM system development in all regions will be completed by 2040**.**

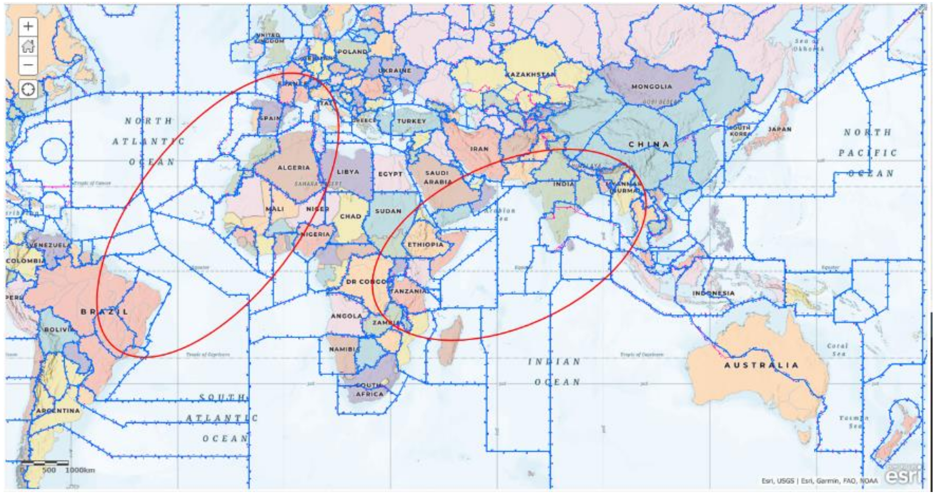


Figure 74: RoT31 In-Trail Procedure (ITP) potential FIR for implementation

2.10.10 The ATM systems required for ITP have already been developed in North America, EU, and Japan, so the global cost should be estimated for oceanic ATM systems in the southern Atlantic Ocean, Southeast Asia Ocean, and the Indian Ocean: a) the southern Atlantic Ocean 8～9 oceanic FIR, b) the Indian Ocean 8～9 oceanic FIR and c) Southeast Asia Ocean 9～10 oceanic FIR and d) total 25～28 oceanic FIR.

2.11 **RoT 45: Formation Flight** *Supporting Information & Summary of Analyses and Results*.

2.11.1 ***General description of approach***: Formation flight is a common practice in military operations and is used for fuel savings. The use of formation flight in commercial aviation would reduce the operation costs for airlines and help reduce CO_2 emissions. Formation flights take longer time than regular flights and therefore operation costs (crew …) would be higher for the airlines. There would also be an incremental cost of ATC training to prepare ATC operators to handle the formation flight plans.

2.11.2 ***Basis for estimates***:

a) Flight Operations: Based on a study from 2014, flights operated in formation flights can take up to 6.9% longer in time[40]. This time addition would reflect in Crew cost. The average hourly cost per crew is $1.6k[41]. With an average flight time of 6 hours, it brings the cost up $670 per flight. The total number of flights in 2019 was 38.9M[42].

b) Aircraft Equipment: So far, there is less knowledge about what kind of aircraft system can make an automatic formation flight function. In this analysis, it is assumed that the required technologies

---

[40] Brigham Young University, "Aircraft Route Optimization for Formation Flight", 2014, available at: https://scholarsarchive.byu.edu/facpub/1675/

[41] Simple Flying, "The Cost of Flying: What Airlines Have to Pay to Get You in The Air", 24 Dec. 2020, available at: https://simpleflying.com/the-cost-of-flying/

[42] Statista, "Number of flights performed by the global airline industry from 2004 to 2021, 17 Aug. 2021, available at: https://www.statista.com/statistics/564769/airline-industry-number-of-flights/

are well generic, and the function can be implemented from same level of effort as Runway Overrun Awareness and Alerting System (ROAAS). Based on EASA NPA 2018-12, the cost for the introduction of a ROAAS for a new aircraft is estimated to range from EUR 10,000 to EUR 30,000 per aircraft. Considering the readiness of formation flight, retrofit updates can be assumed to vary between 30% and 70% of the global fleet.

c) Training of air traffic controllers: The total number of ATC operators was estimated to be 70,000 globally (based on 14,000 ATC operators in the US scaled based on global operations in 2019). The average ATC salary is $120,000/year and the average certification takes 2 to 4 years. The certification would be a variable cost that increases with the deployment of the program. For formation flight, a complete certification of 2 to 4 years will not be needed for ATC operators (they already went through this certification process). The assumption is that ATC operators will be in training for 2 months (low estimate) to 6 months (high estimate)

d) ATM cost: Assumed that the cost of implementation of ATM system is $3 million, the number of ANSP in the world is 170 according to GANP.

	Low	Mid	High	Scope	Comments
State					
OEM					
ANSPs	**$1.0B** = *$20k * 70,000 +$3M * 170 * 10%*	**$2.4B** = *$40k * 70,000 +$3M * 170 * 50%*	**$4.7B** = *$60k * 70,000+$3M * 170 * 90%*	Global Implementation	2, 4 or 6 months certification 10%,50%,90% Average implementation cost
Airline	***$0.82T***=*$670 * 0.8 * 38.9M * 40 +* $11K*25,000*0.3	***$1.0T***=*$670 * 1.0 * 38.9M * 40 +* $71K*25,000*0.5	***$1.2T***= *$670 * 01.2 * 38.9M * 40 +* $132K*25,000* 0.7	Global Implementation	+/- 20% on crew cost annually $11K, $71K, $132K 30%,50%, 70% fleets
Airport					

Figure 75: Summary of costs (investments) by stakeholders

Year	Low	Mid	High	Readiness (% of all flights)
2020	$82M	$890M	$2.3B	0
2030	*$9B*	*$12B*	*$14B*	3
2040	*$19B*	*$23B*	*$28B*	3
2050	*$56B*	*$70B*	*$83B*	15

Figure 76: Temporal distributions of costs (investments) for airlines

Year	Low	Mid	High	Readiness (% of all flights)
2020	$0	$0	$0	0
2030	*$31M*	*$72M*	*$141M*	3
2040	*$0*	*$0*	*$0*	3
2050	*$126M*	*$288M*	*$564M*	15

Figure 77: Temporal distributions of costs (investments) for ANSPs

2.12 **RoT 63 Airline Fuel Management System** *Supporting Information & Summary of Analyses and Results*.

2.12.1 ***General description of approach***: Sourced from IATA's fuel efficiency consultancy services – between 2004 and 2017 the program enabled airlines to identify more than 15 million tons of CO_2 in annual emissions reductions. The program was used by over 100 different airlines of various sizes operating in all regions. Various software solutions were used by different airlines with the above figures representing estimated averages. In this analysis, followings are not included. The cost of training or staff costs to manage these programs. The costs of individual measures that would require additional investment are not considered within the scope – for example, installation of lighter weight onboard equipment, pilot training for new procedures or other additional measures

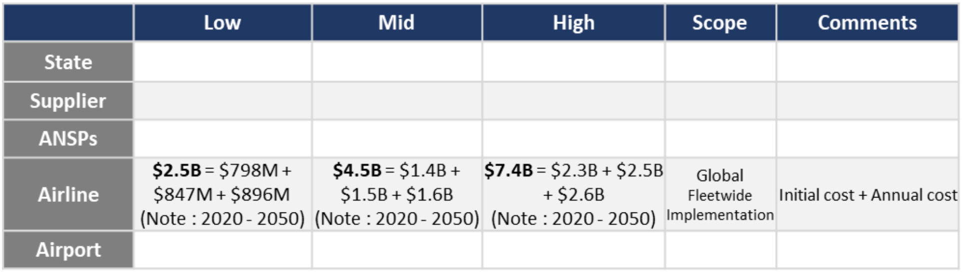
2.12.2 ***Basis for estimates***:

a) Initial cost for introduction of the system: Set-up fees is typically $ 50,000 to 100,000. Typical consulting services of establishing a fuel efficiency program where none existed, ranges between USD240,000 and USD 320,000.

- Low: $94M = ($50K + $240K) * 1,300 airlines * 0.25
- Mid: $115M = ($75K + $280K) * 1,300 airlines *0.25
- High: $136M = ($100K + $320K) * 1,300 airlines *0.25

b) Annual cost of the system: Annual software fee paid by airline is dependent on fleet size: 25-50 aircraft: USD75,000, 50-100 aircraft: USD 135,000 and 150-250: > USD 225,000

- Low: $97M = $75K * 1,300 airlines
- Mid: $175M = $135K * 1,300 airlines
- High: $292M = $225K * 1,300 airlines



	Low	Mid	High	Scope	Comments
State					
Supplier					
ANSPs					
Airline	**$2.5B** = $798M + $847M + $896M (Note : 2020 - 2050)	**$4.5B** = $1.4B + $1.5B + $1.6B (Note : 2020 - 2050)	**$7.4B** = $2.3B + $2.5B + $2.6B (Note : 2020 - 2050)	Global Fleetwide Implementation	Initial cost + Annual cost
Airport					

Figure 78: Summary of costs (investments) by stakeholders

Year	Low	Mid	High	Readiness (% of all flights)
2020	***$0***	***$0***	***$0***	75
2030	***$798M*** *= $290K * 1.3K * 0.05 + $75K *10* 1.3K *0.8*	***$1.4B*** *= $355K * 1.3K * 0.05 + $135K *10* 1.3K *0.8*	***$2.3B*** *= $420K * 1.3K * 0.05 + $225K *10* 1.3K *0.8*	80
2040	***$68M*** *= $290K * 1.3K * 0.05 + $75K *10* 1.3K *0.05*	***$111M*** *= $355K * 1.3K * 0.05 + $135K *10* 1.3K *0.05*	***$174M*** *= $420K * 1.3K * 0.05 + $225K *10* 1.3K *0.05*	85
2050	***$68M*** *= $290K * 1.3K * 0.05 + $75K *10* 1.3K *0.05*	***$111M*** *= $355K * 1.3K * 0.05 + $135K *10* 1.3K *0.05*	***$174M*** *= $420K * 1.3K * 0.05 + $225K *10* 1.3K *0.05*	90

Figure 79: Temporal distributions of costs (investments) for airlines

2.13 RoT 88: Optimized Runway Delivery Support tool and Reduced Pair-Wise Weather Dependent Separation between Arrivals *Supporting Information & Summary of Analyses and Results*.

2.13.1 ***General description of approach***: Optimized Runway Delivery Support tool and Reduced Pair-Wise Weather Dependent Separation between Arrivals has for goal to reduce delays in airports with the increase of flights. The cost of the project is going to be incremental with the deployment as well as the cost for ATC training.

2.13.2 ***Basis for estimates***:

a) Project cost: The European SESAR project PJ.02 that covers Optimized Runway Delivery Support tool and Reduced Pair-Wise Weather Dependent Separation between Arrivals was used in a set of airports (Paris CDG, Leipzig-Halle, London Heathrow, and Vienna) for the cost of $43.5M[43]. These airports represent 5% of passengers worldwide ($870M worldwide cost by extrapolation).

b) Training of air traffic controllers: The total number of ATC operators was estimated to be 70,000 globally (based on 14,000 ATC operators in the US scaled based on global operations in 2019). Training would only be for Approach ATCOs so maybe around ~30% of total ATCOs. Approach ATCOs is estimated to be 20,000. The average ATC salary is $120,000/year and the average certification takes 2 to 4 years. The certification would be a variable cost that increases with the deployment of the program. In this case, a complete certification of 2 to 4 years will not be needed for ATC operators (they already went through this certification process). The assumption is that ATC operators will be in training for 1 month (low estimate) to 6 months (high estimate).

---

[43] SESAR, "SEPARATION DELIVERY TOOL INCREASES CAPACITY IN THE ARRIVAL STREAM", available at: https://www.sesarju.eu/sesar-solutions/optimised-runway-delivery-final-approach

	Low	Mid	High	Scope	Comments
State					
Supplier					
ANSPs	**$896M** = _$696M + $10k * 20,000_	**$1.5B** = _$870M + $30k * 20,000_	**$2.2B** = _$1.0B + $60k * 20,000_	Global Implementation	Project cost +/-20% + ATC training
Airline					
Airport					

Figure 80: Summary of costs (investments) by stakeholders

Year	Low	Mid	High	Readiness (% of all flights)
2020	$0	$0	$0	0
2030	_$224M_	_$375M_	_$550M_	25
2040	_$224M_	_$375M_	_$550M_	50
2050	_$448M_	_$750M_	_$1.1B_	100

Figure 81: Temporal distributions of costs (investments) for ANSPs

2.14 **RoT 91: Geometric Altimetry and RVSM Phase 2** *Supporting Information & Summary of Analyses and Results*.

2.14.1 ***General description of approach:*** The RVSM Phase 2 is based on the reduction of wake and radar separation minima to 500 ft. It will let aircraft fly at their optimum flight level and therefore reduce the CO_2 emissions. An aircraft must be approved to fly at RVSM which means fleets will need to be updated. Also, crew and ATC training will be necessary.

2.14.2 ***Basis for estimates***:

a) Aircraft fleet upgrade: RVSM requirements include 2 Independent Altitude Measuring Systems, Secondary Surveillance Radar Altitude Reporting Transponder, Altitude Alert System and Autopilot.

b) Crew Training: There are 333k active pilots in the aviation industry (2019). The average salary for an airline pilot is $140,000/year[44]. It is expected that pilots would need 1 month (low) to 3 months (high) training for RVSM.

c) Training of air traffic controllers***:*** The total number of ATC operators was estimated to be 70,000 globally (based on 14,000 ATC operators in the US scaled based on global operations in 2019). The average ATC salary is $120,000/year and the average certification takes 2 to 4 years. The

---

[44] Salary.com, "Airline Pilot Salary in the United States?", 27 Aug. 2021, available at: https://www.salary.com/research/salary/alternate/airline-pilot-salary

certification would be a variable cost that increases with the deployment of the program. In this case, a complete certification of 2 to 4 years will not be needed for ATC operators (they already went through this certification process). The assumption is that ATC operators will be in training for 1 month (low estimate) to 3 months (high estimate).

	Low	Mid	High	Scope	Comments
State					
Supplier					
ANSPs	**$700M** = _$10,000* 70,000_	**$1.4B** = _$20,000* 70,000_	**$2.1B** = _$30,000* 70,000_	Global Implementation	1,2,3 months certification
Airline	**$3.9B** = _$11.6k * 333k_	**$7.8B** = _$23.3k * 333k_	**$11.7B** = _$35k * 333k_	Global Implementation	Pilot training of 1,2 or 3 months
Airport					

Figure 82: Summary of costs (investments) by stakeholders

Year	Low	Mid	High	Readiness (% of all flights)
2020	_$0_	_$0_	_$0_	0
2030	_$0_	_$0_	_$0_	0
2040	_$140M_	_$280B_	_$420M_	20
2050	_$70M_	_$140M_	_$210M_	30

Figure 83: Temporal distributions of costs (investments) for ANSPs

Year	Low	Mid	High	Readiness (% of all flights)
2020	_$0_	_$0_	_$0_	0
2030	_$0_	_$0_	_$0_	0
2040	_$773M_	_$1.6B_	_$2.3B_	20
2050	_$386M_	_$780M_	_$1.2B_	30

Figure 84: Temporal distributions of costs (investments) for airlines

2.15 **RoT 92: Global Air Management** Supporting Information & Summary of Analyses and Results.

2.15.1 ***General description of approach***: Global Air Management is expected to be implemented by Airports through ATM capabilities infrastructure upgrades (assumed as variable costs function of rate of implementation) and incremental training of controllers (assumed as variable costs function of rate of implementation).

2.15.2 ***Basis for estimates***:

a) Global Air Management: Global Air Management was implemented in Paris CDG and Orly, London Heathrow and Gatwick, and Zurich (trial) for $6.8M[45]. These 5 airports represent 5% of global traffic in 2019 (Extrapolation on Global Passenger Counts in 2019). Worldwide cost is estimated to be $136M. The program hasn't been implemented worldwide so it was estimated as +/- 20% for the low and high estimates.

b) Training of air traffic controllers: There are 70,000 ATC operators globally (based on 14,000 ATC operators in the US scaled based on global operations in 2019). The average ATC salary is $120,000/year◊ and the average certification takes 1 to 3 years. The certification would be a variable cost that increases with the deployment of the program. This program was assumed to take less training from ATC operators compared to RoT15. The length of training was estimated from 1 month to 3 months.

	Low	Mid	High	Scope	Comments
State					
Supplier					
ANSPs	**$809M** *= $108M* *+ $10,000** *70,000*	**$1.5B** *= $136M* *+ $20,000** *70,000*	**$2.3B** *= $163M* *+ $30,000** *70,000*	Global Implementation	Average program cost (+/- 20%) and 1,2,3 months certification
Airline					
Airport					

Figure 85: Summary of costs (investments) by stakeholders

Year	Low	Mid	High	Readiness (% of all flights)
2020	0	0	0	0
2030	*$202M*	*$375M*	*$575M*	25
2040	*$202M*	*$375M*	*$575M*	50
2050	*$404M*	*$750M*	*$1.15B*	100

Figure 86: Temporal distributions of costs (investments) for ANSPs

2.16 **RoT 1: Electrical Tug Detachable Aircraft Towing Equipment** *Supporting Information & Summary of Analyses and Results.*

2.16.1 ***General description of approach***: This measure would consist of introducing additional tugs (electrical tugs is assumed). Those would cover additional demand which will come from longer convey time (pushback + taxi) and would result in a cost to airlines (or airport operators support services, depending on how towing services are organized at airports). This cost was modelled as variable cost

---

[45] SESAR, "CROSS BORDER SESAR TRIALS FOR ENHANCED ARRIVAL MANAGEMENT", available at: https://www.sesarju.eu/projects/xstream

subject to deployment. The transition to electrical tugs is likely to require additional infrastructure changes at airports (e.g. electrical grids and charging stations) also subject to deployment schedule and assumptions.

2.16.2 *Basis for estimates*:

a) Electrical Tug Price: A heavy-duty pushback tug, "Super Tug", costs $1.4M[46] and a charging station $140k[47]. Electrical tugs costs 30% to 35% more than regular tugs[48] . An electrical "Super Tug" is estimated to cost $1.8M. The cost of the tugs can be approximated to +/- 20% for the low and high estimates.

b) Number of additional Tugs: Delta airlines owns 6 tugs at JFK airport[49] for 60 to 70 flights per day (a tug can manage 10% of daily flights). The 20 busiest airports (2017 data) account for 15,000 take-offs per day[50] and 35% of passenger traffic (4300 tugs worldwide, Extrapolation on Global Passenger Counts). For simplicity, assuming that the duration of pushback is 5minutes and subsequent taxi time is 15 minutes, convey time for each flight will be 4 times. Thus, 3 times of tugs would be required to satisfy the additional demand. Almost 13,000 additional tugs worldwide. Existing tugs would be replaced to electrical tug naturally at the end of the product life.

	Low	Mid	High	Scope	Comments
State					
Supplier	Expected to support airline capabilities but difficult to price out/isolate.				
ANSPs					
Airline	**$18.2B**= 3K * $1.4M	**$25.1B** = 13K * $1.8M + ($1.8M-$1.4M) * 4300	**$32.0B** = 13K * $2.2M + ($2.2M-$1.4M) * 4300	Global Implementation	Electric SuperTug Price +/- 20%
Airport	**$2.4B**= $140k * (4300 + 13K)	**$2.4B**= $140k * (4300 + 13K)	**$2.4B**= $140k * (4300 + 13K)	Global Implementation	$140k charging stations

Figure 87: Summary of costs (investments) by stakeholders

Year	Low	Mid	High	Readiness (% of all flights)
2020	$0	$0	$0	0
2030	$1.8B	$2.5B	$3.2B	10
2040	$3.6B	$5.0B	$6.4B	30
2050	$9.1B	$12.5B	$16.0B	80

Figure 88: Temporal distributions of costs (investments) for ANSPs

---

[46] Aviation Pros, "Delta's Other Fleet: The Science Behind Ground Equipment", Mar. 17, 2016, available at: https://www.aviationpros.com/gse/article/12177348/deltas-other-fleet-the-science-behind-ground-equipment

[47] Property Manager Inside, "How Much Do Commercial DC Fast Chargers Cost?", Jun. 1, 2021, available at: https://www.propertymanagerinsider.com/how-much-do-commercial-dc-fast-chargers-cost-2/

[48] Eagle Tugs, "WHY AN ELECTRIC AIRCRAFT TUG MAY COST YOU LESS OVER TIME", available at: https://eagletugs.com/electric-aircraft-tug-cost

[49] ABC7NY, "Behind the scenes at JFK: Super tugs in action", Dec. 22, 2017, available at: https://abc7ny.com/super-tugs-in-action-behind-the-scenes-at-jfk/2540197/

[50] ACI, "World's 20 busiest airports", 2019, available at: https://aci.aero/wp-content/uploads/2019/03/2486_Top-20-Busiest-Airport_passenger_v3_web.pdf

Year	Low	Mid	High	Readiness (% of all flights)
2020	$0	$0	$0	0
2030	*$240M*	*$240M*	*$240M*	10
2040	*480M*	*$480M*	*$480M*	30
2050	*$1.2B*	*$1.2B*	*$1.2B*	80

Figure 89: Temporal distributions of costs (investments) for Airports

2.17 RoT 9-ground: APU Shut Down *Supporting Information & Summary of Analyses and Results*.

2.17.1 ***General description of approach***: The APU of the aircraft is mainly used to provide power when its engines are off. The APU can be replaced on the ground by two products are referred to as pre-conditioned air and 400 Hertz power.

2.17.2 ***Basis for estimates***:

a) Ground operations cost***:*** In Japan, 380 fixed GPUs have already been deployed at Mega-airports (9 international airports), and 180 mobile GPUs have been deployed at 49 airports including Mega-airport.

- Fixed GPU (Buried pipes underground in the apron): $ 2.2 million per spot: (running cost $0.14M per year),
- Mobile GPU (Vehicle type with power supply / air conditioning function): $0.7 million per unit (running cost $0.1M per year).

b) A replacement for 530 GPUs will be needed to cover Japan’s air transport volume finally. Assuming that the number of spots and the number of take-offs is in a proportional relationship, by 2050, 5000 GPUs will be required worldwide. (Only GPUs that contribute to international flights are calculated from the ratio of international flights to domestic flights). For simplicity, set the average cost of various types of GPUs at 1.5M USD and calculated the global cost to be 6.8B USD as of 2050.

c) Cost (Japan case): Fixed GPU (Buried pipes underground in the apron): 2.2 million USD/ one spot. Mobile GPU (Vehicle type with power supply / air conditioning function)0.7 million USD/ one mobile GPU unite. In Japan, there is no development of Fixed GPU (shares the top of the apron with a cable without burying the piping), although it has already been introduced overseas. Japan's Fixed GPU introduction rate at Passenger Boarding Bridge (PBB) spots is about 60%, and other mobile GPU rate is even lower. Calculation of deployment costs for the entire world: Assuming an average GPU cost of 1.5 million USD for simplicity. In Japan where all airports depart about 1.3 million times a year, the number of GPUs required is about 530. Japan (2019: 1.3M departures), the world (2019: 38M departures[51]) ⇒Japan accounts for 3.4% of the world total ⇒15,600 GPU necessary in the world (additional 14,040GPU).

	Low	Mid	High	Scope	Comments
State					
Supplier					
ANSPs					
Airline					
Airport	*$5.4B*	*$6.8B*	*$8.1B*	Global Implementation	+/- 20% of infrastructure cost

Figure 90: Summary of costs (investments) by stakeholders

Year	Low	Mid	High	Readiness (% of all flights)
2020	*$340M*	*$430M*	*$520M*	10
2030	*$680M*	*$860M*	*$1.0B*	30
2040	*$680M*	*$860M*	*$1.0B*	60
2050	*$1.4B*	*$1.7B*	*$2.1B*	100

Figure 91: Temporal distributions of costs (investments) for Airports

2.18 **RoT 10-Ground: Maintenance** *Supporting Information & Summary of Analyses and Results*.

2.18.1 ***General description of approach***: The dirt on compressor vanes of aircraft engines reduces the efficiency of the compressor and as a result they increase fuel burn. Water wash are effective counter measure for this matter, and they require airlines to invest on manhours of maintenance personnel associated with equipment's and fuel for engine run.

2.18.2 ***Basis for estimates***:

a) *Airlines Cost:* $3500 per engine 18 manhours per engine (work of 4man for 4hours). Unit cost: $180 (including personnel expenses, and equipment cost). Fuel cost: Few hundred $ $3500 per engine x 2 x 25,000 aircraft = $175 million. All engines are washed twice a year $175M*2 (High Case). All engines are washed once in every two years $175*1/2 (Low Case).

---

[51] ICAO Annual report 2019, https://www.icao.int/annual-report-2019/Documents/ARC_2019_Air%20Transport%20Statistics.pdf

	Low	Mid	High	Scope	Comments
State					
Supplier					
ANSPs					
Airline	**$ 1.3 B** = $262M + $437M + $ 612M (Note : 2020 - 2050)	**$ 2.6 B** = $525M + $875M + $ 1.2B (Note : 2020 - 2050)	**$ 5.1 B** = $1.0B + $1.7B + $2.4B (Note : 2020 - 2050)		
Airport					

Figure 92: Summary of costs (investments) by stakeholders

Year	Low	Mid	High	Readiness (% of all flights)
2020	0	0	0	30
2030	**$437M** = $87.5M * 0.5 * 10 yr.	**$875M** = $175M * 0.5 * 10 yr.	**$1.7B** = $350M * 0.5 * 10 yr.	50
2040	**$612M** = $87.5M * 0.7 * 10 yr.	**$1.2B** = $175M * 0.7 * 10 yr.	**$2.4B** = $350M * 0.7 * 10 yr.	70
2050	**$875M** = $87.5M * 1.0 * 10 yr.	**$1.7B** = $175M * 1.0 * 10 yr.	**$3.5B** = $350M * 1.0 * 10 yr.	100

Figure 93: Temporal distributions of costs (investments) for airlines

2.19 Summary of results across operational measures

2.19.1 **Figure** 94 shows the costs and investments associated with operations measures considered in the LTAG-TG integrated scenarios.

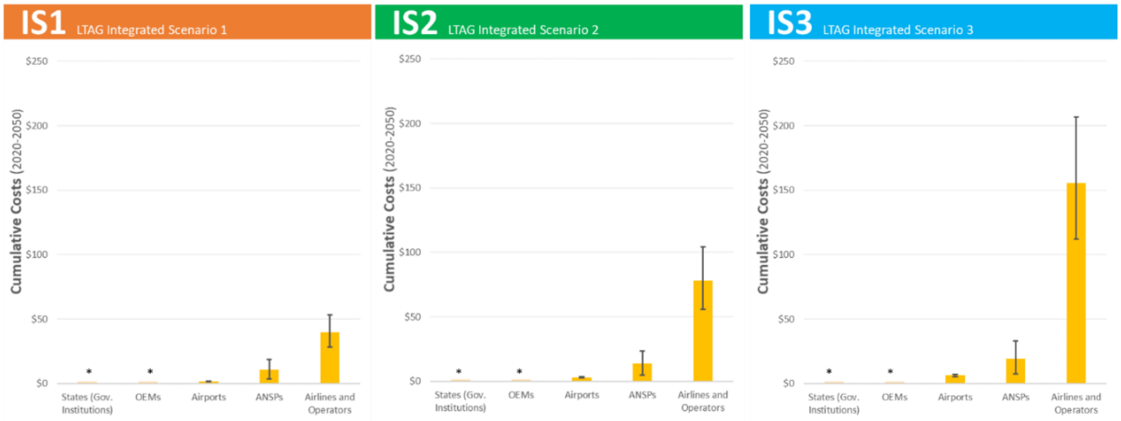


Figure 94: Costs and investments associated with operations measures

3. FUEL COSTS (SAVINGS) FROM OPERATIONS IMPROVEMENTS

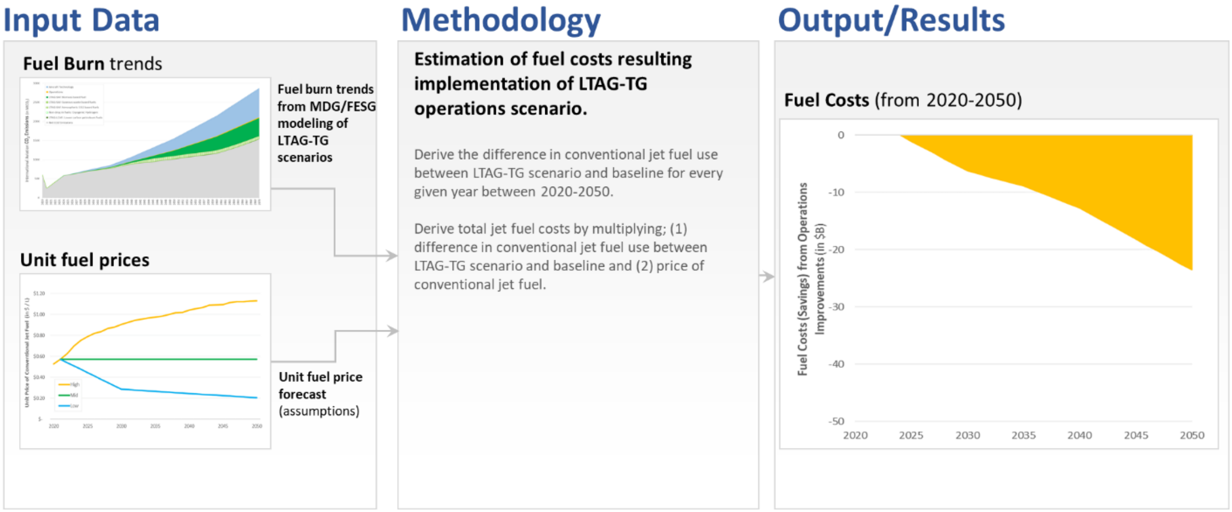
3.1 The CEahg developed a methodology for estimating fuel costs (i.e. savings) resulting from operational improvements specific to each LTAG-TG Scenarios. **Figure** 95 shows the high-level modelling approach for fuel costs (savings) related to operational measures.

3.2 ***Description of Cost Element:*** Fuel costs (i.e. savings) resulting from the operations and infrastructure improvements associated with a given LTAG-TG Integrated (Tech) Scenario. Applicable to Conventional Jet Fuel use.

3.3 ***Input:*** (1) Conventional jet fuel burn for each LTAG-TG scenario from 2020-2070. Source: MDG Trends (LTAG) output. (2) Forecast of price of conventional jet fuel. Source: IEA (TBC)

3.4 ***Methodology:*** Derive the difference in conventional jet fuel use between LTAG-TG scenario and baseline for every given year between 2020-2050. Derive total jet fuel costs by multiplying; (1) difference in conventional jet fuel use between LTAG-TG scenario and baseline and (2) price of conventional jet fuel.

3.5 ***Output:*** The methodology yields Fuel cost resulting from the operations of aircraft types exhibiting the technology improvement associated with a given LTAG-TG Integrated (Tech) Scenario (in billion dollars). Temporal distribution of fuel costs (expected based on time series of conventional jet fuel burn from MDG Trends+ and conventional jet fuel price projections.



Estimation of fuel costs resulting implementation of LTAG-TG operations scenario.

Derive the difference in conventional jet fuel use between LTAG-TG scenario and baseline for every given year between 2020-2050.

Derive total jet fuel costs by multiplying; (1) difference in conventional jet fuel use between LTAG-TG scenario and baseline and (2) price of conventional jet fuel.

Figure 95: High-level modelling approach for fuel costs (savings) related to operational measures.

3.6 Improvements in operational efficiency as captured in O1, O2 and O3 scenarios (see LTAG-TG Operations section for details) would result in fuel savings. Figure 96 shows operators' fuel costs (savings) from operations improvements across scenarios. Under an IS1 scenario, operations improvements could reduce operators fuel costs by ≈ $210 billion from 2020-2050. This would increase to ≈ $300 and $490 billion from 2020-2050 under IS2 and IS3 respectively.

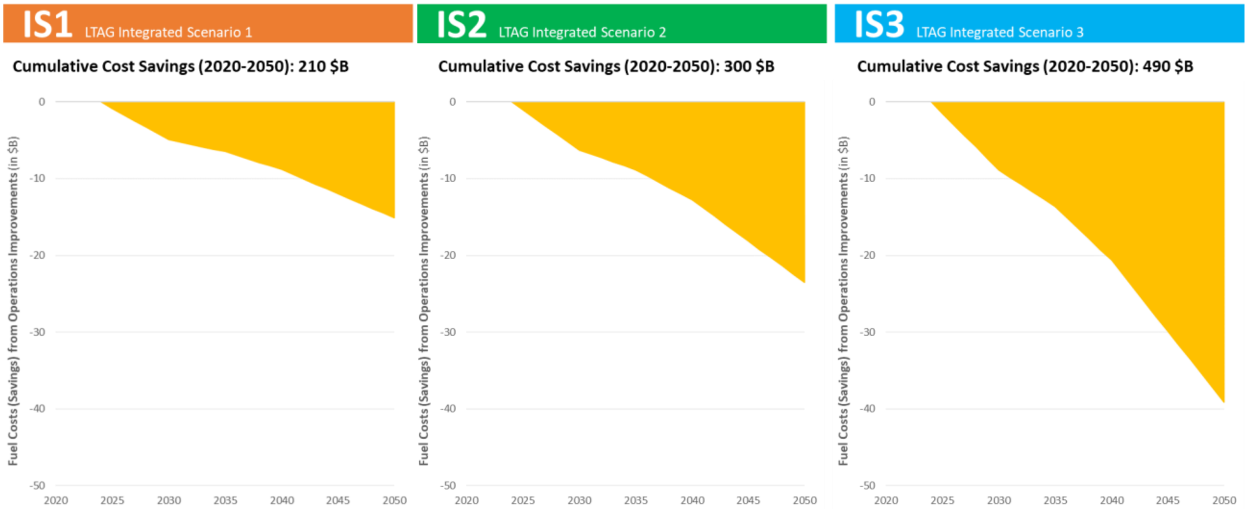


Figure 96: Operators' Fuel Costs (Savings) from Operations Improvements

4. CONSIDERATIONS ON REGIONAL DISTRIBUTIONS OF OPERATIONS RELATED COSTS AND INVESTMENTS

4.1 The LTAG-CEahg analysis of costs and investments focused on (1) the development and implementation of operational measures, supported by governments through research and development support and (2) the fuel burn reductions from the implementation of operational measures.

4.2 Costs (savings) resulting from operational improvements

4.2.1 The potential benefits from operational measures were estimated at the route group level. The LTAG-Operations subgroup considered 124 route groups while developing the operations improvements scenarios O1, O2 and O3. These operations measure level benefits were implemented into the operations of the global international fleet through 2070. Figure 97 shows the regional distribution of costs (savings) resulting from operations improvements.

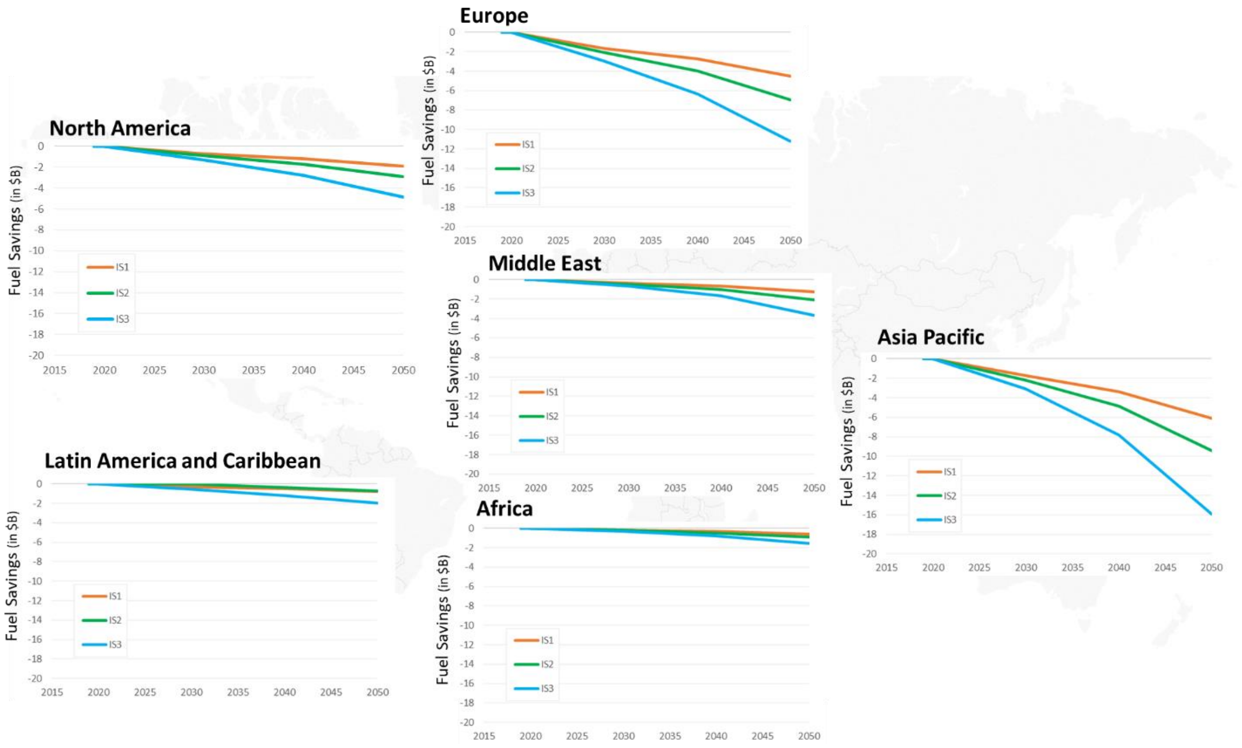


Figure 97: Regional distribution of fuel costs (savings) resulting from operations improvements.

— — — — — — — —

ATTACHMENT C TO APPENDIX M1

COST (INVESTMENT) ESTIMATIONS: FUELS

Note. - This Attachment provides a summary of the approaches and methodologies considered by the SDSG Cost Estimation ad hoc group towards the estimation of costs (investments) associated with fuels scenarios.

1. OVERVIEW OF THE SCOPE OF COST (INVESTMENT) ESTIMATIONS FOR (ALTERNATIVE) FUELS

1.1 Based on the type of cost modelling approach (described in section 3), the expected definition of integrated scenarios, the CEahg has identified several costs elements associated with fuels that will be either assessed quantitatively or described qualitatively (see Figure 98):

- ***Research and Development (R&D)*** support from States (i.e. governments) towards the development of new aviation fuels;
- ***Total capital investment (TCI)*** from fuel suppliers towards the production of LTAG-SAF, LTAG lower carbon aviation fuels (LTAG-LCAF) and Hydrogen (H2) portions of the energy (fuel) use under a given LTAG-TG Integrated Scenario (ISx);
- ***Total feedstock costs*** for the LTAG-SAF and Hydrogen portions of the energy (fuel) use under a given LTAG-TG Integrated Scenario (ISx);
- ***Total infrastructure cost*** of developing Hydrogen distribution network from production facility to airport (aircraft) under LTAG-TG Integrated Scenario (i.e. IS3);
- ***Minimum Selling Price (MSP) of fuels vs. conventional jet fuel:*** Fuel costs resulting from using LTAG-SAF, LTAG-LCAF or Hydrogen vs. conventional jet fuel; and
- **Airline operating costs** resulting from longer aircraft turnaround times due to longer refuelling process.

Note. — Asset Value Loss: The LTAG-TG CEahg also discussed that the transition from conventional jet fuel production to sustainable aviation fuels (SAF) and non-drop in fuels may have some impacts on the value of conventional jet fuel production assets. However, it was deemed difficult to quantify such impacts. Furthermore, some LTAG-TG SAF scenarios assume some level of repurposing of existing jet fuel production facilities.

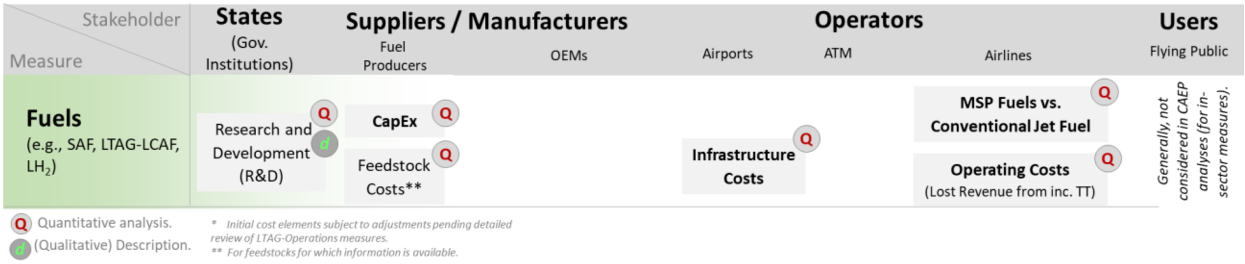


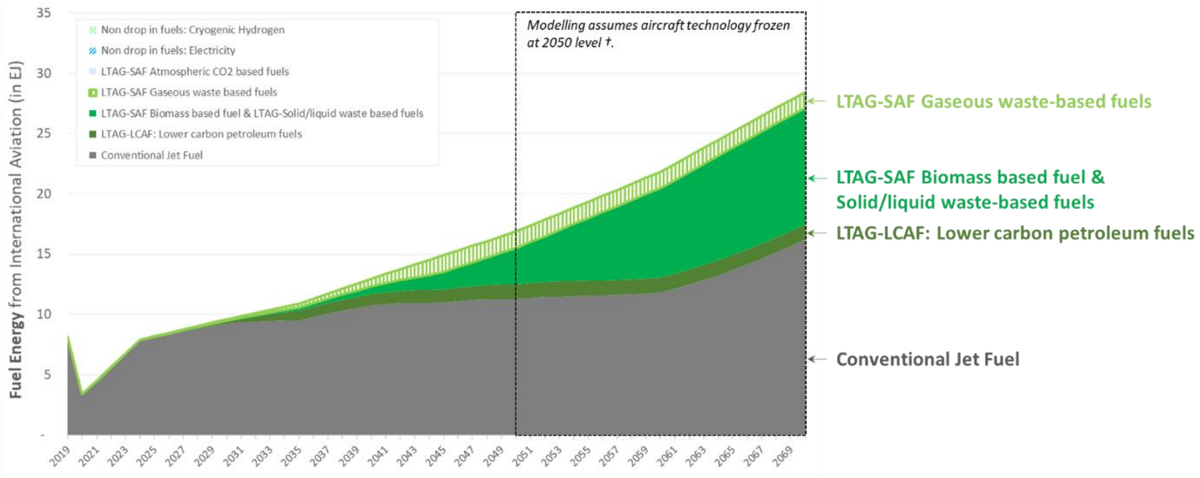
Figure 98: Fuels related cost (investment) elements considered by the LTAG-TG

Note. — The LTAG costs and investments analyses of fuels are complemented information and details presented in the LTAG Fuels Appendix M3.

2. BACKGROUND: FUEL ENERGY FROM INTERNATIONAL AVIATION BY FUEL TYPE

2.1 IS1 (LTAG Integrated Scenario 1 based on Fuel Scenario F1)

2.2 Fuels scenarios are also expected to result in a range of costs and investments from several stakeholders. The LTAG-TG CEahg used as input the fuels scenarios including volumes of fuels by fuel types as developed by the LTAG Fuels group and reflecting the demand for fuels given a traffic forecast and after technology and operations improvements. **Figure** 99 shows the fuel energy from international aviation by type of fuel for LTAG Integrated Scenario 1 based on Fuel Scenario F1.

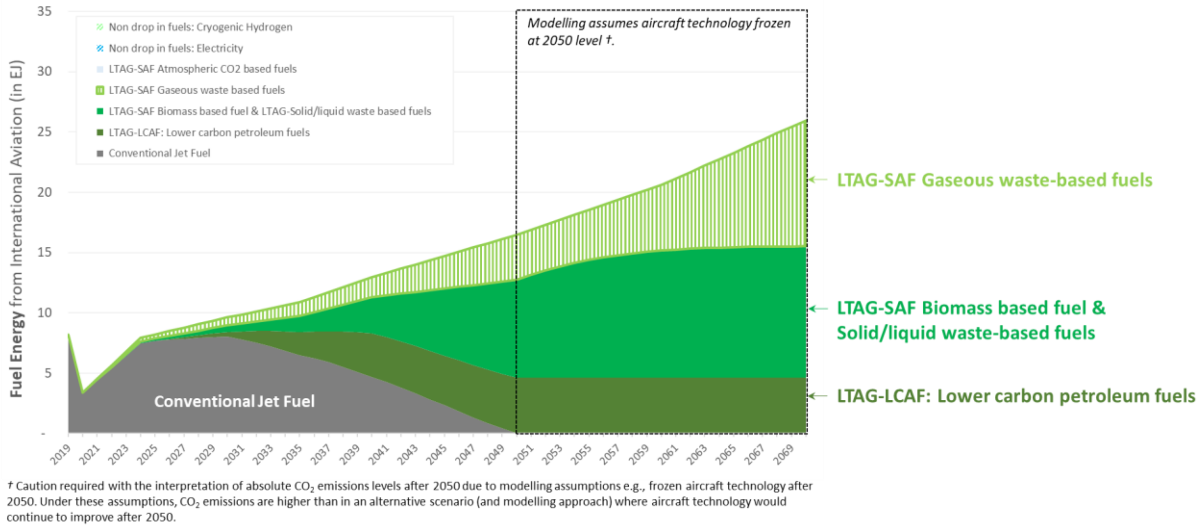


† Caution required with the interpretation of absolute CO_2 emissions levels after 2050 due to modelling assumptions e.g., frozen aircraft technology after 2050. Under these assumptions, CO_2 emissions are higher than in an alternative scenario (and modelling approach) where aircraft technology would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

Figure 99: LTAG Integrated Scenario 1 based on Fuel Scenario F1

2.3 IS2 (LTAG Integrated Scenario 2 based on Fuel Scenario F2)

2.3.1 **Figure** shows the fuel energy from international aviation by type of fuel for LTAG Integrated Scenario 2 based on Fuel Scenario F2.

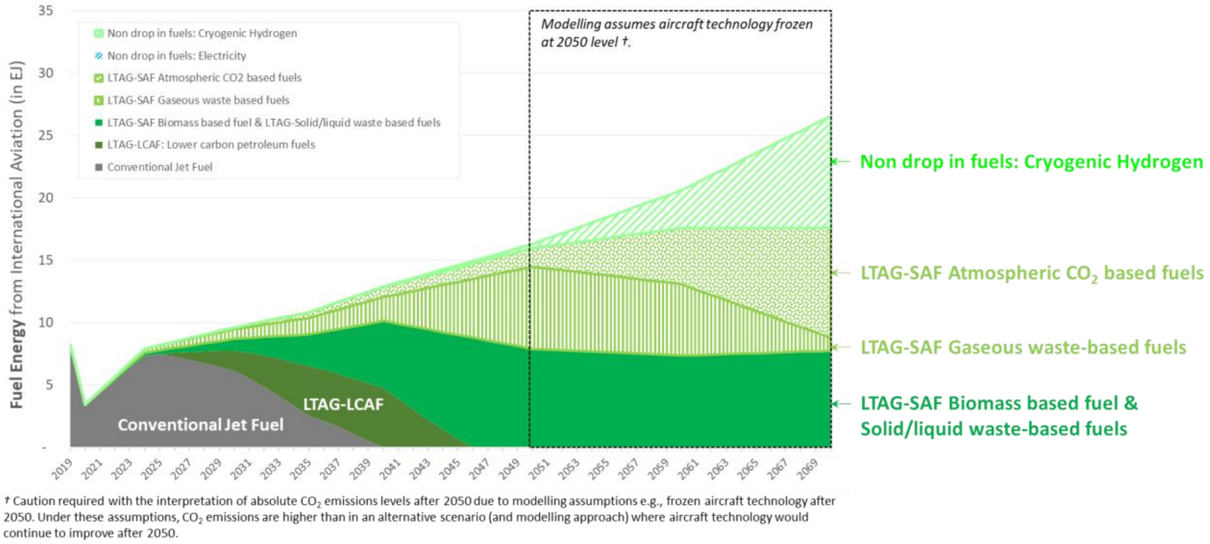


† Caution required with the interpretation of absolute CO_2 emissions levels after 2050 due to modelling assumptions e.g., frozen aircraft technology after 2050. Under these assumptions, CO_2 emissions are higher than in an alternative scenario (and modelling approach) where aircraft technology would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

Figure 100: LTAG Integrated Scenario 2 based on Fuel Scenario F2

2.4 IS3 (LTAG Integrated Scenario 3 based on Fuel Scenario F3)

2.4.1 Figure 101 shows the fuel energy from international aviation by type of fuel for LTAG Integrated Scenario 3 based on Fuel Scenario F3.



† 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 101: LTAG Integrated Scenario 3 based on Fuel Scenario F3

3. RESEARCH AND DEVELOPMENT (R&D)

3.1 The LTAG cost and investment analysis considered the potential Research and Development (R&D) from States (i.e. governments) to research institutions that help support the development of Fuels (e.g. LTAG-SAF, LTAG-LCAF, LH_2).

3.2 Historical information on past and current funding programs were gathered to provide a basis for the estimation of future R&D costs associated with the development of Fuels.

3.3 Sample R&D budgets include publicly available information from the European Union (EU) and the Federal Aviation Administration (FAA). Programs in additional global regions were included to provide more accurate cost modelling.

3.4 The EU Horizon 2020 (H2020) program included funding for the Jet Fuel Screening and Optimisation (JETSCREEN) project. This multi-year project focused on quantitative and qualitative assessments of alternative jet fuels. The JETSCREEN program lasted three years at a funding level of €7.5 million.

3.5 H2020 also investigated cryogenic hydrogen under ENABLEH2, Enabling Cryogenic Hydrogen Based CO_2 Free Air Transport. This program addressed key challenges for cryogenic hydrogen as well as investigated novel technologies. ENABLEH2 was a three-year program with €4 million in funding.

3.6 In the United States, the FAA supports aviation fuel research through two primary programs, the Aviation Sustainability Center (ASCENT) and the Continuous Lower Emissions, Energy and Noise (CLEEN) program. Additional programs at the Department of Energy (DOE) and Department of Agriculture (USDA) support aviation fuel R&D across the fuel development process from feedstock optimization to process scale-up and market integration.

4. CAPEX BY FUEL PRODUCERS

Sustainable Aviation Fuels (SAF)

4.1 ***Description of Cost Element:*** Total capital investment (TCI) for the SAF portion of the energy (fuel) use under a given LTAG-TG Integrated Scenario (ISx)

4.2 ***Input:*** (1) Total capital investment (TCI) for each technology and feedstock combination for nth plant and pioneer facilities. (2) Number of plant and pioneer facilities to produce quantity of SAF associated with an LTAG-TG Integrated Scenario (ISx).

4.3 ***Methodology:*** Total capital investment (TCI) derived by summing (across all technology and feedstocks), (1) Number of plant and pioneer facilities to produce quantity of SAF associated with an LTAG-TG Integrated Scenario (ISx) multiplied by (2) Total capital investment (TCI) for each technology and feedstock combination for nth plant and pioneer facilities.

4.4 ***Output:*** Total capital investment (TCI) for the SAF portion of the energy (fuel) use under a given LTAG-TG Integrated Scenario (ISx).

4.5 The CEahg leveraged the information on scenarios and costs (investments) developed as part of the "CAEP12 FTG Fuel Production Assessment (FPA)".

4.6 To facilitate the interpretation of scenario outcomes and provide context to the scenario results, a set of interpretative metrics for the different scenarios was calculated:

a) capital investment requirements per year out to 2035,

b) required number of new/retrofitted facilities per year,

c) financial support required out to 2035,

d) feedstock needs, and

e) analogical comparison to historical precedents.

4.7 CAEP estimated capital expenditure (CapEx) requirements towards the development of facilities (plants) that would produce fuels (e.g. sustainable aviation fuels, low carbon aviation fuels, hydrogen). Figure 102 shows the unit CapEx is expressed in $ billion required to develop an incremental production capability of 1 Mt Fuel in a given year. The figure shows the unit CapEx associated with LTAG-SAF biomass & solid/liquid waste-based fuels. For this category of fuel, the unit CapEx is expected to increase over time (despite learning curve effects, economics of scale) because this type of fuel includes a sub-portfolio of feedstock and pathways (e.g. HEFA, lignocellulosic) and a shift towards more expensive feedstock/pathways processes over time.

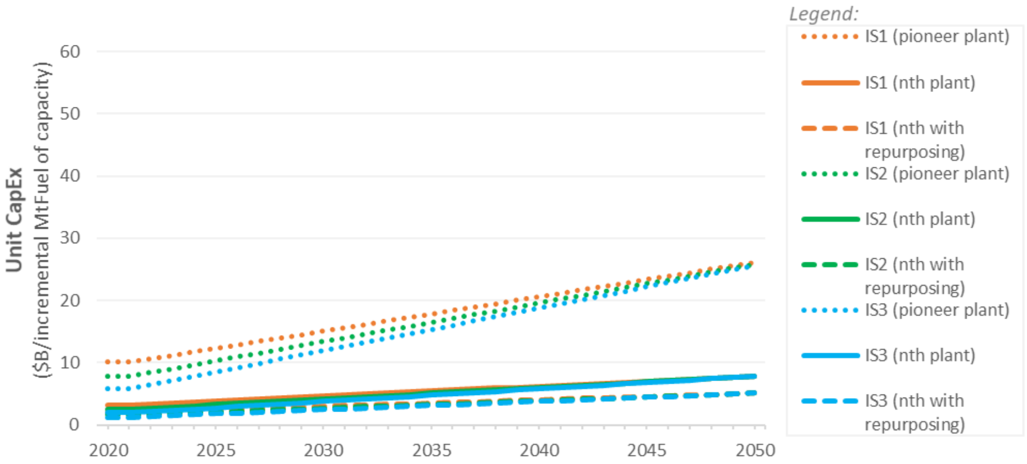


Figure 102: Fuels CapEx: Unit CapEx Assumptions for LTAG-SAF Biomass & solid/liquid waste-based fuels

4.8 Figure 103 shows the unit CapEx for LTAG-SAF gaseous waste-based fuels which is expected to decrease over time due to learning curve effects, economics of scale, etc.

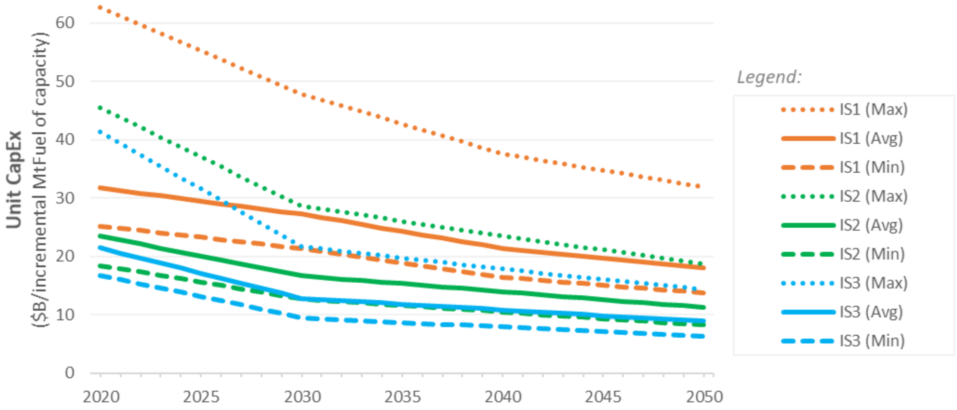


Figure 103: Fuels CapEx: Unit CapEx Assumptions for LTAG-SAF Gaseous waste-based fuels

4.9 Figure 104 shows the unit CapEx for LTAG-SAF atmospheric CO_2 based fuels which is expected to decrease over time due to learning curve effects, economics of scale, etc.

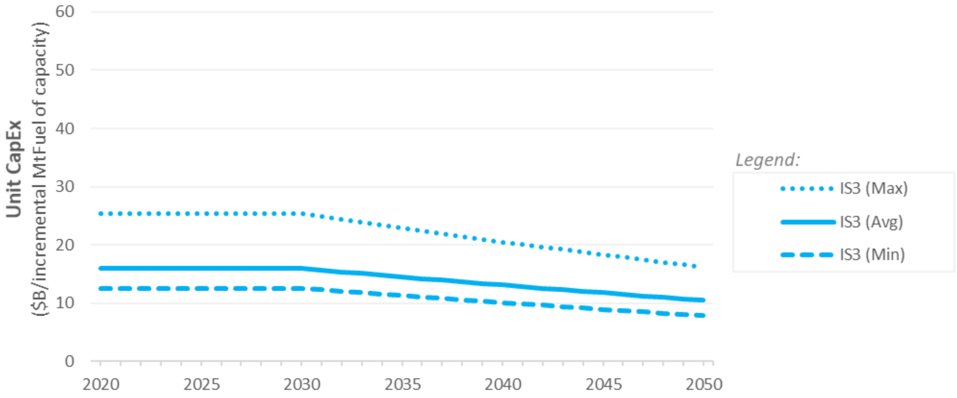


Figure 104: Fuels CapEx: Unit CapEx Assumptions for LTAG-SAF Atmospheric CO_2 based fuels

LTAG Low Carbon Aviation Fuels (LCAFs)

4.10 The LTAG-TG Fuels group estimated of upstream capital investments for LCAF required to implement lower carbon technologies towards the production of LCAF. Investments were expressed in $ / tCO_2 abated. Figure 105 shows the cost abatement associated with implementation of lower carbon technologies to LCAF production across IS1, IS2 and IS3 scenarios.

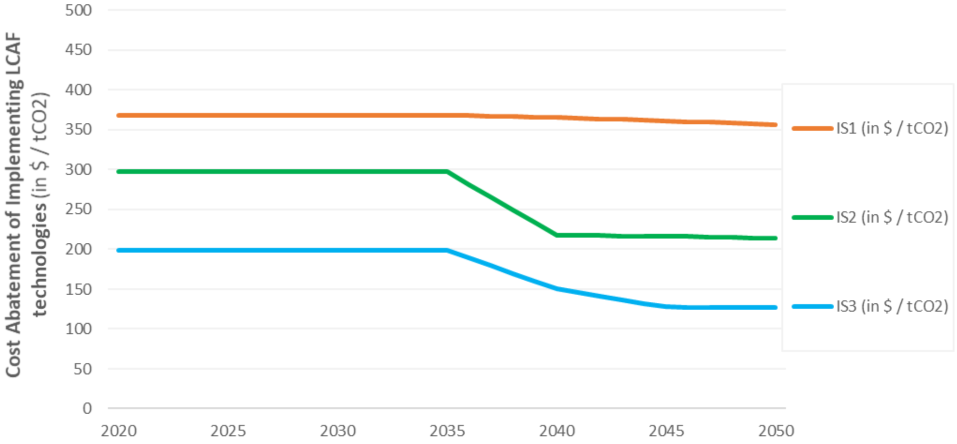


Figure 105: Cost abatement associated with implementation of lower carbon technologies to LCAF production

Hydrogen

4.11 The LTAG-TG Fuels group estimated of upstream capital investments for LH_2 fuel production infrastructure for notional/illustrative scenarios. These analyses were enhanced and updated with the relevant demand for hydrogen associated with the LTAG-TG integrated scenario (IS3). Figure 106 shows the unit CapEx assumptions for cryogenic hydrogen.

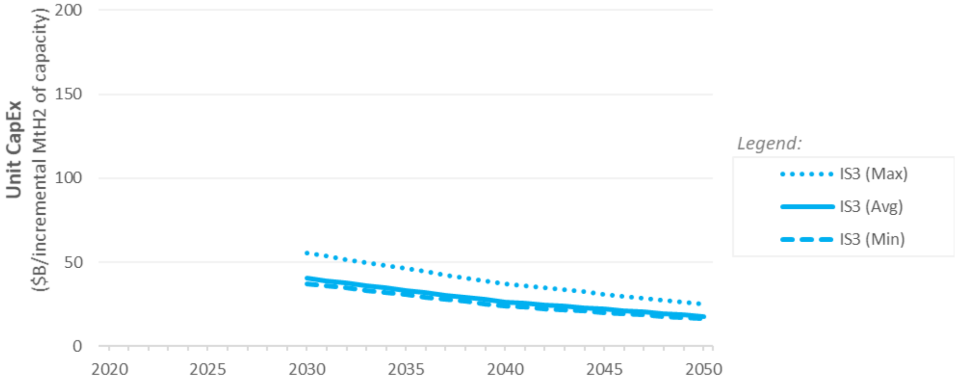


Figure 106: Fuels CapEx: Unit CapEx Assumptions for Non drop in fuels: Cryogenic Hydrogen

5. INFRASTRUCTURE COSTS

5.1 ***Description of Cost Element:*** Total infrastructure cost of developing H_2 distribution network from production facility to airport (aircraft) under LTAG-TG Integrated Scenario (i.e. IS3).

5.2 ***Input:*** Scenarios of potential fuelling system layout. Airport database (i.e. number of airports). Estimates of hydrogen uptake specific LTAG scenarios (i.e. actual H2 requirements associated with LTAG-TG IS3 scenario run by MDG/FESG).

5.3 ***Methodology:*** Bottom-up up build-up of infrastructure costs at given set of airports (dependent on H2 scenarios).

5.4 ***Output:*** Total Global Capital Cost ($ billion). Global Annualized Cost ($ billion per yr.). Geographical distribution of costs (investments).

5.5 Figure 107 shows a sample problem assessment of the total annualized cost of hydrogen refuelling system across a global set of airports for various scenarios of hydrogen powered aircraft with range capabilities (to be updated and harmonized with LTAG Technology scenarios for the final analysis).

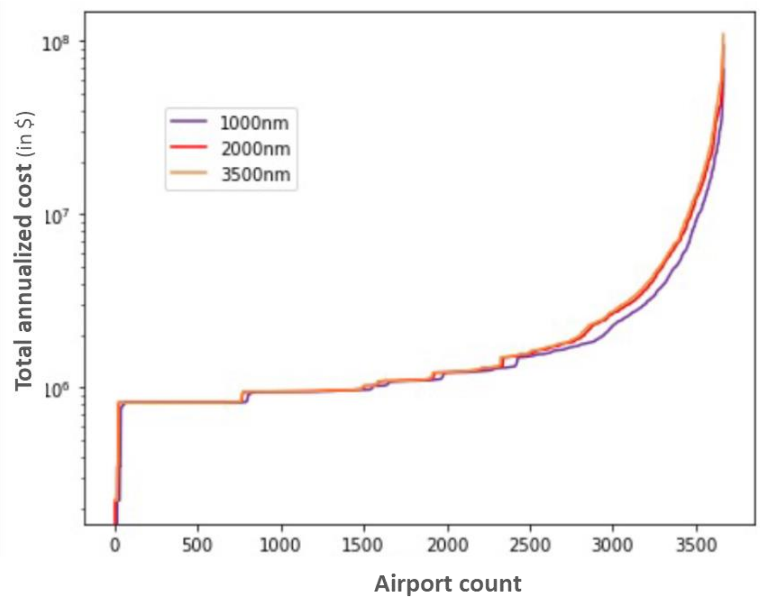


Figure 107: Total annualized cost of LH2 refuelling system across set of airports (global investment scenario)

6. MINIMUM SELLING PRICE VS. CONVENTIONAL JET FUEL

6.1 Using SAF vs. conventional jet fuel may result in additional costs in the event the Minimum Selling Price of SAF is higher than conventional jet fuel price.

6.2 ***Description of Cost Element:*** Fuel costs resulting from using SAF vs. conventional jet fuel, based on Minimum Selling Price of SAF vs. conventional jet fuel price.

6.3 ***Input:*** (1) Minimum selling price for each technology and feedstock combination weighted across portfolio of feedstock/pathways. High based on pioneer facilities, Mid based on nth facility and Low assuming reduced CapEx due to reproposing of production facilities. (2) Quantity of SAF for each technology and feedstock associated with an LTAG-TG Integrated Scenario (ISx). (3) Forecast of price of conventional jet fuel.

6.4 ***Methodology:*** (a) Total cost of using SAF derived by summing (across all technology and feedstocks), (1) Minimum selling price for each technology and feedstock combination for nth plant and pioneer facilities by (2) Quantity of SAF for each technology and feedstock associated with an LTAG-TG Integrated Scenario (ISx). Relative cost (SAF vs. conventional jet) derived by subtracting (a) with cost of using conventional jet fuel.

6.5 ***Output:*** Fuel costs resulting from using SAF vs. conventional jet fuel, based on Minimum Selling Price of SAF vs. conventional jet fuel price.

6.6 Figure 108 shows the minimum selling price of LTAG-SAF biomass & solid/liquid waste-based fuels across the LTAG integrated scenarios as well as associated ranges of uncertainty.

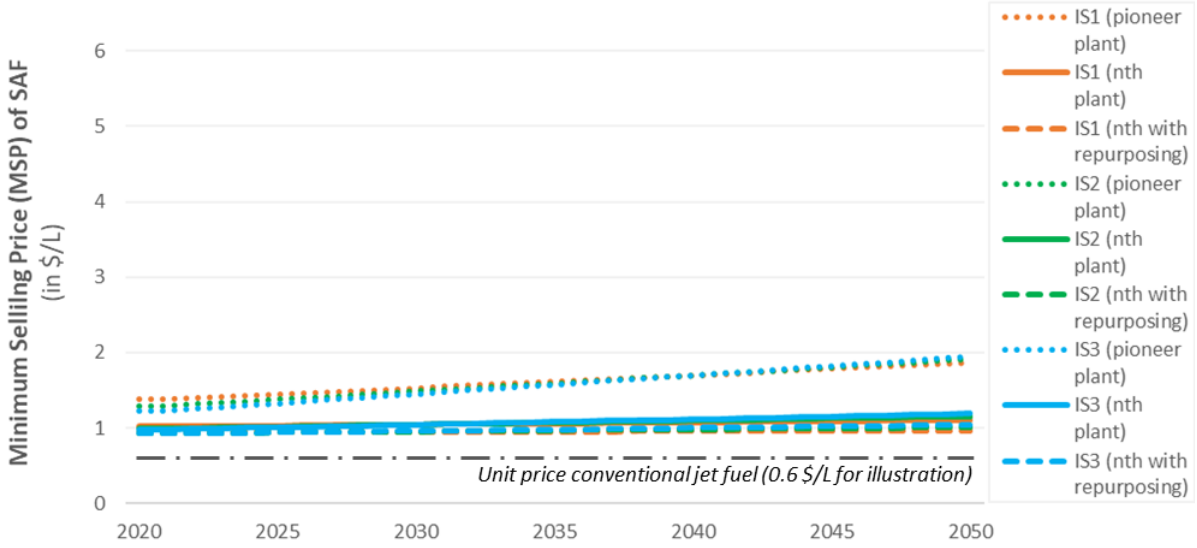


Figure 108: MSP Assumptions: LTAG-SAF biomass & solid/liquid waste-based fuels

6.7 Figure 109 shows the Minimum Selling Price from 2020 to 2050 for LTAG-SAF gaseous waste-based fuels. The MSP of the fuel is expected to decrease over time due to declining CapEx requirements, learning curve effects, economics of scale, etc.

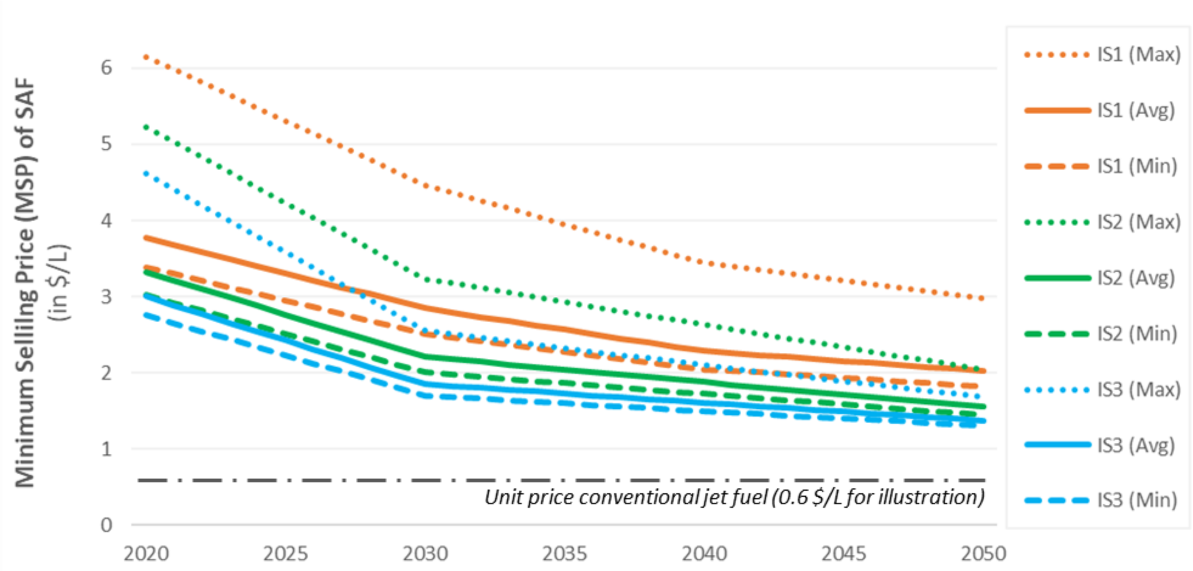


Figure 109: MSP Assumptions: LTAG-SAF Gaseous waste-based fuels

6.8 **Error! Reference source not found.**110 shows the Minimum Selling Price from 2020 to 2050 for LTAG-SAF atmospheric CO_2 based on fuels. The MSP of the fuel is expected to decrease over time due to declining CapEx requirements, learning curve effects, economics of scale, etc.

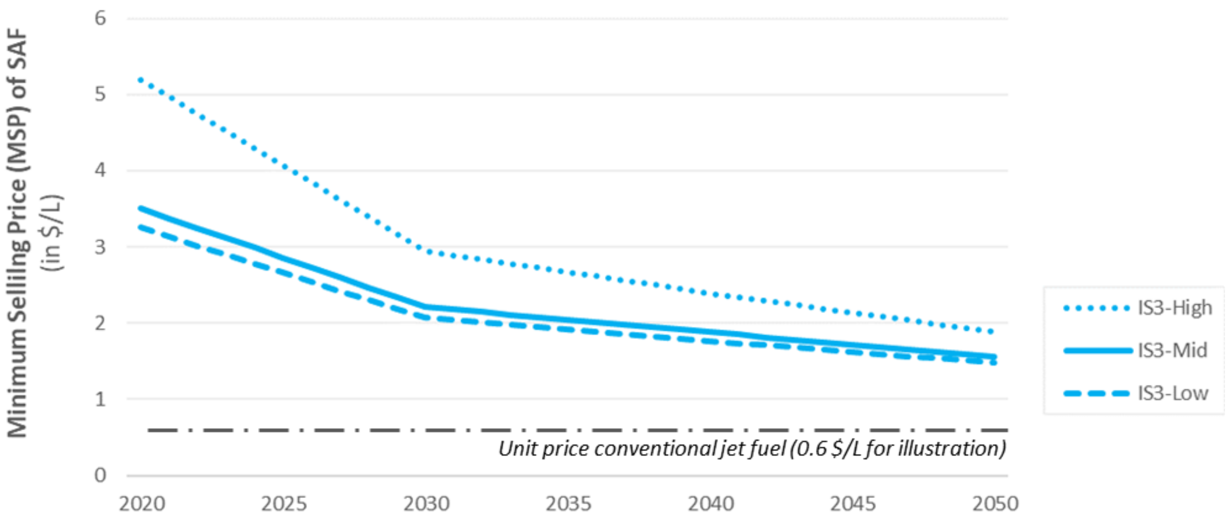


Figure 110: MSP Assumptions: LTAG-SAF Atmospheric CO_2 based fuels

LTAG Low Carbon Aviation Fuels (LCAF)

6.9 The LTAG-TG Fuels group estimated of upstream capital investments for LCAF required to implement lower carbon technologies towards the production of LCAF. The group assumed that the incremental investments into lower carbon technologies would be passed on to the fuel suppliers and operators in the form of an incremental unit cost. The group expressed the incremental costs in \$ / tCO_2 abated. Figure 111 shows the cost abatement associated with implementation of lower carbon technologies to LCAF production across IS1, IS2 and IS3 scenarios.

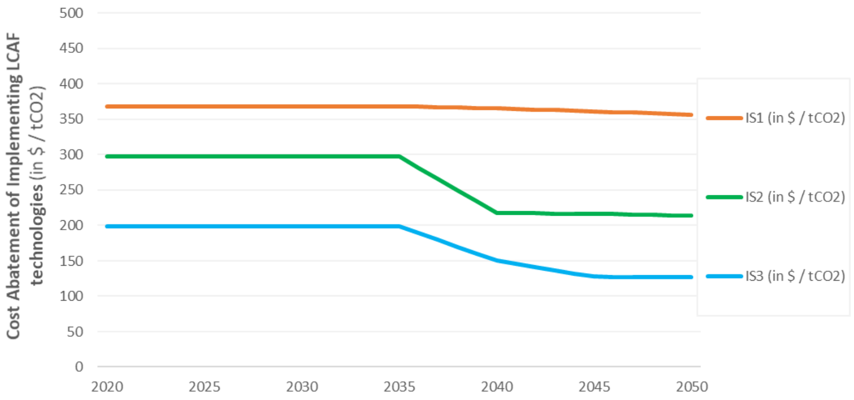


Figure 111: Cost abatement associated with implementation of lower carbon technologies to LCAF production

Hydrogen

6.10 ***Description of Cost Element:*** Fuel costs resulting from using H_2 vs. conventional jet fuel, based on Minimum Selling Price of H_2 vs. conventional jet fuel price.

6.11 ***Input:*** Unit costs include costs from electrolyzers, cost of electricity, O&M unit costs, and cost of liquefaction. Estimates of hydrogen uptake specific LTAG scenarios (i.e. actual H2 requirements associated with LTAG-TG IS3 scenario run by MDG/FESG).

6.12 ***Methodology:*** Technical Economic Assessment

6.13 ***Output:*** Minimum Selling Price of LH2.

6.14 Figure 112 shows the Minimum Selling Price (MSP) from 2020 to 2050 for cryogenic hydrogen. The MSP of the fuel is expected to decrease over time due to declining CapEx requirements, learning curve effects, economics of scale, etc.

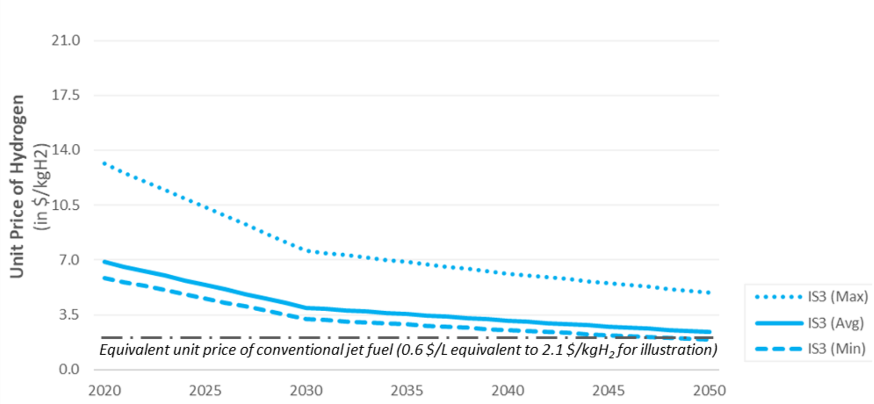


Figure 112: MSP Assumptions: Non drop in fuels: Cryogenic Hydrogen

7. OPERATING COSTS: LOST REVENUE FROM INCLUDING TURN AROUND TIME IMPACTS

7.1 Indirect costs (impacts of fuelling time on turnaround times and aircraft utilization) can be substantial if high transfer rates of LH_2 cannot be achieved, and safety requirements do not allow loading and boarding to commence during fuelling. With high transfer rates and pipeline- or tanker-truck-based fuelling at the gate, the effects on turnaround times for flights below 2,000 NM are found to be on the order of 1% (on average); they are less than 0.1% if parallel boarding/refuelling is allowed. For longer flights, parallel boarding and loading as well as achieving high transfer rates are essential to contain large impacts on turnaround times.

8. CONSIDERATIONS ON REGIONAL DISTRIBUTIONS OF FUELS RELATED COSTS AND INVESTMENTS

8.1 Given the nascent nature of the LTAG-SAF industry, it is difficult to predict specific regional level production and use (uptake) of LTAG-SAF. This section provides some considerations of some of the key drivers for potential regional distribution.

8.2 **Potential for fuels uptake across regions (demand driven)**

8.2.1 The potential for uptake of LTAG-SAF (and replacement of conventional jet fuel) is dependent on the demand (i.e. uplift) for jet fuel across regions. Figure 113 shows the regional distribution of demand for fuel uplift across regions (i.e. fuel use attributed to the departure airport of international flights aggregated by ICAO Statistical Region).

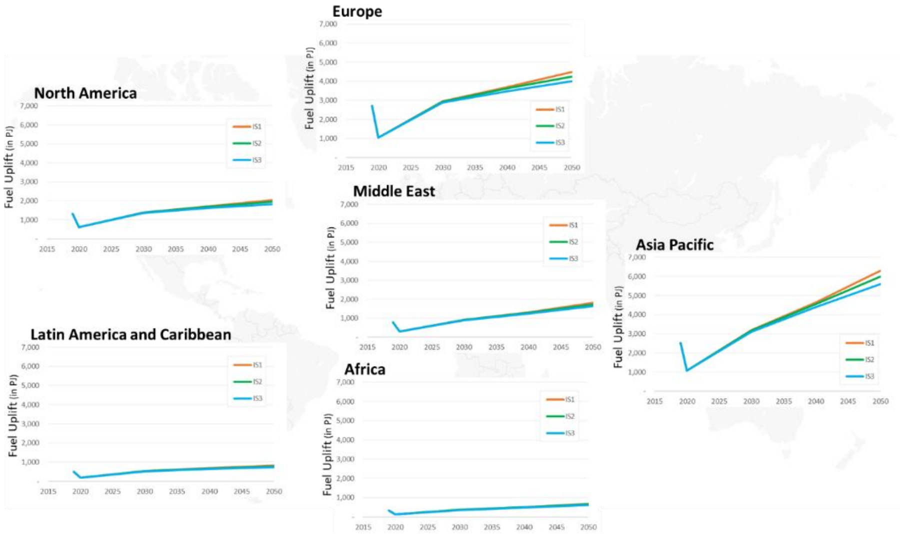


Figure 113: Regional distribution of demand for fuel across regions.

8.3 It should be noted that with accounting mechanisms such as book and claim, the location of the physical use of the fuel and the location of where the benefits (e.g. crediting of the benefits) of the fuels can be decoupled.

— — — — — — — —

ANNEX 1: LIST OF ACRONYMS

ACA	Advanced Concept Aircraft
ADAP	Aviation Data and Analysis Panel
ANSP	Air Navigation Service Provider
ASCENT	Aviation Sustainability Center
ATC	Air Traffic Control
ATCO	Air Traffic Control Operators
ATM	Air Traffic Management
ATW	Advanced Tube and Wing
CAEP	Committee on Aviation Environmental Protection
CapEx	Capital Expenditures
CDP	Carbon Disclosure Project
CEA	Cost Effectiveness Analysis
CEahg	Cost Estimation ad hoc group
CLEEN	Continuous Lower Emissions, Energy and Noise
CORAC	French Civil Aviation Research Council
DLR	Deutsches Zentrum für Luft (The German Aerospace Center)
DOE	Department of Energy
EIS	Entry Into Service
ENABLEH2	Enabling Cryogenic Hydrogen Based CO_2 Free Air Transport.
ERAM	En Route Automation Modernization
EU	European Union
FAA	Federal Aviation Administration (U.S.)
FESG	Forecast and Economic Analysis Support Group
FIR	Flight Information Region
FPA	Fuel Production Assessment
GANP	Global Air Navigation Plan
GDP	Gross Domestic Product
GPU	Ground Power Unit
H2020	EU Horizon 2020
HEFA	Hydro processed Esters and Fatty Acids
IATA	International Air Transport Association
IBC	Incremental Built Cost
ICAO	International Civil Aviation Organization
IS	Integrated Scenario
ITP	In-Trail Procedure
JAXA	Japan Aerospace Exploration Agency
JETSCREEN	Jet Fuel Screening and Optimization
LCAF	Low Carbon Aviation Fuels
MDG	Modelling and Databases Group
MSP	Minimum Selling Price
MTOM	Maximum Take-Off Mass

NASA	National Aeronautics and Space Administration
NRC	Non-Recurring Costs
O&M	Operations and Maintenance
OEM	Original Equipment Manufacturer
ONERA	National Office for Aerospace Studies and Research *(translated from French)*
PANS	Procedures for Air Navigation Services
PATR	Price After Technology Response
PBB	Passenger Boarding Bridge
R&D	Research & Development
RAE	Russian Academy of Engineering
RNP	Required navigation performance
RVSM	Reduced Vertical Separation Minima
SAF	Sustainable Aviation Fuels
SDSG	Sustainable Development Steering Group
STARS	Standard Terminal Automation Replacement System
TCI	Total capital investment
USDA	United States Department of Agriculture

— — — — — — — —

ANNEX 2: LIST OF UNITS

Mt	Million tonnes
B	Billion
$ (USD)	U.S. Dollars
kg	Kilograms
gal.	Gallons
M	Millions
€	Euros
K	Thousand

— — — — — — — —