

Technological and Operational Scenarios on Aircraft Fleet-Level towards ATAG and IATA 2050 Emission Targets

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In the face of global climate change various private and public stakeholders of the commercial aviation industry have proclaimed ambitious goals aimed at reducing the global fuel consumption and thus mitigating the future environmental impact of aviation by halving aviation's fleet-level emissions by 50 % compared to year 2005. Here, the potential of aircraft technologies, production ramp-ups and operational improvement options are assessed to quantify the global fleet-level emissions up to the year 2050. Based on the estimation of impact of next-generation aircraft types with market entries until 2020, fifteen fleet-level emission scenarios based on various technology, production and operational scenarios with their single contribution towards long-term emission goal, are the objectives of this paper. A numerical model of the global air transport fleet is employed to quantify the fleet-wide fuel demand and carbon-emissions reduction impact and conduct sensitivity analyses. New aircraft technologies together with up to radical ramp-up timelines might lower fleet-level fuel burn until year 2050 between -17 % to -27 %. Increasing aircraft productivity by increasing loadfactors, installed seats and increased aircraft utilisation further reduce fleet-level fuel burn until year 2050 by -7 % to -8 %. The application of retrofit solutions for in-fleet aircraft can reduce the fleet-level fuel burn until year 2050 by around -3 %. Halving regional RPK growth rates might lead to fleet-level fuel burn reductions by around -6% until year 2050. The results obtained clearly indicate that the climate goals cannot be reached solely by following long-term research goals for aircraft technology improvements, because of slowing effects on fleet level. Even following the long-term research goals for aircraft technology improvements combined with radical production ramp-ups and significant improvements in aircraft productivities will lead to a carbon-neutral growth until year 2050 but at roughly 10% higher emission compared to the IATA goals until year 2035.

I. Long-term goals for aviation

Over the last 100 years, aviation transformed from an elite mode of transport for niche markets to a mass transportation system serving long-haul as well as medium and short-haul markets worldwide. The aviation industry has grown strongly over the past decades at a global rate of around 5 % per year¹ and above, measured in transport capacity (revenue passenger kilometres, RPK). Forecasts for market developments issued by all main aviation stakeholders²⁻¹² predict further growth in transport capacity by 4 to 5 % annually until 2030 at global average - roughly

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translating into doubling of transport capacity by 2030 compared to today. Particularly high growth rates, partly surpassing 6 % per year, are expected for emerging countries, for example in the Asia-Pacific region, driven by the transition to middle- or even high-income countries with a growing middle class and the associated changes in travel behaviour¹³. Within the context of this rapid growth, environmental awareness of societies and general actions to mitigate global climate change have led various institutions and stakeholders to formulate and proclaim aspirational, partially non-binding quantitative goals for limiting greenhouse gas emissions (GHG) of the future global air transport fleet. Among these institutions are the International Civil Aviation Organization (ICAO)¹⁴, the International Air Transport Association (IATA)¹⁵, the Air Transport Action Group (ATAG)¹⁶ and the European Union (EU)¹⁷. The most prominent and frequently cited targets addressing the emission quantities of carbon dioxide (CO₂) at global aircraft fleet level have been published by IATA and ATAG and comprise three major items:

- (1) Fleet-wide efficiency improvement of 1.5 % annually from the present until 2020
- (2) Cap of CO₂ emissions from 2020 onwards (“carbon-neutral growth”) enabled by market-based measures
- (3) Halving of the global fleet’s overall CO₂ emission quantities by 2050 relative to 2005 levels

At aircraft level, the EU envisages in its long-term research agenda¹⁷, a reduction of CO₂ emissions by 75 % compared to typical aircraft in service in the reference year 2000. The EU targets are considered as being on an equal footing with those announced by ICAO¹⁴, IATA¹⁵, and the U.S. National Aeronautics and Space Administration (NASA)¹⁸, levelling the long-term research goals for aircraft technologies. Technology goals for CO₂ emissions, as originally defined in Vision 2020¹⁹ and AGAPE 2020²⁰, were categorised into airframe, propulsion and other areas like air traffic management (ATM) and airline operations. Up to the year 2035, a 60 % reduction in fuel burn and CO₂ emissions per RPK is to be achieved, and a 75 % reduction in CO₂ emissions is set as a target for the year 2050, relative to technology standards of the reference year 2000.

A. Short-to-medium term developments in aviation

Besides these long-term research goals to reduce the ecological footprint at aircraft level, aircraft manufacturers are continuously updating their current product portfolio with completely new aircraft programmes and performance improvement packages for existing product lines. Over the last 10 to 15 years, a strong focus, and hence competition, was set on new long-haul aircraft programmes like Airbus A380, Boeing 787, Boeing 747-8, and Airbus A350, which entered the markets in 2005, 2011, 2012 and 2014, respectively. A block fuel reduction of the Boeing 787 compared to its predecessor – the Boeing 767 – of around 20 % was achieved²¹. For the Airbus A350, a 25 % block fuel reduction compared to the current Boeing 777 family is claimed²². Besides new aircraft programmes, both Airbus and Boeing will also improve their existing A330 and 777 programmes by more efficient wing designs and incorporating latest available engine technologies, resulting in the Airbus A330neo (new engine option) and Boeing 777-X family (incl. 777-8/9), achieving block fuel reductions between 13% and 20 %.

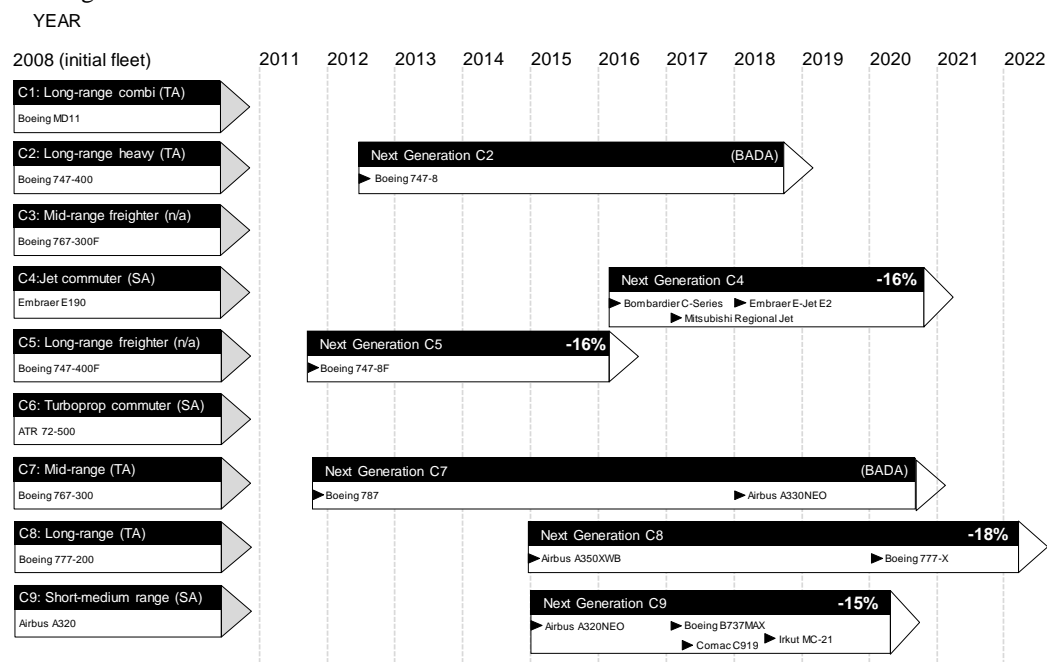


Figure 1: Next-generation aircraft types and associated gains in fuel efficiency²³ launched until 2017

For the short-haul markets, the availability of the Geared Turbofan engine technology, offering promising fuel burn reductions of around 15 %²⁴, led to several launches of new programmes like Bombardier's C Series or existing aircraft programmes like Airbus' A320 and Boeing's 737 families being updated with this latest engine technology.

However, despite these substantial efforts to develop new or upgraded aircraft programmes in order to increase fuel efficiency, it is obvious that the target of carbon-neutral growth from 2020 onwards will not be met. Today, more than 14,000 single-aisle aircraft are operating, and a growth to over 30,000 aircraft within the next 20 years is expected²⁵. Even at current highest production rates of around 120 aircraft per month for Airbus A320 and Boeing 737 single-aisle aircraft families, the rate of market penetration of new and more efficient aircraft is slowing down the achievement of overall ambitious emission reduction targets on fleet level.

II. Review of Aviation Fleet-Level Emission Scenarios

Several studies have investigated scenarios of future fleet-level emissions at different geographical scales, time horizons, considering fuel life-cycle emissions and/or full-flight emissions.

Dray et al.²⁶ investigated the effect of global emissions trading on global aviation demand and emissions using the Aviation Integrated Model (AIM). Three scenarios were used, combined differently with five stringency levels of atmospheric CO₂ stabilization, each with an associated carbon price. Main differences in the scenarios are in global distribution of GDP per capita growth and in oil and carbon prices, with carbon prices directly affected by the level of stringency simulated. Main fuel reduction options are the open rotor technology assumed to enter the fleet in 2020 and biomass-derived synthetic jet fuel, in a 20% blend with Jet A, also assumed to be available from 2020. Other mitigation options were incorporated, like winglets as aircraft retrofit option which has a low effect on global emissions. Also, air traffic management (ATM) improvement was assumed to be non-optional, resulting in a 4% decrease in total global fuel burn. Furthermore, engine upgrade kits were assumed to have low adoption rates.

By 2050, their result reveals that aviation-related CO₂ emissions may range from double the 2005 level (under the most stringent atmospheric CO₂ stabilization target of 450 ppm) to five times the 2005 levels (when no emissions trading took place). The authors found out that the adoption of new technologies in response to increased carbon costs resulted in approximately two-third of the total emissions reductions while the last third was a result of demand reduction. The open rotor as a new technology option was particularly incorporated into the fleet in scenarios with high oil prices in order to save total fuel and carbon costs. On the other hand, biofuels, assumed to be priced at similar prices or higher than Jet A, were incorporated into the fleet in high stringency scenarios. The functionality of the emissions trading scheme is such that the expected increase in aviation CO₂ will be offset by reductions in emissions from other sectors.

Owen et al.²⁷ developed aviation emission scenarios to 2050 that were designed to interpret the IPCC storylines under four main families A1B, A2, B1 and B2 with a further outlook to 2100. Additionally, a scenario was developed assuming the ambitious technology targets of ACARE would be achieved. Scenarios were defined assuming that political and societal factors affect future travel both globally and with different regional impacts. Aircraft added to the fleet after the base year (e.g. B787, A380) in order to replace retired older aircraft were estimated with about 20% fuel efficiency such that a fleet-wide efficiency improvement of approximately 1% year⁻¹ from 2000 up to 2020 was estimated. Beyond 2020, ACARE technology goals and ICAO's Committee on Aviation Environmental Protection (ICAO/CAEP) long term technology goals (LTTG) were used in the scenarios.

Their work was implemented using the Future Aviation Scenario Tool (FAST model). This global model of aircraft movements and emissions has a baseline year of 2000 and combines a global aircraft movement's database of scheduled and non-scheduled air traffic with data on fuel flow provided by a separate commercial aircraft performance tool *PIANO*. They normalized the CO₂ emissions in the base year to the IEA total aviation fuel sales figure of 214 Mt/year, to account for previous differences in the emissions estimate due to assumption of great circle distances and the difficulty in estimating military emissions. Until the year 2020, traffic growth rate projection of ICAO/CAEP (4.3% annual average) was used; whereas, traffic demand for each scenario was calculated using global GDP growth as the main driver, in addition to relative maturity of aviation demand in the regions. Their result shows that aviation emissions grow from 2000 to 2050 by a factor of one and a half (with fuel efficiency improvement of 2.1% per year between 2020 and 2050) and three and a half (with fuel efficiency improvement of 1% per year between 2020 and 2050)²⁷.

ICAO's CAEP assessed the present and longer-term impact and trends of aircraft noise and engine emissions starting from a base year of 2005 till a target year of 2050²⁸. Their study was conducted using United States Federal Aviation Administration's (FAA) Aviation Environmental Design Tool (AEDT), EUROCONTROL's IMPACT and the FAST model. Measures considered to reduce fuel burn include contribution of aircraft technology, improved ATM, and operational improvements resulting from better infrastructure use. The analysis was centered on emissions from

international aviation. Given that international and domestic aviation represented 65% and 35% of global aviation traffic in 2010, with projected values of 70% and 30% for 2050²⁸, values of global aviation emissions in 2005 and 2050 were calculated using their results, with the 2005 values extrapolated based on this information.

An RPK annual growth rate of 4.9% between 2010 and 2030 was assumed, with nine scenarios of fuel efficiency improvements developed to simulate the contribution of aircraft technology improvement to emissions reduction. An aircraft fuel efficiency improvement scenario of 1.4% together with ATM and operational improvements resulted in 1039 Mt more CO₂ emission above the net emissions values estimated for 2020. Thus, in order to achieve the carbon neutral growth target as from 2020, the contribution of alternative jet fuels (AJF) from feasible stocks (starchy crops, sugary crops, lignocellulosic crops, oily crops, agricultural residues, forestry residues, waste fats, oils and greases, microalgae, and municipal solid waste) to fuel replacement and GHG trends was investigated. The most effective scenario assumed production ramp ups for AJF in 2050 to completely replace petroleum-derived jet fuel. This scenario resulted in global aviation emission in 2050 growing by a factor of less than one and a half compared to the estimates for 2005.

Hassan et al.²⁹ proposed a framework to assess the performance of the future NAS under different scenarios that consider varying technology, operation, and biofuel contributions to mitigate the environmental impacts of aviation.

Vehicle performance was determined for different combinations of airframes, engines, and technology packages. Seven vehicle classes of tube and wing aircraft configurations with Geared Turbo fan engine were considered, namely turboprop, regional jet, small single aisle, large single aisle, small twin aisle, large twin aisle and very large aircraft, simulating only domestic operations in the United States. Technology improvements were modeled as continuous improvements in fuel efficiency and thus reduced CO₂ emissions. The best improvement at aircraft level, the N+3 technology, was to achieve an aircraft fuel consumption reduction of 60% referenced to the B737-800 with CFM56-7B engines. Scenarios were based on their best estimates of available technology sets within the simulation timeframe without use of biofuels and operational measures. Their study results showed, however, that the carbon-neutral growth goal could be reached using technology improvements, claiming that the goal of reducing CO₂ emissions in 2050 relative to 2005 values could not be reached by technologies alone. They suggested that operational measures and more biofuels would be needed to fill the remaining gap.

Schilling et al.³⁰ reported of a study conducted by the German Aerospace Center (DLR) in cooperation with the International Air Transport Association (IATA) to investigate the benefits, challenges and resulting CO₂ emissions reduction potential at fleet level of three kinds of novel aircraft configurations- a fully-electric aircraft concept, a strut-braced wing with open rotor configuration and a blended wing body configuration; and two sustainable fuel technologies- a sun-to-liquid drop-in fuel, and a liquid non-drop-in fuel. The DLR fleet and fuel forecast tool FFWD³¹ was used in forecasting the potential impact of each configuration as well as a combination of the three configurations and excluding potential economically-driven delays such as poor world economics or reluctance to invest in large high-risk projects. The block fuel burn saving potential results bases on assumptions of 100% for universally-electric aircraft assumed to have entry into service (EIS) between 2030 – 2035, 50% for blended wing body aircraft assumed to have EIS at the earliest in 2040, and 29% up to 62% for strut-braced wing with open-rotor having EIS years 2030 and 2045 respectively. Furthermore, an underlying RPK annual growth scenario of 2.0% from 2005-2010, 5.3% from 2010-2020, 4.5% from 2020-2030, 4.0% from 2030-2040, and 3.7% from 2040-2050 was used²⁹. By 2050, the result reveals that aviation-related CO₂ emissions may range from three and a half times (under the baseline scenario) to four and a half times the 2005 levels (with three aircraft configurations considered).

Table 1 (overleaf) summarizes the different studies reviewed, the measures of their baseline and strictest scenarios and the respective resulting factors of increase or decrease in the fleet CO₂ emissions, with estimates given where available. Although these studies involve extensive assumptions on different combinations of future aircraft technologies, alternative fuels, fuel efficiency improvements and operational measures, none of them evaluated these measures in combination with production ramp-up or aircraft productivity measures.

Therefore, all studies showed that available aircraft technology improvements are outpaced by the strong growth in aviation today. The reviewed studies revealed an increase in global emission of a factor of up to 6 for the baseline scenarios in 2005. Assuming future novel and more radical technologies on aircraft level and alternative fuel paths, the studies concluded that global emissions growth can be limited to a factor of 1.5 to 3.5 compared to the 2005 baseline. Only the study of Hassan et al. 2015²⁹ calculated a reduction of aviation's emissions in the US to a factor of 0.9 compared to 2006 baseline only enabled by large usage of alternative fuels. Most of the studies do not take into account that future novel and more radical technologies with large CO₂ emission reduction potentials are still at very low technology readiness levels and hence far from industrial implementation leading to large challenges to the aviation industry in terms of technology maturation, design and development as well as production. Even in the case of a rapid technology maturation, a fleet-wide penetration would require radical production ramp-ups and an

aggressive industrialisation strategy for such novel technologies. Therefore, in the following chapter, four different scenarios were defined to quantify the impact of novel technologies, operational improvements, aircraft ramp-up and production scenarios as well as future RPK growth rates.

Table 1. Summary of considered technological and operational cases: Baseline and Strictest Scenario Assumptions and CO₂ Emissions Results from Studies Reviewed

Study	Baseline Scenario		Strictest Scenario		
	Base year - Target Year (Geographical scope, CO ₂ estimation type)	Description	CO ₂ emissions in target year as factor of base year values (estimates, if available)	Scenario Description	CO ₂ emissions in target year as factor of base year values (estimates, if available)
Dray et al. 2010 ²⁶	2005 – 2050 (Global, fuel life-cycle CO ₂ emissions)	MIT's IGSM scenario, with no emissions trading scheme	4.8 (3000 Mt)	MIT's IGSM scenario of high oil prices and high rates of economic growth in US, western Europe, and low levels of economic growth in the developing world, high carbon prices at high stringency levels (450ppm) of carbon trading. Aircraft technology available in final simulated year are open rotor engine aircraft and biofuel	2.0 (1200 Mt)
Owens et al. 2010 ²⁷	2000 – 2050 (Global, full-flight CO ₂ emissions)	Fuel Efficiency grows at 1% per year from 2000 to 2050	3.5 (2418 Mt)	Aircraft technology available in final simulated year complying with ACARE targets: aircraft fuel efficiency [kg/seat km offered] reduction of 83% compared to base year. Demand growth is slower	1.5 (1025 Mt)
ICAO 2016 ²⁸	2005 – 2050 (Global, full-flight CO ₂ emissions)	Fleet renewal. No technology and operational improvement	6.0 (3750 Mt)	Fuel efficiency grows at 1.4% per year. Improved ATM and infrastructure use, petroleum-based jet fuel completely replaced by alternative jet fuel	1.4 (940 Mt)
Hassan et al. 2015 ²⁹	2006 – 2050 (USA, full-flight CO ₂ emissions)	Business as usual, no new technology introduced	1.9	Aircraft technology available in final simulated year complying with CLEEN, ERA and FW program targets of aircraft fuel consumption reduction of 60% compared to B737-800 with CFM 56-7B engines	0.9
Schilling et al. 2016 ³⁰	2005-2050 (Global, full-flight CO ₂ emissions)	Global aircraft fleet and fuel consumption development considering only evolutionary technologies as detailed by IATA ³¹	4.5	Electric Aircraft + Strut-braced wing + Blended wing body	3.5

III. Technological and Operational Scenarios on Aircraft Fleet-Level

To be able to quantify the effectiveness of various technological and operational improvement on global emissions in 2050 as well as cumulative global emissions up to the year 2050, scenarios were defined taking aircraft technologies and configurations, aircraft production ramp-ups, aircraft productivities, RPK growth changes and retrofit options similar to Dray et al.²⁶ into account.

For aircraft technologies and configurations, three cases were setup taking fuel reductions on aircraft level into account. In the first case (1.1), it is assumed that the aviation industry can develop and deliver new aircraft following the SRIA goals of -43% fuel burn reduction of all new aircraft with EIS between 2020 and 2035, -60% fuel burn with EIS between 2035 and 2050. In Case 1.2, only a -22% fuel burn reduction (~50% shortfall due to no new A/C programs) for aircraft between 2020 and 2035 are assumed taking into account that most of the current aircraft programs will be upgraded by re-engined, re-winged options³². Between 2035 and 2050, it is assumed that aviation industry can deliver a 60% fuel reduction for all aircraft programs. In Case 1.3, shortfalls in block fuel reductions on aircraft level until 2050 are assumed incorporating block fuel results for future short and long-haul conventional aircraft up to year 2050³³ without any radical new aircraft technologies like hybrid-propulsion or novel airframe morphologies.

Possible effects of new aircraft technologies on their market penetration are captured by three different aircraft production ramp-up cases. For this study, production rates and production increases of current aircraft programs following an analysis of Leeham³⁴ until year 2020 were used, after 2020 it is assumed that aircraft production increases with RPK growth. In Case 2.1, it is also assumed that new aircraft programs will follow current ramp-up timelines as seen for the B787 or A350XWB of six years³⁵ from first delivery to full-production. In Case 2.2, all new aircraft programs will face more ambitious ramp-up timelines resulting in timelines of 3 years until full production. In Case 2.3 all new aircraft programs will have a radical ramp-up timeline of one year to full production.

Besides the aircraft technologies and production capabilities, also possible emission reduction options on an operational level like aircraft productivity were analysed. In Case 3.1, the average loadfactor is increase to 95% (from 80.4% in 2015³⁶) in three different timelines (see also scenario descriptions). In Case 3.2, the average number of installed seats is increased by 10% for all aircraft programs taking additional fuel burn into account. In Case 3.3, the average aircraft utilization (measured by number of flights per years) is increased by 10%.

In Case 4, regional RPK growth rates inside EU, North America and Asia are halved from 2017 until 2050 using initial growth rates provided by Boeing²⁵ until year 2035 with the assumption of unchanged growth rates until year 2050. In Case 5, fuel reduction retrofit solutions with a 4% block fuel reduction for in-fleet aircraft are modelled. A full market penetration of all in-service aircraft is assumed within eight years following conventional heavy maintenance timeframes.

Table 1. Summary of considered technological and operational cases

Category	Input for Fleet Simulation Framework
Aircraft technologies & configurations	Case 1.1: -43% fuel burn of all new aircraft with EIS between 2020 and 2035, -60% fuel burn of all new aircraft with EIS between 2035 and 2050 Case 1.2: -22% (~50% shortfall due to no new A/C programs) fuel burn of re-engined, re-winged A/C between 2020 and 2035, -60% fuel burn of all new aircraft with EIS between 2035 and 2050 Case 1.3: -22% (~50% shortfall due to no new A/C programs) fuel burn of re-engined, re-winged A/C between 2020 and 2035, -48% (~20% shortfall) fuel burn of all new aircraft with EIS between 2035 and 2050
Aircraft production ramp-up	Case 2.1: New aircraft programs with current ramp-up timelines of six years (status quo) Case 2.2: New aircraft programs with ambitious ramp-up timelines within three years Case 2.3: New aircraft programs with radical ramp-up timelines of one year to full production
Aircraft productivity	Case 3.1: Increase of average load factor to 95% Case 3.2: Increase of average number of installed seats by 10% Case 3.3: Increase of average aircraft utilization by 10%
Change of RPK growth rates	Case 4: Reduction of regional RPK growth rates (e.g. inside EU, North America and Asia) of 50%
Fuel reduction retrofit solutions for in-fleet aircraft	Case 5: Application of retrofit solution for in-fleet aircraft from 2008 until last retired A/C from initial fleet

IV. Air transport fleet modelling

Given the goals of this paper, a simplistic comparison of the performance of current and next-generation aircraft types at a single-mission level is insufficient. Instead, fleet-wide effects resulting from the phase in and decommissioning processes of aircraft types that enter the global fleet at a certain moment in the future have to be taken into account. Once a new type has reached technological maturity for commercial operations with an airline, it will not simply replace all of the corresponding older types at once but gradually replace these aircraft and, in this way, replenish the airline's fleet. In order to capture the integration and penetration effects of the next-generation aircraft and technologies, the "Fleet System Dynamics Model (FSDM)" has been developed and further extended^{37,38,39}. The fundamental functioning of this model has been derived from the "macro" or "top-down" approach to fleet planning that is based on a relatively high-level aggregated analysis^{39,40}. The FSDM translates air traffic market data (e.g., growth rates in different regional markets, payload factors, and aircraft production rates) into quantitative data that addresses the future fleet size, composition, and age distribution. This is achieved through the simulation of the global aircraft commissioning, operations, and retirement procedures for distinct world regions and at a global level as a function of time.

A. FSDM: Overview

The FSDM is divided into two model components: the air transport fleet model and the air transport network model. The former dynamically determines the size and structure of the global fleet of commercial transport aircraft on a year-by-year basis. The time-step used in the model is hence one year. The latter defines the air routes that interconnect intra- and intercontinental air traffic markets with each other to form and represent the global network of air transport routes on which the air transport fleet operates. The macro approach to fleet planning underlying the FSDM has two decisive consequences for the basic functioning of the model: (1) For each year of simulation, the model requires a target amount of ASKs and ATKs, or alternatively, a target amount of RPKs and RTKs along with load factor data, in order to determine the "capacity gap," which in turn stipulates the amount of new aircraft units to be added to the fleet. For each year of simulation, the model hence determines the fleet that is required to deliver a certain transport performance. (2) The user must initialize the model by defining a start year of simulation along with an initial fleet of aircraft (including a definition of the fleet size, composition, and age distribution) as well as the initial transport supply that this fleet must deliver. To capture the dynamic evolution of the global air transport fleet, the FSDM uses the principles of System Dynamics⁴¹. In particular, interdependent stocks and flows are utilized to capture the dynamics of the fleet evolution as a function of time. The fleet (stock) is essentially determined by two flows, the 'Aircraft introduction'-inflow and the 'Retire aircraft'-outflow. The 'Aircraft introduction'-inflow is aimed at delivering new aircraft to the fleet, depending on the growth rates of air traffic defined by the user. In addition, it is constrained by both the availability of aircraft (in terms of whether or not a particular type of aircraft is being produced in a specific year of simulation) and the capability of the aircraft manufacturers to deliver the amount of aircraft units required. The 'Retire aircraft'-outflow is determined by an FESG-based aircraft retirement model⁴² that is a part of the FSDM using aircraft-specific survival curves. Given an initial age distribution of the fleet, the model will apply predefined survival curves to the various types of aircraft simulated by the model to statistically determine the amount of aircraft to be retired in each year of simulation.

B. Model assumptions and limitations

This section presents the various underlying model assumptions and limitations employed in the FSDM. Randt⁴⁶ similarly employed most of these in his work. Some assumptions however, have been further developed here to increase model fidelity.

1. Airline competition: Commercial aviation is an industry sector that is strongly characterized by competition among airlines courting passengers at a local, regional, and global level. However, the modelling of airline competition requires profound economic understanding and modelling capability that was not available during the work of this paper. As a result, similar to the work of Tetzloff and Crossley³⁴, the model simulates "one benevolent, monopolistic airline" that exists to meet all transport demand worldwide.

2. Fleet allocation: Usually, airlines will assign their fleets to a route network in a way to maximize profit. Profit maximization is then used as the objective function required for solving the "Fleet Assignment Problem (FAP)"⁴⁴. The simulation of the model in the absence of airline competition uses a fuel burn optimization function instead of profit maximization. Hence, the FSDM assigns aircraft to the route network in order to minimize the total fleet fuel consumption. This ensures consistency with the other model assumptions and at the same time enables the simulation and development of a fuel-optimal fleet.

3. *Representation of the global air transport fleet:* Almost 200 different types of aircraft were part of the global air transport fleet that contributed to the total transport supply in 2008¹³. Including all types would lead to a very high degree of complexity of the FSDM. Therefore, to keep complexity within manageable limits, the model defines nine distinct aircraft categories to represent the global fleet in 2008. New aircraft programmes up to the year 2050 can be added indefinitely as separate aircraft categories.

4. *Representation of the global route network:* More than 37,000 different O-D pairs formed the global network of air routes in 2008⁴⁵. Again, representing the entire set of O-D pairs in the FSDM would lead to a significant degree of complexity of the model that would make its handling very difficult. Therefore, the FSDM fundamentally defines six global regions (Africa, Asia, Europe, Latin America, North America, and the Middle East) that together form twenty-one intra- and interregional connections referred to as ‘routes’⁴⁶. These routes establish the simulated global air transport network. Three distinct stage lengths and their route specific distribution are furthermore employed to characterize each route. To initialize the FSDM, statistical analyses of the OAG database were conducted to supply a definition of the aircraft categories and route-specific stage lengths. During the simulation of the subsequent years, the stage lengths are considered to be constant over time.

5. *Further model limitations:* In its current version⁴⁶, the FSDM features four additional methodological limitations that decrease the model accuracy. (1) First the user has to define the utilization characteristics of each aircraft category. (2) The FSDM always retires aircraft on a statistical basis, regardless of the current situation of aircraft demand. (3) The FSDM does not support the modelling of temporary aircraft storage that airlines undertake in reality during short periods of economic decline in order to adapt their transport capacities accordingly. On the one hand, integrating the above capabilities into the FSDM would certainly increase the overall model accuracy (and equally raise the model complexity by the same degree). On the other hand, a validation of the current version of the model (not presented in this paper) revealed that even without these capabilities, the FSDM is very well capable of determining a realistic development of the global air transport fleet.

C. User input data required

The FSDM requires a range of input data that have to be supplied by the user in order to enable the proper functioning of the model⁴⁶. The *target year of simulation* stipulates the final year of the fleet simulation. *Current aircraft production capacities* define the number of aircraft with which the types of the initial fleet are produced. *Next-generation aircraft data* define which types of aircraft will enter the fleet in the future. The user must provide the full range of aircraft data including performance and utilization data, and survival curves. *Next-generation aircraft production capacities* define the number of aircraft with which the future types are produced. *Regional market growth factors* define the year-on-year change of the RPKs and RTKs in each one of the 21 route groups between 2008 and the target year of simulation⁴⁶.

D. Aircraft performance modelling

Aircraft performance modelling is a core capability of the FSDM. The performance modelling tool employed in the FSDM utilises the aircraft performance model (APM) that is fundamentally based on the Base of Aircraft Data (BADA) that has been created and is now being maintained and distributed by Eurocontrol³⁷. Over the last years, BADA has become a widely utilized and recognized APM in the international scientific community. Today, it can certainly be considered as a standard tool for performance simulation purposes of civil aircraft. Response surfaces of the BADA APM have been used in the FSDM to primarily determine the fleet-wide fuel consumption and CO₂ emission quantities. The model can also calculate further emission substances like NO_x, CO, and unburned hydrocarbons, provided that adequate data is available (e.g., supplied by the ICAO Aircraft Engine Emissions Databank). The model then determines the quantities of these substances through the “Boeing Fuel Flow Method 2”⁴⁶. Next-generation aircraft that are not officially captured by the BADA database are simulated by target mission performance (i.e., fuel burn in particular) enhancements.

III. Reference air-traffic-growth scenario and future fleet inventory

A. Market forecasts considered

In order to derive air traffic growth rates for a future reference scenario, industry growth data forecast²⁵ were used up to the year 2035. From 2035 onwards, a constant growth rate was assumed.

B. Fleet inventory

To estimate the fuel- and emissions-reduction potential of the next-generation aircraft types under different technology-improvement scenarios (i.e., by varying the fuel efficiency improvements associated to each next-

generation aircraft type), today’s air transport fleet was reduced to nine representative aircraft categories, in which each one of the categories is represented by a typical aircraft type. The assignment was done on an ASK/ATK-share basis for each category. The nine aircraft categories comprise two different types of freighters (mid- and long-range freighters), four clusters for different twin-aisle long-range aircraft, and three single-aisle categories, of which two are powered by a turbofan and one by a turboprop propulsion system.

IV. Aircraft fleet level results of technological and operational scenarios

Based on the results up to the year 2025²³, a baseline and three overall emission reduction scenarios -namely *Conservative*, *Ambitious* and *Radical*- were calculated taking new aircraft programs (Case 1.1-1.3), aircraft production ramp-ups (Case 2.1-2.3), increased aircraft productivities (Case 3.1-3.3), change of regional RPK growth rates (Case 4) and aircraft retrofit technologies (Case 5) into account. A full list of considered cases in each of the scenarios can be found in Table 2. For the Baseline scenario, no new aircraft programs with reduced fuel burns are introduced after 2017 (see also Figure 1). Based on forecasted production rates for cluster 2 to 9 (see Annex 1), production rates after year 2020³⁴ follow the growth rates from the industry forecast²⁵ and seat loadfactors will linearly increase from 80.2% in 2015³⁶ to 95% in 2050.

The *Conservative* scenario consists of shortfalls in fuel burn reductions compared to SRIA goals, status-quo production ramp-ups and increase of aircraft productivity within six years.

The *Ambitious* scenario consists of shortfalls in fuel burn reductions compared to SRIA goals before 2035, production ramp-ups and increase of aircraft productivity within three years as well as retrofit solutions for current in-service aircraft fleet.

The *Radical* scenario consists of new aircraft programs meeting the SRIA goals until 2050, production ramp-ups and increase of aircraft productivity within only one year, reduction of regional RPK growth rates to 50% assuming a stronger shift from air to ground on a regional level, as well as retrofit solutions for current in-service aircraft fleet.

Besides the consolidated three scenarios, each case inside each scenario was consecutively calculated and a summary of all simulations in each of the scenarios as well as considered cases are shown in Table 2.

Table 2. Summary of technological and operational cases for *Conservative*, *Ambitious* and *Radical* scenarios

	Scenarios: Conservative			Ambitious					Radical						
	Cases: 1	2	3	4	1	2	3	4	5	1	2	3	4	5	6
Case 1.1: -43% fuel burn of all new aircraft with EIS between 2020 and 2035, -60% fuel burn of all new aircraft with EIS between 2035 and 2050										X	X	X	X	X	X
Case 1.2: -22% (~50% shortfall due to no new A/C programs) fuel burn of re-engined, re-winged A/C between 2020 and 2035, -60% fuel burn of all new aircraft with EIS between 2035 and 2050					X	X	X	X	X						
Case 1.3: -22% (~50% shortfall due to no new A/C programs) fuel burn of re-engined, re-winged A/C between 2020 and 2035, -48% (~20% shortfall) fuel burn of all new aircraft with EIS between 2035 and 2050	X	X	X	X											
Case 2.1: New aircraft programs with ramp-up timelines of 6 years	X	X	X	X											
Case 2.2: New aircraft programs with ramp-up timelines of 3 years					X	X	X	X	X						
Case 2.3: New aircraft programs with ramp-up timelines of 1 year										X	X	X	X	X	X
Case 3.1: Increase of average load factor to 95% until 2025		X	X	X	X	X	X	X	X	X	X	X	X	X	X
Case 3.2.A: Increase of average number of installed seats by 10% from 2017 within 6 years			X	X											
Case 3.2.B: Increase of average number of installed seats by 10% from 2017 within 3 years							X	X	X						
Case 3.2.C: Increase of average number of installed seats by 10% from 2017 within 1 year											X	X	X	X	X
Case 3.3.A: Increase of average aircraft utilization by 10% from 2017 within 6 years				X											
Case 3.3.B: Increase of average aircraft utilization by 10% from 2017 within 3 years								X	X						
Case 3.3.C: Increase of average aircraft utilization by 10% from 2017 within 1 year												X	X	X	X
Case 4: Reduction of regional RPK growth rates (e.g. inside EU, USA and Asia) of 50%														X	X
Case 5: Application of retrofit solution for in-fleet aircraft from 2008 until last retired A/C from initial fleet									X						X

As shown in Figure 2, the introduction of new aircraft programmes with lower fuel burn (-22 % in 2020-2035 and -48% in the timeframe 2035-2050) show a significant reduction on fleet level fuel burn for the *Conservative 1* scenario compared to the *Baseline* after 2035. With rising aircraft productivity by increasing loadfactors (*Conservative 2-4*) and average number of installed seats (*Conservative 3-4*) a further decrease of growth of fleet level fuel consumption after the year 2020 can be observed. These modelled improvements lead to a decrease of fleet level fuel burns in the years 2024-2025. After 2025, modelled aircraft productivity enhancements reach their maximum, hence fleet level fuel burns start to rise again. Aircraft utilisation increase (*Conservative 4*) does not result in major fleet level fuel burn improvements because the fleet model retirements are based on static survival curves, hence the model does not consider shorter aircraft lifetimes due to higher utilisation. However, the number of required aircraft is reduced by -10 %. A similar impact of aircraft productivity enhancements could be observed for the *Ambitious* and *Radical* scenarios. The *Conservative 1* and *Conservative 2* scenarios resulted in similar fleet level fuel burn values due to same target load factors in 2050.

Comparing the *Conservative 1-4* with the *Baseline* scenarios, fleet level fuel burns in 2050 can be reduced by -40 % (*Conservative 1*) up to -45 % (*Conservative 4*). Comparing the 2050 results with 2008, fleet level fuel burns will increase by a factor of 4.5 for the *Baseline*, 2.7 for *Conservative 1* and 2.5 for *Conservative 4* scenario.

Comparing cumulative fleet-level fuel burns from year 2008 to year 2050 (see Figure 3), the introduction of new aircraft programs will lower cumulative fleet-level fuel burn by -17 %. This reduction shows significantly the slowing effect of market penetration of lower fuel burn technologies and aircraft programs on global fleet level. The increase of loadfactor further reduces cumulative fleet level fuel burns by additional -5 %, an increase of installed seats further reduces cumulative fuel burns by another -2 %. As mentioned before, aircraft utilisations does not show significant fuel burn reduction potential. In total *Conservative 4* delivers a -25 % lower cumulative fleet-level fuel burn compared to the *Baseline*.

Comparing cumulative fleet-level fuel burns for the *Ambitious 1* to 5 (see Figure 4), the introduction of new aircraft programs will lower cumulative fleet-level fuel burn by -22 %. Comparing it with the *Conservative 1*, the slowing effect of market penetration of lower fuel burn technologies and aircraft programs on global fleet level even with more ambitious production ramp-ups of only three years until full production can be observed. The increase of loadfactor further reduces cumulative fleet level fuel burns by additional -6 %, an increase of installed seats further reduces cumulative fuel burns by another -2 %. The application of retrofit solutions for in-fleet aircraft from 2008 with a full market penetration until 2025 will

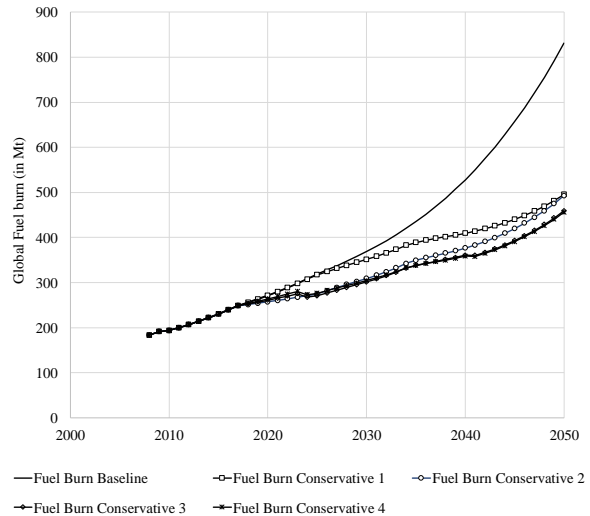


Figure 2: Fleet-level fuel burn from 2008 to 2050 for *Baseline* and *Conservative 1-4* scenarios

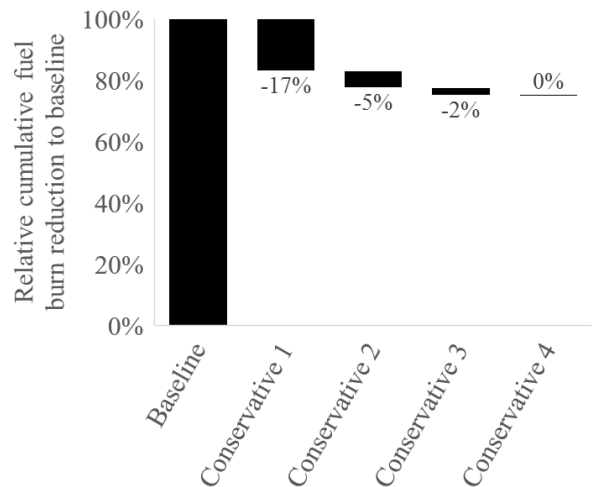


Figure 3: Cumulative fleet-level fuel burns from 2008 to 2050 of *Conservative 1-4* relative to *Baseline*

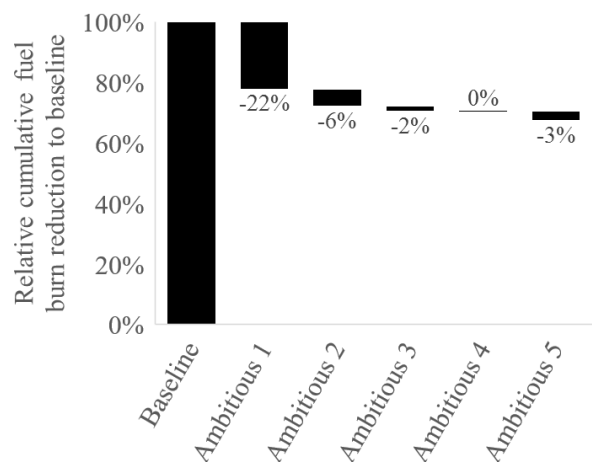


Figure 4: Cumulative fleet-level fuel burns from 2008 to 2050 of *Ambitious 1-5* relative to *Baseline*

reduce the cumulative fleet-level fuel burns by another -3 %. In total, *Ambitious 5* delivers a -31% lower cumulative fleet-level fuel burn compared to the *Baseline*.

Finally comparing cumulative fleet-level fuel burns for the *Radical 1* to 6 (see Figure 5), following the SRIA fuel burn reduction goals together with radical aircraft production ramp-ups of one year lower cumulative fleet-level fuel burn by -27 %. Similar to *Conservative* and *Ambitious* scenarios, the slowing effect of market penetration of lower fuel burn technologies and aircraft programs on global fleet level even at radical production ramp-ups limits the effectiveness of fleet-level fuel burns.

The increase of loadfactor further reduces cumulative fleet level fuel burns by additional -6 %, an increase of installed seats further reduces cumulative fuel burns by another 1%. As mentioned before, aircraft utilisation increase does not show additional fuel burn saving potentials (*Radical 4*). Halving the RPK growth rates for the North American, European and Asian region leads to a further decrease of cumulative fleet-level fuel burns of another -6 %. The application of retrofit solutions for in-flight aircraft from 2008 with a full market penetration until 2025 will reduce the cumulative fleet-level fuel burn by another -3 %. In total, *Radical 6* delivers a -43 % lower cumulative fleet-level fuel burn compared to the *Baseline*.

Comparing the scenarios with the lowest fleet-level fuel burns like *Conservative 4*, *Ambitious 5* and *Radical 6* with the *Baseline* as well as with the ATAG targets (as shown in Figure 6), it can be seen that even for the *Radical 6* scenario a negative fleet-level fuel burn year-over-year change cannot be achieved. Only a carbon neutral-growth until 2050 can be almost achieved in case of the *Radical 6* scenario. However, delivering new aircraft programs with an average fuel burn reduction of -43 % covering all current market segments from regional turbo-prop to large long-range aircraft until 2035 and -60 % fuel burn consumptions between 2035 and 2050, will greatly challenge the aviation industry. Therefore, even with these technology improvements, significant operational improvements as well as reduction of RPK growth rates will not fulfill the ATAG 2050 goals. Therefore, alternative fuels are required to limit fleet-level fuel burn to meet the ATAG 2050 goals for the given RPK growth until year 2050.

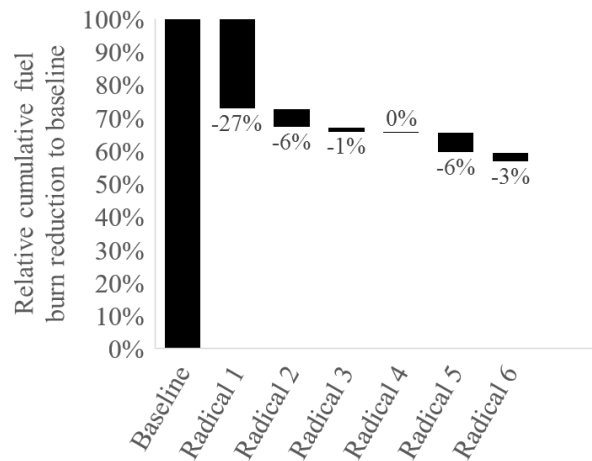


Figure 5: Cumulative fleet-level fuel burns from 2008 to 2050 of *Radical 1-6* relative to *Baseline*

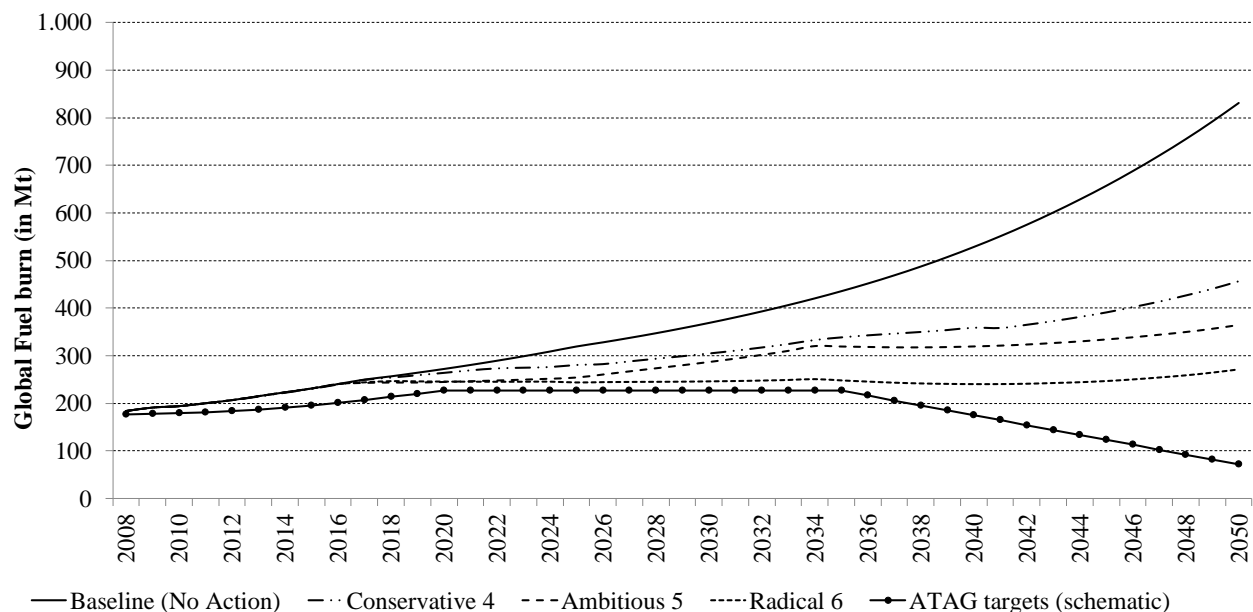


Figure 6: Fleet-level fuel burn of *Baseline*, *Conservative 4*, *Ambitious 5*, *Radical 6* and ATAG targets from year 2008 to year 2050.

V. Conclusion and Outlook

Simulating the impact of new aircraft programs with lower fuel consumptions together with aircraft production ramp-ups, increased aircraft productivities, change of regional RPK growth rates and aircraft retrofit technologies led to fifteen different scenarios. New aircraft technologies together with up to radical ramp-up timelines might lower fleet-level fuel burn until year 2050 between -17 % to -27 %. Increasing aircraft productivity by increasing loadfactors, installed seats and increased aircraft utilisation further reduce fleet-level fuel burn until year 2050 of -7 % to -8 %. The application of retrofit solutions for in-fleet aircraft can reduce the fleet-level fuel burn until year 2050 of around -3 %. Halving regional RPK growth rates might lead to fleet-level fuel burn reductions of around -6 % until year 2050.

Comparing the cumulative fleet-level fuel burns for the *Baseline*, *Conservative*, *Ambitious*, *Radical* with the ATAG goals from 2008 to 2050, none of these fifteen scenarios is able to fulfil the ATAG long term goal of a -50 % reduction global emission reduction compared to the year 2005.

The emission of the *Baseline* scenario exceeds the ATAG goal in 2050 by a factor of 11.7. The *Conservative 4* scenario exceeds the goal by a factor of 6.4 and 5.1 for *Ambitious 5* scenario. Even for the most stringent scenario (*Radical 6*), fleet-level fuel burn exceeds the ATAG goals by a factor of 3.8.

Comparing the cumulative fleet-level fuel burn results of the scenarios with the ATAG goals, in the *Baseline* scenarios, 2.2 times more fuel is consumed. For the *Conservative 4* scenario, the factor is 1.6. The *Ambitious 5* scenario delivers 1.5 times higher cumulative fuel burn values. Even the stringent *Radical 6* scenario exceeds the emission by a factor of 1.3 compared to the ATAG goals. Therefore, even more radical aircraft technologies and morphologies with higher CO₂ emissions reduction potential with EIS well before 2050, lower RPK growth rates or renewable, “drop-in” fuels, offering substantially smaller CO₂ footprints compared to conventional jet fuel have to be considered to fill this gap.

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Annex 1:

Table 2: Summary of monthly production rates for cluster 2 to 9 from 2008 until 2020³⁴

	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
C2: Long-range heavy (TA)	1	1	2	2	4	3	3	4	4	4	4	3	3
C3: Mid-range freighter (n/a)	2	2	2	2	2	2	2	2	2	2	2	2	0
C4: Jet commuter (SA)	18	15	12	11	10	10	8	10	13	21	30	30	30
C5: Long-range freighter (n/a)	0	0	0	1	1	2	1	1	1	1	1	1	1
C6: Turboprop commuter (SA)	9	9	9	8	8	9	7	7	8	9	10	10	10
C7: Mid-range (TA)	7	7	8	9	14	16	19	21	20	20	25	23	23
C8: Long-range (TA)	7	9	7	7	7	9	9	12	15	16	17	18	22
C9: Short-medium range (SA)	57	65	65	67	73	78	82	84	93	93	106	116	126