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IDENTIFYING CARBON DIOXIDE REDUCING AIRCRAFT TECHNOLOGIES AND ESTIMATING THEIR IMPACT ON GLOBAL CO2 EMISSIONS

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Abstract

Increasing CO2 emissions and associated fuel consumption of the world's aircraft fleet are a serious threat for both the world climate and the profitability of commercial aviation. CO2 emission can be analyzed on the local – i.e. single aircraft – and global – i.e. world fleet – level. Methods to reduce CO2 on the former are identified and the consequent future evolution of global CO2 is estimated. A method is developed and applied to assess the future fleet built-up through 2036. New aircraft programs as well as phase-out of in-service aircraft are considered. Individual aircraft's projected fuel efficiency and operational characteristics are introduced to assess the overall fleet's CO2 emission development over the considered time frame. Three scenarios are assumed to show the effect of different rates of technology progress in terms of fleet-wide aircraft fuel efficiency. Besides the individual aircraft's technological advances, further measures to reduce CO2 emissions on a fleet level are analyzed: Bio fuels, shorter aircraft program cycles and shorter aircraft life. It is shown that the sole aircraft-related technology improvements will not be sufficient to reach such goals as 'carbon neutral growth' due to a constantly high traffic growth rate. Bio fuels seem to be the only solution for this problem, however, this technology is still immature and thus subject of high uncertainty in terms of economic viability as well as net-carbon footprint.

INTRODUCTION

Global air traffic has shown a strong and continuous growth since the beginning of the commercial jet age. Between 1960 and 2000, air travel has grown at an average rate of 9 % per year (data of FAA and IPCC [1]) and at approximately 5.4 % between 1991 and 2007 [2]. Not considering serious economic downturns or significant policy changes, air traffic is expected to maintain similar growth rates in the future. ICAO assumes an average annual growth of 5 % for the years 2006 through 2036 [3]. It is expected, that air traffic will recover from the dampening effects of the current financial crisis by approximately 2012 [2] [4].

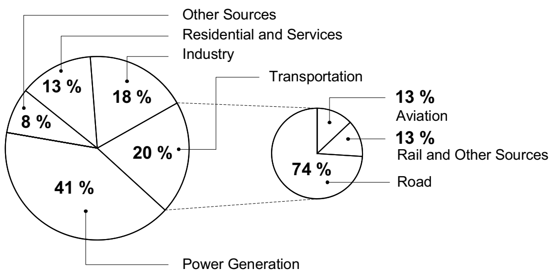

FIG 1. Global Transportation and Global Aviation's Contribution to Man-made Carbon Dioxide Emissions 2004

While of importance for the worldwide economic advance, strong growth rates in air traffic imply increasing harmful influence on the environment. Aircraft fuel burn per seat-km has been reduced by nearly 70 % since 1960 [5]. Nevertheless, energy efficiency improvements were not able to keep pace with industry growth. As a result, global aviation's fuel use and emissions have continually been rising [1].

Aviation's impact on the environment has become ever more important since the extent to which global warming can negatively influence living conditions on Earth is known.

The International Panel on Climate Change (IPCC) estimates air traffic to account for around 3 % of total human-generated positive radiative forcing [6] and to about 2.6 % of global anthropogenic CO2 emissions today (FIG 1). As air travel shows the fastest growth among all modes of transport and emissions at high altitude are affecting the climate potentially twice as severe as ground level emissions, its relative impact is expected to increase in the future [1] [7] [8]. Carbon dioxide emitted from aircraft engines plays a major role in the global warming potential of worldwide air travel: According to the latest IPCC estimate, about half of the global aviation's radiative forcing is attributed to the emission of CO2 [6]. Thus, research into, and the identification of, CO2 reducing aircraft technology is of high importance.[1]

The goal of this paper is to assess the capability of primarily technological measures to reduce individual aircraft as well as global aviation CO2 emission. Therefore, this paper will

[1] The impact of CO2 emission might only be outclassed by the warming effect of so-called cirrus clouds. However, cirrus clouds are not considered in the calculations of the IPCC, as exact quantifications are not yet possible due to missing scientific understanding.

1) Identify technology that is likely to be found on future aircraft projects as well as operational and technological system-level approaches capable of reducing CO2 and
2) Project future CO2 emissions of global aviation using different assumptions on the future implementation of technologies and operational instruments.

First, the results of a literature study on anticipated future aircraft, their entry into service date as well as their potential technology implementations are introduced. After that, a world-fleet forecast ranging up to 2036 is established in order to analyze the advent of new technologies on a worldwide, yet aircraft specific level. Finally, the development of future CO2 emission is projected for different technology scenarios.

1. AIRCRAFT TECHNOLOGY TRENDS

It is assumed that eleven entirely new aircraft families enter the market in the 2030 timeframe. Three of them are regional jets, four are narrow-body and four are wide-body aircraft. Further, two derivatives of already existing aircraft are expected, the CRJ1000 and the 747-8. Their impact on traffic growth and CO2 production is dependent on their respective fuel consumption and transport performance. Eight of the 13 considered future aircraft programs are expected to have an entry into service (EIS) before 2015. They are considered as near- to medium-term projects, whereas later EIS programs are treated as medium- to long term in the following.

1.1 Near- to Medium-Term Entry Into Service

Eight future aircraft programs are expected to have a service entry prior to 2015. These projects have already been officially launched by the manufacturers and the general design and major technology features are frozen. TAB 1 gives those aircraft, including assumed EIS, major technology feature for fuel and CO2 emission reduction and an assumed fuel reduction potential compared to a relevant, substituted reference aircraft. For this purpose, a comprehensive literature revue has been conducted using published sources of information.

TAB 1. Assumed major technology advances for fuel burn reduction and assumed resulting reduction of seat fuel burn compared to reference Future aircraft with Near- to Medium-term Entry-into-Service Date

Aircraft	EIS	Fuel/CO2-Relevant Technology Implementations	Version	Reference Aircraft	Change in nominal Seat Fuel Burn	Data Sources
Bombardier CRJ-1000	2009	-	-1000	CRJ-900	± 0.0%	[41], [42], [43], [44], [45]
ACAC ARJ21	2009	-	-700	CRJ-700	± 0.0%	[46], [42], [9], [47]
			-900	CRJ-900	± 0.0%	
Sukhoi SSJ100	2009	· More efficient conventional turbofan engine	-75	E-170	-2.0%	[48], [10], [49], [42]
			-95	E-190	-2.0%	
Boeing 747-8	2010	· New wing design · More efficient conventional turbofan engine		B747-400	- 13.8%	[50], [51], [52], [53], [54], [55]
Boeing 787	2010	· Composite primary structures: increased wing span/aspect ratio · New wingtip design · More efficient conventional turbofan · 'No-bleed' engine/ MEA architecture · Increased cruise speed	-3	A300[2]	(up to -47%)	[56], [17], [57], [58], [59], [60], [61], [62], [63], [23], [64], [54], [11], [65], [54], [66]
			-8	A330-200 / B767-300ER	ca. -20%	
			-9	A330-200 / B767-300ER	ca. -20%	
Airbus A350	2013	· Composite/Al-Li primary structures: Reduced empty weight · Variable camber wing · Improved high lift systems · New wingtip design · More efficient conventional turbofan · Increased cruise speed	-800	B787-9	-5.5%	[67], [11], [68], [69], [70], [71], [72], [73], [74], [74], [12], [75], [68], [17], [73]
			-900	B777-200ER	-23%	
			-1000	B777-300ER	-20%	
Mitsubishi MRJ	2013	· Wings and empennage of composite · Geared turbofan engine	-70	E-170	-10%	[76], [11], [21] ,[77], [42], [78]
			-90	E-190	-10%	
Bombardier CSeries	2013	· Specifically designed for 110-130 seat range: more coherent wing and fuselage design · Composite/Al-Li primary structures: increased wing span/aspect ratio · Geared turbofan engine	C100	E-195	-20%	[11], [79], [17]
			C300	B737-700	-20%	

[2] No modern reference aircraft available in terms of size and range.

1.2 Medium- to Long-Term Entry Into Service

These aircraft projects are still in a very early stage of development, which does not allow for definite projections of the technology implemented. Boeing's new short-range aircraft project, currently titled Y1, is assumed to be delivered from the year 2016 on. Similarly, the successor to the Airbus A320 aircraft family, currently titled A30X, is expected for 2018. New long-range aircraft in the range of 300 to 400 seats from both manufacturers Airbus and Boeing are anticipated to enter service in 2025 and in 2027 respectively. A new Chinese aircraft with a size of 150 seats, the COMAC 919, is due in 2016. There is an array of new technologies under development that could significantly improve the performance of the aircraft within this longer time scope. However, the further maturing of those technologies is associated with a relatively high degree of uncertainty. Three different technology scenarios are introduced in order to meet these uncertainties. A pessimistic (low) scenario and an optimistic (high) scenario cover the extreme developments and mark the lower and upper boundaries of the 'actual' future technology development; a trend scenario describes a moderate but likely development of aircraft technology levels. FIG 2 gives for the three different scenarios a range of possible technologies that could be integrated into new aircraft. An increasing CO2 reduction potential (horizontal axis) is in general linked to an increased technology risk (vertical axis).

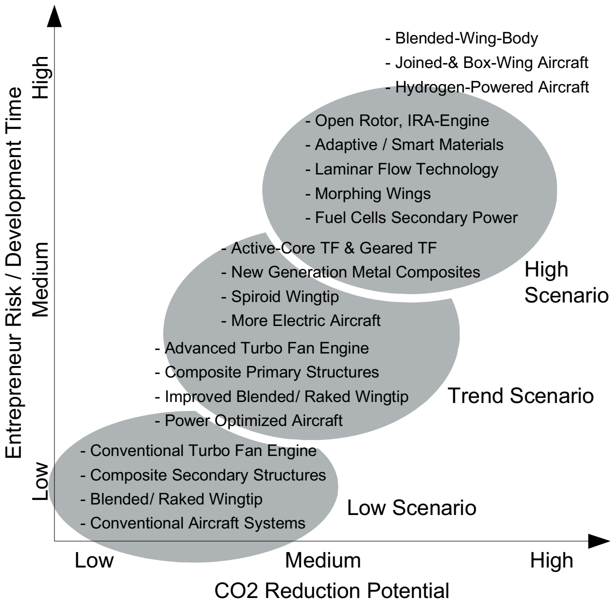

FIG 2. Potential Technologies for Three Different Scenarios (see below)

The story of the scenarios is summarized in the following:

<u>Pessimistic Scenario</u>

Due to adequate technology being unavailable, immature or too expensive, the successors to the 737 and A320 families will not be able to realize a reduction of 20 % in seat fuel. Manufactures decide to stick with the existing models, fostered by continuously high orders and the chance to avoid the financial risk of a completely new aircraft development. Similarly, the major manufacturers' development of long-range aircraft is assumed to be cancelled. While Boeing continues selling the 777 and 747-8, the A350-1000 and A380 remain the only Airbus competitors. Airbus keeps selling the A330-300. The COMAC 919 is released according to plan in 2016 showing similar fuel burn to the current A320.

<u>Optimistic Scenario</u>

The best possible fuel consumption reduction technologies will be the manufacturers' choice. To accomplish this strategy, they are willing to implement also radical and high-risk design changes, such as a forward swept wing for natural laminar flow, open rotor designs and recuperative engines. In accordance with the Airbus statement in [11], fuel burn of the new narrow-body aircraft shows a reduction in excess of 30 %. Each variant of the A30X and Y1 families features a seat-fuel reduction of 35 % compared to its respective predecessor. The new long-range aircraft are assumed to be the first aircraft to achieve the ACARE Vision 2020 goal of a 40 % fuel reduction over the 777 (A340 and 777 replacements) and over the 747-400 (747 replacement) through advanced airframe and engine technology. The COMAC 919 shows fuel consumption similar to the 150-seat A30X variant.

<u>Trend Scenario</u>

Manufactures make business as usual and continue implementing technological innovations at a modest scale to not risk high development cost and low customer acceptance. This implies rather evolutionary than revolutionary technologies. However, the minimum fuel reduction requested by aircraft operators for the A320 and 737 replacements is achieved. Each variant of the A30X and Y1 families thus features a seat-fuel reduction of 20 % compared to its predecessor. The efficiency of conventional technologies is assumed to have slightly increased from the 787 and A350 when the new long-range aircraft are introduced in the late 2020s. While the 787 and A350 show a seat-fuel advantage of around 20 % over the A330 and 777, this is increased to 25 % for the 777/747 and A340 replacements. Similar to the ARJ21, the intent behind building the COMAC 919 is assumed to be the establishment of a stable Chinese aircraft industry rather than to build revolutionary fuel-efficient aircraft. It is assumed that due to the company's experience to build the ARJ21, a seat-fuel reduction of 15 % compared to the current A320 is possible.

TAB 2 gives an overview over the future aircraft and their fuel burn reduction for the three different scenarios on a long-term perspective.

TAB 2. Reference Aircraft and Seat Fuel Burn of Future Aircraft with Medium- to Long-term EIS

Future A/C	**Reference A/C**	**Seat Fuel Burn to Reference according to Scenarios:**		
		Low	**Trend**	**High**
A30X	A320 Fam.	Cancelled	-20 %	-35 %
Y1	737NG Fam.	Cancelled	-20 %	-35 %
A340 Suc.	777 ER Fam.	Cancelled	-25 %	-40 %
777 Suc.	777 ER Fam.	Cancelled	-25 %	-40 %
747 Suc.	747-400	Cancelled	-25 %	-40 %
COMAC 919	A320	±0 %	-15 %	-35 %

Finally, FIG 3 summarizes entry-into-service and end-of-production years that are adopted for the study at hand and plots them along a time bar for a short, medium and long-term perspective.

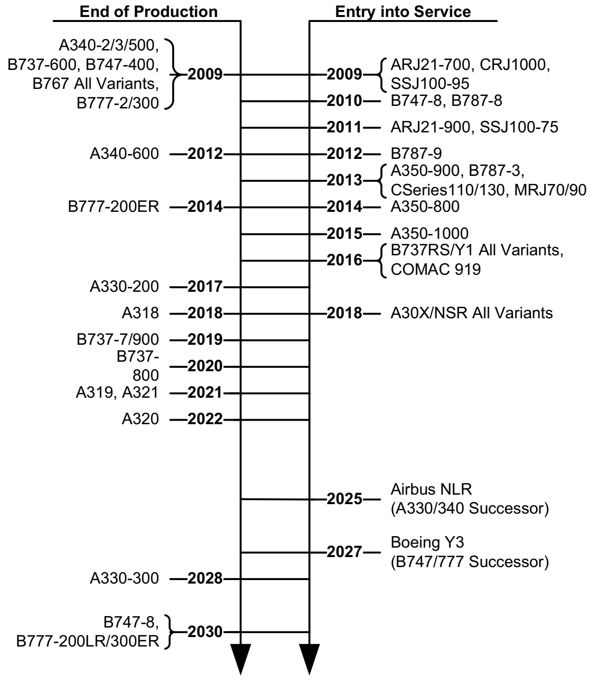

FIG 3. Assumed Entry-into-Service and End-of-Production Dates of Aircraft

2. FLEET FORECAST

After examining the individual CO2 emission potentials of new aircraft, it is necessary to analyze the previous findings within a global scope in order to assess the future over-all 'carbon footprint' of aviation.

2.1 Process Overview

Global CO2 emission is dependent on the number of active aircraft in the world fleet, their utilization and their individual CO2 emission, i.e. their individual fuel consumption and the type of fuel used.

A methodology is developed, shown in FIG 4, to project future global CO2 emissions. First, the size of today's world aircraft fleet is determined, focusing on commercial, turbo-fan powered aircraft, which account for the vast majority of air transportation at date [12]. Second, a fleet size forecast is established on the basis of a consensus-based ICAO forecast (FESG forecast). With respect to the current global economic downturn, the growth rates for the first decade are re-adjusted downwards. Third, based on an extensive literature research, assumptions for future retirements and consequent replacements, the emergence of new aircraft, the phase-out of current models and future market shares are computed. This results in a forecast of the size and make-up of the passenger world fleet up to the year 2036. In Chapter 3, by applying the transport performance and fuel consumptions for current and future aircraft, the CO2 emission of global aviation for this time frame will be assessed.

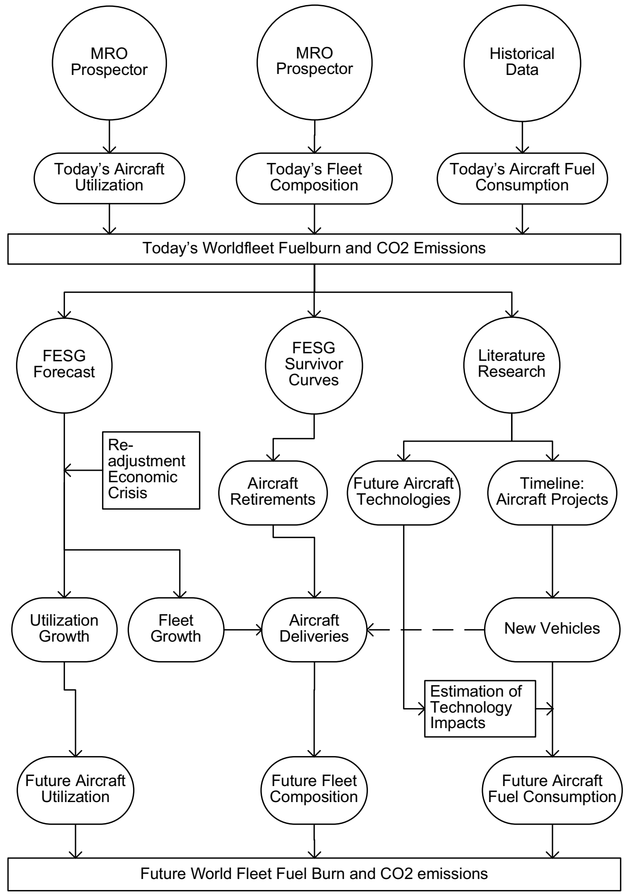

FIG 4. Schematic of the Approach to Computing Future World Fleet CO2 Emissions

2.2 World Fleet Growth

An independent forecast on future fleet growth is issued by the Forecasting and Economic Support Group (FESG) to the Committee on Aviation Environmental Protection (CAEP), which is a working group of the International Civil Aviation Organization (ICAO). At regular intervals, the FESG prepares a 'consensus-based' forecast for the next twenty to thirty years. For the study at hand, the most recent FESG forecast [3] is used. It represents a balanced approach to combining the forecasts from Airbus, Boeing, General Electric, ICAO and Rolls Royce. They all feature an identical time scope from 2006 to 2026 which was extended by the FESG by ten years up to 2036. The FESG forecast features growth rates for nine generic aircraft seat categories: 20-50, 51-100, 101-150, 151-210, 211-300, 301-400, 401-500, 501-600 and 601-650 seats. For the study at hand, the real aircraft are assigned to these categories according to their average seat capacity [28].

The number of active aircraft in the world will change with the demand for air-traffic, usually with a short time-delay. Even though a downturn in air traffic will not lead to an immediate cancellation of all aircraft orders and deliveries or retirements, as airlines are planning acquisitions of new aircraft in the long term, it will however reduce future orders and thus slow down fleet growth. For the study at hand, FESG growth rates are re-adjusted strongly downwards for the years 2009 to 2011 and slightly downwards for the years 2012 to 2016. This has been done in orientation towards the readjusted OAG fleet forecast [4].

TAB 3 gives the total number of active aircraft for each capacity class in 2008 and the expected annual growth for each decade. The original FESG growth p.a. was calculated from the absolute 'number of aircraft' given for 2006, 2016, 2026 and 2036 in [3] assuming an exponential growth over ten years. For the category of 501 to 600 seats, an exponential curve does not seem to be applicable due to the small initial fleet size of only five aircraft. A linear growth shows more realistic results and is thus applied. The conclusive growth of the pre-defined world fleet model up to the year 2036 is shown in FIG 5.

TAB 3. Annual Fleet Growth Rates as Applied to the Generic Seat Categories

Seat Category	51-100	101-150	151-210	211-300	301-400	401-500	501-600
Active Fleet of Base Year (2008)							
	1452	6318	3635	1961	899	132	5
Fleet Growth p. a. [%]							
2009-2011	2.48	0.62	1.17	1.07	1.20	2.45	1.98[3]
2012-2016	7.43	1.87	3.51	3.20	3.59	7.34	5.93[1]
2017-2026	4.04	2.13	3.16	3.88	4.54	8.92	18.7[1]
2027-2036	3.31	2.09	2.84	3.87	4.76	6.13	63.1[1]

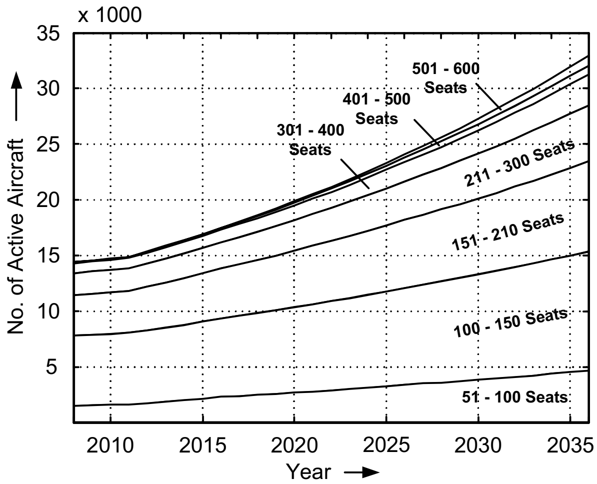

FIG 5. Expected Growth of the Pre-Defined World Fleet of Passenger Aircraft

2.3 Aircraft Retirements

New aircraft will not only enter the market to service traffic growth but also to replace old aircraft. Reasons for the retirement might be a more efficient aircraft entering the market, stricter airworthiness requirements that lead to high maintenance costs, low passenger acceptance, a change in the route network of the airline, etc. An aircraft may change the operator several times during its life or finally be converted to an all-cargo aircraft. For our study of passenger aircraft, it is important to expand the definition of retirement also on freighter conversions. Although freighter conversions are subtracted from the passenger aircraft fleet and thereby reduce CO2 emission, they continue being in service and emitting CO2.

The typical useful life of an aircraft today is around 25 to 35 years. However, assuming a fixed specific age, say 30 years, to forecast aircraft retirement would misrepresent reality. A more accurate method to predict aircraft retirements is the one applied, using 'aircraft survival curves' (FIG 6). Survival curves plot the percent of still active aircraft (that originate from a specific year of delivery) over time. Historical retirement recordings show that real world survival rates are represented reasonably accurate [13]. For the study at hand, aircraft survival curves defined by [14] and [3] are used to forecast aircraft retirements. The curves are calculated from

(1) $S = A + B \cdot t + C \cdot t^2 + D \cdot t^3 + E \cdot t^4$

using coefficients A to E given in [15]. The coefficients are based on year-end 2006 fleet data and historical retirements up through 2006 [15]. According to [3], active and future aircraft fleets can be assigned to four different survival curves. As can be seen from Group 1 in FIG 6, which the vast majority of aircraft fleets are assigned to, the large part of aircraft is retired between the ages of 25 to 35 years, with a yearly rate of 4-5% of the original fleet. 20% of the original fleet is retired prior to the age of 25 and again the same amount after the age of 40. Only the future survival of DC10, B707, B727 and MD11 aircraft fleets need to be calculated separately. Note that the MD11 curve is mainly accounting for freighter conversions.

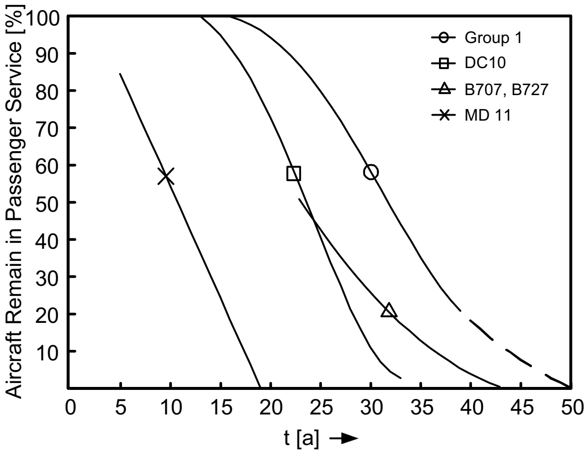

FIG 6. Assumed Aircraft Survival Curves for the Calculation of Future Aircraft Retirements

For the study at hand, it is assumed that airlines will replace a retired aircraft with an identical one if the model is still in production. Retirements of out-of-production models however increase the worldwide demand for new aircraft: All in-production models that belong to the same seat category are treated as potential replacements. The final decision for a certain model is thus depending on the market shares.

3.4 Market shares

Market share is a measure of how dominant a company or product is in its industry or product category. It is given as the proportion of the total available market that is serviced by the company. For the fleet forecast at hand, an estimation of future market shares is needed to estimate the penetration of the market by the different aircraft models. Market shares can be estimated from the number of expected deliveries per aircraft type given in the current aircraft order book in [12] and the *Traffic & Fleet Forecast*

[3] Linear Annual Gradients

2008-2030 in [2]. This approach is schematically shown in FIG 7.

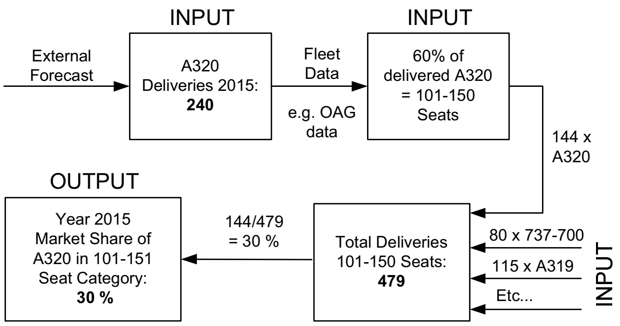

FIG 7. Schematic of Computing Market Shares from Expected No. of Deliveries given in [2] and other Forecasts

However, [12] and [2] do not include information on all considered aircraft. Further assumptions are necessary, especially for the calculation of market shares of the new regional aircraft (AVIC ARJ, Mitsubishi MRJ, Sukhoi SSJ, etc.) and the new large long-range aircraft of Airbus and Boeing. It is assumed that market shares of similar aircraft tend to be identical under normal production conditions (after ramp-up). It is also necessary to have a closer look at production ramp-ups and phase-outs when new configurations succeed today's models, e.g. A320 → A30X and B737 → Y1. The transition time from the first delivery of a new model to the last delivery of its predecessor is estimated from historical data of similar aircraft successions [26].

With the beginning of the forecast, the following aircraft models are out of production and do not hold any shares within the aircraft entering the market:

- Airbus: A300, A310, A340-2/3/500
- Boeing: B717, B727, B737-2/3/4/500, B747-1/2/3/400, B757, B767, B777-2/300 (only normal range variants)
- Others: BAe146/AvroJet, DC9, DC10, MD11, MD80, MD90, Fokker 70/100

3.5 Results: Future Fleet Composition

The following figures show the projected world fleet make-up for regional aircraft (FIG 8), narrow-body aircraft (FIG 9) and wide-body aircraft (FIG 10) from 2009 through 2036.

It is shown that new aircraft work their way only slowly into the world fleet and that a large share of currently active aircraft will probably still be in service many years from now. As the results provide the absolute number of aircraft active per year and type, it is now possible to calculate CO2 emission and transport performance of the global fleet given that fuel burn and utilization of the individual aircraft is known.

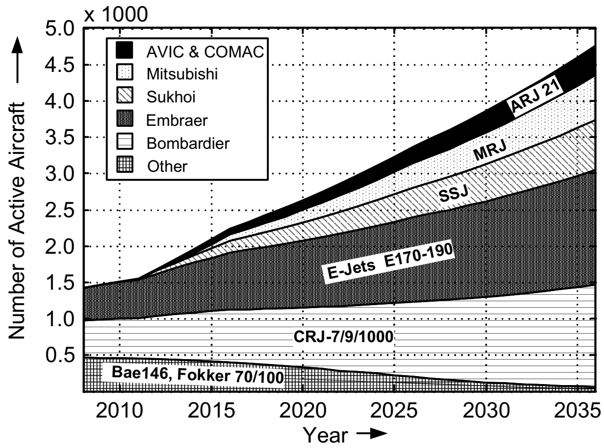

FIG 8. Make-up of the Future World Fleet of Regional Jet Aircraft 2009-2036

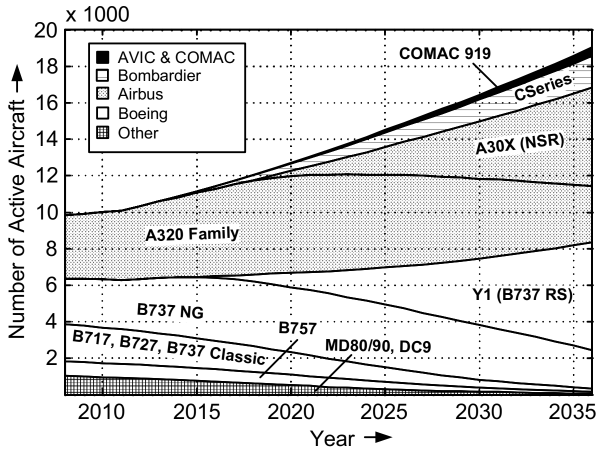

FIG 9. Make-up of the Future World Fleet of Narrow-Body Aircraft 2009-2036

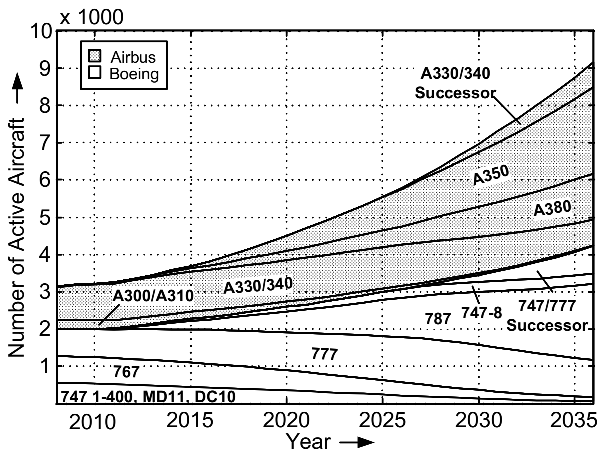

FIG 10. Make-up of the Future World Fleet of Wide-Body Aircraft 2009-2036

3. CO2 EMISSION FORECAST

3.1 Methodology

An aircraft's respective share in global CO2 emission is dependent on the single aircraft's typical fuel consumption per unit time and its typical time in use, i.e. the aircraft's utilization. If alternative fuels are considered, it will be further a function of the fuel's specific carbon dioxide emission (SCE), which is the amount of CO2 emitted per kg fuel burned.

The average mass of CO2 emitted daily from a single active aircraft in the global fleet can be approximated from

(2) Daily Aircraft CO2 Emission = $BF \cdot U_d \cdot SCE$

where BF is the average fuel consumption per block hour and U_d is the average daily utilization (block hours per day). Block fuel weight increases with aircraft weight and flight distance and decreases with aerodynamic and engine efficiency. To compare aircraft of different sizes and ranges, it is necessary to calculate fuel burn per seat-km. If block speed, fuel burn per block hour and average capacity are known, this is possible using following equation.

(3) $SFB = BF/(v_b n_S f_L)$

where v_b is the block speed, n_S is the seating capacity and f_L is the load-factor. Seat fuel burn SFB is not only a function of the fuel consumption per unit time, but also of the block speed – i.e. cruise speed and range – and the ratio of sold to available seats.

In most cases, average block speed and fuel burn is adopted from historical fleet data of the last ten years (on a yearly basis) using published sources, see [16 - 26].

Given that there are no technology changes to the aircraft, block speed and fuel burn of currently active aircraft are taken as constant during the timeframe of the forecast. This assumes future flight distances (of a single aircraft family) to be relatively consistent with historic data. Even though this corresponds to the assumptions made in a similar fleet forecast in [27], a more detailed analysis would be needed to justify this approach.

The average seating capacity per aircraft type is calculated from OAG data for the year 2008 [28]. The average of available seats per aircraft type for all scheduled flights in 2008 is taken to be the respective fleet average.

Average daily utilization can be determined from single aircraft data given in the MRO Prospector [12]. Dividing the total number of block hours by the number of days in service gives the average daily utilization U_d.

The operational performance of future aircraft is adopted from similar existing aircraft. Block speed v_b and daily utilization U_d are dependent on the cruise speed and the average distance flown. It is assumed that existing and future aircraft showing similar cruise Mach numbers and design ranges feature identical block speeds and identical daily block hours. Excepted are the 787 and A350 aircraft families. These show increased cruise Mach numbers and design ranges from currently active aircraft. Block speeds for all variants of both 787 and A350 are adopted from [17]. These are in reasonable accordance with the increase in speed and range. For all future aircraft, the relative deviation of average seat capacity from nominal seat capacity is taken to be identical to a comparable reference aircraft.

For the study at hand, FESG estimations concerning future utilization growth are adopted for the years 2012 to 2036. In accordance with [3], it is assumed that average aircraft utilization per aircraft type experiences a total increase of 5 % by 2026, and a total increase of 6% by 2036. Growth in between is assumed exponential. As air traffic is currently affected by a significant economic crisis, utilization in 2009 is expected 4 % lower than the aircraft utilization in 2008. Utilization is expected to remain low (at 2009 level) also for the following two years. In 2012, air traffic is expected to have recovered and a daily utilization according to FESG estimations is applied. This affects all aircraft considered.

3.2 Base Forecast: Impact of Technology Improvements on Future Aircraft

This chapter shows results for a base forecast of future global CO2 emissions. The forecast is based on the assumption that changes to the fuel/CO2 efficiency of the global air traffic system stem from technologically advanced future aircraft only. Neither technological nor operational measures with the capability to provide benefits to existing aircraft or to existing aircraft programs are considered. This forecast is elementary as it allows simulating the potential impact of instruments that have a fleet-wide impact in the next chapter. For this forecast, all aircraft are assumed as kerosene-powered. As single aircraft block fuel burn is set, global fuel consumption and CO2 emission per day can then be calculated from

(4) World Fleet Fuel Consumption = $\sum_{j=1}^{n_{A/C}} (U_d BF)_j$ and

(5) World Fleet CO2 Emission = $\sum_{j=1}^{n_{A/C}} (U_d BF \cdot SCE)_j$

where $n_{A/C}$ is the number of aircraft in the world fleet and SCE is that of kerosene, i.e. 3.15 (kg CO2 per kg kerosene). Global air traffic per day is calculated in available seat kilometers (ASK) from

(6) Air Traffic (in ASK)= $\sum_{j=1}^{n_{A/C}} (U_d v_b n_{Seats})_j$

The development of fuel burn or CO2 emission per seat-km can easily be calculated from dividing the outcome of equation (4) or (5) by global daily air traffic, i.e. by the outcome of equation (6). The reciprocal of seat fuel burn, i.e. ASK per kg fuel, is generally called global fleet fuel efficiency.

3.2.1 Results

Long-term developments with respect to the different scenarios are shown in FIG 11. For all scenarios, air traffic (ASK) is expected to have nearly increased threefold by the end of the forecast in 2036. Unsurprisingly, the pessimistic scenario shows the highest increase in fuel consumption and CO2 emission (258 %) and the optimistic scenario the lowest (231 %). Fuel consumption has increased to 244 % of the 2008 value for the trend scenario. Interestingly, the curve of fuel consumption for the optimistic scenario remains nearly attached to the curve of fleet size. This indicates a constant average daily fuel consumption (and CO2 production) per aircraft in service with increasing transport performance (ASK).

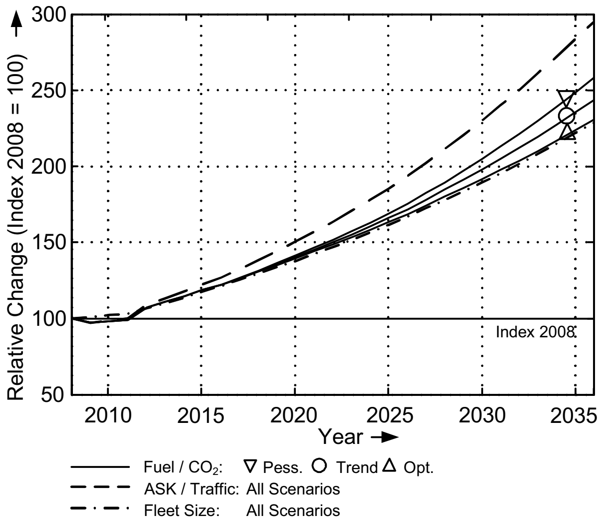

FIG 11. Base Forecast 2009-2036: Relative Growth from Base Year 2008

Annual average growth rates are shown in TAB 4. In between 2009 and 2016, as a result of the economic crisis, growth rates are rather low. This is not beneficial for the economy, but favorable to the global emission of CO2, which grows with only 2.6 % p.a. in average. Under normal circumstances (2017-2036), air traffic grows by around 4.3 % p.a., CO2 by at least 3.23 % p.a. (optimistic scenario).

TAB 4. Annual average Growth Rates of Fleet Size, ASK, Fuel/CO2 and Seat Fuel/CO2

Time Span	Parameter	Annual Average Growth Rates		
		Low	Trend	High
		[%]	[%]	[%]
2009-16	Fleet Size	2.47	2.47	2.47
	ASK (Traffic)	3.06	3.06	3.06
	Fuel/CO2	2.60	2.59	2.58
	Seat Fuel/CO2	-0.45	-0.46	-0.46
2017-26	Fleet Size	3.23	3.23	3.23
	ASK (Traffic)	4.27	4.30	4.30
	Fuel/CO2	3.66	3.45	3.27
	Seat Fuel/CO2	-0.59	-0.81	-0.99
2027-36	Fleet Size	3.20	3.20	3.20
	ASK (Traffic)	4.21	4.32	4.32
	Fuel/CO2	3.95	3.56	3.19
	Seat Fuel/CO2	-0.26	-0.73	-1.08
2009-36	Fleet Size	3.00	3.00	3.00
	ASK (Traffic)	3.91	3.95	3.95
	Fuel/CO2	3.46	3.24	3.04
	Seat Fuel/CO2	-0.43	-0.62	-0.87

The advance in world fleet fuel efficiency for the different scenarios is easier to observe from FIG 12, showing the development of average fuel consumption of the world fleet in liters per seat and 100 km. Seat fuel consumption in 2015, before the curves of the scenarios separate, is around 3 % lower than in 2008.

The curve for the optimistic scenario reaches an average of 3.0 liters per 100 km in 2031 for the first time, while the curve for the trend scenario is at 3.01 liters in 2036. While it seems that the world fleet of the pessimistic scenario would reach its maximum in efficiency prior to crossing an average of 3.2 liters per seat and 100 km (due to the absence of new aircraft models), lowest seat fuel burn for the trend and optimistic scenario is expected to come in considerably lower than 3.0 liters. The old A320 and 737 NG families alone still feature fleets of more than 5000 aircraft in 2036 (around 16 % of the world fleet) that are likely to be replaced by the A30X and Y1 in the future.

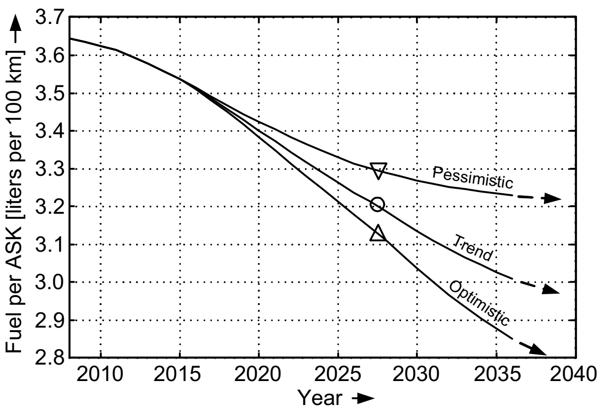

FIG 12. Base Forecast 2009-2036: Development of Global Average Seat Fuel Burn: Pessimistic, Optimistic and Trend Scenarios. * Average Seat Capacities, Kerosene Jet A-1

3.2.2 Comparison to Major External Forecasts

Prior to the year 2000, technological improvements have resulted in an average 1 - 2 % increase in fuel efficiency per year for new production aircraft [7]. In 1999, the IPCC adopted a forecast of the International Coordinating Council of Aerospace Industries (ICCAIA) saying that, if engine manufacturers continue focusing on improvements in specific fuel consumption (SFC), the annual efficiency improvement for new production aircraft will be 0.95 % between 1997 and 2015, and 0.57 % between 2015 and 2050 [7]. Recently, the ICCAIA has set up a new estimate, consisting of two new scenarios. ICCAIA's new scenario 'A' assumes that the intensive current and future research efforts produce an average 0.96 % annual improvement through the year 2050. Its new scenario 'B' requires even higher research commitment and effort than scenario A, and assumes that ambitious EU and US research projects will be funded and successful: an annual improvement of 1.16 % would then be achievable [29].

FIG 13 shows the future development of fuel efficiency of new production aircraft for the different ICCAIA scenarios and the three scenarios of the base forecast. The average annual improvement is 0.84 % for the trend base scenario, a value in between the assumptions of the 1999 IPCC scenario and that of the new ICCAIA scenario A. For the high base scenario, the annual improvement is 1.26 % and thus reasonably similar to the ICCAIA scenario B. In both trend and high scenarios, the impact of the new short-range and new long-range aircraft is clearly observable. Contrary, the low base scenario shows no improvement beyond 2015 due to the absence of new aircraft. In the years prior to 2015, impacts are mainly due to the introduction of the Boeing 787 in 2010, and the Airbus A350 and Bombardier CSeries in 2013. Disregarding the pessimistic forecast, projections of future aircraft fuel efficiency show high resemblance to the ICCAIA scenarios.

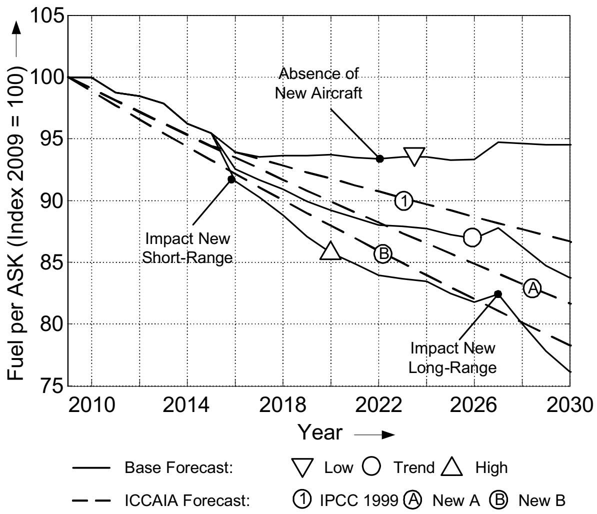

FIG 13. Base Forecast 2009-2030: New Production Aircraft Fuel Efficiency Scenarios

Note that there is a similarity not only in the results but also in the definitions of the base and ICCAIA scenarios. More precisely, both the ICCAIA scenario A and the base trend scenario assume an evolutionary technological advance, while the ICCAIA scenario B and the base high scenario assume revolutionary technologies on-board future aircraft and a broad success for ambitious research projects. This reinforces our assumption of the trend forecast modeling the most realistic case. Both ICCAIA scenarios and FESG fleet growth rates have also been used to model the recent ICAO CO2 forecast [30]. The ICAO forecast can be regarded optimistic, as it adopted the 'high technology scenario' (scenario B) of the ICCAIA and did not re-adjust the basic FESG forecast with respect to the economic crisis.

3.2.3 Consequences

As the IPCC [7] writes, "Although fuel efficiency has increased steadily over the past few decades, improvements in fuel efficiency are becoming less dramatic over time". This is due to conventional aircraft technology maturing to efficiencies where improvements are possible only on a small scale. If historical improvements in fleet fuel efficiency should be continued, more radical technological changes – see e.g. the ICCAIA and base forecast 'high technology scenarios' – are necessary. Even though such high annual improvement rates for new aircraft could be achieved, the presented results indicate clearly that the process of increasing over-all fleet efficiency through the continuous, but rather slow replacement of old aircraft by more efficient ones is not sufficient to stabilize or even lower the over-all carbon footprint of aviation.

Nevertheless, increases in over-all fuel efficiency have traditionally not only come from the introduction of new type of aircraft. In the base forecast, we have disregarded several other measures that have historically provided the fleet with further fuel savings. Most importantly, these are advances in air traffic management (ATM) and operations. Further, existing aircraft and existing production lines have occasionally been updated with new technology. All of these instruments will also help to increase fleet fuel efficiency in future.

The future fuel benefit from advances in ATM technology is however assumed rather small. Today, the world's air traffic environment is already between 92 to 94 % efficient [31] [27]. The long-term goals of the Civil Air Navigation Services Organization (CANSO) see system efficiency between 95 to 98 % in 2050, equal to a total increase of 4 % from the level of 2008 [31]. This calculates to an additional annual improvement in fleet fuel efficiency of 0.1 % between 2009 and 2050. In 2036, the air traffic environment would then be about 2.8 % more efficient then it is today, even though the net benefit in terms of increased capacity will be considerably higher. This has been strongly different in the past: a 4 % ATM efficiency improvement has been achieved only between 1999 and 2005 [30]. The low future benefit is due to the system being already highly efficient and further, due to a strong traffic growth. Air traffic control will have to cope with a continuously increasing traffic density and simultaneously lower fuel consumption on individual flights. Even keeping up to current efficiency levels will then be manageable only with large changes to the ATM system [31]. The European and US airspace might hold a slightly higher potential for improvement, as due to already dense en-route and terminal areas, ATM efficiency today is lower than the average worldwide.

Similar is true for future benefits from operational improvements. The IATA has carried out a survey on possible future operations that hold a potential to lower fuel consumption. The full implementation could lead to an average 5 % fuel saving for the world fleet [30]. If we assume the operations to be fully implemented in 2036, this yields in about 0.17 % additional annual fuel reduction in the time horizon of the fleet forecast.

It is theoretically possible to improve the fuel consumption of individual, already existing aircraft by a technology retrofit. Retrofits incorporate R&D costs and purchasing costs for the operator. The expected cost savings from burning less fuel need to outbalance these costs to allow for an economically sound implementation. Wingtip technologies (e.g. winglet retrofits) are assumed to provide the highest retrofit potential [32]. However, wingtip devices need to be individually designed and certified for the respective aircraft. This is generally true for every retrofit that affects the flight performance of the aircraft. A commercially viable implementation is hence imaginable only for aircraft models that feature large world fleets. Due to their small impact, it is assumable that retrofits will play a minor role in increasing the average world fleet fuel efficiency of the future compared to other approaches. Nevertheless, they may increase the profitability of existing aircraft for individual airlines.

While retrofits are limited to technologies that result in rather small efficiency increases, existing aircraft programs may be updated with innovations that are more relevant. This includes for example the possibility of an update to an entirely new engine or even material changes to major structural parts [32]. Some of the most dominate fleets in terms of global fuel consumption in the forecast at hand are the fleets of the A320, 737NG and 777, which are all assumed to be in production with high market shares for at least one decade. Improvements to the existing production lines of these models could thus play a considerable role in reducing world fleet's CO2 production.

As both Airbus and Boeing continue postponing a replacement aircraft to the A320 and 737NG families [33], a re-engineered version could become even more important in terms of increasing fleet fuel efficiency. Similar is true for the regional jet market (Bombardier CRJ and Embraer E-Jets), where only the Mitsubishi MRJ is expected to offer significant fuel savings. The benefit of technology updates to existing production lines are however hard to capture in the forecast at hand, as it cannot be foreseen, which technologies are applicable to certain aircraft without considering a complete redesign. In history, the benefit over an existing model has been rather small. For example, the A320 was launched with the CFM56-5A engine and is now produced with the improved CFM56-B, which offers a 3 % fuel burn advantage over the earlier version [34].

Not considering retrofits and updates to existing production lines, the forecast at hand suggests a maximum achievable increase in fleet efficiency of 1.3 % annually using traditional technological and operational measures (high technology scenario). This is however only true for the years 2017 to 2036, after the air traffic industry has completely recovered from the current economic downturn. In the preceding time span 2009-2016, annual improvement rates of only 0.73 % are projected (including benefits from advanced ATM and operations).

Finally, there are approaches to improving fleet CO2 efficiency that go beyond traditional schemes. Some ideas are briefly discussed in the following chapter.

3.3 Alternative Approaches to CO2 Reduction

Beyond traditional instruments to increase fleet fuel efficiency, alternative approaches could considerable reduce global CO2 emissions in the future. Currently widely discussed is the use of so-called ‘bio’-fuels. Further, independent of technological advances, rethinking the lifetime of both aircraft and their respective programs may also hold high potential.

3.3.1 Using Bio-Fuels

There is the plan to use so-called ‘bio’-fuels to diminish the over-all carbon footprint of aviation. In this context, bio-fuels term fuels that are derived from plant products. Burning fuel that is made of plants does not necessarily lower the amount of carbon dioxide emitted on the local, i.e. aircraft level. These fuels are considered less CO2-effective as the plants absorb carbon dioxide from the atmosphere while growing, which is said to offset the CO2 emitted by the aircraft engines. In theory, there are several kind of bio-fuel that are assumed being technologically mature enough in the next decade to be used as a drop-in aviation fuel [35 - 38]. Today, major unknowns concern the feasibility of growing sufficient feedstock to produce a cost-effective fuel for wide application. Although 2nd and 3rd generation bio-fuels promise to need much less farm land than today’s fuel crops [35], it is still highly uncertain to which maximum quota bio-fuels can replace classic kerosene in aviation and how fast this quota will be reached.

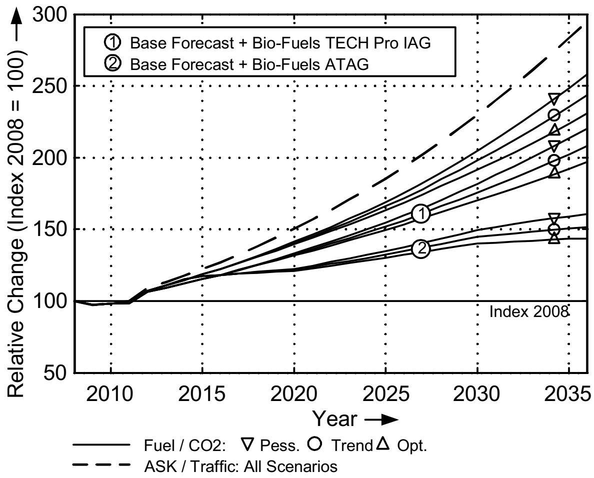

FIG 14. Base Forecast + Bio-Fuels 2009-2036: Relative Growth from Base Year 2008

The impact of two different scenarios is plotted FIG 14. The first scenario is based on assumption adopted from the TECH Plus scenario of the International Energy Agency (IEA) [39]. It assumes that bio-fuels hold a share of 25 % of total fuel consumed in the transport sector in 2050. The share is expected to increase linearly between 2010 and 2050. An alternative, highly optimistic scenario is adopted from a document of the Air Transport Action Group (ATAG) [35]. The scenario assumes a bio-fuel share of 1 % in 2015, 15 % in 2020, 30 % in 2030 and 50 % in 2040. The rate of increase in the years in between is taken as linear. The life-cycle CO2 emission of the bio-fuel is assumed 10 % that of kerosene, which is according to the current expectations for a 2nd or 3rd generation bio-fuel that is produced using renewable energy [32] [36] [27]. For both assumptions, the remaining share in fuel burned is assumed kerosene.

As observable, bio-fuels have theoretically a large potential to lower the CO2 emission of air traffic. The most distinct advantage of bio-fuel over conventional aircraft technology is its ‘backward compatibility’. If the blended fuel’s characteristics are similar to kerosene, it can be used on both new and old aircraft. As the market penetration with bio-fuel is thus independent of the introduction of new aircraft, benefits show immediately. For the best case, where the optimistic scenario concerning new aircraft and the ATAG scenario of bio-fuels (numbered ‘2’ in FIG 14) fall together, global CO2 emissions remain below the original 2020 emission level for nearly the entire forecast, even though air traffic shows a strong continuous growth.

Besides noticing the high potential of bio-fuels, it must be stressed that forecasts concerning their influence on global CO2 emission hold large uncertainties. Even though the bio-fuel roadmap of ATAG assumes considerably larger bio-fuel quotas, already a 25 % share in global transport fuel consumption by 2050 (according to the TECH Pro Scenario) is considered a highly optimistic forecast by the IAG [39]. In the end, the feasibility of providing large CO2 benefits for the air traffic system using bio-fuels will depend on the outcome of current research into finding and cultivating appropriate feedstock. The fact that for a considerable reduction in life-cycle CO2 emission, feedstock for both the fuel itself and its production must be of renewable nature [36], makes this task even more important.

3.3.2 Shortening Aircraft Production Runs

It is shown in FIG 13 that new aircraft are required in regular intervals to guarantee a continuous improvement of fleet fuel efficiency. Two main parameters set the impact of a new aircraft on the development of fleet fuel efficiency: The year in which the aircraft becomes available to the market and the magnitude of fuel advantage over the aircraft it replaces. The question that remains is which one of these two influencing factors is of higher importance for the goal of reducing CO2 emissions. In other words, is it beneficial to global CO2 emissions to delay new aircraft projects for the sake of implementing better technology?

FIG 15 shows the outcome of a small case study on this matter. An alternative scenario to the base trend scenario has therefore been established, assuming Airbus and Boeing to introduce successor aircraft to the A320 and 737 already five years earlier (2013/2011). Due to the earlier design freeze, these aircraft feature less advanced technology and a seat fuel burn that is by only 15.0 % (instead of 20 % in the trend scenario) lower than the one of their respective predecessor.[4] Further assumptions concerning the new aircraft and the rest of the scenario are identical to the trend forecast.

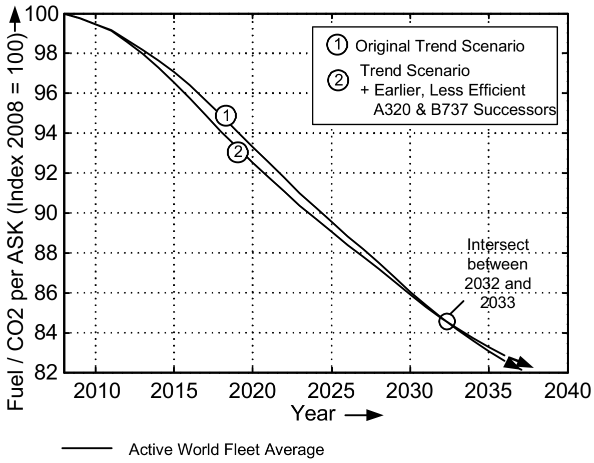

FIG 15. Shortening Aircraft Production Runs: Effect of Earlier A320 and 737 Successors on Global Fleet Fuel Efficiency

The results of this short case study suggest that albeit the ultimate fuel burn advantage over a predecessor is lower, considerable amounts of fuel and CO2 could be saved if new aircraft were released earlier. According to our calculations, the earlier introduction of the new short-range aircraft saves 47.97 million tons of fuel between the years 2011 and 2030. Benefits of an early introduction will sustain only if a follow-up successor model is introduced inside a certain period.[5] The replacement to the first successor needs to show a seat fuel consumption at least as good as the seat fuel consumption of the originally planned aircraft (here Y1 and A30X of the trend forecast).

The advantage of the early introduction is mainly attributed to two fundamental changes in the forecast. First, delivery of the 737 and A320 ends earlier. This prevents the demand for fleet growth to be met with considerably less-efficient aircraft. Second, the new aircraft and not their respective predecessors replace a large amount of out-of-production aircraft. The earlier aircraft release generates something like an ‘efficiency buffer’. The later aircraft release in the original forecast has to first make up for the lost time before its seat fuel advantage can show.

3.3.3 Reducing Aircraft Lifetime

Improvements in the fuel efficiency of new production aircraft translate only slowly to similar improvements in fuel efficiency of the active fleet as older, more inefficient aircraft remain in service for up to 50 years (see FIG 6) Theoretically, the process of fleet modernization could be accelerated by shifting aircraft retirements to earlier ages. This will however only benefit global CO2 if more efficient aircraft are readily available. For a rough estimate of the potential benefit from earlier retirements, an alternative scenario is established that assumes aircraft to be retired ten years earlier than it is presumed from the FESG survival curves in FIG 6. The development of average CO2 emitted per seat-km for the new scenario is compared to the results of the original trend forecast in FIG 16.

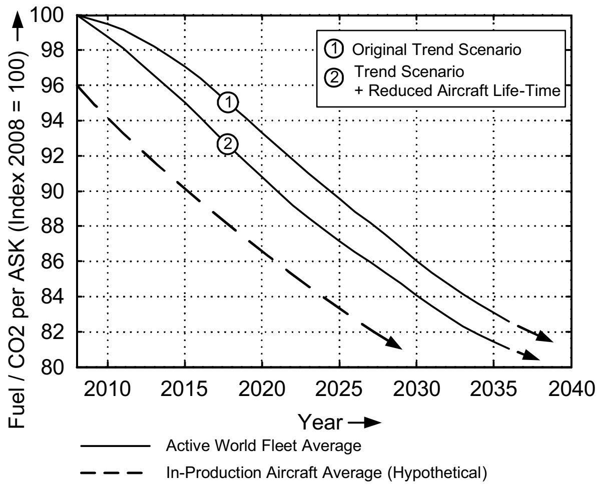

FIG 16. Reducing Aircraft Lifetime: Effect of Earlier Aircraft Retirements (-10 years) on Global Fleet Fuel Efficiency

The case study at hand suggests that reducing average aircraft life can foster the modernization of the active fleet and thereby assist the reduction of CO2 emissions per seat-km. This is however only the case if new aircraft are brought to the market in regular intervals. It is important to realize that earlier aircraft retirements can only accelerate the shift to higher fleet efficiencies. Once the whole fleet consists of the most efficient aircraft available, the curves of the original trend and the earlier retirement scenario show the same fuel burn per seat-km. However, the curve with the earlier retirements will reach this level earlier in time. Moreover, a generally reduced aircraft life could provide benefits that go beyond the ones of an

[4] Each year of further development is thus assumed to generate a seat fuel advantage of an extra 1.0 %, which is in accordance with historical and future annual improvements in fuel efficiency of new production aircraft: see FIG 13.
[5] For the case study at hand, this period is twenty years, which is in accordance with historical periods of a successful production run (15 to 20 years): see [7], chapter 7.2.3.

accelerated fleet turnover. According to [40], reducing aircraft life could allow for lighter primary structures in new aircraft designs and thus for additional fuel savings for the single aircraft and the global fleet. However, not only the operation but also the production of aircraft generates carbon dioxide. If aircraft life expectancy is lower, more aircraft need to be produced in the same period. This could offset the benefit of an earlier reduction in fleet fuel burn. In general, a more detailed long analysis including calculations of aircraft life-cycle CO2 is needed to draw definite conclusions.

4. CONCLUSION

The scope of this paper has been the projection of possible technology implementations on future aircraft and their potential impact on global CO2 emissions. Its main conclusions are:

In the short-term up to the year 2015, we can expect an evolutionary technological development on future aircraft. Most new aircraft will feature primary structures of advanced materials such as composite, improved conventional turbofan engines and new improved high-lift systems and wingtip technologies. The most advanced technology will be a new engine architecture, the geared turbofan, which is expected to enter service on two aircraft in 2013.

In the medium- to long-term of 2015 to 2030, technology implementations cannot yet be defined. However, potential technologies have been identified. The ultimate efficiency improvement will depend on the success of currently ongoing research projects and the readiness of manufacturers and airlines to assume risk of high development cost and time for achieving high benefits.

Despite the current economic downturn, world fleet size and traffic is expected to grow over the next three decades. In 2036, the world fleet size of turbofan-powered passenger aircraft is projected having more than doubled, while traffic is assumed having nearly increased threefold from 2008 levels by that time.

Future aircraft will enter the world fleet to satisfy the increased demand in traffic and to replace aging out-of-production aircraft. Over-all fleet fuel and CO2 efficiency will thereby continue to increase. As however only small fuel benefits are expected from advances in the air traffic environment and operations, it is projected that future aircraft will need to provide radical fuel efficiency leaps for the air traffic system to keep up to historical improvement rates. Traditional means to decrease the fuel consumption per seat-km are forecasted to achieve a cumulative maximum annual efficiency increase of 1.3 % between 2017 and 2036. Long-term effects of the economic downturn are expected to restrain efficiency growth in the preceding years.

Beyond traditional instruments to increase fleet fuel efficiency, alternative approaches could considerable reduce global CO2 emissions in the future. Bio-fuels show a high potential, it is however unclear if a large-scale production will be environmentally, ethically and economically feasible. Independent of technological advances are approaches that aim at re-structuring traditional life-cycles of both aircraft and aircraft programs. It has been found that shifting delivery dates to later years for the reason of achieving further technology improvements does not ultimately have to be the best choice for the goal of reducing global CO2 emission. Both the reduction of aircraft lifetime and shortened aircraft production runs – i.e. earlier implementation of successor aircraft – may however positively affect fleet fuel efficiency.

A carbon neutral growth from e.g. 2020 defines an environmental goal, which aims at a medium term time span and is heavily discussed at date. That is, traffic growth from 2020 is possible without a further growth in global CO2 emission. Under regular economic circumstances, traffic is expected to grow by around 4.3 % p.a. between 2021 and 2036. This calculates to a required average annual reduction in seat-km-specific CO2 of 4.1 % if carbon-neutral growth is to be enabled. Regarding the findings of the CO2 forecast at hand, it is reasonable to state that in the medium-term, annual improvement rates in the necessary order of magnitude are realizable only through the combination of revolutionary fuel-efficient future aircraft with a strongly increasing share of bio-fuels in global fuel consumption.

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