ASSESSING THE IMPACT OF NEW TECHNOLOGIES IN AVIATION USING A GLOBAL AIRCRAFT FLEET FORECASTING MODEL

TOULOUSE, FRANCE / 23 – 25 OCTOBER 2018

Ivan Terekhov [(1)], Thomas Schilling [(2)], Malte Niklaß [(3)], Robin Ghosh[(4)]

[(1)] DLR Air Transportation Systems, Blohmstraße 20, 21079 Hamburg, Germany,
Email: ivan.terekhov@dlr.de
[(2)] DLR, Institute of Maintenance, Repair and Overhaul, Hein-Saß-Weg 22, 21129 Hamburg, Germany,
Email: thomas.schilling@dlr.de
[(3)] DLR Air Transportation Systems, Blohmstraße 20, 21079 Hamburg, Germany,
Email: malte.niklass@dlr.de
[(4)] DLR Air Transportation Systems, Blohmstraße 20, 21079 Hamburg, Germany,
Email: robin.ghosh@dlr.de

KEYWORDS: technologies, aviation, assessment, global aircraft fleet, forecast, modelling, technology roadmap, scenario, CO_2.

ABSTRACT:

The paper presents the global fleet forecast model FFWD which forecasts world fleet fuel consumption and CO_2 emissions. This forecast is based on current demand forecasts, fleet data, retirement curves, expected future aircraft entry into service timelines, and market penetrations. To assess the influence of novel aircraft configurations (fleet renewal) on global CO_2 emissions, a yearly fuel consumption and utilization value is assigned to each active aircraft. For the new aircraft in the fleet, different technology combinations can be modelled, which lead to variations in CO_2 emissions level. Thus, different technology scenarios can be built, where each scenario represents different technology combinations and entries into service. Therefore, the proposed modelling approach allows for an estimation of the future CO_2 level evolution for each technology scenario.

1. INTRODUCTION

All global aviation stakeholders recognize the growing and urgent need for society to address the global challenge of climate change, to which aviation currently contributes around 2% of global man-made CO_2 emissions. In 2009 the aviation industry has committed to a set of ambitious high-level goals to reduce its carbon emissions at a global level (see Figure 1):

- 1.5% average annual fuel efficiency improvement between 2009 and 2020
- Carbon-neutral growth from 2020
- 50% reduction in net CO_2 emissions by 2050 relative to 2005 levels

To achieve these goals, IATA and DLR are working together on a technology roadmap based on a four-pillar strategy which is composed of new technology options, effective operations, efficient infrastructure and positive economic measures, see Figure 1. The technology roadmap aims to identify future aircraft concepts that might reduce, neutralise and eventually eliminate the carbon footprint of aviation.

Evolutionary aircraft technologies, including new engine concepts that can be fixed on classical tube-and-wing aircraft configurations, have the potential to improve fuel efficiency in the order of 30% by around 2030 compared to 2005 (IATA, 2013). For the long-term reduction goal of 50% in net CO_2 emissions by 2050 relative to 2005 levels, evolutionary technology improvements will no longer be sufficient. To fill the gap between evolutionary technology progress and the long-term emission reduction goal, additional radical solutions, such as new aircraft concepts and sustainable energies, have to be introduced to the air transport system with appropriate lead times.

2. TECHNOLOGY DATABASE

A number of aviation technologies are currently under research and development. The technology database was established within the IATA-DLR cooperation based on the updated 2013 Technology Roadmap [1]. To assess aircraft technologies with regard to their fuel saving potential, key performance indicators have to be defined first. The required block fuel, W_f, for a given mission (range, R, and cruise speed, v_c) can be estimated roughly by the Bréguet range equation[1] for cruise flight:

$$W_f = W_0 \cdot \left[1 - \exp\left(-\frac{R \cdot \mathrm{SFC} \cdot g}{v_c \cdot L/D}\right)\right] \cdot \sum_{i=1}^{N} \omega_i \quad \text{(Eq.1)}$$

where the lift over drag ratio (L/D) expresses the aerodynamic efficiency (glide ratio) of the aircraft.

[1] The fuel required for taxiing, climb and descent is relatively small compared to the cruise fuel. Hence, it can be modeled as constant mass fraction $(\omega_i = {}^{m_i}/_{m_{i-1}})$ of the total mission fuel for all flight phases (*i*).

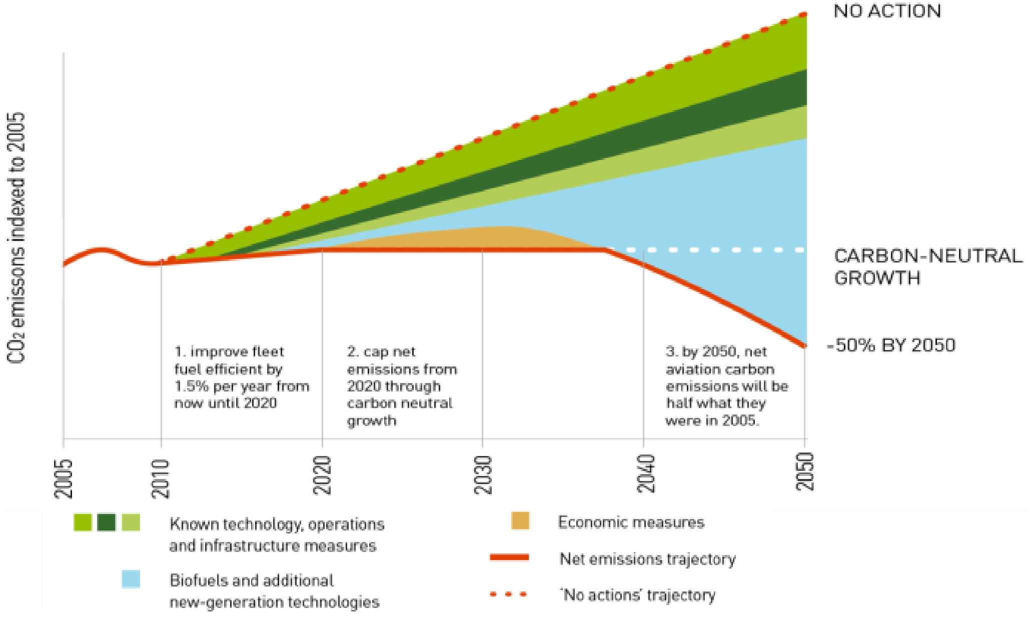


Figure 1: Schematic CO2 emissions reduction roadmap (IATA, 2013).

SFC is defined as (thrust) specific fuel consumption, g as the gravitational constant and W_0 as take-off weight of the aircraft with:

$$W_0 = W_{OE} + W_f \qquad \text{(Eq.2)}$$

where W_{OE} denotes the operational empty weight of the aircraft. From Eq.1 it becomes apparent that the required fuel for a given mission, $m_f(R, v_c)$, can be reduced either by lowering weight and specific fuel consumption or by increasing the aerodynamic efficiency:

$$m_f(R, v_c) \approx \mathrm{SFC} \cdot W_{OE} \cdot \left({}^{L}/_{D}\right)^{-1} \qquad \text{(Eq.3)}$$

The identified three main factors for fuel burn reduction $(\mathrm{SFC}, W_{OE}, L/D)$ are selected as key performance parameters for the following technology assessment. They address the technological areas of propulsion, structures and aerodynamics.
In order to forecast world fleet fuel consumption and CO_2 emissions, a single figure of merit (m_f) is required. Identified key performance parameters are transferred to mission fuel according to Figure 2.

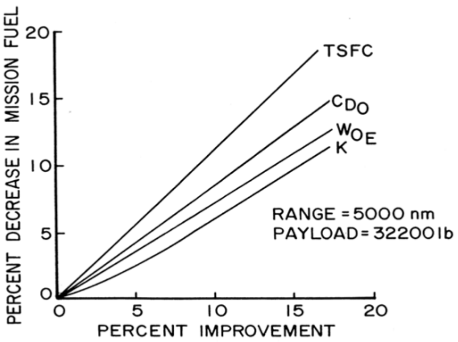


Figure 2: 'Leverage potential' of identified key performance indicators on fuel consumption [2].

Snowball effects[2,3] might amplify improvements of thrust specific fuel consumption (TSFC) to a leverage factor slightly greater than one. Improvements in aerodynamics impact fuel burn reduction in two ways, first reducing zero-lift drag (C_{D0}) with leverage factor close to one and second via a reduction of lift induced drag(k). The leverage factor of weight reductions (W_{OE}) is between those of C_{D0} and k [3]. The representation of the key performance indicators for the assessment of airframe and engine technologies and the final figure of merit mission fuel are presented in Figure 3.

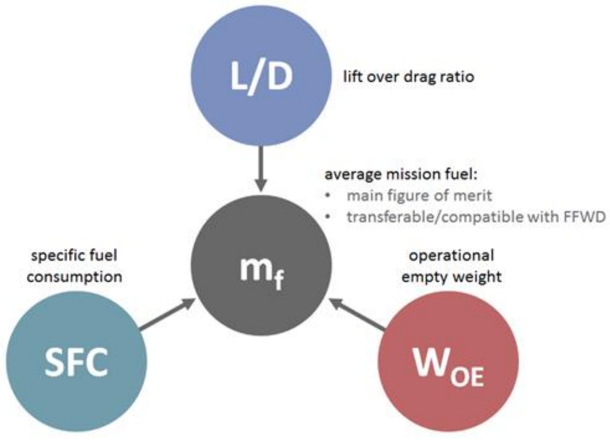


Figure 3: Key performance indicators for the assessment of airframe and engine technologies and the final figure of merit mission fuel.

---

[2] TSFC reductions result in a decrease of fuel burn and take-off weight (W_0). This leads to a reduced thrust demand and, hence, to a reduction of SFC.

[3] Even though leverage factors might vary between short- and long-haul aircraft, the average values for medium-haul aircraft (range 5000nm, payload 32200lb) shown in Figure 2 are assumed to be sufficiently precise for relative considerations for the purpose of this analysis.

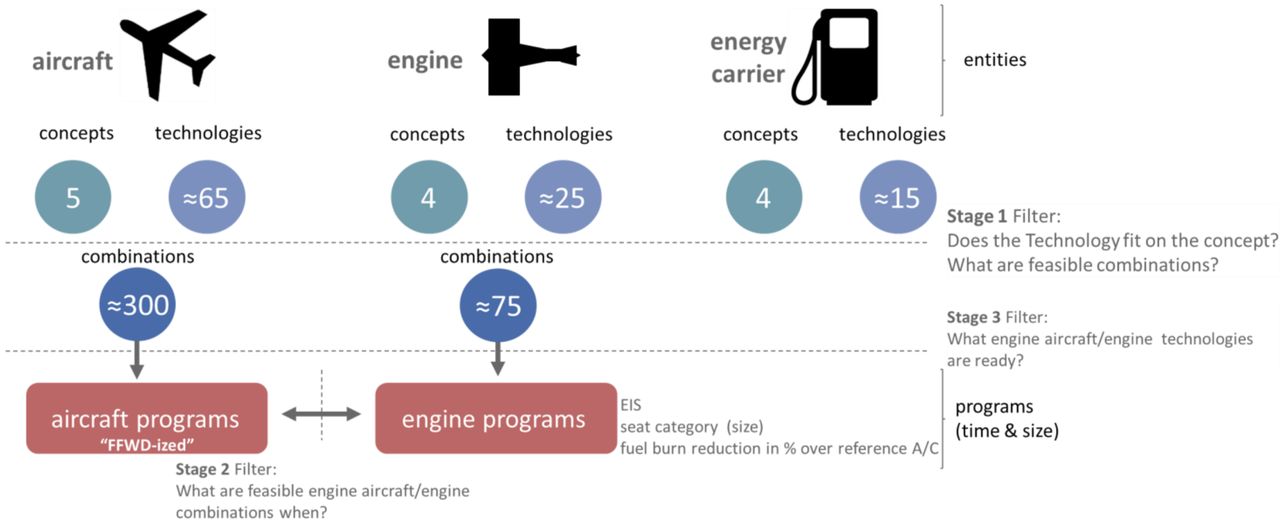


Figure 4: Database structure and combinatorial logic.

In order to design a process of using the Technology Database to create future aircraft programs that can be modeled in the fleet renewal model, the database structure depicted in Figure 4 has been developed. It is associated with combinatorial logic where technologies (e.g. natural laminar flow) and concepts/configurations (e.g. BWB) are allocated to the three entities:

- Aircraft (airframe)
- Engine
- Energy carrier

The assessments are conducted for combinations of concepts/configurations and technologies grouped by entity. Here the Stage-1 Filter is applied where by expert judgment it is decided whether a specific technology is applicable on a configuration or concept. That means that in this database structure, technologies can be assessed differently dependent on which aircraft or engine concept they are implemented on (varying values for the same technology on different configurations).

The Stage-2 Filter has the purpose to select those aircraft and engine configurations that are expected to be ready at entry into service (EIS). It is also checked at this point if a specific engine configuration is applicable on a specific aircraft configuration or vice versa for a given technology scenario.

When aircraft and engine programs are defined in later process steps of program timeline generation for a given seat category and aircraft generation, the combinations of aircraft configurations and aircraft technologies as well as engine configurations and engine technologies are filtered with respect to the technology readiness level (TRL) at estimated EIS of a conceived aircraft program. This is named Stage-3 Filter in the process chain.

3. SIMULATING FUTURE AIRCRAFT PROGRAMS

The final step in building up a model of the future global fleet is to derive conceivable future aircraft programs containing technologies from the database, which would enter the fleet after today. This section describes how configurations, technologies and timing are combined to define future aircraft program scenarios. This includes fuel burn improvements of those program timelines by seat category and generation over their respective reference aircraft and the according clustered technologies. Future aircraft programs consist of aircraft configurations, airframe technologies and engine programs available in the year of EIS. A stepwise process has been established in order to derive future aircraft programs, find feasible and promising aircraft-propulsion combinations and to allocate specific aircraft and engine technology sets and associated fuel-burn efficiency improvements to those aircraft programs. The process steps of conceiving future aircraft programs are:

1. Discrimination of fixed and unfixed aircraft
2. Literature research of data for fixed aircraft programs
3. Deduction of EIS of unfixed aircraft programs for each seat category and generation until time horizon
4. Selection of aircraft and engine concepts for each unfixed aircraft program
5. Selection of aircraft and engine technologies
6. Estimation of fuel burn improvement [%] over reference for unfixed aircraft programs and each technology scenario

3.1. Discrimination of fixed and unfixed aircraft

In a first step for simulating future aircraft programs and make use of the Technology Database, it is required to identify those aircraft programs with an EIS in the future that are already planned. These programs are called “fixed” aircraft programs in this paper. It can be taken as certain that they will enter the market, contrary to “unfixed” aircraft programs (see Section 3.3), whose EIS can only be assumed. Furthermore, the area of action – the design space which can be influenced – applies to unfixed aircraft programs. This is why fixed and unfixed programs have to be differentiated first. Figure 5 shows the fixed programs for the generation N+1 and the unfixed aircraft programs from generation N+2 onwards (green aircraft symbols). Some of the fixed programs are already in production to substitute the old fleet or satisfying the fleet growth.

seat category	successive aircraft generations			
	reference	N+1	N+2	N+3
51-100	AT76 CRJ9	MRJ		
101-150	A320 B737	A320neo B737MAX		
151-210	A320 B738	A320neo B737MAX		
211-300	B763	A350 B787		
301-400	A333 B773	A330neo 777X		
401-500	A388 B748	B777X		
501-600	A388 B748	A380neo		
601-650	A388	A380neo		

fixed programs unfixed programs

Figure 5: Step 1 - Discrimination of fixed and unfixed aircraft programs.

3.2. Research of data for fixed aircraft programs

For the fixed aircraft programs, data for EIS and fuel improvement are retrieved from literature and manufacturer announcements in the media. The AIRCAT report already provides most of the assumptions required [4], except for a potential A380neo, which is in discussion. If Airbus launches the A380neo, it may be scheduled for an EIS not before 2025 [5]. With a timeframe of 18 years between the EIS of the A380 in 2007 and the assumed EIS of the A380neo in 2025, a 15% improvement through engine technology enhancements seems realistic. Figure 6 displays the assumptions – EIS and fuel burn improvement in percent over reference – for fixed aircraft programs. It is debatable if the A380neo can be considered a fixed program, but since the new engine option is already in discussion, the program is simulated here as fixed.

The reference or N-generation aircraft are defined for the reference year 2010 as representative of a given sub-fleet. Subsequent generations (N+1, N+2, …) are counted from there on.

3.3. Deduction of EIS for unfixed aircraft programs

After defining the fixed aircraft programs, the EIS of unfixed N+2 and N+3 aircraft programs are derived as a function of the EIS of the previous aircraft program. It is assumed that a subsequent aircraft program has an EIS about 20 years after the EIS of the previous aircraft program. For the 211-300 seat category an early new aircraft program is assumed with an EIS in 2027, according to Boeing’s announcement to consider a middle-of-the-market (MOM) aircraft. [6] 18 years later in that seat category, in 2045, the N+3 generation is introduced. The EIS of N+3 generation aircraft programs for other seat categories are timed after the time horizon 2050. Figure 7 illustrates the derived EIS of unfixed successive aircraft programs in the respective seat categories.

seat category	fixed aircraft programs			
	reference	N+1	EIS	Δ fuel
51-100	AT76 CRJ9	MRJ	2025	-15%
101-150	A320 B737	A320neo B737MAX	2015	-15%
151-210	A320 B738	A320neo B737MAX	2015	-15%
211-300	B763	A350 B787	2012	-20%
301-400	A333 B773	A330neo 777X	2018	-15%
401-500	A388 B748	B777X	2025	-15%
501-600	A388 B748	A380neo	2025	-15%
601-650	A388	A380neo	2025	-15%

Figure 6: Step 2 - Research of data for fixed aircraft programs.

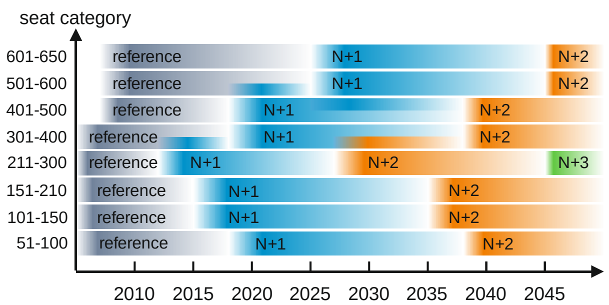


Figure 7: Step 3 - Deduction of EIS for unfixed aircraft programs.

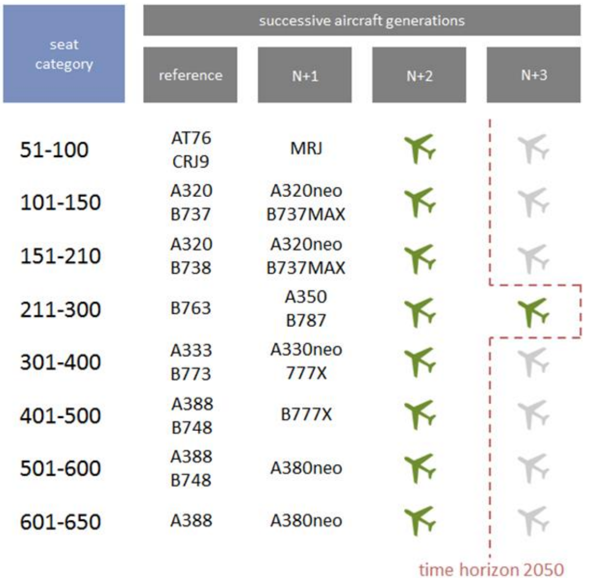


Figure 8: Step 3 - Unfixed aircraft programs with EIS within the time horizon 2050 (green) and beyond (light grey).

Figure 8 depicts the unfixed future aircraft programs after the derivation of their EIS. To begin with, the EIS for unfixed aircraft programs are held constant under all technology scenarios which are developed in the next step. Hence, for each technology scenario the same amount of 9 unfixed aircraft programs has to be designed.

3.4. Selection of aircraft and engine concepts for each unfixed aircraft pro-gram (Stage-2-Filter)

In step 4, aircraft and engine concepts need to be selected for each of the 9 unfixed aircraft pro-grams. One set is considered as a technology scenario, consisting of 9 aircraft programs. Each aircraft program is defined by the choice of one aircraft configuration and one engine configuration and a degree of hybridization where applicable to create an aircraft program matrix.

The choice of aircraft and engine configuration needs to be available at the EIS of the simulated aircraft program. Through the Stage-2 Filter, availability of configurations is matched with the derived EIS of aircraft programs throughout seat categories. The result of step 4 is an aircraft program matrix per technology scenario. Within this paper two scenarios are considered:

- Technology scenario 1 (only N+1 aircraft, then no introduction of new aircraft program (hypothetical))
- Technology scenario 2 (conventional fuel, additional improvement by new configurations (aircraft and engine))

For each aircraft program, always one aircraft configuration and one engine configuration is combined. In the following figures, the combinations of aircraft and engine configurations for each aircraft program are defined and visualized by pictograms. These are explained in Figure 9.

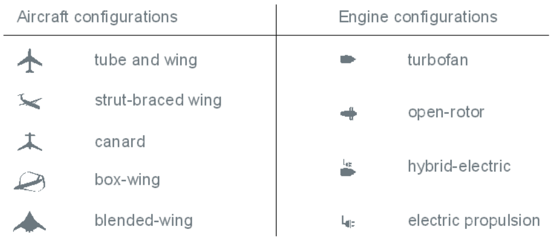


Figure 9: Pictogram legend of aircraft and engine configurations used for the aircraft program matrix.

Scenario 1 examines the fuel burn development of the fleet under the prevailing growth scenario, if only the fixed aircraft programs as defined in sub-sections 3.1 and 3.2 were introduced. This equals the introduction of an N+1 generation in all seat categories only with no generation following until the time horizon. Scenario 1 represents a more hypothetical “reference” or “no additional action” or “baseline” scenario. It is not considered a realistic case though that there will be no next aircraft generation in the timeframe until 2050. Figure 10 illustrates the aircraft program matrix associated with scenario 1.

Figure 10: Technology scenario 1: Aircraft program matrix (by seat category and aircraft generation) for "only fixed aircraft programs" scenario.

Scenario 2 in addition introduces new aircraft and engine configurations in the generation N+2 and N+3. In the N+2 generation in the 101-150 and 151-210 seat categories a strut-braced wing (SBW) aircraft configuration is chosen, for the 501-600 and 601-650 seat categories the blended-wing body (BWB). Figure 11 illustrates the aircraft program matrix for scenario 2.

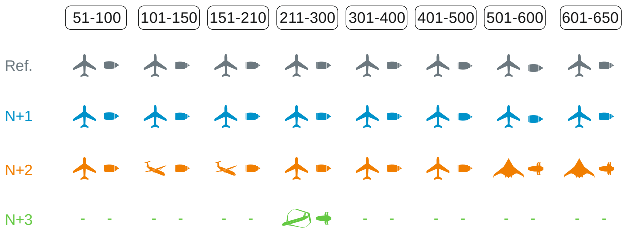


Figure 11: Technology scenario 2: Aircraft program matrix (by seat category and aircraft generation) for conventional fuel scenario.

Scenario 2 considers only propulsion by jet fuel (which can be conventional or ASTM (American Section of the International Association for Testing Materials) certified biofuels). In addition the open rotor concept is applied to the BWB entering as N+2 aircraft to further increase the CO_2 reduction potential. Here, by the location of the open rotor over the body, an introduction may be possible earlier than on tube-and-wing aircraft because of noise shielding effects. Later, in 2045, when N+3

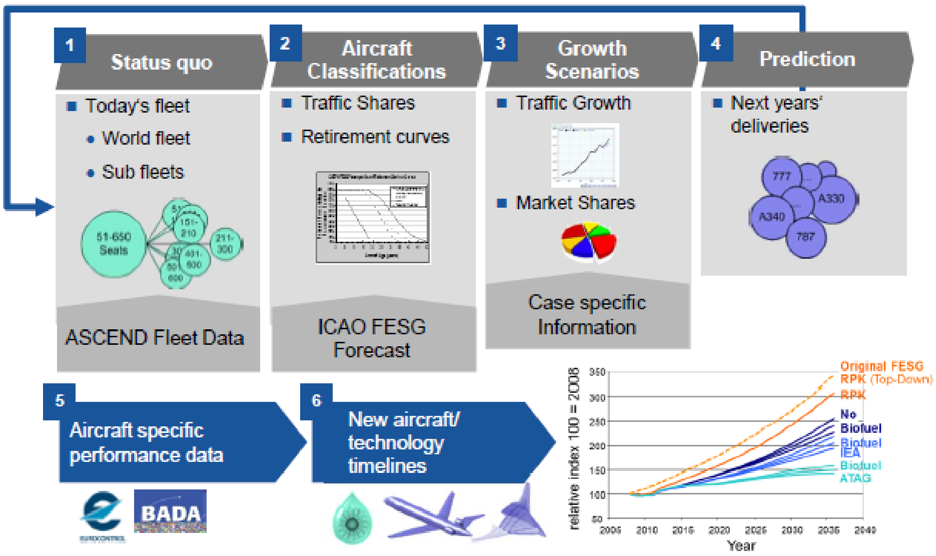


Figure 12: General CO2 forecast schematic: bottom-up forecast based on year-to-year dynamics.

aircraft are introduced, open rotor technology is assumed to have advanced in a way that the noise impact is manageable also on non-shielding aircraft configurations. Advancements in aircraft design allow the introduction of a box-wing configuration as an N+3 aircraft in the 211-300 seat category.

3.5. Selection of aircraft and engine technologies for unfixed aircraft programs (Stage-3 Filter)

In step 5, the process of simulating aircraft programs is firstly combined with the information from the Technology Database. In this step, a selection is made of the technologies from the database that are implemented on an aircraft program. This needs to be performed individually for each aircraft program of a technology scenario.
Step 5 has the following sub-steps:
5.a: From the Technology Database, filter the airframe technologies that will reach TRL9 at the aircraft EIS and match the selected aircraft configuration from step 4.
5.b: Filter the engine technologies that will reach TRL9 at the aircraft EIS and match the selected engine configurations.
5.c: Selection of technologies to be implemented on aircraft program (airframe and engine) out of the available technologies of 5.a and 5.b; simultaneous technology compatibility check.

3.6. Estimation of fuel burn improvement over reference for unfixed aircraft programs

After the selection of technologies from the Technology Database for each unfixed aircraft program in the four technology scenarios, in step 6, the fuel burn improvement is estimated. The fuel burn reduction relative to the reference aircraft results from the application of these technologies on aircraft programs as well as from the additional fuel burn improvement that can be expected from new configurations (scenario 2). Table 1 shows the assumed fuel burn reductions of all unfixed aircraft programs in this study for scenario 2 including the consideration of an empirical interference factor[4] with the value of 0.85. The technology scenario an aircraft program is used for can be retrieved from the table.

Table 1: Total fuel burn improvement of unfixed aircraft programs (Scenario 2).

Seat Category	Aircraft Generation	Total fuel saving [%]		
		min	mean	max
51-100	N+2	27%	36%	48%
101-150	N+2	27%	38%	48%
151-210	N+2	27%	38%	48%
210-300	N+2	24%	30%	40%
210-300	N+3	31%	43%	57%
301-400	N+2	28%	38%	50%
401-500	N+2	28%	38%	50%
501-600	N+2	31%	42%	57%
601-650	N+2	31%	42%	57%

4. ESTIMATION OF THE CO_2 EMISSION REDUCTION POTENTIAL ON GLOBAL FLEET LEVEL

A methodology developed by DLR [7] is used to model the introduction of novel aircraft configurations into the world fleet and to assess their impacts on global CO_2 emissions of air transport. It consists of two separate modules (see Figure 12):

(1) Evolution of the world fleet of commercial passenger aircraft (Figure 12: steps 1-4).
(2) Forecast of the evolution of fuel and CO_2 efficiency based on fuel consumption and performance information of each aircraft

[4] Assumed benefit reduction through technology interferences when combining multiple technologies

model, and global CO_2 emissions and traffic calculated by aggregating the single aircraft estimates (Figure12: steps 5-6).

4.1. Fleet renewal modelling and a fleet scenario

The fleet forecast used here is a bottom-up forecast based on year-to-year dynamics.

- The first step is to identify today's fleet of aircraft.
- From the detailed information provided by the fleet database, the following year's retirements are then projected for each make and model in the world fleet, based on the specific age of each active aircraft.
- The next step is estimating the number of additional aircraft needed to satisfy the selected traffic growth scenario
- The sum of aircraft needed for replacement and growth constitutes the next year's aircraft demand is equal to new aircraft deliveries. The original aircraft that are forecasted to remain active (i.e. are not retired) plus the new aircraft deliveries (including yet unfixed make and model) make up the new world fleet. This process of simulating yearly fleet changes is repeated until the final year of the forecast period is reached.

New aircraft configurations enter the world fleet through projected deliveries of “fixed demand” and “unfixed demand” (future generic aircraft to satisfy the projected demand, but that are not ordered yet).

It is not aimed to detail the realization of unfixed demand by forecasting market shares for specific makes and models. Instead, the demand in each seat category is represented by a “generic aircraft”. This generic aircraft stands for the average delivered aircraft of a specific forecast year. An increasing share of more efficient aircraft is represented by a gradually improving fuel efficiency of the generic aircraft over the years. This modelling method thus accounts for the combined impact of a fleet of multiple aircraft models. All assumptions regarding the impact of new aircraft projects, market shares, ramp-up times and technology on aircraft fuel efficiency in a specific size category can be reflected by adjusting a single parameter: the technology factor (fuel function multiplier) of the generic aircraft in the respective size category. [4]

In the following, an illustration of the methodology is presented with a certain choice of input data for FFWD fleet model:

- 2005 Fleet in service: IATA fleet reference point for goal definition (the FlightGlobal database[5] [9]).
- 2016 Fleet in service [9]: FFWD fleet base year for this study.
- 2016 Orders and planned delivery year [9].
- Traffic growth forecast (Table 2) (in this study was used information on traffic shares in the latest ICAO FESG forecast [8]).
- FESG Retirement Curves. The retirement process is accounted for using the methodology by the Forecast and Economic Support Group (FESG) of the ICAO Committee on Aviation Environmental Protection (CAEP) [10].
- The number of seats for each aircraft obtained from the FlightGlobal database [9].

Table 2: CAEP/9 Passenger Traffic Growth Rate Forecast.

Most likely scenario, [% growth]			
	2010-2020	2020-2030	2030-2040
Global	5.3	4.5	4.2

FFWD is based on past and current fleet information from the ASCEND database [9] including aircraft size (51-650 seats), aircraft usage, number of aircraft “in service”, and build year for passenger aircraft operated by airlines. One part of the forecast also includes the current order books including the number of fixed orders and the (expected) build year. The retirement of aircraft is determined by using CAEP retirement curves implemented into FFWD. Based on projected traffic growth FFWD determines the gap between fixed orders entering the fleet and the number of aircraft required to deliver a certain transport performance per seat category [4]. The projected traffic growth is derived from ICAO FESG traffic and fleet forecast, CAEP/9 most likely scenario. The modelling logic is such that fleet orders from FlightGlobal database overwrite projected growth from traffic growth scenarios.

The fleet modelling results for CAEP/9 “most likely” growth scenario and order backlog are shown in Figure 13.

4.2. Fleet fuel consumption and CO_2 estimation

To assess the influence of novel aircraft configurations (fleet renewal) on global CO_2 emissions, yearly fuel consumption and traffic is assigned to each active aircraft. For existing aircraft of given make and model, the EUROCONTROL Base of Aircraft Data (BADA) Aircraft Performance Model (APM) is used[6]. In particular, the block fuel consumption is estimated using BADA Datasets[7], a given flight distance, and a given payload, to generate a huge dataset over the entire operational range of an aircraft type. For

[5] https://www.flightglobal.com, the database contains aircraft information from the 1950s up to the current world fleet and aircraft on order.

[6] http://www.eurocontrol.int/products/bada

[7] BADA datasets contain the specific values of the coefficients present in the model specification that particularize the BADA model for a specific aircraft type.

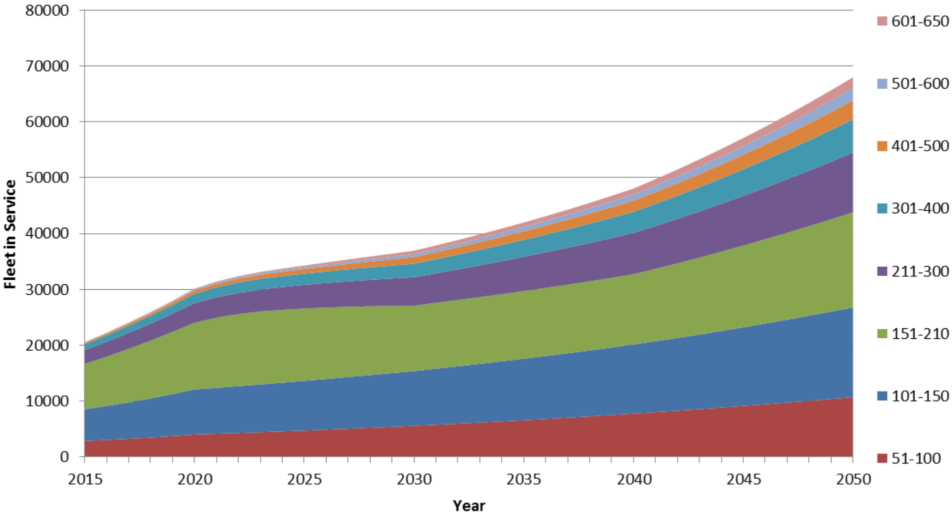


Figure 13: Fleet modelling results for CAEP/9 "most likely" growth scenario and order backlog

distance, load factor, and flights the average values of the corresponding size categories (different for each year) from the ICAO CAEP/9 forecast are taken.

For each new aircraft model a ramp-up time of 7 years is assumed, starting with the EIS until it takes over 100% of the production within each seat category (see Figure 14). Figure 14 also shows that the market penetration of new aircraft types continues to grow well after the end of the production ramp-up phase.

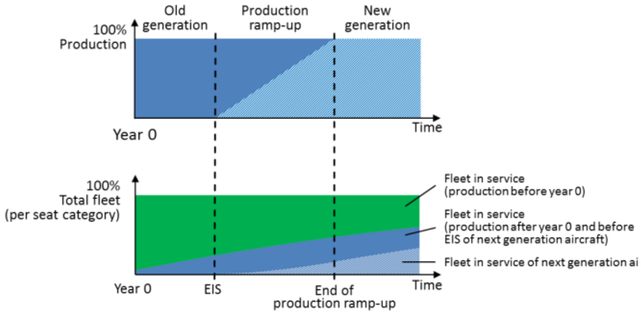


Figure 14: Schematic diagram of new aircraft introduction within global fleet model [4].

Sensitivity studies are performed using the DLR FFWD model by addressing technology sensitivities and time sensitivities. Following cases/sensitivities are covered:

- One reference scenario (scenario 1)
- Aircraft and engine configuration sensitivity (scenario 2)
- Technology sensitivity: Using minimum, mean and maximum estimates for fuel saving potentials for single technologies and simulated unfixed aircraft programs (see Table 1)
- Time sensitivity of unfixed aircraft programs
    - Base EIS as initially
    - Earlier EIS assuming a 5 year earlier EIS for all unfixed aircraft programs.

The impacts of technology and program sensitivities on assumptions of fuel consumption of generic aircraft are illustrated for the base EIS case in Figure 15. The generic aircraft improvement factor stands for the average delivered aircraft in a given future build year. [1] With these assumptions world fleet CO_2 emissions are calculated for each scenario.

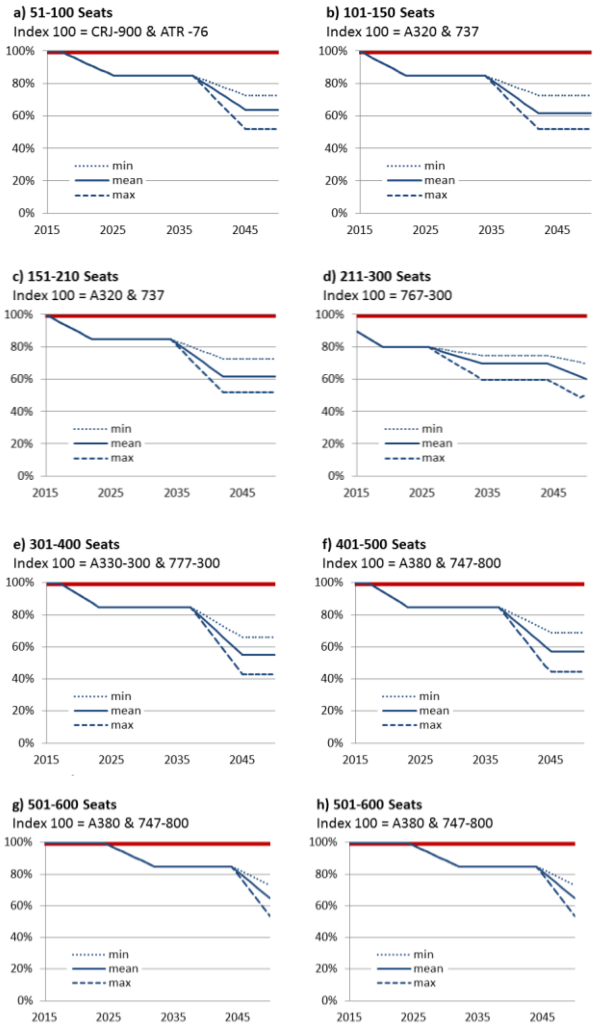
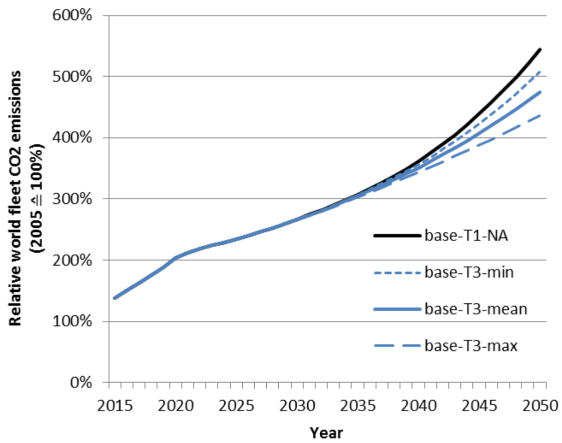


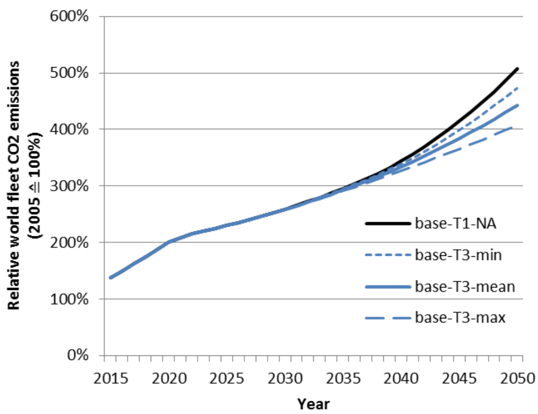
Figure 15: Scenario 2 - Fuel improvement factors for future build years by seat categories and minimum, mean and maximum fuel saving potentials (base EIS) according to Table 1

The results of FFWD calculations to estimate the yearly CO_2 emissions are displayed in the following figures. Figure 16 shows the sensitivity of the minimum, mean and maximum aircraft program improvement assumptions (Table 1) for a technology scenario (scenario 2 indicated as T3 and scenario 1 as T1) for the initial or "base" assumption for the EIS of future unfixed aircraft programs. While Figure 16a shows the fleet emissions without considering additional operational or infrastructure improvements, Figure 16b includes the effect of a yearly additional improvement by operational and infrastructural measures of 0.2%

In addition to the analysis of sensitivities of improvement factors of single technologies and the sensitivities of choices on aircraft configurations and propulsion concepts, timing of the introduction of new aircraft programs throughout all seat categories is another important factor. For this aspect a sensitivity analysis has been performed. In order to do so, the same FFWD simulations from the previous section have been conducted, but with an EIS for all unfixed aircraft programs that is scheduled 5 years earlier compared to the initial estimated "base" EIS. Table 3 lists the difference in EIS for the respective seat category and aircraft generation (N+2 or N+3).



a) without operational and infrastructure improvements



b) with additional improvements of 0.2% per year

Figure 16: Overview of CO_2 emissions for the different technology scenarios and for the minimum mean and maximum estimated fuels saving potentials of respective unfixed aircraft programs (base EIS)

The CO_2 emissions have been calculated for an earlier EIS and are depicted in Figure 7. The calculations are performed as above with and without considering additional improvements by operations and infrastructure (Figure 17a and Figure 17b respectively). The maximum technology assumptions for T3 show a near to CO_2 neutral growth from 2030 on.

In the following, the results of the calculated yearly fuel efficiency improvement at global fleet level for the respective scenarios and fleet CO_2 emission results are presented.

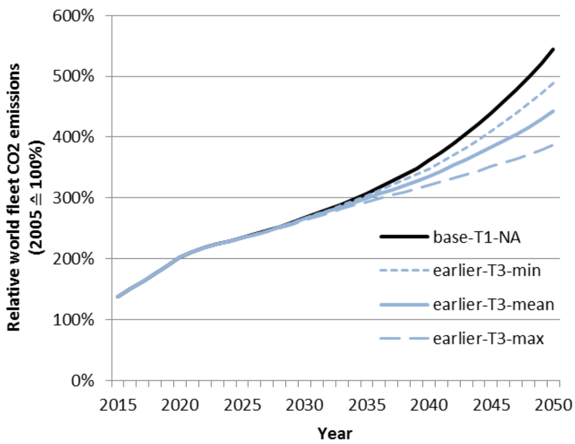
Yearly fuel efficiency improvements are calculated using the metric CO_2 intensity for a given year. Year-to-year changes of CO_2 intensity in percent are calculated for each scenario. For this study, the CO_2 intensity for a given year is defined as:

$$CO_2\ intensity = \frac{fleet\ CO_2\ emissions\ [kg]}{total\ RPK} \qquad \text{(Eq.4)}$$

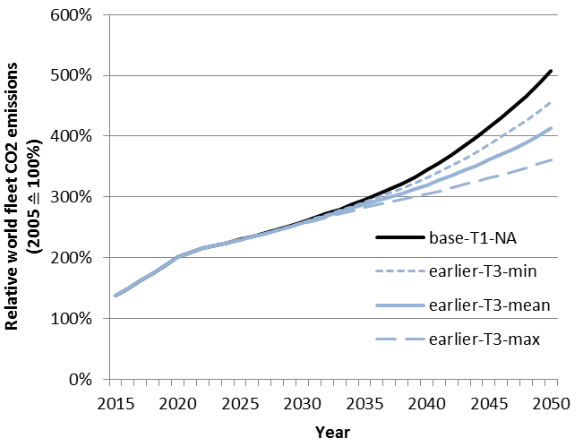
For the scenarios in Figure 18a and Figure 18b the development of average fleet CO_2 intensity for each technology scenario is shown in terms of kilograms of CO_2 emitted per passenger and 100 km.

Table 3. Time sensitivity analysis: comparison of the assumed EIS of unfixed aircraft programs for the "base" case and the "earlier" case

Seat Category	**base EIS**		**earlier EIS**	
	N+2	**N+3**	**N+2**	**N+3**
50-100	2038		2033	
101-150	2035		2030	
151-210	2035		2030	
211-300	2027	2045	2022	2040
301-400	2038		2033	
401-500	2038		2033	
501-600	2045		2040	
601-650	2045		2040	



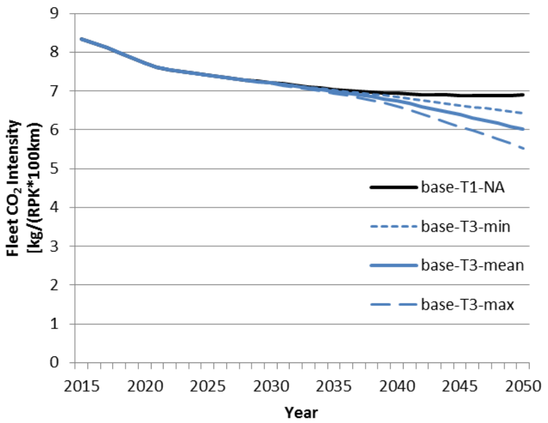
a) earlier EIS without additional operational improvements



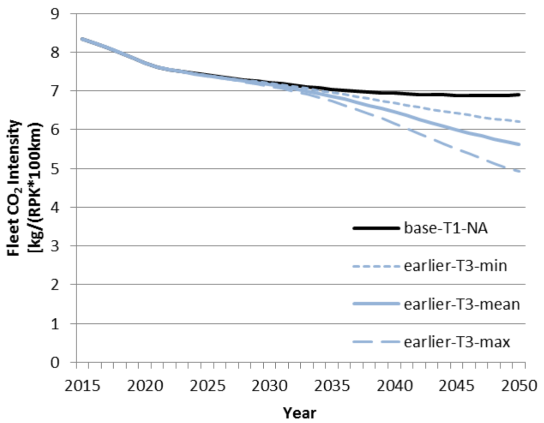
b) earlier EIS with additional operational improvements of 0.2 % per year

Figure 17: Comparison of estimated CO_2 emissions for scenario 2

Year-to-year changes of the CO_2 intensity of the global fleet for the base EIS case are depicted in Figure 19. Negative values represent an improvement of a certain percentage compared to the previous year. In comparison to the results of the base EIS, the results of the simulations with an EIS five years earlier are shown in Figure 20.



a) base EIS without considering additional operational improvements



b) earlier EIS without considering additional operational improvements

Figure 18: Comparison of estimated developments of CO_2 intensity per passenger and 100 km for scenario 1 and scenario 2

The fleet forecast is based on real orders, which are available until 2030, and air traffic demand prediction from FESG until 2050; real orders are treated as predominant. Since these orders provide transport capacity (in RPKs) that from now to the 2020s exceed the FESG-predicted air traffic RPK demand, an order-demand incongruity occurs. The resulting effects are noticeable until 2040. This means that for a given period of time more aircraft are entering the fleet through orders than is in accordance with the FESG RPK growth forecast. From 2025 onwards a period of a very few planned deliveries is following in the order backlog, at a time where the fleet is still overfull due to the order-demand incongruity. Hence, the demand for generic aircraft of the N+1 generation is low; “too many” aircraft have been delivered in previous years. With the continuing growth of air traffic the effect of the order bubble decreases slowly over time until 2040. Relatively high orders compared to the predicted traffic growth (in between 2015 and 2025) lead to high calculated efficiency improvements in early periods. Later, efficiency improvements are decreasing as the demand is saturated until 2040 and not so many (прикрепленно) new aircraft are entering the fleet.

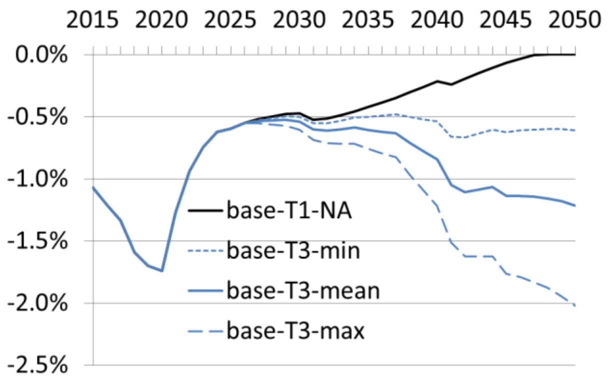


Figure 19: Year-to-year improvement in CO2 intensity of the global fleet for the base EIS case

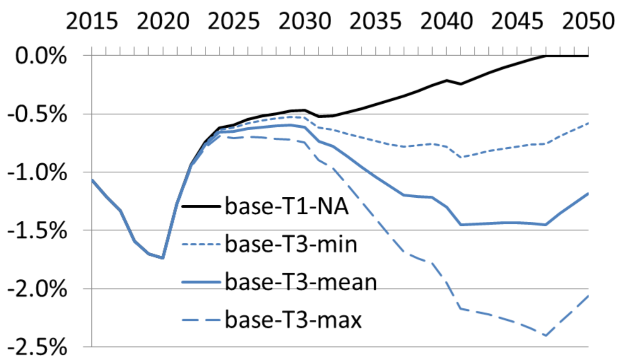


Figure 20: Year-to-year improvement in CO2 intensity of the global fleet for the earlier EIS case

Table 4: Fleet average improvements of CO2 intensity over the observation period 2015-2050 for each scenario and technology assumption, %

scenario	technology assumption	average yearly CO_2 intensity improvement ($\zeta_{2015-2050}$)	
		base EIS	earlier EIS
T1	-	0,54	
T3	min	0,74	0,84
	mean	0,92	1,12
	max	1,16	1,50

The yearly improvements of fleet CO_2 intensity for each scenario are associated with an average per year improvement ζ_{avg} over the whole observation period. Usually, efficiency goals are expressed in average yearly improvements over the observation period. The observation period in this study is the period from 2015 (t_{start}) to 2050 (t_{end}). With the fleet CO_2 intensity in the start year 2015 (I_{start}) and in the end year 2050 (I_{end}), ζ_{avg} is calculated:

$$\zeta_{avg} = 1 - \sqrt[t_{end}-t_{start}]{\frac{I_{end}}{I_{start}}} \qquad \text{(Eq.5)}$$

Table 4 displays the average yearly CO_2 intensity improvements ζ_{avg} for the scenarios and technology assumptions for the time period from 2015 until 2050. Table 5 shows the fleet average improvements of CO2 intensity in the decades.

Table 5: Fleet average improvements of CO2 intensity in the decades 2015-2020, 2020-2030, 2030-2040 and 2040-2050 for each scenario and technology assumption, %

scenario	technology assumption	$\zeta_{2015-2020}$		$\zeta_{2020-2030}$		$\zeta_{2030-2040}$		$\zeta_{2040-2050}$	
		base EIS	earlier EIS	base EIS	earlier EIS	base EIS	earlier EIS	base EIS	earlier EIS
T1	-			0,67		0,39		0,07	
	min			0,68	0,70	0,52	0,72	0,62	0,75
T3	mean		1,51	0,69	0,73	0,66	1,04	1,13	1,39
	max			0,70	0,80	0,85	1,43	1,76	2,24

5. CONCLUSION

Within this study, an existing airframe and engine technology database from 2013 has been adapted and updated; hybrid and battery-electric technologies were also included. In order to cover uncertainties of emission saving potentials estimations originating from various studies, the technology database structure has been modified to accept ranges of values instead of single values only. For assessing technologies and aircraft concepts a systematic bottom-up approach from technology database structure to fleet modelling has been designed. Combinations of climate-friendly aviation technologies and concepts are necessary to meet the aviation industry's long-term emissions reduction goal. For the methodology illustration two scenarios were considered: the baseline scenario and a scenario with additional improvements by new configurations (aircraft and engine). The selection of technologies and the timing of new aircraft programs (scenario 2) are key levers to significantly lower the global fleets CO_2 emissions until 2050. As the market penetration of new aircraft programs is slow by nature, these can only contribute partially to the required emissions reduction. Thus, another part will have to come from sustainable alternative fuels and operational measures.

Therefore, the developed tool FFWD showed efficiency for assessing future technological scenarios. Based on the pledged flexibility and additivity the tool allows to assess and compare a number of various scenarios and programs on a global level.

6. REFERENCES

1. International Air Transport Association. (2013). IATA Technology Roadmap. June 2013.

2. Nicolai, L. (1975). Fundamentals of Aircraft Design. 6520 Kingsland Court, San Jose, CA, 95120: Mets.

3. Rossow, C.-C. (2010). Aerodynamics - A discipline swept away? The Aeronautical Journal, 599-609.

4. Schilling, T. (2016). AIRCAT - Assessment of the Impact of Radical Climate-Friendly Aviation Technologies. International Air Transport Association (IATA), Deutsches Zentrum für Luft- und Raumfahrt (DLR).

5. Aero. (10. May 2016). Emirates erwägt 58 neue Aufträge für aktuelle A380-Generation. Accessed on 13 December 2016 from http://www.aero.de/news-24059/Emirates-erwaegt-neue-Auftraege-fuer-aktuelle-A380-Generation.html

6. Aviation Week. (8. July 2016). Airlines To Boeing: 'Get Moving' On Middle Of The Market Aircraft. Accessed on 13 December 2016 from http://aviationweek.com/commercial-aviation/airlines-boeing-get-moving-middle-market-aircraft

7. Nolte, P. (2012). Quantitative Assessment of Technology Impact on Aviation Fuel Efficiency. Air Transport Operation Symposium. Delft.

8. Report of the Ninth Meeting of the Committee on Aviation Environmental Protection, ICAO Doc. 10012, Montreal, 4-15 February 2013.

9. Ascend Worldwide Ltd. (2016). Ascend Aircraft & Airline Data. (A. W. Ltd, Editor) Retrieved 11 15, 2016, from www.ascendworldwide.com

10. CAEP, FESG CAEP/8 Traffic and Fleet Forecasts, in CAEP/8-SG/20082-IP/02. 2008, Committee on Aviation Environmental Protection: Seattle, Washington.