AIRCAT

Assessment of the Impact of Radical Climate-Friendly Aviation Technologies

DLR

Institutsbericht
IB 328-2016-17

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Assessment of the Impact of Radical Climate-Friendly Aviation Technologies

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Stufe der Zugänglichkeit: A - Offen

Hamburg, 29.04.2016

		Unterschriften:
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Summary

In 2009 the aviation industry has committed to a set of ambitious high-level goals to reduce its carbon emissions at a global level:

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

The long-term reduction goal of 50% in net CO_2 emissions by 2050 relative to 2005 levels cannot be met with evolutionary technologies only, but radically new technologies and aircraft concepts as well as sustainable propulsion energies are necessary in addition to obtain the needed fuel burn and emissions reductions. A variety of novel aircraft concepts and new technologies are proposed by manufacturers, research institutions and academia.

To ensure a frictionless implementation of these new concepts into the air transport system, their impacts on all aviation stakeholders (manufacturers, aircraft operators, airports, air navigation service providers (ANSP)) have to be investigated. For this purpose, IATA and DLR worked together in the AIRCAT project (**A**ssessment of the **I**mpact of **R**adical **C**limate-Friendly **A**viation **T**echnologies) to identify possible challenges, obstacles and roadblocks to the introduction and deployment of different technologies, with a multi-stakeholder expert workshop as a main element of the project. The AIRCAT project study comprised a selection of three aircraft designs, representative for different categories of low-emissions concepts (battery-driven aircraft, hybrid wing body and strut braced wing with open rotor design) and two types of low-carbon alternative fuels (drop-in solar jet fuel as well as liquid natural gas as a typical example of a non-drop-in fuel). Based on the outcome of this workshop, key conclusions and recommendations for future work and support actions have been derived to support the introduction of radical new concepts.

Finally, an assessment of the carbon emissions reduction potential of the discussed concepts at world fleet level has been performed to derive its contribution to aviation's emission reduction goals. **The total CO_2 reduction from radical aircraft concepts in 2050 shows to be about 25% compared to the emissions in a scenario without radically new technologies.** This means that the majority of emissions reductions necessary to meet the 2050 goal would have to come from low-carbon fuels (i.e. a combination of currently known alternative fuels (mostly biojet fuels), and radically new fuels, such as the solar jet fuel mentioned in the present report). The benefits of radically new aircraft concepts could increase significantly after 2050 as their market penetration is expected to continue growing gradually.

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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 2% of global man-made CO_2 emissions. In 2009 the aviation industry, as the first industrial sector, 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, all stakeholders in the air transport industry have united their efforts by focusing on a four-pillar strategy composed of new technology options, effective operations, efficient infrastructure and positive economic measures. 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. Radically new technologies such as new aircraft concepts and sustainable energies will have to substantially contribute to these ambitious emissions reductions. (IATA, 2013)

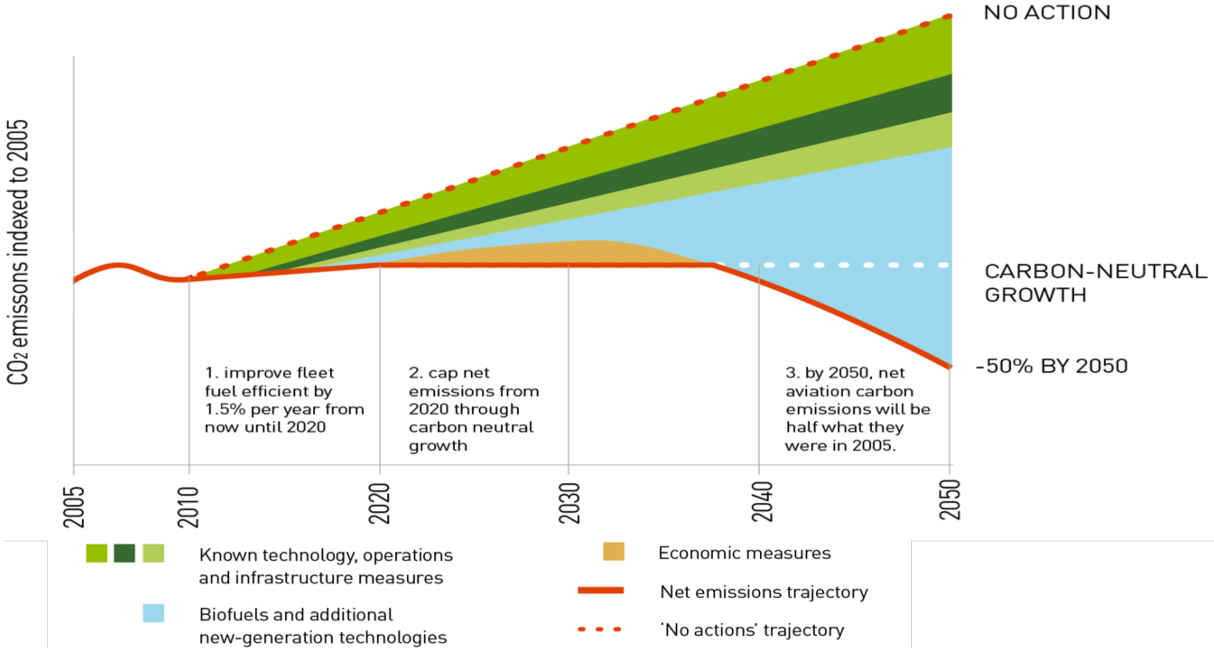


Figure 1: Schematic CO2 emissions reduction roadmap (IATA, 2013)

Evolutionary aircraft technologies including new engine concepts that can be fixed on classical tube-and-wing aircraft have a potential to improve fuel efficiency in the order of 30% by around 2030 compared to 2005 (IATA, 2013). To fill the gap between evolutionary technology progress and the long-term emission reduction goal, additional radical solutions have to be introduced to the air transport system with appropriate lead times. For the timeframe after 2030, various novel aircraft concepts, which represent a wide choice of radically new technologies and shall help to substantially reduce the carbon footprint of aviation, are proposed by aircraft manufacturers, research institutions and academia (Airbus, Boeing, DLR, NASA, ONERA, Bauhaus Luftfahrt, TU Delft, among others). In most cases the technical feasibility of these concepts has been assessed, and the benefits and the potential fuel savings have been determined at aircraft level. However, a more holistic assessment of these concepts at an integrated air transport system level is necessary, and an involvement of all relevant stakeholders is needed to ensure a frictionless adoption of such novel concepts. Impacts of radical solutions on aircraft and engine manufacturers, aircraft operators, airports, air navigation service providers (ANSP) and other stakeholders, such as energy providers, need to be identified and potential benefits and arising challenges for each of them described thoroughly, in order to allow timely preparations and infrastructural adaptations in view of an operational deployment once the technologies have achieved maturity.

1.1 Project Objective

The chance of achieving the goal of a reduction of the net emissions to 50% of the 2005 level until 2050 depends, among others, on the implementation of radically new aircraft concepts and technologies. As an essential part of the roadmap towards the 2050 goal, potential challenges, obstacles and roadblocks to implementation have to be identified in time and a way forward to the development of solutions needs to be determined.

IATA and DLR started the AIRCAT project (**A**ssessment of the **I**mpact of **R**adical **C**limate-Friendly **A**viation **T**echnologies) to investigate a representative choice of most promising technologies from novel aircraft concepts and alternative fuels in terms of their impact on the different aviation stakeholders and the related challenges, as well as their carbon emissions reduction potential at world fleet level. As part of this project, a workshop was held bringing together experts representing all major aviation stakeholders to produce a consistent view on the needs for the integration of novel concepts into the air transport system. In addition to showing significant interactions between stakeholders, the AIRCAT project focuses especially on identifying necessary long lead-time preparations. This allows the development of coordinated actions between stakeholders in view of a successful concept introduction. Finally, a rough estimate of the overall emissions reduction potential of such novel technologies is made at world fleet level, based on typical market penetration rates, to show the potential to achieve the 50% goal by 2050.

2 Novel aircraft and sustainable energy concepts

This chapter starts with an overview of a selection of radically new technology concepts, comprising three novel aircraft configurations and two sustainable fuel technologies. Both areas have high emission improvement potentials, which will decisively contribute to emission reduction targets of the aviation industry (as shown in Figure 1).

These aircraft configurations were chosen to represent major trends in future aircraft design (e.g. more fuel-efficient aerodynamic structural and engine design, electrification) to enable a more sustainable aviation. By investigating a wide range of future aircraft configurations and sustainable fuels, most relevant impacts have been captured within this project (see chapter 4). The electric aircraft and strut-braced wing are both short- to mid-range aircraft; the strut-braced wing is a structurally optimized configuration but can fly with conventional fuel, while the electric aircraft concept is optimized around a fully battery-powered propulsion system. The blended wing body develops its advantages over conventional aircraft especially on large-capacity long-range flights, and with its unconventional external shape and spacious cabin, it represents a fully new aircraft category in civil aviation.

Sustainable fuels can be divided into drop-in and non-drop-in fuels. SOLAR-JET is one representative of sustainable drop-in fuels which can be easily introduced into aircraft operations, since no or only minor adjustments are necessary regarding the aircraft and infrastructure. Non-drop-in fuels are represented within this project by liquid natural gas requiring major changes to the aircraft and high investments in new infrastructure worldwide.

A technical overview of the selected concepts and technologies as a basis for the following analyses is presented below.

Potential timelines for the availability of these future aircraft configurations and sustainable fuel technologies are shown in Figure 2. While the introduction of radically new aircraft concepts is not realistic before 2030 due to long development times, liquid drop-in fuels have already been introduced and will become more relevant in the future.

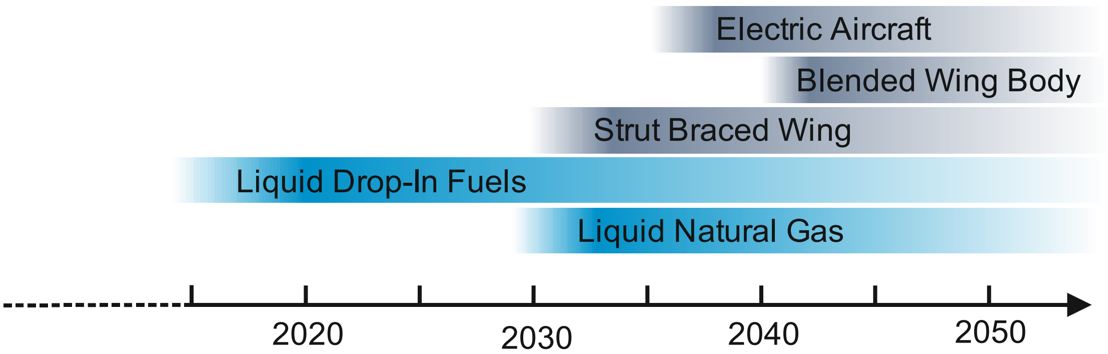


Figure 2: Possible timeframes for analyzed aircraft and fuel concepts

2.1 Future aircraft configurations

Currently multiple novel aircraft concepts are under investigation at different research institutions worldwide. Electrically propelled aircraft, hybrid wing body and strut or truss braced wing concepts have been selected in the AIRCAT project as representative examples of promising concepts. For all of these concepts various configurations are available from different research groups. It can be expected that the impact on aviation stakeholders' operations will be similar for similar concepts; therefore only one promising example for each configuration is presented in the following sections.

2.1.1 Fully electric aircraft (Ce-Liner by Bauhaus Luftfahrt)

A recent preliminary design study for a fully electric aircraft was performed by Bauhaus Luftfahrt (Hornung, Isikveren, Cole, & Sizmann, 2013) (Bauhaus Luftfahrt, 2012). The so-called Ce-Liner is a fully electric commercial passenger airplane which would carry nearly 200 passengers. The aircraft concept incorporates numerous innovative technologies and ideas potentially available towards the projected entry into service in 2035 to 2040. The distinctive "C-wing" substantially improves aerodynamic efficiency and thus reduces energy consumption to further increase achievable design ranges which are one of the critical aspects of fully electric aircraft. If battery technology advances at a similar pace as in the last years, however without exceeding physical limitations, it is estimated that by 2035 this will allow a flight range of nearly 700 nautical miles. That will rise after 2035 to 1000 nautical miles and more if the energy density of batteries will develop further as assumed. (Bauhaus Luftfahrt, 2012)

The Ce-Liner is designed to have a turnaround time of 30 minutes, which requires easy access to the battery packs. Lithium ion batteries are carried in specially modified containers, compatible with conventional LD3 cargo containers, to be exchanged during turnaround and recharged at the airport.

Besides fully electric aircraft like the Ce-Liner, hybrid electric concepts are investigated by various research institutes and industrial companies. These combine the advantages of both combustion and electric engines. While the combustion and electric propulsion systems can be used in combination during take-off to provide maximum lift, the combustion engine can be throttled back when the aircraft is in cruise flight or descending.

CO_2 emissions during operations are zero for fully electric aircraft. Lifecycle emissions strongly depend on the primary energy mix for electricity generation; if fully renewable sources are used, they could be close to zero as well. As described in further detail in chapter 4, the CO_2 emission reduction potential of short-range fully electric aircraft, assuming a trend market growth, is up to 15% of the global emissions in 2050. The reduction potential is highly depending on its entry into service, ramp-up scenario and operational route lengths.

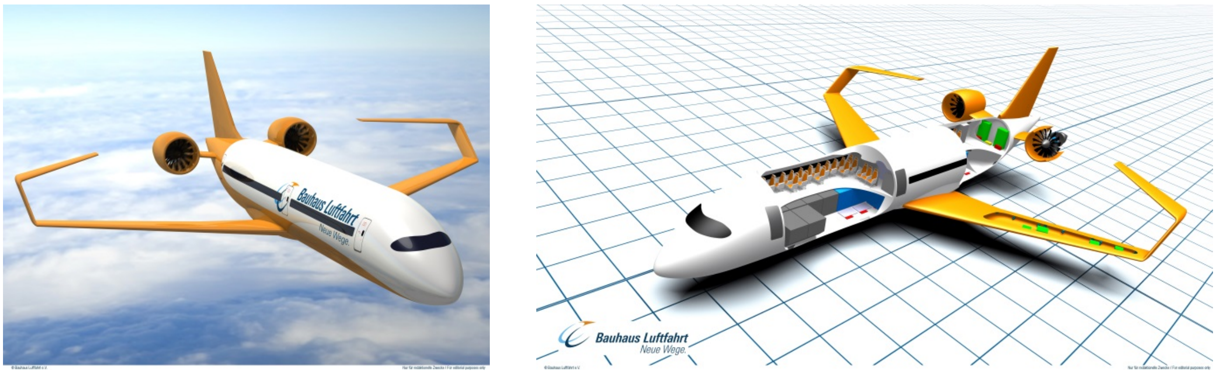


Figure 3: Ce-Liner by Bauhaus Luftfahrt (Bauhaus Luftfahrt e.V., 2015)

2.1.2 Hybrid wing body (by DLR, German Aerospace Center)

The hybrid wing body (HWB) configuration was originally introduced at concept study level in the late 1980s and further analyzed in the 1990s. Research on HWB was intensified again in 2002 (Liebeck, 2002). The HWB is essentially a large flying wing, which houses a payload area within its center section. The motivation for the HWB concept was primarily its superior aerodynamic efficiency compared to conventional tube-and-wing configurations, as the design has been mainly driven by aerodynamic performance optimization. In addition, new engine integration concepts allow for a reduction in noise emissions and fuel consumption. A typical example out of various HWB concepts is the 500-seat blended wing body developed at the German Aerospace Center (DLR) with an estimated entry into service at the earliest in 2040. Since the fuel efficiency of HWB configurations increases with aircraft size, the DLR-HWB was especially designed for long-range operations with a design range of 7.500 nautical miles. For operations near its design range, fuel consumption is expected to be up to 50% less compared to current aircraft.

The market potential for future HWB aircraft can be estimated from published market projections: While Airbus expects in its current market forecast a demand for very large aircraft of about 1,550 till 2034 (Airbus, 2015), Boeing forecasts the demand to 670 for the same period (Boeing, 2015). Current production rates for very large aircraft like the Airbus A380 and Boeing 747 are about 20 to 30 aircraft per year each[1] and for newer long range aircraft like the Airbus A350 or Boeing 787 about 150 to 170 per year each[2] are planned. Considering a fast production ramp up and production rates similar to current long range aircraft, up to about 1000 HWBs[3] could enter the world fleet between 2040 and 2050, more to follow. Due to its entry-

[1] Airbus A380 deliveries 2014: 30 per year (http://speednews.com/airbus-deliveries)
Boeing 747 deliveries 2014: 19 per year (http://speednews.com/boeing-deliveries)

[2] Airbus A350 production rate goal from 2018 on: 156 per year
Boeing 787 production rate goal from 2018 on: 168 per year
(http://i1.wp.com/leehamnews.com/wp-content/uploads/2015/02/AB-BA-WB-Rates.png)

[3] This number is an optimistic average between the current rates for very large (A380/747) and newer long range aircraft (A350/787), assuming that similar rates may be realistic for unconventional aircraft concepts in the same market segment in 25 years.

into-service as late as 2040, the global CO_2 emission reduction potential is forecasted (see chapter 4) to about 1-2%[4] in the first 10 years until 2050, but could expand substantially in the following decades.

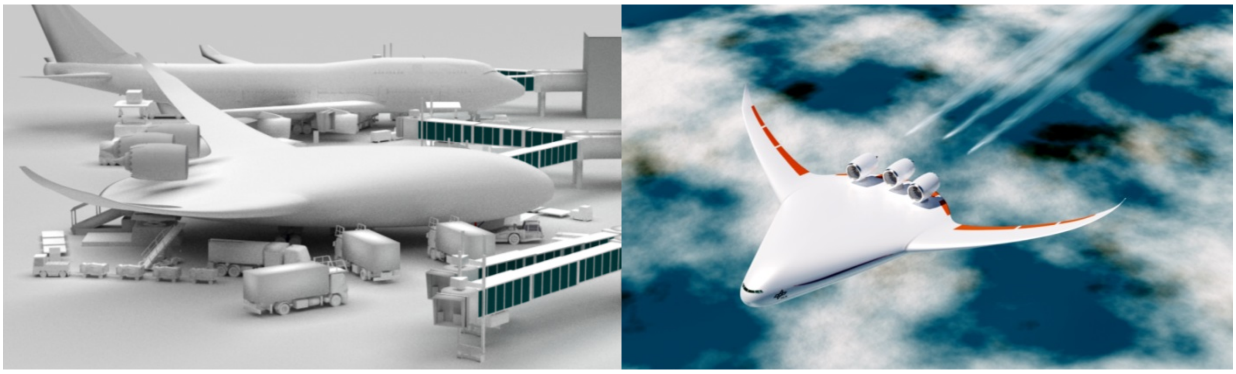


Figure 4: Blended Wing Body designed by German Aerospace Centre (DLR)

2.1.3 Strut braced wing with open rotor design (by Boeing, NASA, et al.)

The strut braced wing is a concept which is also under current attention by various research entities (Bradley & Droney, 2011) (Moerland, Becker, & Nagel, 2015). The concept utilizes a structural wing support to allow for larger wing spans without increases in structural weight. By increasing the span the induced drag is reduced and therefore the engine performance can be reduced as well. The high wings allow for bigger engine sizes, e.g. open rotors. The increased wing span may also require a redefinition of current airport compatibility categories.

Within the "Subsonic Ultra Green Aircraft Research" (SUGAR) studies by Boeing (see (Bradley M. , 2010) (Bradley M. , 2012)) a 154-seat high aspect-ratio, low induced-drag strut braced wing aircraft was designed and used as a platform to integrate multiple novel technologies. A first configuration was designed with advanced turbo-fan engines (SUGAR High) for an entry into service in 2030-35. This configuration offers a block fuel saving of about 29% over a 900-nm mission (design range of 3500nm) in comparison to a Boeing 737-800 with CFM56 engines. Further wing-weight optimization of this configuration combined with an open rotor results in a block fuel saving of about 53% and an entry-into-service by 2040. Its large wing span puts the aircraft into a higher airport design group classification than other aircraft of comparable size. To avoid the higher airport classification and the related higher airport charges, the wing tips could designed to be foldable. . To account for radically new aircraft configurations with different handling characteristics at the airport an adjustment of current airport design group classifications might be an appropriate option in the long term as well.

A second study (N+4, SUGAR Freeze) looked one generation further combining even more technologies with an entry-into-service about 2040-50. An update of the airframe and even more

[4] Forecast performed with the DLR fleet and fuel forecast tool FFWD (Fast Forward)

advanced turbo-fan engines is expected to be available by 2045 resulting in a fuel saving of about 54%. Further combining this concept with an adaptation to liquefied natural-gas (LNG) fuel results in a reduction of 57% and is raised to 62% by the use of open rotor engines. Additionally, the adaption to LNG results in about 15% lower carbon dioxide and 40% lower nitrogen oxides emissions than conventional jet fuel (Warwick, Alternative View - Could liquified natrual-gas and hybrid-electric propulsion be the future of aviation?, 2012) (Bradley M. , 2012). If LNG of fossil origin is replaced by biogas, CO_2 emissions would be further reduced, depending on the lifecycle emissions of the biogas production.

With its short-range specifications the strut-braced wing aircraft is a concept aiming at the same market segment as the battery aircraft presented above, but offers less emission reduction potential than a fully electrical aircraft (under the assumption of CO_2 emission free electrical energy supply).

Figure 5: Strut braced wing design with open rotor (NASA/The Boeing Company, 2015)

2.2 Sustainable fuel technologies

The use of alternative fuels in the aviation industry is not only a possible but a mandatory strategy. This development is not only driven by climate change issues, but limited fossil fuel resources make it necessary to search for possible alternatives to current crude-oil based jet fuel. However, this step will have to be chosen wisely. Social and economic acceptance of large-scale growth of crop-derived energy requires solving sustainability issues, such as competition with food sources, land use, and the need for public incentives. Therefore there is an increasing trend for using alternative jet fuels from wastes and residues (produced e.g. by the Fischer-Tropsch [biomass-to-liquid] process) rather than from dedicated crops.

Alternative fuels and energies in general can be divided into liquid drop-in fuels, liquid non drop-in fuels, gaseous fuels, electric power and others. An electric power approach is already covered within this report in chapter 2.1.1 (Ce-Liner). In the following section sun-to-liquid drop-in fuel (SOLAR-JET) and liquid natural gas (LNG) as a liquid non drop-in fuel are presented. In evaluating alternative fuels, it is important to consider the overall lifecycle emissions instead of combustion emissions only in determining aviation's overall CO_2 reductions. Even though combustion of non-fossil fuel has a theoretically zero carbon footprint, greenhouse gas emissions from agricultural and chemical processes as well as transport have to be accounted for.

2.2.1 Liquid Drop-In Fuel: SOLAR-JET

The use of fuels chemically similar to existing Jet A-1 but without the use of fossil carbon is a possible way to reduce lifecycle greenhouse gas emissions without requiring changes to the current fleet of aircraft. The need for compatibility with the current fleet of aircraft and the existing infrastructure for Jet A-1 impedes a complete turn towards non-drop-in fuels within the next decades. Moreover, non-fossil fuels help reduce the dependence on declining crude oil resources. Current aviation biofuels are all drop-in fuels that can be blended with conventional Jet A-1 fuel over wide ranges of blend percentages; this applies to the certified pathways (Fischer-Tropsch, HEFA fuels from vegetable oils and animal fats, SIP fuels from sugars) as well as to the numerous pathways currently preparing for certification.

However, availability of biomass for biofuel production is limited, and sustainability requirements need to be met. This triggered the search for non-biomass based drop-in fuel solutions. With the first ever production of synthesized "solar" jet fuel, the EU-funded SOLAR-JET project has successfully demonstrated the entire production chain for renewable jet fuel obtained directly from sunlight, water and carbon dioxide (CO_2) (Marxer, et al., 2015).

SOLAR JET potentially achieves carbon neutral production of jet fuel by a chemical reaction that reveres fuel combustion by means of very high temperatures and a metal-oxide redox reaction. This reaction produces syngas, a mixture of hydrogen and carbon monoxide, which is finally converted into kerosene using the well-proven Fischer-Tropsch technology. (SOLAR-JET, 2014) With an expected solar-to-kerosene process efficiency of 4-14%[5], SOLAR JET exceeds efficiency potential of processes like biomass-to-liquid (BTL) of about 1.75%[6]. Consequently, the required total ground area for producing a given amount of solar fuel is assumed to be less than half of

[5] See (Falter, Batteiger, & Sizmann, 2014):
Solar radiation concentration: 50-58%
Thermochemistry: 20-30%
Fischer-Tropsch: 50%
Total: ≈ 4-14%

[6] Current average conversion efficiency of BTL is below 1%.

that for the same amount of BTL, i.e. the conversion efficiency is higher for SOLAR JET than for similar fuels.[7] (Furler, 2015) As the SOLAR-JET infrastructure has no requirements regarding land fertility, the availability of potential land area, and therefore of future production capacity, is almost unlimited.

SOLAR-JET is not the only principle to generate syngas for Fischer-Tropsch synthesis from CO_2 and external energy. A similar technology (however not discussed in detail in the AIRCAT workshop) is power-to-liquid (PtL), which uses (preferably renewable) electric energy to produce hydrogen through electrolysis, which is then reacted with CO_2 from industrial sources or absorption from air to produce syngas. Also the potential of this technology strongly depends on techno-economical improvement of single process steps (electrolysis, CO_2 absorption from air, Fischer-Tropsch synthesis).

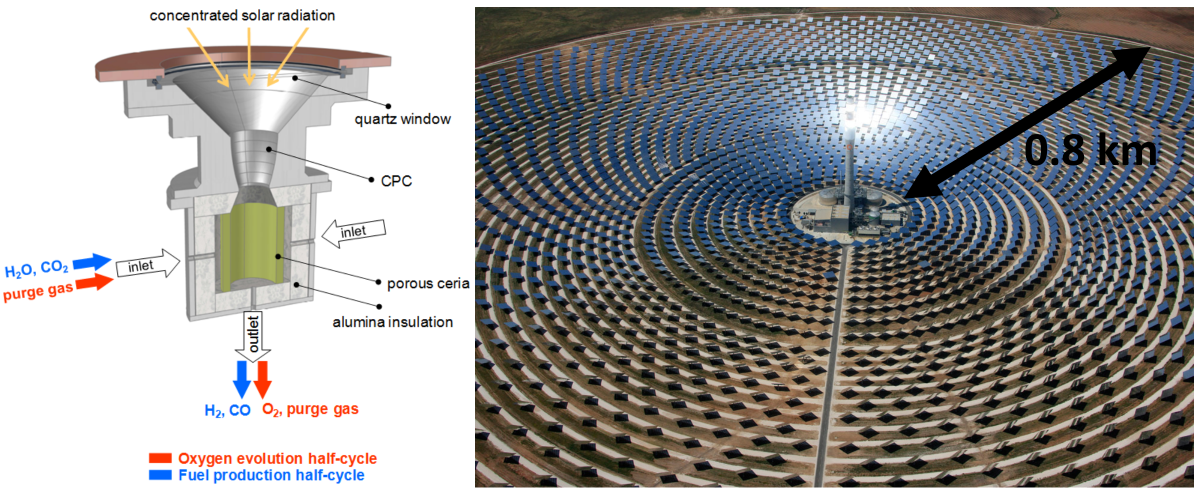


Figure 6: Schematic of the solar reactor configuration for the 2-step solar-driven thermochemical production of fuels (SOLAR-JET, 2014) and perspective industrial scale plant (CSP World, 2015).

2.2.2 Liquid Non-Drop-In Fuel: Liquid natural gas (LNG)

Natural gas is a fuel consisting of 90% - 99% methane (CH_4) and short chain hydrocarbons (e.g. butane and propane). Natural gas has a slightly higher energy density per unit of mass, but a significantly lower energy density per unit of volume relative to conventional jet fuel. Existing aircraft engines can be operated with natural gas after a combustion chamber retrofit/upgrade. When stored in liquid form as liquid natural gas (LNG), the energy density is up to 600 times higher than in unpressurized gaseous form and is approximately two thirds the energy density of jet fuel. Special vacuum insulated fuel tanks are used to maintain the extremely low temperatures to keep the liquid below its boiling point of -162°C (-260°F). This would require funda-

[7] 1,7Mha required area for 100% substitution of European jet fuel demand with solar fuel. (EIA, 2008)
20Mha required area for 100% substitution of European jet fuel demand with BTL. (FAO, 2010)
European agricultural area (2005): 250Mha. (Bauhaus Luftfahrt, 2010)

mental changes to the airframe and the supply infrastructure at airports. LNG is currently in use in sea and land transportation.

LNG is also one of the few fuels that have lower cost and lower life cycle and combustion emissions of CO_2 and other greenhouse gases as well as pollutant exhaust products that harm air quality, such as NO_x, SO_x, and $PM_{2.5}$ and CO (20%-90% for reductions, depending on the mission and feedstock source), compared to conventional jet fuel and diesel (AHEAD Project, 2011). While Jet A fuel emits about 90 grams of CO_2 per MMBtu[8] of fuel energy, LNG emits about 68 grams including fuel production and transport (about 12 grams) and combustion (about 56 grams) (Energy Systems Argonne National Laboratory, 2015). Combustion of LNG produces more water vapor compared to conventional jet fuel, but due to around 80% less sulfur and particulate matter it results in up to 15% less contrails (AHEAD Project, 2011).

Fossil LNG could easily be blended or fully replaced with biogas, which essentially consists of methane as well. Biogas is already blended to fossil natural gas in car fuel and public gas supply networks in various countries.

[8] 1MMBtu ≈ 1055 MJ ≈ 293 kWh

3 Methodology

As a basis for this report and further research, a workshop on the identification and assessment of significant impacts of new concepts on different aviation stakeholders was conducted in April 2015. During this workshop the concepts presented in Chapter 2 were discussed as representatives of future radical technologies, capturing major expected impacts with the need for long lead time preparations. Therefore, in a first step a qualitative multi-stakeholder system analysis was performed to identify impacts specific to each of the different aviation stakeholders. In a second step, the impacts were assessed by identifying major enablers and prerequisites for the expected technical and operational feasibility, and by estimating the needed lead time to operational readiness.

3.1 Multi-stakeholder system analysis

The Air-Transport-System model shown in Figure 7 is used as a framework for the identification of stakeholder-specific impacts. The four main stakeholder groups (manufacturer, operator, air traffic management and airports) together with the aircraft as the linking element between all of them form the core. The surrounding system is defined by the five areas environment, economy, technology, society and politics, which all link the core to the surrounding system. The node "Society" also includes the customer of the air transportation system

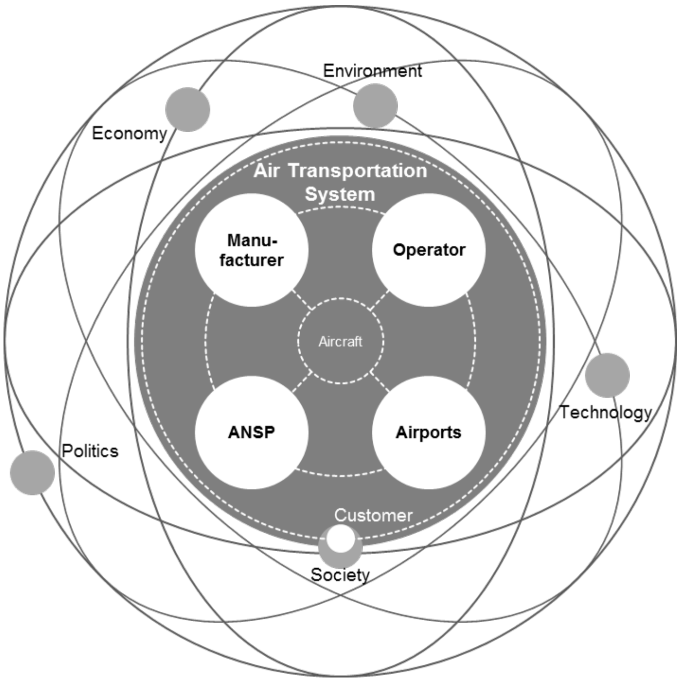


Figure 7: Air-Transport-System Model (Ghosh, Schilling, & Wicke, 2014)

Based on this model the workshop participants identified within four brainstorming sessions (electrical aircraft, blended wing body, strut braced wing, sustainable fuels) different impacts of each concept and fuel on each of the four major stakeholders (manufacturer, operator, ANSP, airports) and others. At the end of each session the participants were ask to award points to the identified impacts by criticality regarding a seamless technology introduction. The detailed results are listed in Table 6 to 9 of the appendix.

3.2 Identification of enablers and impact assessment

For a successful introduction of new concepts and technologies to the current air transport system, key enablers and solution gaps need to be identified. Therefore, the identified impacts from the multi-stakeholder system analysis were discussed in detail within the aforementioned expert workshop to identify critical challenges regarding for example the infrastructure, operational processes, performance thresholds, legislation or environmental issues.

Additionally an impact analysis was conducted, addressing the technical and operational feasibility and lead time till operational readiness for the identified impacts and their enablers. To ensure a seamless introduction of such concepts and technologies it has to be ensured that the technical and operational prerequisites to handle such impacts to the current system and stakeholders will be available. Further, the rough lead time till operational readiness serves as an indicator to assess the criticality of needed coordinated actions.

Based on the ranked impacts from the multi-stakeholder system analysis, key enablers to ensure successful introduction of novel aircraft and fuel concepts were identified within further workshop sessions. This was done by the participants by focussing for each of the ranked impacts on the following questions:

- What are key enablers to ensure a successful aircraft or fuel concept introduction?
- What are significant interfaces and challenges?

In a second step the participants had to assess the technical and operational feasibility of each identified impact by using a semi-quantitative scale from 5 (already feasible) to 0 (not feasible) considering following questions:

- Will the technical and operational expertise be available to handle this impact?
- Will the anticipated impact be technically and operationally manageable?

At last the participants had to estimate the lead time needed to adjust the air transportation system, stakeholders or interfaces to the anticipated implications until full operability for each concept is available, starting today with current technological and operational conditions. The detailed results of the identification of enablers and impact assessment can be found in Table 10 to 13 of the appendix.

3.3 Estimation of the CO2 emission reduction potential on global fleet level

A methodology developed by DLR (Nolte, 2012) was used to assess the introduction of the three novel aircraft configurations into the world fleet and its impacts on global CO_2 emissions of air transport. It consists of two separate modules (see Figure 8):

(1) Evolution of the world fleet of commercial passenger aircraft (Figure 8: steps 1-4).
(2) Forecast of the evolution of fuel and CO_2 efficiency based on fuel consumption and performance information of each aircraft model, and global CO_2 emissions and traffic calculated by aggregating the single aircraft estimates (Figure 8: steps 5-6).

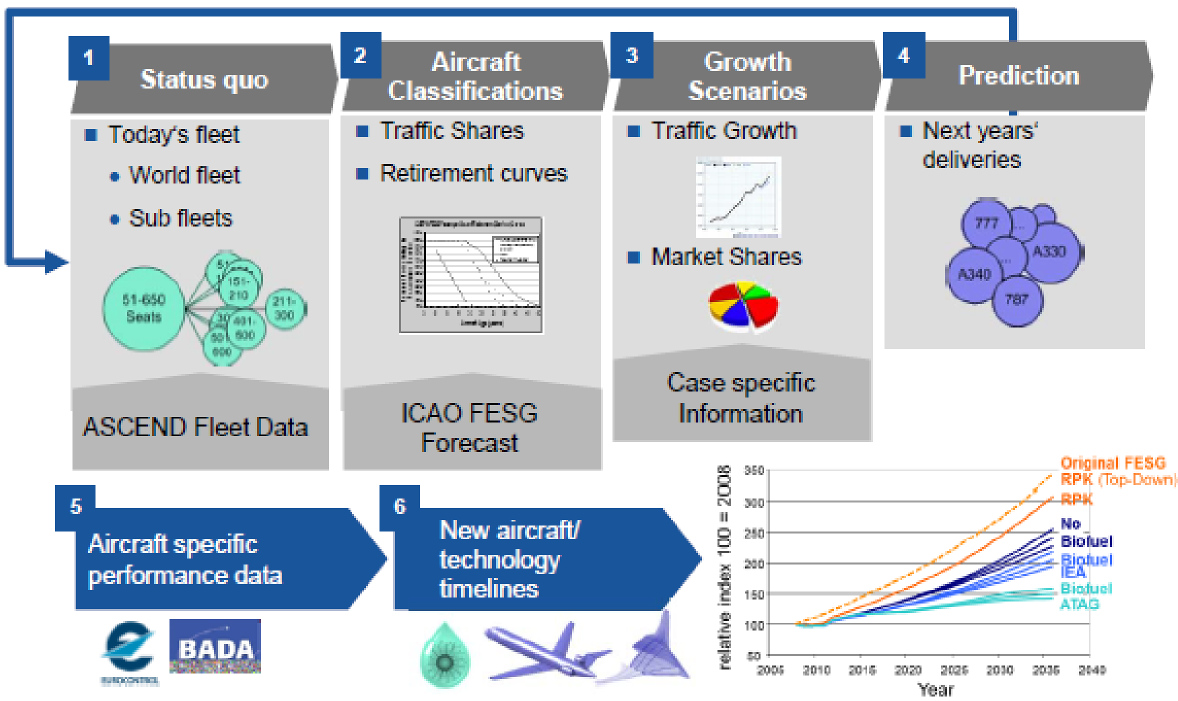


Figure 8: General CO2 Forecast Schematic: Bottom-up Forecast based on Year-to-Year Dynamics

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 ASCEND Fleet Database[9]
- From the detailed information provided by ASCEND, 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 retirement process is driven by so-called 'retirement curves', which have been estimated through a survival analysis from historical data for the ICAO Committee on Aviation Environmental Protection (CAEP) (Pratt & Whitney, 2007).

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

- The next step is estimating the number of additional aircraft needed to satisfy the selected traffic growth scenario (with the help of information on traffic shares in the latest ICAO FESG forecast)[10] (ICAO, 2012).
- The sum of aircraft needed for replacement and growth constitutes the next year's aircraft demand = 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.

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[11]. In particular, the block fuel consumption is estimated using BADA Datasets[12] a given flight distance and a given payload, to generate a huge dataset over the entire operational range of an aircraft type. For distance, load factor, and flights we take the average values of the corresponding size categories (different for each year) from the ICAO CAEP/9 forecast.

The number of seats is individual for each aircraft and is taken from the ASCEND database.

New aircraft configurations enter the world fleet through projected deliveries of "New Technology/Aircraft" (assumptions see appendix,Table 14) and "Unfixed Demand" (future generic aircraft).

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. A higher 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.

Combining the fleet forecast with the estimates of future development of fuel consumption and utilization of the individual aircraft and with the assumptions concerning novel aircraft configurations throughout the forecast horizon, an estimate of the impact of these novel aircraft configurations on global fuel and CO_2 efficiency can be derived.

[10] The Forecasting and Economic Analysis Support Group (FESG) is a working group of the Committee on Aviation Environmental Protection (CAEP) of the International Civil Aviation Organization (ICAO) and develops traffic and fleet forecasts. The forecast is based on a broad consensus, inputs and models by ICAO, member states, and observer organizations (Eurocontrol, IATA, aircraft and engine manufacturers).

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

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

4 Analysis and Assessment of Technical Concepts and Deployment Challenges

During the AIRCAT workshop, the participating experts analyzed the presented novel aircraft and sustainable energy concepts (see Chapter 2 and 3) and identified major impacts and enablers for all discussed concepts. These cover a comprehensive range of innovation trends, so that the identification of related stakeholder impacts and implementation enablers yielded a representative scope of challenges and solutions for the deployment of novel concepts that help achieve the long-term CO_2 emissions reduction goal.

4.1 Electrical Aircraft

Electrical aircraft are one of the most accepted solutions in the broad public to achieve environmental goals due to advanced electrification in other industries (e.g. automotive industry). For a successful introduction of electrical aircraft sufficient battery performance is the major enabler. Besides general battery improvements across multiple industries, electrical aircraft have to meet more stringent requirements compared to other industries, especially for the energy density of batteries, temperature-sensitive performance variations, and safety.

Additional standardizations of batteries to be used as primary energy source in future aircraft as well as with other industries are necessary to maximize economies of scale for battery production and availability, as well as for quick exchange during turnaround, including between different aircraft types. Besides the weight and performance of the batteries, the weight and performance of the electrical engines and the onboard high power electronics (e.g. superconductors) are further technological challenges that have to be met.

If electrical aircraft are introduced on a large commercial scale, aviation will significantly increase its role as an electricity consumer within the general electricity market. While the overall share of aviation amongst all electricity demand remains modest[13], reliable supply concepts for the increasing electricity demand at airports are necessary. Therefore, electricity companies could become new stakeholders of the aviation industry by introducing new market rules and energy supply chains.

Focusing on the contribution of such aircraft to carbon emission reduction goals, the overall lifecycle emissions have to be taken into account including the contribution of battery production and the sources of electrical energy. Consequently, the carbon emissions of electrically powered aircraft do highly depend on the future energy mix to be supplied by the electricity industry. As for every other technology in aviation, electrical aircraft have to comply fully with

[13] Analysis for Germany have shown that replacing all A320 & 737 flights from and in Germany will rise overall German electricity demand by 2% which is in the same order of magnitude as for railway transportation (Plötner, Vratny, Schmidt, Isikveren, & Hornung, 2013)

current and future high safety standards, especially regarding batteries and high power electronics.

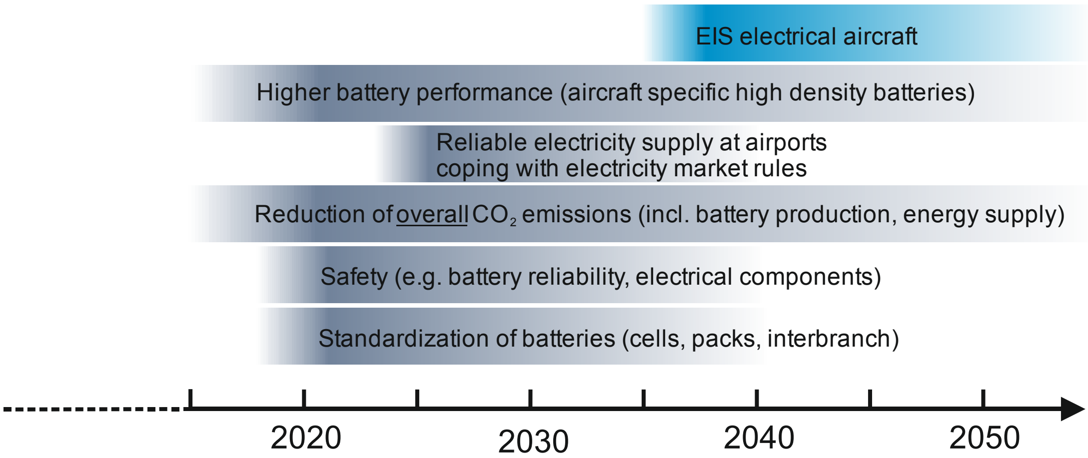


Figure 9: Major enablers for electrical aircraft introduction

Table 1: Basic information about electrical aircraft introduction

CO_2 saving potential on aircraft level (compared to current aircraft)	**CO_2 saving potential on global fleet level in 2050**[14]	**Seats and design range**	**Estimated market potential** (# of aircraft)	**Estimated entry-into-service (EIS)**
-100%[1]	up to 15%	up to 200 seats 700-1.000nm	~ 6.000 aircraft[3]	2035+
-80%[2]	up to 12%	up to 200 seats 700-1.000nm	~6.000 aircraft[3]	2035+

[1]for CO_2 emission free electrical energy supply (e.g. through "green energy" contracts)
[2]for greenhouse gas emission reduction by 80% as endorsed among others by the European Parliament (European Commission, 2011)
[3]Estimation based on future demand and market forecast for aircraft with 100-210 seats

Recommendations for accelerating the implementation of electrical aircraft:

- Focus research and development on high performance batteries with high energy density.
- Support novel battery technologies and battery production technologies.

[14] Forecast performed with the DLR fleet and fuel forecast tool FFWD (see chapter5)

- Support the development of strategies for building up worldwide battery supply networks and airport infrastructure.
- Strengthen links between R&T organizations in the aviation and in the energy area to realize the above targets.

4.2 Blended Wing Body (BWB)

With its futuristic shape the Blended Wing Body (BWB) represents a new aircraft category which potentially could enter into service in civil aviation beyond 2040. The aerodynamically optimized shape favors large sizes for more efficient cabin integration. Optimized for cruise flight it also favors long-range flights; therefore its advantages over conventional aircraft are particularly high on long-range flights with high passenger number or payload.

The novel design is subject to high uncertainties because design methods developed for conventional aircraft configurations (especially in respect to aerodynamics, flight mechanics, and trade-offs between structural weight and the integration of the pressurized cabin) are not directly applicable to non-tube-and-wing configurations. To reduce these uncertainties, high investments in new design methods and tools as well as expertise in handling them are necessary. Research projects to reduce such uncertainties and the clear identification of overall benefits are one of the major enablers.

The development of a family concept for BWBs is an essential requirement for a successful market introduction. Due to the aerodynamic shape of BWBs, which is more complex than for tube-and-wing configurations, it is a complex challenge to design modular aircraft family concepts for fuselage and equipment systems, which would be necessary for the viability of the BWB concept. The complex structure of a large non-cylindrical BWB body and cabin also requires an early adoption of the production, assembly and logistics (transportation) of parts and components produced at decentralized sites.

Operational challenges are seen in payload weight distribution and loading procedures, since the BWB design requires more restricted center-of-gravity limits. Additionally, operators and airports have to cope with the more complex accessibility for ground services and maintenance of BWBs. While the large space inside the BWB airframe allows for a variety of cabin designs, new operational processes (e.g. adaptation of the current aircraft size restriction at airports in an 80x80 m box) and procedures (e.g. situation awareness) have to be defined to comply with current safety requirements.

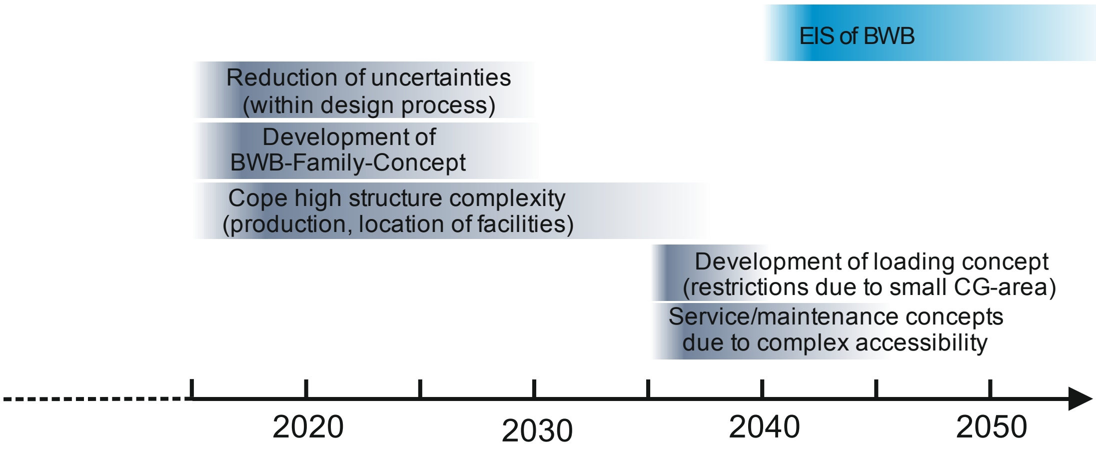


Figure 10: Major enablers for BWB introduction

Table 2: Basic information about BWB introduction

CO_2 saving potential on aircraft level (compared to current aircraft)	**CO_2 saving potential on global fleet level in 2050**[15]	**Seats and design range**	**Estimated market potential** (# of aircraft)	**Estimated entry-into-service (EIS)**
up to -50%	~ 1-2%*	~500 Seats 7.500nm	up to 1.000 aircraft	2040+

*number of aircraft will expand substantially in the following decades

Recommendations for accelerating the implementation of BWB:

- Focus research and technology activities on the reduction of uncertainties in the aircraft design process by strengthening overall aircraft design capabilities.
- Strengthen concepts and strategies for the production, assembly, supply, and logistics of large and complex structural components.

4.3 Strut Braced Wing (SBW) with Open Rotor

The Strut Braced Wing (SBW) aircraft configuration by NASA that was investigated in the present study combines the SBW concept with multiple additional technologies, such as aerodynamic optimizations, open rotor, fuel cell and boundary layer ingestion. Therefore, challenges and enablers identified here relate to this specific overall concept. However, other technology

[15] Forecast performed with the DLR fleet and fuel forecast tool FFWD (see chapter 5)

and concept combinations are possible and have been studied among others within the Boeing and NASA SUGAR studies.

A property of the open rotor that could reduce the productivity/utilization compared to current aircraft is the lower cruise speed of around Mach 0.7 compared to Mach 0.75 to 0.79 of comparable current aircraft types.[16] Therefore, the net benefit of this concept has still to be proven, considering the possible aircraft utilization drawback. Additionally, air traffic management has to work in time on ensuring the integration of such aircraft with lower cruise speed into the flight network. While the open rotor reduces the fuel consumption substantially, a major challenge is to reduce the noise impact in- and outside the aircraft. Even if big improvements have been achieved for open rotor noise, the noise levels are still higher than for other future advanced engines. (Hendricks, Berton, Haller, & Tong, 2013). To meet current blade-off safety requirements for open rotor engines, some weight penalty is necessary. This has to be kept to a minimum to avoid cancelling the fuel consumption benefit (Warwick, Aviation Week & Space Technology, 2014).

Reliably designed foldable wings are additional enablers from technical and operational perspectives. Since experience with foldable wings already exist for military aircraft and Boeing announced this technology for the upcoming 777X, solutions to build on are already available.

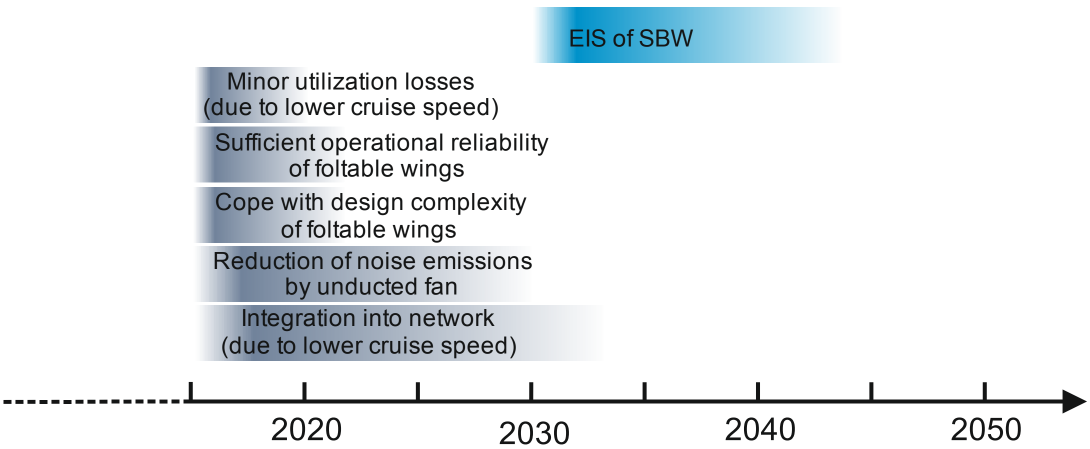


Figure 11: Major enablers for SBW introduction

Table 3: Basic information about SBW introduction

[16] This could also be an issue with other aircraft concepts (e.g. electrical, LNG) using technologies motivating lower cruise speeds. By reducing cruise speeds of current aircraft significant reductions of drag and fuel consumption are already possible today.

CO_2 saving potential on aircraft level (compared to current aircraft)	**CO_2 saving potential on global fleet level in 2050**[17]	**Seats and design range**	**Estimated market potential** (# of aircraft)	**Estimated entry-into-service (EIS)**
-29 to -62%*	up to 7%**	154 Seats 3.500nm	~6.000 aircraft	2030+

* -29% expected for the 2030 version and 62% for the 2045 version
**applies for entry-into-service of -29% concept version in 2030 and -62% version in 2045

Recommendations for accelerating the implementation of SBW:

- Expand efforts in network and air traffic management research, focusing on an increasing variety of aircraft with different operational characteristics (for open rotor SBW e.g. lower speed, potentially lower wake vortex separation due to larger wingspan).
- Reduce noise emissions by open rotors through increasing research and development efforts.

4.4 Sustainable drop-in fuel technologies – SOLAR-JET

There is no perspective of replacing current Jet A-1 fuel with a physically and chemically different substitute within the next one or two decades. The necessity to remain compatible with the current fleet of aircraft and the existing fuel supply infrastructure, considering the prohibitive costs of building up and maintaining a parallel supply infrastructure or adapting the entire existing aircraft fleet, prevents the introduction of non-drop-in fuels in the near to mid-term future. On the other hand, to effectively reduce global aviation emissions, it is necessary to find more sustainable aviation fuels, which at the same time could reduce the dependence on crude oil resources with its high price fluctuation and declining reserves in the long term. Blending current jet fuel with drop-in fuels, which are chemically similar substances, is the most promising way.

One pathway for producing drop-in jet fuel is the Fischer-Tropsch synthesis process, which can use any carbon-containing feedstock (e.g. coal, natural gas or biomass). The presented SOLAR-JET fuel process uses very high temperatures from concentrated sunlight to decompose CO_2 captured from air and H_2O into syngas to produce kerosene through the Fischer-Tropsch process. Since it is a drop-in fuel, it can be introduced into the network successively in the same way as is already the case for current drop-in alternative fuels such as biojet fuels.

To estimate the potential of this technology, as a basis for further research and development, a robust scientifically-based estimate is needed regarding the conversion efficiency, the demonstration outside a laboratory environment, and reliable estimations of the number and size of

[17] Forecast performed with the DLR fleet and fuel forecast tool FFWD (see chapter 3.3)

large-scale plants that can be built. In addition to the technical feasibility the economic competitiveness compared to other sustainable fuels has to be assessed. Furthermore, to enable successful implementation of SOLAR-JET and other Fischer-Tropsch fuels, efficiency improvements are necessary. As the Fischer-Tropsch process is already a technically mature process, only minor improvements can be expected. The main focus will therefore be on improving the efficiency of solar energy capture and conversion process. Also improvement of technologies for CO_2 absorption from air is necessary to make the process fully sustainable and independent from fossil industrial CO_2 exhaust gas sources (Falter, Batteiger, & Sizmann, 2015).

Similar considerations are valid for the power-to-liquid technology, whose potential also depends on significant innovation to reduce fuel production costs along the whole process chain.

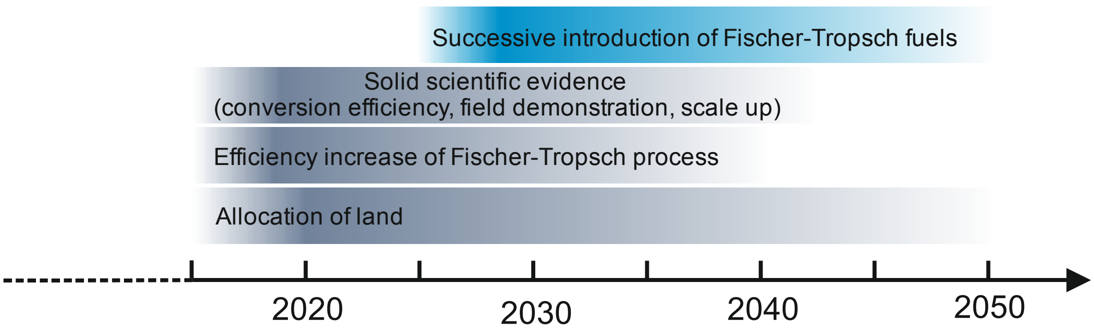


Figure 12: Major enablers for Fischer-Tropsch fuels introduction

Recommendations for accelerating the implementation of novel sustainable drop-in fuels:

- Focus research on improved techno-economic performance of renewable synthetic drop-in fuels.
- Expand efforts on field demonstration and scale up capabilities of promising synthetic fuels.

4.5 Sustainable non-drop-in fuel technologies - liquid natural gas

In the long term, new fuels and energy sources are needed to replace current Jet A-1 fuels for significant emission reduction. Being a typical representative of non-drop-in fuel solutions, liquid natural gas (LNG) is currently investigated from both an economic and an overall lifecycle emissions aspect as a potentially interesting replacement for current crude-oil based aircraft fuels.[18] Although mostly from fossil sources today, it can easily be replaced by biogas if available in larger quantities. In 2013, LNG was about 70-80% cheaper than jet fuel on an energy basis and therefore may reduce operating costs (Withers, et al., 2014). Additionally, natural gas has 23% lower CO_2 combustion emissions than conventional jet fuel on a per-unit energy basis (Argonne

[18] Decrease of CO_2 by up to 25%; decrease of NO_X by up to 80%; particulate emissions eliminated (AHEAD Project, 2011)

National Laboratory, 2012) and is expected to result in lower emissions of particulate matter and SO_2 (Carter, Stratton, & Bredehoeft, 2011).

However, new fuselage designs are necessary for LNG-aircraft. LNG requires different tank and fuel systems compatible with cryogenic fuels and complying with current high safety standards in aviation (e.g. tank reinforcements, leakage exclusion). To maintain equal productivity and useful payload volume, an LNG aircraft would likely have either a wider or longer fuselage than a comparable jet-fuel powered one. But fundamental technical aspects of using LNG in for-purpose designed aircraft do not show any technical barriers that would prevent the use of natural gas as an alternative aviation fuel (Carson, Davis, & Versaw, 1980).

To enable a seamless introduction of such non-drop-in fuels, sufficient availability at airports, i.e. operational LNG supply chains and infrastructure, are essential. LNG is a widespread energy source in industry and households with a good existing distribution network. However, neither LNG nor other non-liquid hydrocarbon fuels are currently common in aviation; therefore specific supply chains and infrastructures would have to be built up. The launch of a LNG-powered aircraft program is viable only if LNG is supplied at a sufficient number of airports within the worldwide network to allow operations with a large number of aircraft customers in all parts of the world under the same reliability conditions as with current jet fuel.

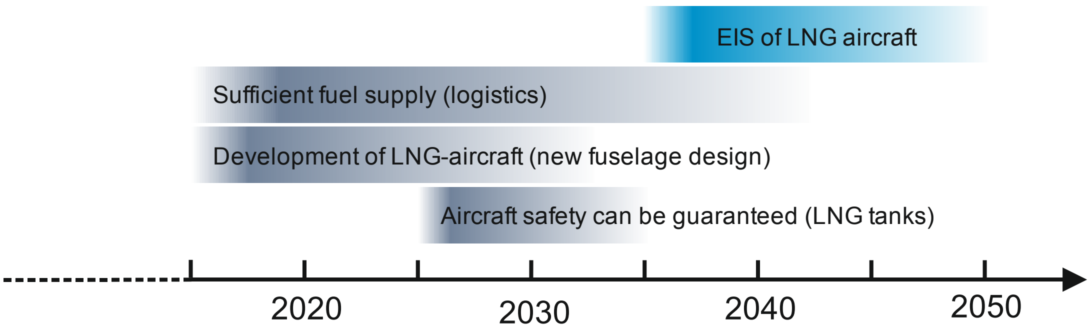


Figure 13: Major enablers for LNG aircraft introduction

Recommendations for accelerating the implementation of novel sustainable non drop-in fuels:

- Development of strategies for building up worldwide supply networks and infrastructure for new non-drop-in fuels.
- Strengthening research regarding the integration of non-drop-in alternative energy sources (e.g. LNG) in the aircraft design processes.

4.6 Further identified technologies

In addition to the presented fuels and aircraft concepts, and to the technologies included in the IATA Technology Roadmap (IATA, 2013), a series of further technologies, shown in Table 4, were identified at the AIRCAT expert workshop, which are currently under research or development. These technologies should be assessed in the near future in a similar way as done in the AIRCAT project. Besides research and development on single technologies, effort is needed on radically new aircraft concepts combining multiple technologies.

Table 4: Further possible concepts and technologies and their applicability

	Applicability		
Concept / Technology	Short-Range	Long-Range	Retrofit/Adaptable
Hybrid electrical propulsion	X		
Distributed propulsion	X	X	
Fuel cell	X	X	X
Aircraft without landing gear (ground-based landing gear system		X	
Laminar air flow (hybrid, natural)	X	X	
Formation flight		X	X (operational)
Integration of engines into the fuselage	X	X	
Morphing technology	X	X	
Flying lower and/or slower	X		X (operational)
Modular aircraft (e.g. Clip-Air)	X	X	

5 CO2 saving potential at global fleet level

In addition to the identification of the main challenges, obstacles and roadblocks expected from the introduction into the air transport system, the quantitative assessment of the contribution of the discussed aircraft concepts to the CO_2 emission reduction goals on global fleet level till 2050 is important for the deduction of further actions. The forecast of the future CO_2 emissions on global fleet level and the contribution of each concept and the combination of all three were performed with the DLR fleet and fuel forecast tool FFWD (Fast Forward) as described in chapter 3.3.

FFWD is based on past and current fleet information 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 FESG retirement curves (CAEP/8). 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. The projected traffic growth is derived from ICAO FESG traffic and fleet forecast (ICAO, 2012) including ASK, RPK, yearly flights, number of aircraft, and number of seats (for more details see Appendix B – Forecast model assumptions).

Based on a reference (baseline) scenario for the development of the global aircraft fleet and its fuel consumption till 2050 considering evolutionary technologies only, four scenarios are modeled to estimate the contribution of each of the three new aircraft concepts investigated (Electrical, SBW, BWB) and a combination of all three concepts. The specific assumptions for each scenario are listed in

Table 5, containing the expected reduction in fuel consumption for the next aircraft generation compared to the current aircraft generation and its expected entry into service (EIS) year. 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). The underlying growth scenario till 2050 is shown in Figure 15.

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.

It can be seen that the total CO_2 reduction from radical aircraft concepts in 2050 is about 25% compared to the emissions in the baseline scenario (considering evolutionary technologies only). This means that the majority of emissions reductions necessary to meet the 2050 goal would have to come from low-carbon fuels. These would include both the currently known alternative drop-in fuels (mostly biojet fuels, which are already in their deployment phase today) and radically new fuels, such as the solar jet and power-to-liquid fuels mentioned in the present report.

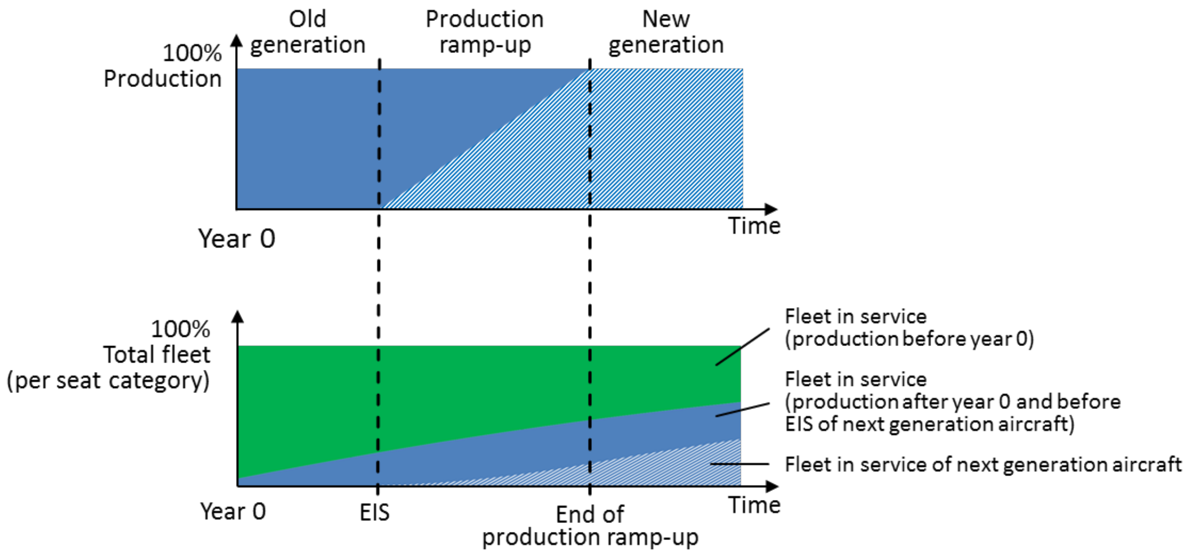


Figure 14: Schematic diagram of new aircraft introduction within global fleet model

Table 5: Assumed improvements in fuel consumption (%) and entry-into-service (EIS) years for baseline scenario and new aircraft concepts scenarios

Seat Category	**Baseline**		**Electric**		**SBW**				**BWB**		**SBW + BWB + Electric**			
	%	EIS	%	EIS	%	EIS	%	EIS	%	EIS	%	EIS	%	EIS
50-100	-15%	2035	-100%	2035	-29%	2030	-62%	2045	-15%	2035	-29%	2030	-100%	2035
101-150	-15%	2035	-100%	2035	-29%	2030	-62%	2045	-15%	2035	-29%	2030	-100%	2035
151-210	-15%	2035	-100%	2035	-29%	2030	-62%	2045	-15%	2035	-29%	2030	-100%	2035
211-300	-20%	2035	-20%	2035	-20%	2035			-20%	2035	-20%	2035		
301-400	-20%	2035	-20%	2035	-20%	2035			-20%	2035	-20%	2035		
401-500	-15%	2045	-15%	2045	-15%	2045			-15%	2045	-15%	2045		
501-600	-15%	2045	-15%	2045	-15%	2045			-50%	2040	-50%	2040		
601-650	-15%	2045	-15%	2045	-15%	2045			-50%	2040	-50%	2040		

As a result of this modelling, the impact of the three radical aircraft concepts investigated in the AIRCAT study on the CO_2 emissions relative to 2005 is plotted in Figure 16.

Taking into account that the new aircraft models, with EIS between 2030 and 2045, will not have reached full market penetration in 2050 and their share will continue growing well beyond that date, it can be expected that the CO_2 emissions reduction from these aircraft will be considerably higher than 25% in the years after 2050. The milestone of the long-term industry goal is actually too early to take full benefit of radically new aircraft concepts that still need around two decades of maturation.

Since the electric aircraft and the strut-braced wing are direct competitors within the seat categories up to 210 seats, the combined scenario favors the electrical aircraft for the identification of the maximum combined emission reduction potential. This maximum potential does just apply for this specific combination, but does not represent the maximum technological potential that could possibly be achieved till 2050. Therefore, it would be beneficial to assess the market response and manufacturers benefit of both concepts in further studies and if a parallel development would be economically worth. While the development cost of a strut-braced wing seems to be lower than of a fully electrical aircraft, the economic and ecological potential of a fully electrical aircraft is significantly higher. Additionally the economic benefit of combining both concepts to maximize the technological potential has to be investigated considering a possible postponement of the market entry.

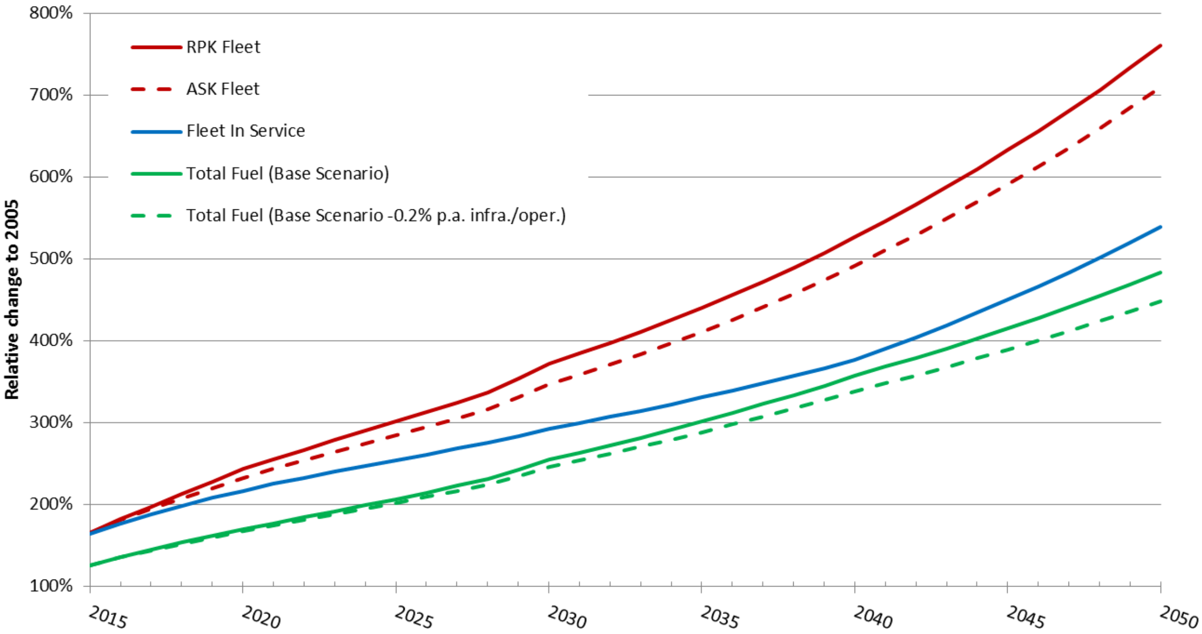


Figure 15: Basic growth forecast scenario (2005 ≙ 100%)

It should be noted that the fuel burn forecast done here, using the bottom-up FFWD methodology, strongly depends on the assumptions made for future new aircraft type entry into service dates. Since 2010, a number of postponements for after-2020 aircraft have been announced especially in the single-aisle market, which leads to a relatively slow improvement rate in the next decade. Very recently, plans for additional new aircraft types for the next decade have been announced, such as a clean-sheet design for a "middle-of-the-market" successor of the Boeing 757[19] as well as a high-capacity A350 derivative[20]. Such introductions of new aircraft, and especially of fully new designs, to the future world fleet might accelerate the fuel efficiency improvement trend and reduce the fuel burn projection curves shown here.

[19] https://www.flightglobal.com/news/articles/boeing-plans-new-aircraft-go-ahead-decision-by-end-y-421802/

[20] e.g. http://www.cnbc.com/2016/03/04/airbus-touts-400-seat-a350-8000-jetliner.html

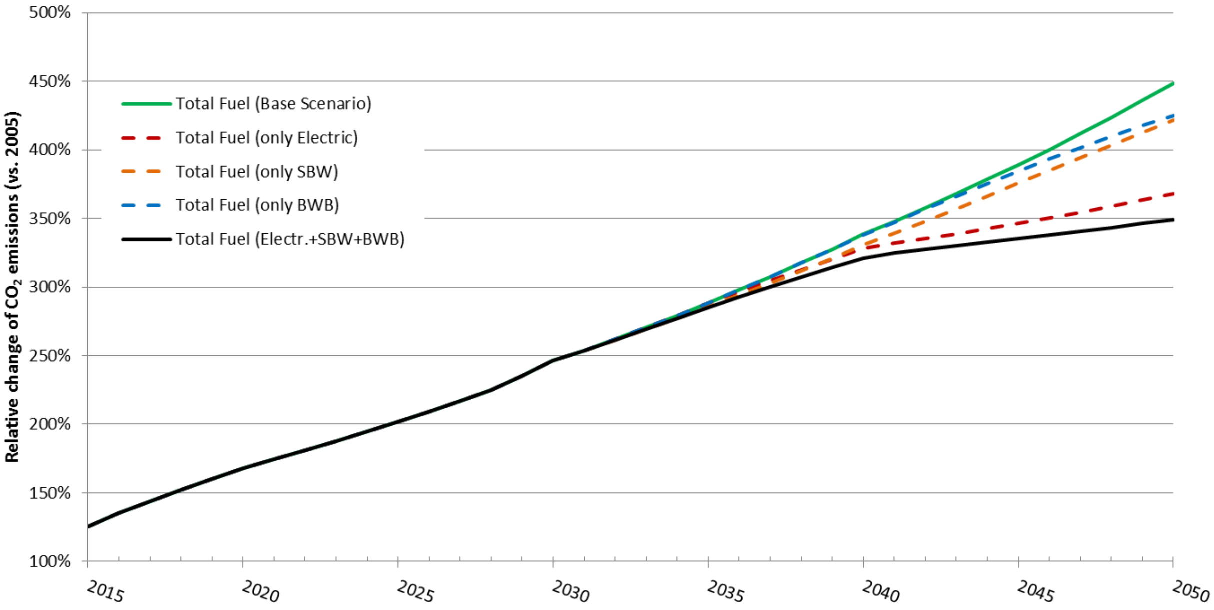


Figure 16: Contribution of presented radically new aircraft concepts to CO2 emission reduction roadmap; including yearly operational and infrastructural improvements of 0.2% (2005 ≙ 100%)

Nevertheless, the forecasted contribution of radically new aircraft configurations, within the accuracy limits of a 2050 projection, is only weakly influenced by the details of the baseline scenario. The order of magnitude of the expected improvements from radical technologies is therefore valid independently of the coming evolutionary aircraft developments.

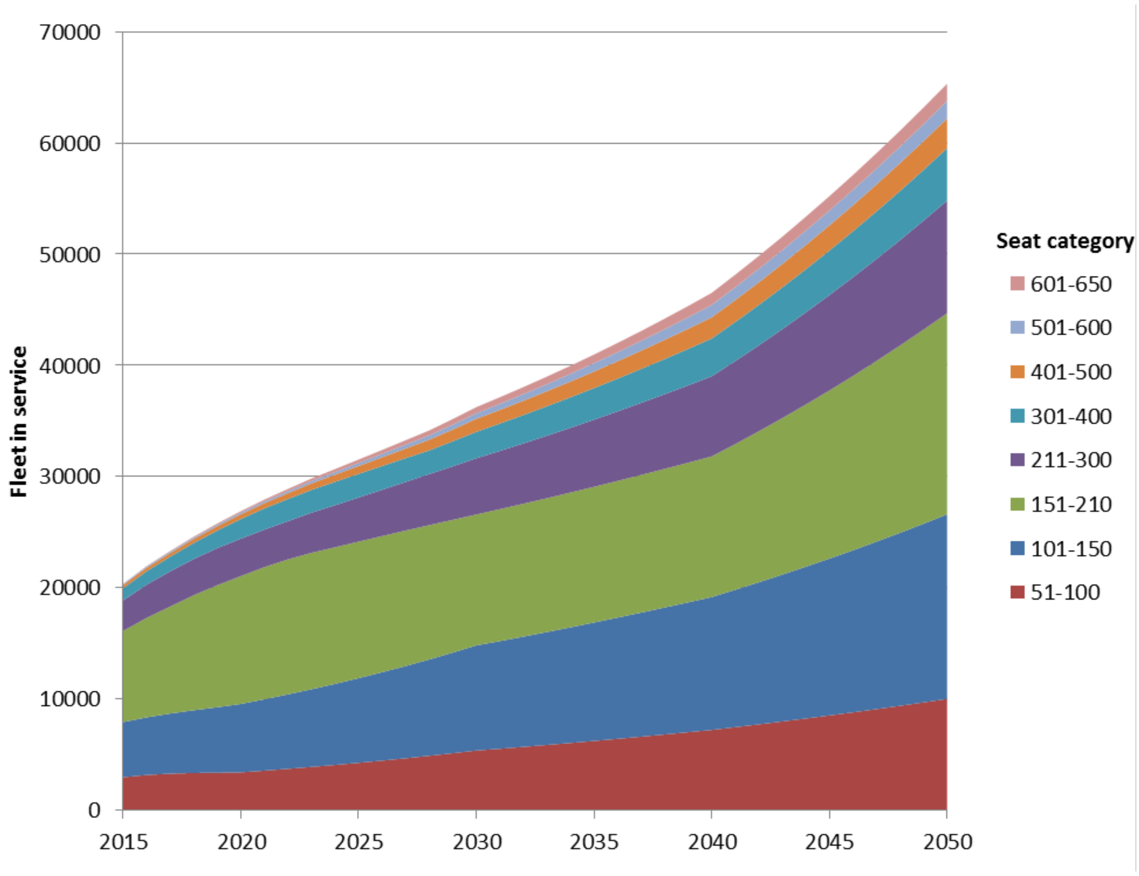


Figure 17: Fleet forecast by seat category till 2050

All forecast scenarios are based on the same fleet forecast predicting the number of aircraft in service for different seat categories between 51 and 650 seats. The predicted fleet mix can be found in Figure 17. An overview of the assumptions/data the forecast model is based on can be found in Appendix B – Forecast model assumptions.

The projection presented in this chapter accounts for the three radical aircraft concepts presented in chapter 2 and shows a rough CO_2 reduction potential of about 25% compared to the "evolutionary" emissions scenario till 2050. Additionally it is expected that an even larger share will come from sustainable fuel technologies, especially from low-carbon drop-in fuels. Many projections consider availability of biojet fuels, but do not yet take into account radically new fuels, such as SOLAR-Jet and power-to-liquid, which could be produced on top without being in completion with biofuels. To include alternative sustainable fuel technologies into the quantitative analysis, more research is needed regarding the overall CO_2 emission reduction potential (incl. fuel production, build-up of global supply chain and infrastructure) for the global aircraft fleet.

Land for installation of solar collectors is not required to be fertile, and therefore future production capacity for Solar-Jet fuel is currently limited essentially by economic and political conditions.

Overcoming the technological, political and market challenges for the implementation of radically new climate-friendly concepts and technologies requires about 15 to 25 years from now; this is valid for the concepts presented here as well as for other similar ones.

Therefore the market penetration of radical aircraft technologies will still be limited by 2050, although it may significantly increase after that date. As can be seen in Figure 16, they can contribute a reduction of about 25% of global emissions in 2050. The majority of emissions reduction would thus have to come from low-carbon alternative fuels, such as Solar-Jet and power-to-liquid. Moreover, accelerating product cycles and innovation speed in the aviation industry is required in the near future to ensure success of radically new aircraft concepts.

6 Conclusions and Recommendations from the AIRCAT project

Conclusions:

- Radically new climate-friendly aviation technologies are necessary to meet the aviation industry's long-term emissions reduction goal.
- As the market penetration of radically new aircraft concepts is slow by nature, these can only contribute a part of the required emissions reduction. The larger part will have to come from sustainable alternative fuels.
- For the successful introduction of radical concepts, their impact on all major stakeholders within the air transportation system has to be assessed and cooperation between them launched as early as possible.
- To bring radically new technologies with high CO_2 emission reduction potential into the market to reach the 2050 carbon emissions reduction goal, research and industry have to start working now on the prerequisites and long lead-time items of these technologies.
- **Acceleration of product cycles and innovation speed in the aviation industry is important to enable sufficient market penetration of climate-friendly technologies till 2050, while keeping affordability of new products in mind.**
- Politics has to substantially support basic research at low development stages as well as transfer of technologies and concepts to marketable products in time.

Recommendations for further research work:

- **Expand the focus of this study** to further radically new technologies with high CO_2 emission reduction potential (e.g. those in Table 4) and to deeper techno-economical viability analyses to identify the most promising technologies.
- Maximize emission reduction potentials by **combining various promising technologies and aircraft concepts**.
- **Reduce uncertainties** of technical and operational performance indicators of new technologies and concepts **through concentrated research work and quantitative assessments**.
- **Develop and adapt overall CO_2 emission assessment methodologies** for the comparison and identification of most valuable technologies, including non-conventional concepts, on a global (world aircraft fleet) level.
- **Focus research on the improvement of production efficiencies, field demonstration and scale up capabilities** of new fuels and energies (e.g. SOLAR-JET, batteries) **as well as battery energy density.**
- **Develop strategies for building up supply networks and infrastructure for new fuels and energy sources** (e.g. LNG, electricity supply and battery logistics).

Appendix A – Workshop results

Impact analysis (day 1)

The following results are based on the methodology described in chapter 3.1 and were derived in the AIRCAT expert workshop in April 2015.

Table 6: Expected Impacts by BWB (Workshop Results Day 1)

Stakeholder	Impact	Ranking Points
Airports	Less noise emissions	4
	Aircraft separations are different (+-)	2
	Clearance area - rules have to be changed	0
	New cargo-loading system is needed	0
	Anti-icing - new equipment is needed	0
	Less bird injections are expected	0
	Overall minor infrastructure changes at turnaround are expected	0
Operators	More complex accessibility for maintenance/service	5
	Loadability / loading-diagram are more critical (center of gravity area)	5
	Different situation awareness within the cabin	3
	Different noise frequencies due to boundary layers - noise damping	2
	Turnaround-time - critical path de/-boarding - could be positive	2
	Higher risks for damage due to outside design	2
	More difficult exchange of engines - maintenance	1
	High performance changes due to center of gravity shifts	1
	Less noise inside cabin?	0
	Service changes due to possible multi-isle configuration	0
	More individual cabin design for operators possible	0
Manufacturers	Family-Concepts more complex to design/produce compared to conventional aircraft	13
	Very high uncertainties - high investments are needed	13
	More complex structure - production, location of facilities	9
	Passenger-comfort / Riding comfort during aircraft movements	3
	More free design-options for engine-manufacturer	1
	Benefits as cargo-aircraft (high volume) - make it attractive as pax/cargo combination	1
	Potential for new Cabin-Designs - Passenger acceptance?	0
	Stability / control of aircraft is more complex	0
	Good compatibility for new technologies (e.g. LNG) - more integration options	0
	Wind shielding effect of rear-engines	0
	Low wing loading (good)	0
ANSPs	Higher altitudes can be more efficient (vs. cabin pressure)	0
	Curve radius - passenger comfort - impact for ANSP	0
	More steep approaches with BWB are possible	0
Others	Evacuation has to be shown in reality - certification	1
	Different emergency, evacuation procedures due to different places of emergency doors	1
	Engine burst - shilding needed? - certification	1
	Certification of stability / control of aircraft	0

Table 7: Expected Impacts by Fully Electrical Aircraft / Ce-Liner (Workshop Results Day 1)

Stakeholder	Impact	Ranking Points
Airports	Average temperature at airports? Battery pre-conditioning is needed	3
	Standards for electricity at airports (prices) - aviation participating into grid-network	3
	Intermediate storage for energy at airports	2
	Infrastructure investments (e.g. storage)	2
	Back-up solution for airports without needed infrastructure	2
	Local air quality benefits	2
	Storage for batteries is needed	0
	Batteries distribution	0
	Battery loading system	0
	Responsibility for charging/availability of batteries	0
	Noise level of electrical aircraft	0
	Back-up for energy availability at airports (energy shut-down)	0
	High altitude take-off benefits	0
	Critical turnaround-path - is it safe to do boarding while recharging batteries?	0
Operators	Electricity market rules, contracts, prices (who is selling the electricity? Airports?)	9
	Little payload-range flexibility	5
	Improvement-potential by the use of new/upgraded batteries	1
	Battery degradations/thresholds/exchanging strategies - input for operation management	1
	Usage effects of battery-use / lifecycle of batteries	0
	Maintenance - electricity systems are more difficult to maintain	0
	Less maintenance for electrical engines (?)	0
Manufacturers	Battery – performance	14
	Safety	8
	Battery-standards (cells, packs)	6
	Who owns the batteries?	3
	Certification (e.g. safety aspects)	3
	Performance and weight of electrical engines	3
	New manufacturers / suppliers could be introduced	2
	Optimize propulsion system	1
	Reliability of battery-performance / monitoring charging	1
	Who builds the batteries?	0
	Structural aspects (weight, center of gravity)	0
	Battery upgrade is possible for better future batteries	0
	Weight of distribution system	0
	Electrical losses within propulsion system	0
Others	Overall CO_2 emissions (incl. battery and electricity production)	9
	Reporting of energy use by airlines (emission location) - market-based measurements	4
	Certification	1
	Safety	1

Table 8: Expected Impacts by Strut Braced Wing + Open Rotor Aircraft (Workshop Results Day 1)

Stakeholder	Impact	Ranking Points
Airports	Noise perception in the airport vicinity	4
	More damage potential for ground vehicles	3
	Folding wing failures for gate accessibility	1
	More space for engine safety zone (open rotor)	0
	Landing distance	0
Operators	Utilization loss due to lower cruise speed	8
	Folding wing reliability could impact taxi, take-off, safety issues	7
	Ground noise impact	6
	Cabin comfort (sound insulation)	4
	Fleet network management challenges due to utilization losses	3
	Engine damage by ground service equipment	2
	Emission charges at airports	2
	More certainty for performance needed before investing	0
	Height of engine must be accessible for maintenance workers	0
	Folding wing (height) must be accessible for maintenance workers	0
	Fuel efficiency increases - cost	0
Manufacturers	Foldable wings (complexity)	7
	Noise shielding cabin (complexity)	4
	Blade-off scenario - impact protection	3
	Open rotor integration	2
	Anti-Icing (certification)	1
	Evacuation - no over-wing exits - position of open rotor	1
	Passenger comfort - ride quality	1
ANSPs	Integration into network (lower Mach number)	4
	Rate of descend changes	2
	Separation minima driven by vortex	1
	Separation minima driven by approach speed	0

Table 9: Expected Impacts by Fuels (LNG and SOLAR JET) (Workshop Results Day 1)

Stakeholder	Impact	Ranking Points
Airports	LNG Fuel supply (logistics)	11
	Allow blending of bio/fossil fuel with onsite fuel supply	1
	Aircraft refueling time - bigger/better pumps	0
Operators	Reliability of supply / supply network / operational flexibility (LNG)	8
	Purchasing process (LNG/SOLAR JET)	7
	Different maintenance procedures (LNG)	0
Manufacturers	Change in fuselage design / Fuel system design / Tank design (LNG)	11
	Aircraft safety (LNG)	8
	Engine certification (LNG)	4
	Adapt combustor/engine technology (LNG)	3
	Fuel system for more than 50/50 blends (SOLAR JET)	0
	Different wing design (LNG)	0
Others	Political support (LNG/SOLAR JET)	11
	Efficiency of Fischer-Tropsch process (SOLAR JET)	7
	Allocation of land (SOLAR JET)	7
	Certification process (LNG/SOLAR JET)	1
	Introduction into supply chain (SOLAR JET)	0

Impact assessment (day 2)

The following results are based on the methodology described in chapter 3.2. The selected items are those which were ranked most important on day 1 of the AIRCAT expert workshop (see Tables 6 to 9).

Table 10: Impact Assessment BWB

Stakeholder	Impacts	Ranking Points (Day 1)	Enabler	Technical and operational feasibility	Lead-time till operational readiness
Manufacturers	Family concepts more complex to design/ produce compared to conventional aircraft	13	• obvious benefits have to be clearly visible (vs. conventional aircraft) • further gap research necessary • depending on fuel price / CO_2 emissions • industrial processes, workshare, transportation have to be adapted	3	10-15 years
Manufacturers	Very high uncertainties - high investments are needed	13	• scaling of inner-wing (keep outer wing constant) • family concept is a must-have (for manuf./operator) • cargo-market as an entry-point/enabler	3	10-15 years
Manufacturers	More complex structure - production, location of facilities	9	• investigations of new feasible build concepts needed • high risks because no lessons learned/best practices available • risk sharing / governments have to invest	3	20 years
Operators/ Airlines	More complex accessibility for maintenance/service	5	• additional investments for equipment needed • solutions are musts for operations • solutions needed that do not have influence on access time • making lifetimes longer instead of exchanging parts	4	10 year (from concept freeze on)
Operators/ Airlines	Loadability / loading-diagram are more critical (center of gravity area)	5	• hook-up at the back (prevent tilting) • shift fuel to trim aircraft •	5	< 5 years
Operators/ Airlines	Different situation awareness in the cabin	3	• camera / pax-tracking system (certification) • cabin design • situation awareness (outside view) • advanced material (window-replacements)	4	5-10 years
Manufacturers	Passenger-comfort / Riding comfort during aircraft movements	3	• larger /smooth turn radius necessary • providing outer view for passengers • more flexibility for cabin configuration	4	5-10 years

Table 11: Impact Assessment Full Electrical Aircraft / Ce-Liner

Stakeholder	Impacts	Ranking Points	Enabler	Technical and operational feasibility	Lead-time till operational readiness
Manufacturers	Battery – performance	14	• reliable battery performance forecast • battery cost • basic research to push performance • develop batteries for aviation requirements (energy density)	2.5	20-35 years
Operators/ Airlines	Electricity market rules, contracts, prices (who is selling the electricity? Airports?)	9	• agreements between different/new stakeholders • fuel prices vs. electricity prices • supply vs. demand	5	10 years
Others	Overall CO_2 emissions (incl. battery and electricity production)	9	• emissions during battery production • electricity mix (emissions during electricity production) • politics have to push energy industry to lower CO_2 emissions • comparison of total electricity chain vs. fuel chain emissions	5	-
Manufacturer	Safety	8	• -	-	-
Manufacturer	Battery-standards (cells, packs)	6	• -	-	-
Operators/ Airlines	Little payload-range flexibility	5	• -	-	-
Others	Reporting of energy use by airlines (emission location) – market-based measurements	4	• -	-	-
Airports	Average temperature at airports; battery preconditioning is needed	3	• -	-	-
Airports	Standards for electricity at airports (prices) – aviation participating into grid-network	3	• -	-	-
Manufacturer	Who owns the batteries?	3	• -	-	-
Manufacturer	Certification (e.g. safety aspects)	3	• -	-	-
Manufacturer	Performance and weight of electrical engines	3	• -	-	-
Airports	Intermediate storage for energy at airports	2	• -	-	-
Airports	Infrastructure investments (e.g. storage)	2	• -	-	-
Airports	Back-up solution for airports without needed infrastructure	2	• -	-	-
Airports	Local air quality benefits	2	• -	-	-
Manufacturer	New manufacturer / suppliers could be introduced	2	• -	-	-
Operators	Improvement-potential by the use of new/upgraded batteries	1	• -	-	-
Operators	Battery degradations/thresholds/exchanging strategies – input for	1	• -	-	-

Stakeholder	Impacts	Ranking Points	Enabler	Technical and operational feasibility	Lead-time till operational readiness
	operation management				
Manufacturer	Optimize propulsion system	1	• -	-	-
Manufacturer	Reliability of battery-performance / monitoring charging	1	• -	-	-
Others	Certification	1	• -	-	-
Others	Safety	1	• -	-	-

Table 12: Impact Assessment Strut Braced Wing + Open Rotor

Stakeholder	Impacts	Ranking Points	Enabler	Technical and operational feasibility	Lead-time till operational readiness
Operators/ Airlines	Utilization loss due to lower cruise speed	8	• lower aircraft price	3	5 years
Operators/ Airlines	Folding wing reliability could impact taxi, take-off, safety issues	7	• Boeing 777X and military experience evaluation	4	5 years
Manufacturers	Foldable wings (complexity)	7	• design	4	5 years
Operators/ Airlines	Ground noise impact	6	• design (aircraft integration) • adaption of flight path • blade design • electric taxiing	3	15 years
Airports	Noise perception in the airport vicinity	4	• design (aircraft integration) • adaption of flight path • blade design • electric taxiing	3	15 years
Operators/ Airlines	Cabin comfort (sound insulation)	4	• active noise control • materials	-	-
Manufacturers	Noise shielding cabin (complexity)	4	• active noise control • materials	-	-
ANSPs	Integration into network (lower Mach number)	4	• better air traffic management	4	15 years
Airports	More damage potential for ground vehicles	3	• proximity sensors • free zones	5	0 years
Operators/ Airlines	Fleet network management challenges due to utilization losses	3	• modelling and simulation	-	-
Manufacturers	Blade-off scenario - impact protection	3	• improvement in materials	3	15 years
Operators/ Airlines	Engine damage by ground service equipment	2	• proximity sensors • free zones	-	-
Operators/ Airlines	Emission charges at airports	2	• electric taxiing	-	-
Manufacturers	Open rotor integration	2	• good design work	4	15 years
ANSPs	Rate of descend changes	2	• better air traffic management	4	15 years
Airports	Folding wing failures for gate accessibility	1	• remote parking	5	-
Manufacturers	Anti-Icing (certification)	1	• electric	5	-

Manufacturers	Evacuation - no over-wing exits - position of open rotor	1	• door type	5	-
Manufacturers	Passenger comfort - ride quality	1	• oscillation/vibration damping	-	-
ANSPs	Separation minima driven by vortex	1	• better air traffic management	4	15 years

Table 13: Impact Assessment Fuels (LNG and SOLAR-JET)

Stakeholder	Impacts	Ranking Points	Enabler	Technical and operational feasibility	Lead-time till operational readiness
Airports	LNG Fuel supply (logistics)	11	• pipeline / infrastructure (e.g. island supply) • stakeholder willingness (airports ↔ operators)	5	7 years for 1st application 15 years for saturation
Manufacturers	Change in fuselage design / Fuel system design / Tank design (LNG)	11	• composites • production rate • design	5	15 years
Others	Political support (LNG/SOLAR JET)	11	• solid scientific evidence • conversion efficiency • field demonstration • scale up • military interest	techn. feasibility: 4 economic feasibility: 3	technical: 15 years economical: 20 years
Operators/ Airlines	Reliability of supply / supply network / operational flexibility (LNG)	8	• global supply infrastructure • global transport security • global transport market • bio-LNG scale	-	-
Manufacturers	Aircraft safety (LNG)	8	• tank wall	3	10 years
Operators/ Airlines	Purchasing process (LNG/SOLAR JET)	7	• -	-	-
Others	Efficiency of Fischer-Tropsch process (SOLAR JET)	7	• -	-	-
Others	Allocation of land (SOLAR JET)	7	• -	-	-
Manufacturers	Engine certification (LNG)	4	• -	-	-
Manufacturers	Adapt combustor/engine technology (LNG)	3	• -	-	-
Airports	Allow blending of bio/fossil fuel with onsite fuel supply	1	• -	-	-
Others	Certification process (LNG/SOLAR JET)	1	• -	-	-

Appendix B – Forecast model assumptions

Base fleet (2005) input (based on data by Ascend Worldwide)

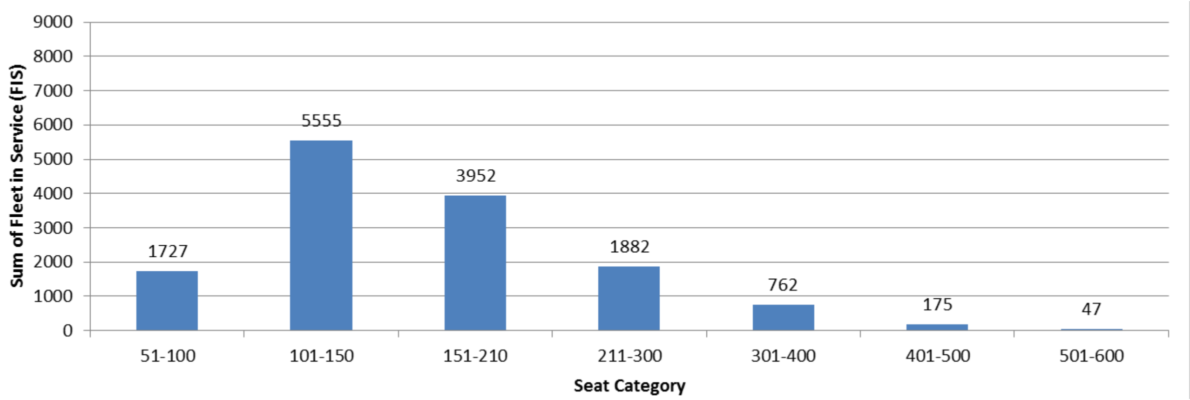


Figure 18: Sum of fleet in service - Base fleet (2005)

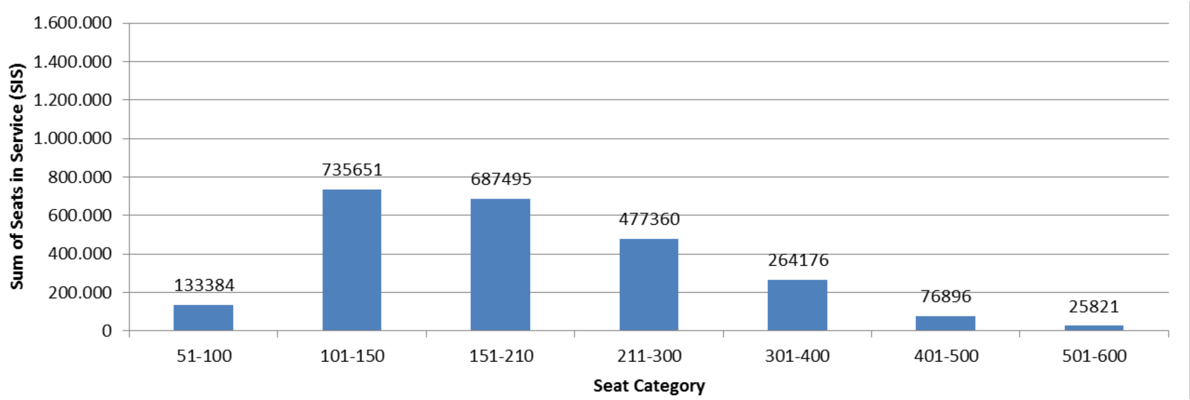


Figure 19: Sum of seats in service - Base fleet (2005)

Current fleet (2015) input (based on data by Ascend Worldwide)

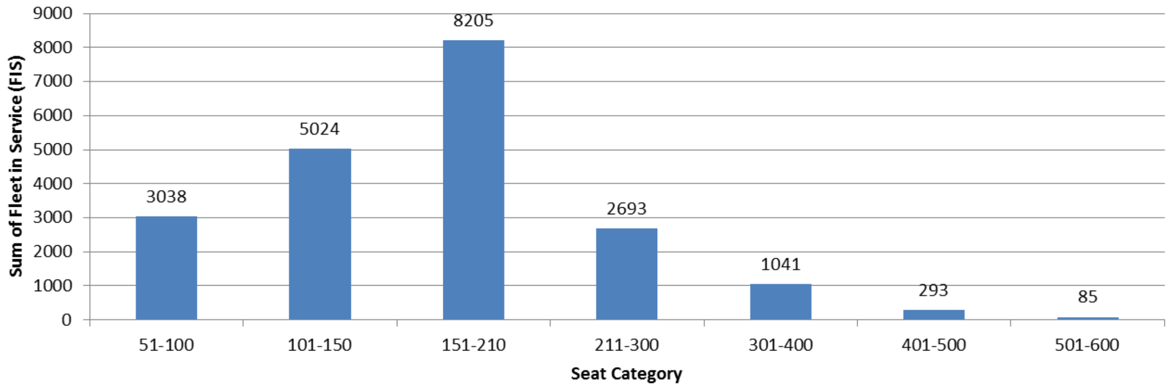


Figure 20: Sum of fleet in service - current fleet (2015)

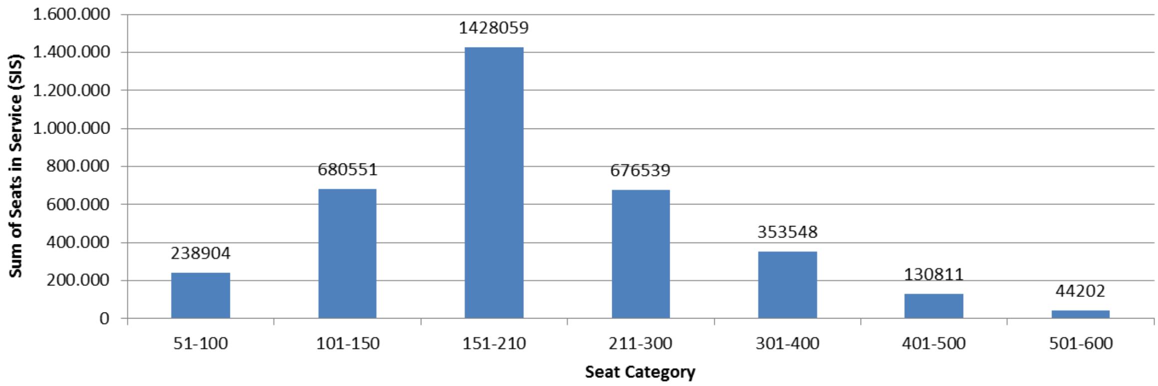
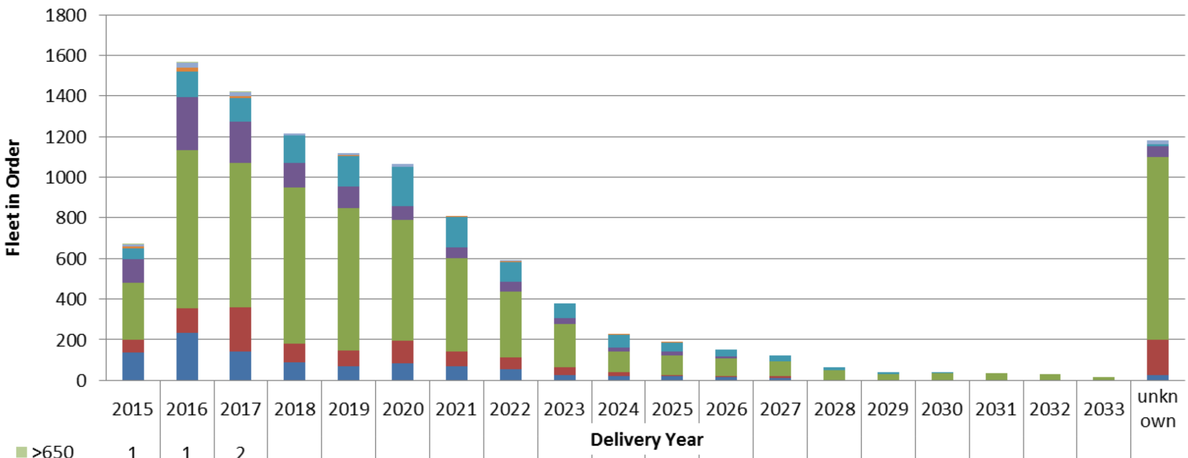


Figure 21: Sum of seats in service - current fleet (2015)

Current orders (2015) input (based on data by Ascend Worldwide)



	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	unknown
>650	1	1	2																	
601-650	1																			
501-600	8	21	20	6	12	11		2												18
401-500	10	21	9	3	3	4	2	3		4	4									2
301-400	55	125	116	136	151	192	150	99	74	67	43	34	25	11	11	7				7
211-300	114	261	202	118	104	65	52	48	29	19	17	10								55
151-210	280	780	711	773	705	598	460	324	215	101	97	85	73	51	30	33	33	28	17	901
101-150	64	120	217	92	73	109	72	55	37	18	6	5	12							173
51-100	138	234	143	86	71	85	69	56	25	21	21	16	10							25

Figure 22: Fleet in order - current orders (2015)

Assumptions for Fleet-Fuel-Forecast Model

Table 14: Assumptions Concerning Fuel Efficiency Improvement and Entry-Into-Service of New (fixed) Aircraft Models

New Aircraft Model	Entry-Into-Service Year	Technology Factor	Reference
A320neo	2015	0.85	A320
737max	2016	0.85	737
A350	2015	0.8	767 / 777
787	2012	0.8	767 / 777
A330neo	2018	0.85	A330
777X	2020	0.85	777
CSeries	2016	0.85	CRJ
MRJ90	2017	0.87	CRJ-900
Superjet 100	2012	1	CRJ-900
ARJ21	2015	1	CRJ-900
MS21 (MC21)	2017	0.9	A320
C919	2018	0.9	A320

Retirement curves (ICAO FESG CAEP/8)[21]

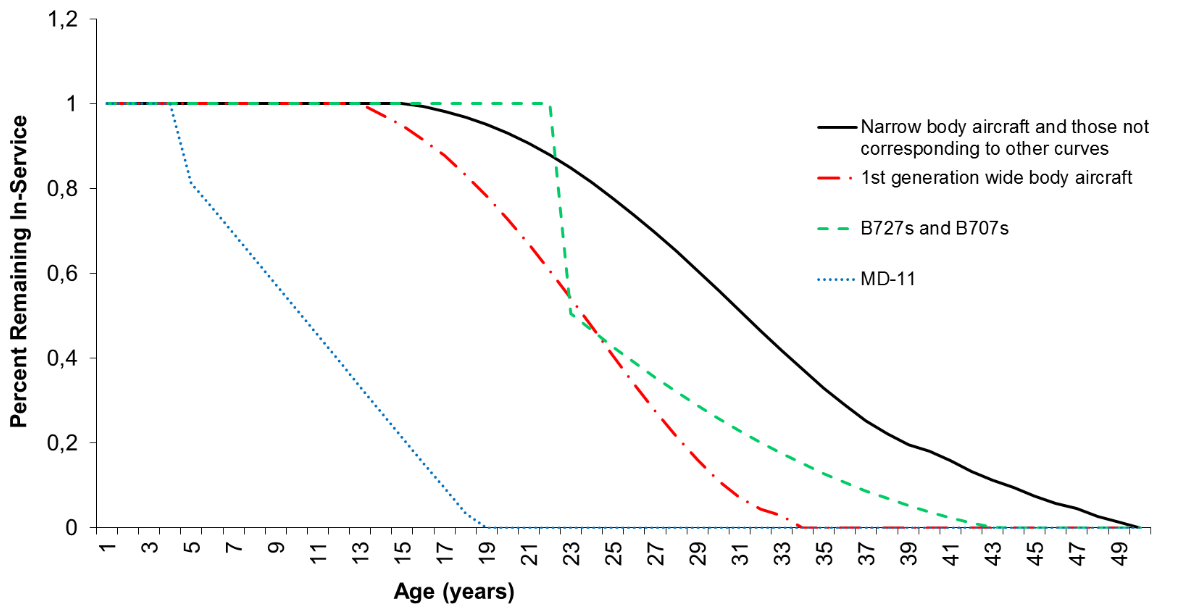


Figure 23: Retirement curves

Global growth scenario

(Source: ICAO 2013 Environmental Report / ICAO FESG CAEP/9)

The growth rates presented in Table 15 are based on the CAEP-produced, unconstrained, central (most likely scenario) demand forecast that used a base year of 2010. Data presented for 2005-2010 were reproduced from earlier trends assessments. The consensus-based FESG forecast was developed on the basis of forecasts, inputs and models provided by ICAO, CAEP Member States, observer organizations and the CAEP Modelling and Databases Group. The traffic forecast is developed over a 20-year time horizon (2010 to 2030), extended by a 10-year estimate to 2040, and further by a polynomial approach to 2050. All of the inputs, assumptions, and methodologies used for the FESG Forecast are defined and agreed through a consensus process among the stakeholders involved in the forecast development. The traffic forecast has been developed for 32 major route groups (23 international, 9 domestic regional). Detailed traffic forecasts for different route groups were obtained from ICAO, the United States Federal Aviation Administration, EUROCONTROL and (aircraft and engine) manufacturers. (International Civil Aviation Organization (ICAO), 2013)

Table 15: Global growth scenario

Growth Rates [% per year]	2005-2010	2010-2020	2020-2030	2030-2040	2040-2050
Revenue Passenger Kilometer (RPK)	2.0	5.3	4.5	4.0	3.7

[21] Retirement curves from FESG CAEP/9 where not publicly available at the time of forecast modelling

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