Assessment of the Impact of Radically Climate-Friendly Aviation Technologies

Thomas Schilling (1), **Thomas Rötger** (2), **and Kai Wicke** (3)

(1)(3) Research Engineer, German Aerospace Center (DLR), Air Transportation Systems, Blohmstrasse 20, 21079 Hamburg, Germany, thomas.schilling@dlr.de, and kai.wicke@dlr.de

(2) Assistant Director Aviation Environment – Technology, International Air Transport Association (IATA), 33 Route de l'Aéroport, Geneva, 1215, Switzerland, roetgert@iata.org

KEYWORDS: aviation, CO_2 goals, new aircraft technologies, new aircraft concepts, global emissions, sustainable fuels

ABSTRACT

In 2009 the aviation industry has committed to a set of ambitious high-level goals to reduce its carbon emissions at a global level. The long-term reduction goal of 50% in net CO_2-emissions by 2050 relative to 2005 levels is unlikely to be met with evolutionary technologies only. Radically new technologies and aircraft concepts as well as sustainable propulsion energies are likely to prove necessary in addition. To ensure a frictionless implementation of these new technologies into the air transport system, their impacts on aviation stakeholders have to be investigated. Within the AIRCAT project (**A**ssessment of the **I**mpact of **R**adical **C**limate-Friendly **A**viation **T**echnologies) IATA and DLR identified challenges and obstacles to the introduction of these technologies with a multi-stakeholder expert workshop. Key conclusions and recommendations for future works and support actions were derived. Finally, an assessment of the global carbon emissions reduction potential of the discussed concepts was performed.

1. INTRODUCTION

All global aviation stakeholders recognize the growing and urgent need for society to address the global challenge of climate change. 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]:

- 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 to 2005 levels.

To achieve these goals, all stakeholders in the air transport industry focusing on a four-pillar strategy composed of new technology options, effective operations, efficient infrastructure and positive economic measures. In order to comply with the long-term reduction goal, 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 emission reductions. [2]

Evolutionary aircraft technologies, including new engine concepts that can be applied on classical tube-and-wing aircraft, have a potential to improve fuel efficiency in the order of 30% by around 2030 compared to 2005 [2]. 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 (ATS) with appropriate lead times. For the timeframe after 2030, various novel aircraft concepts are proposed by aircraft manufacturers, research institutions and academia (Airbus, Boeing, DLR, NASA, ONERA, Bauhaus Luftfahrt, TU Delft, among others). In most cases the technological 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 ATS-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 all stakeholders (aircraft and engine manufacturers, aircraft operators, airports, air navigation service providers (ANSP) and others such as energy providers), need to be identified. Potential benefits and upcoming challenges for each stakeholder need to be described thoroughly, in order to allow timely preparations and infrastructural adaptations in view of an operational deployment once the technologies have achieved maturity. IATA and DLR conducted the AIRCAT (**A**ssessment of the **I**mpact of **R**adical **C**limate-Friendly **A**viation **T**echnologies) project to investigate these benefits and challenges as well as the resulting CO_2-emissions reduction potential on world fleet level.

2. NOVEL AIRCRAFT AND SUSTAINABLE ENERGY CONCEPTS

This chapter gives an overview of a selection of radically new technology concepts representative for a variety of major trends in the development of future more efficient aircraft, which were studied in detail in the AIRCAT project. They comprise three kinds of novel aircraft configurations and two kinds of sustainable fuel technologies, which were chosen to capture the most relevant impacts to the ATS and are possibly available till 2050. Both areas have high emission improvement potentials.

Two aircraft concepts for the short- to mid-range and one for the long-range were selected: structurally optimized configurations such as strut-braced wings (SBW) can be combined with various other technologies and fly with conventional fuel, while the electric aircraft concept is optimized around a fully battery-powered propulsion system. The blended wing body (BWB) concept deploys its advantages over conventional aircraft especially on large-capacity long-range flights, and with its unconventional external shape. In addition it represents a fully new aircraft category in civil aviation with respect to its spacious cabin.

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

Potential timelines for the availability of these future aircraft configurations and sustainable fuel technologies are shown in Fig. 1.

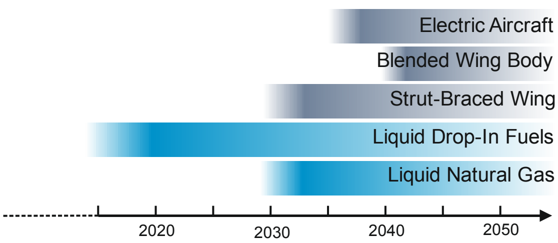

Figure 1: Possible timeframes for analyzed aircraft and fuel concepts

2.1 Fully electric aircraft

Plans to use electricity as a clean propulsive energy for aircraft have recently made strong progress. During the past years a number of key technologies (e.g. batteries, controllers, and motors) became mature and affordable for small planes. In parallel the development of competences needed for larger aircraft are pushed forward by manufacturers like Airbus and Boeing on the long path from vision to reality. One representative vision from academia was published by Bauhaus Luftfahrt, who performed a preliminary design study for a fully electric aircraft [3, 4]. The so-called Ce-Liner (see Fig. 2) is a fully electric commercial passenger airplane with a seat capacity of nearly 200 passengers. The projected entry-into-service (EIS) is 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 (without exceeding physical limitations), it is estimated that by 2035 flight ranges of nearly 700 nm can be reached. After 2035 ranges could rise to 1000 nm and more, if the energy density of batteries will develop further as assumed. [4]

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.

Figure 2: Ce-Liner by Bauhaus Luftfahrt [5]

2.2 Strut-braced wing with open rotor

Structurally optimized aircraft concepts such as SBW are under current attention by various research entities [6, 7]. The SBW 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. An additional advantage is that the high wing arrangement allows for bigger engine sizes, e.g. open rotors.

Within the “Subsonic Ultra Green Aircraft Research” (SUGAR) studies conducted by Boeing (see [8, 9]) a 154-seat high aspect-ratio,

low induced-drag SBW aircraft was designed. 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 3,500nm) in comparison to a Boeing 737-800 with CFM56 engines. Further wing-weight optimizations of this configuration combined with an open rotor (see Fig. 3) result in a block fuel saving of about 53%. The EIS is projected to be around 2040.
A second study (N+4, SUGAR Freeze) looked one generation further combining even more technologies with an EIS about 2040-2050. An update of the airframe and even more 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 LNG results in a fuel 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 [9, 10]. With its short-range specifications the SBW 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 3: Strut braced wing design with open rotor (NASA/Boeing, 2015)

2.3 Blended wing body

The blended (or hybrid) wing body (BWB/HWB) configuration was originally introduced at concept study level in the late 1980s and further analyzed in the 1990s. The BWB is essentially a large flying wing, which houses a payload area within its center section. With its futuristic shape the BWB represents a new aircraft category which potentially could enter into service in civil aviation beyond 2040. The superior aerodynamic shape compared to conventional tube-and-wing configurations 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 of payload.
A typical example out of various BWB concepts is the 500-seat BWB developed at the German Aerospace Center (DLR) with an estimated EIS at the earliest in 2040 (see Fig. 4). Since the fuel efficiency of BWB configurations increases with aircraft size, the DLR-BWB was especially designed for long-range operations with a design range of 7,500 nm. For operations near its design range, fuel consumption is expected to be up to 50% less compared to current aircraft of similar size and range.
The market potential for future BWB aircraft can be estimated from published market projections: While Airbus expects in its current market forecast a demand of approximately 1,550 very large aircraft till 2034 [11], Boeing forecasts the demand to 670 aircraft for the same period [12]. Production rates for very large aircraft like the Airbus A380 and Boeing 747 have been about 20 to 30 aircraft per year during the last years, and for newer long range aircraft like the Airbus A350 or Boeing 787, about 150 to 170 per year are planned. Considering a fast production ramp up and production rates similar to current long range aircraft, up to about 1,000 BWBs could enter the world fleet between 2040 and 2050, more to follow.

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

2.4 Liquid Drop-In Fuel: Fischer-Tropsch kerosene

Replacing current fossil jet fuel by sustainable alternatives is an essential element of aviation's climate strategy. Moreover, non-fossil fuels help reduce the dependence on fluctuating oil prices and declining crude oil resources. However, within the next one or two decades, there is no perspective of replacing current Jet A-1 fuel with a physically and chemically different substitute, regarding the need for compatibility with the current fleet of aircraft and the existing infrastructure for Jet A-1.

There are “drop-in” fuels very similar to existing Jet A-1 which meet these requirements, such as the biojet fuels that are currently being deployed for regular operations. 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. 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). With the first ever production of jet fuel synthetized from solar energy, the EU-funded SOLAR-JET project has successfully demonstrated the entire production chain for renewable jet fuel obtained directly from sunlight, water and CO_2 [13].

Sun-to-liquid drop-in fuel (StL) 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 Fischer-Tropsch technology. [14]

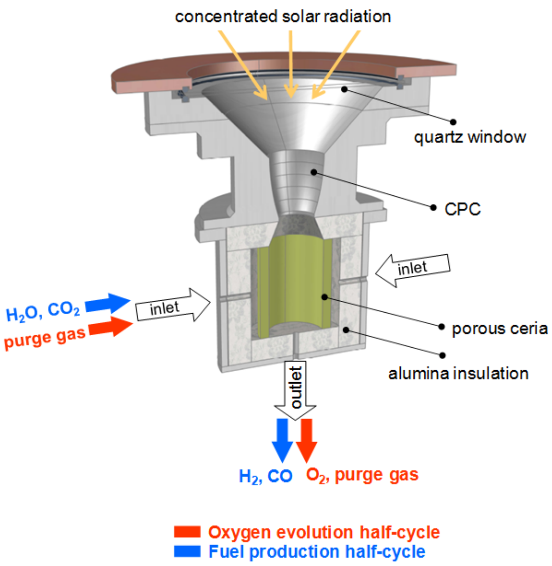

Figure 5: Schematic of the solar reactor configuration for the 2-step solar-driven thermochemical production of fuels [14]

With a forecasted solar-to-kerosene process efficiency of 4-14%, StL could exceed the efficiency potential of processes like biomass-to-liquid (BtL) of about 1.75%. Consequently, the required total ground area for producing a given amount of StL fuel is assumed to be less than half of that for the same amount of BtL, i.e. the conversion efficiency is higher for StL than for similar fuels. [15] As the StL infrastructure does not require fertile land, the availability of potential land area, and therefore of future production capacity, is almost unlimited.

StL 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.

2.5 Liquid Non-Drop-In Fuel: Liquid natural gas

In the long term, non-drop-in fuels and energy sources could also be considered to replace current Jet A-1 fuels if they offer significant emission reduction, even though they would need considerable adaptation of infrastructure and aircraft design. Being a typical representative of non-drop-in fuel solutions LNG is currently investigated from an economic and an overall lifecycle emissions perspective as a potentially interesting replacement for current crude-oil based aircraft fuels. Existing aircraft engines can be operated with natural gas after a combustion chamber retrofit/upgrade. 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, even in compressed (CNG) or liquefied form (LNG). The energy density of LNG is approximately two thirds 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 fundamental changes to the airframe and the supply infrastructure at airports. LNG is currently in use in sea and land transportation.

Although made mostly from fossil sources today, it can easily be replaced by biogas if available in larger quantities. Biogas is already blended to fossil natural gas in car fuel and public gas supply networks in various countries. In 2013, LNG was about 70-80% cheaper than jet fuel on an energy basis and therefore may reduce operating costs [16]. Additionally, natural gas has 23% lower CO_2 combustion emissions than conventional jet fuel on a per-unit energy basis [17] and is expected to result in lower emissions of particulate matter and SO_2 [18].

While Jet A fuel emits about 95 grams of CO_2 per kJ of fuel energy during combustion, LNG emits about 59 grams from combustion (and additional 13 grams during fuel production and transport) [19]. 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 [20].

3. METHODOLOGY

The technology assessment in AIRCAT was done in the following way: 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. Finally, the impact of the expected emissions reduction on the world fleet's carbon footprint was estimated.

3.1 Multi-stakeholder system analysis

The ATS model shown in *Fig. 6* 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 passengers and air cargo customers.

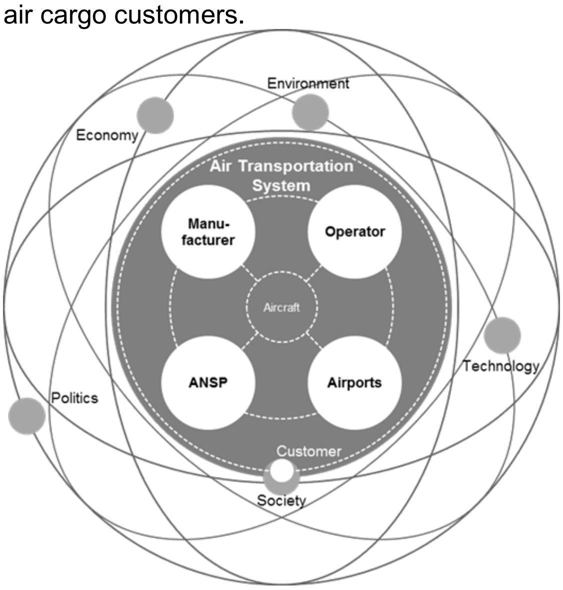

Figure 6: Air Transport System Model [21]

In a multi-stakeholder expert workshop, different impacts of each concept (electrical aircraft, BWB, SBW, sustainable fuels) on each of the four major stakeholders and others were identified in dedicated brainstorming sessions. At the end of each session the identified impacts were rated by criticality regarding a seamless technology introduction.

3.2 Identification of enablers and impact assessment

The identified impacts were discussed in detail to identify critical challenges, such as infrastructure, operational processes, performance thresholds, legislation or environmental issues. Additionally an impact analysis was conducted, addressing the technical and operational feasibility as well as lead time till operational readiness for the identified impacts and their enablers.

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 during further workshop sessions. In a second step the technological and operational feasibility of each identified impact were assessed semi-quantitatively.

The sessions ended with an estimate of the lead times needed to adjust the ATS, stakeholders or interfaces to the anticipated implications until full operability of each concept is available, starting today with current technological and operational conditions.

3.3 Estimation of the CO_2-emission reduction potential on global fleet level

A methodology developed by DLR, named FFWD ("Fast Forward") [22] 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 Fig. 7):

1. Evolution of the world fleet of commercial passenger aircraft (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 (steps 5-6).

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

In a first step today's fleet of aircraft is identified from the ASCEND Fleet Database [23]. 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) [24].

In the next step, the number of additional aircraft needed to satisfy the selected traffic growth scenario is estimated [25].

The sum of aircraft needed for replacement and growth constitutes the next year's aircraft demand and therefore new aircraft deliveries. The original aircraft are forecasted to remain active (i.e. are not retired) plus the new aircraft deliveries (including yet unfixed make and model) compose the new world fleet. This process of simulating yearly fleet changes is repeated until the final year of the forecast period is reached.

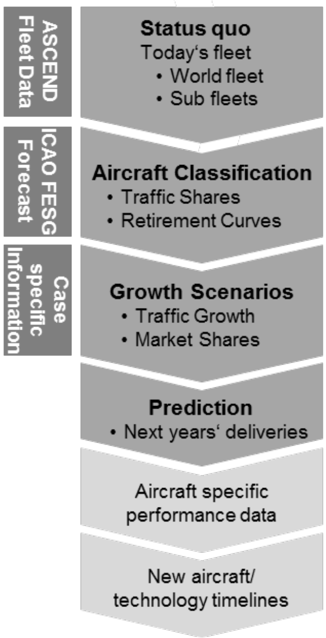

Figure 7: General CO_2 Forecast Schematic: Bottom-up Forecast based on Year-to-Year Dynamics

To assess the influence of novel aircraft configurations (fleet renewal) on global CO_2-emissions, a yearly fuel consumption and provided transport service 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. In particular, the block fuel consumption is estimated using BADA datasets at a given flight distance and a given payload, to generate a dataset over the entire operational range of an aircraft type. For 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.

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

New aircraft configurations enter the world fleet through projected deliveries of "New Technology/Aircraft" and "Unfixed Demand" (future generic aircraft). The demand in each seat category is represented by a "generic aircraft". This generic aircraft stands for the average delivered aircraft of a specific forecasted year. A higher share of more efficient aircraft is represented by a gradually improving average 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.

Combining the fleet forecast with the estimates future fuel consumption and utilization of the individual aircraft and with the assumptions regarding 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.

4. ANALYSIS AND ASSESSMENT OF TECHNICAL CONCEPTS AND DEPLOYMENT CHALLENGES

During the aforementioned AIRCAT workshop major impacts by the presented novel aircraft concepts and sustainable energy concepts were identified, and upcoming challenges and enablers were discussed. 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 which help to achieve the long-term CO_2-emissions reduction goal.
Basic information about the investigated novel aircraft concepts are consolidated in Tab. 1. Major enablers and recommendations for accelerating the implementation of each concept are presented in the following sections.

4.1 Electrical Aircraft

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, reliability at extreme temperatures, and safety.
If electrical aircraft are introduced on a large commercial scale, 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.

Table 1: Basis information about aircraft concept introductions

Concept	CO_2 saving potential on aircraft level (compared to current aircraft)	Seats and design range	Estimated market potential (# of aircraft)	Estimated entry-into-service (EIS)	CO_2 saving potential on global fleet level in 2050 (Results from FFWD-Model)
Electric Aircraft	-100%[1]	up to 200 seats 700-1.000nm	~ 6.000 aircraft[3]	2035+	up to 15%
	-80%[2]	up to 200 seats 700-1.000nm	~6.000 aircraft[3]	2035+	up to 12%
Blended Wing Body (BWB)	-50%	~500 Seats 7.500nm	up to 1.000 aircraft	2040+	~ 1-2%[4]
Strut Braced Wing (SBW)	-29% to -62%[5]	154 Seats 3.500nm	~6.000 aircraft	2030+	up to 7%[6]

[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 [26]
[3]Estimation based on future demand and market forecast for aircraft with 100-210 seats
[4]Number of aircraft will expand substantially in the following decades
[5] -29% expected for the 2030 version and 62% for the 2045 version
[6]Applies for EIS of -29% concept version in 2030 and -62% version in 2045

Standardization of batteries to be used as propulsive energy source in future aircraft, and possibly across industries, is necessary to maximize economies of scale for battery production and availability. This applies also for quick exchange during turnaround, including between different aircraft types.
Focusing on the contribution of such aircraft to CO_2-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.
The estimated CO_2-emission reduction potential of such an aircraft, assuming a trend market growth, could reach up to 15% of the global emissions in 2050. The modeled reduction potential is highly depending on EIS, ramp-up scenario and operational route lengths.

Recommendations for acceleration of 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
- Support the development of strategies for building up worldwide battery supply networks and airport infrastructure

4.2 Strut Braced Wing with Open Rotor

The NASA-SBW aircraft configuration which was investigated in this study, as a representative example of structurally optimized aircraft concepts, combines the SBW concept with multiple additional technologies, such as open rotor, fuel cell and boundary layer ingestion. Therefore, the identified challenges and enablers are related to this specific overall concept. However, other technology and concept combinations are possible and were studied among others within the Boeing and NASA SUGAR studies.
A characteristic of the open rotor that could reduce the productivity/utilization is the lower cruise speed of around Mach 0.7 compared to Mach 0.75 to 0.79 of comparable current aircraft types. 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 into the flight network of a strongly increasing number of aircraft with lower than current typical cruise speeds. 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. [27] To meet current blade-off safety requirements for open rotor engines, some weight penalty for structural reinforcements is

necessary. This has to be kept to a minimum to avoid setbacks in fuel consumption benefits [28].
Its large wing span puts the aircraft into a higher airplane design group [29] than other aircraft with comparable number of seats. To avoid the higher classification and the related higher airport charges, the wing tips could be designed to be foldable. To account for radically new aircraft configurations with different handling characteristics at the airport a re-definition of current airplane design group classifications might be an appropriate option in the long term as well.

Recommendations for acceleration of the implementation of SBW open rotor aircraft:

- 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

4.3 Blended Wing Body

The BWB-design is subject to high uncertainties since today's design methods for conventional aircraft configurations 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 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 challenging to design modular aircraft family concepts for fuselage and equipment systems. Completely new aircraft programs are usually viable as family concepts. The unusual 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 of ground services and maintenance. 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 (see [29])) and procedures (e.g. situation awareness inside the cabin) have to be defined to comply with current safety requirements.
Due to its EIS as late as 2040, the global CO_2-emission reduction potential is forecasted to about 1-2% in the first 10 years until 2050, but could expand substantially in the following decades.

Recommendations for acceleration of the implementation of BWB aircraft:

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

4.4 Sustainable drop-in fuel technologies: Sun-to-Liquid

To estimate the potential of StL, a robust scientifically-based estimate is needed regarding the conversion efficiency, the demonstration outside laboratory conditions, and reliable estimations of the number and size of large-scale plants that can be built. In addition to the technical feasibility the economic competitiveness compared to other sustainable fuels needs to be assessed. Furthermore, to enable successful implementation, efficiency improvements of the solar energy capture and conversion process are necessary. 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 [30].
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.

Recommendations for acceleration of 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

For the introduction of aircraft powered by LNG or other liquefied or compressed gaseous fuels, new fuselage designs are necessary. LNG requires different tank and fuel systems compatible with cryogenic fuels and complying with current high safety standards in aviation. 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 aircraft. 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 [31].
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 an extensive and reliable existing distribution network. However, neither LNG nor other non-liquid hydrocarbon fuels are currently common in aviation; therefore specific supply chains and infrastructures for airports must be built up. The launch of a LNG-powered aircraft program is only viable 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.

Recommendations for acceleration of 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 process

5. CO_2 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 potential impact of each concept as well as of the combination of all three on the future CO_2-emissions at global fleet level was forecasted with the DLR fleet and fuel forecast tool FFWD as described in section 3.3.
Based on a reference scenario (baseline) for the development of the global aircraft fleet and its fuel consumption until 2050 (considering only evolutionary technologies), 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 taken from Tab. 1. The model assumes EIS dates as early as technically feasible and does not include potential economically driven delays, such as poor world economics or reluctance to invest into large high-risk projects. 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. The underlying growth scenario until 2050 is shown in Fig. 8.

As a result of this modelling, the impact of the three radical aircraft concepts investigated in the AIRCAT study on CO_2-emissions relative to 2005 is plotted in Fig. 9. There it can be seen that the total CO_2 reduction potential from radical aircraft concepts in 2050 can reach about 20 to 25 % compared to the emissions in the baseline scenario (considering evolutionary technologies only), assuming optimal economic conditions allowing to realize all technically feasible programs. Even under such favorable conditions, the expected market penetration of most radically new aircraft concepts is still relatively low in 2050. This means that the majority of emissions reductions necessary to meet 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 deployment today) and radically new fuels, such as the sun- and power-to-liquid fuels mentioned in the present report.

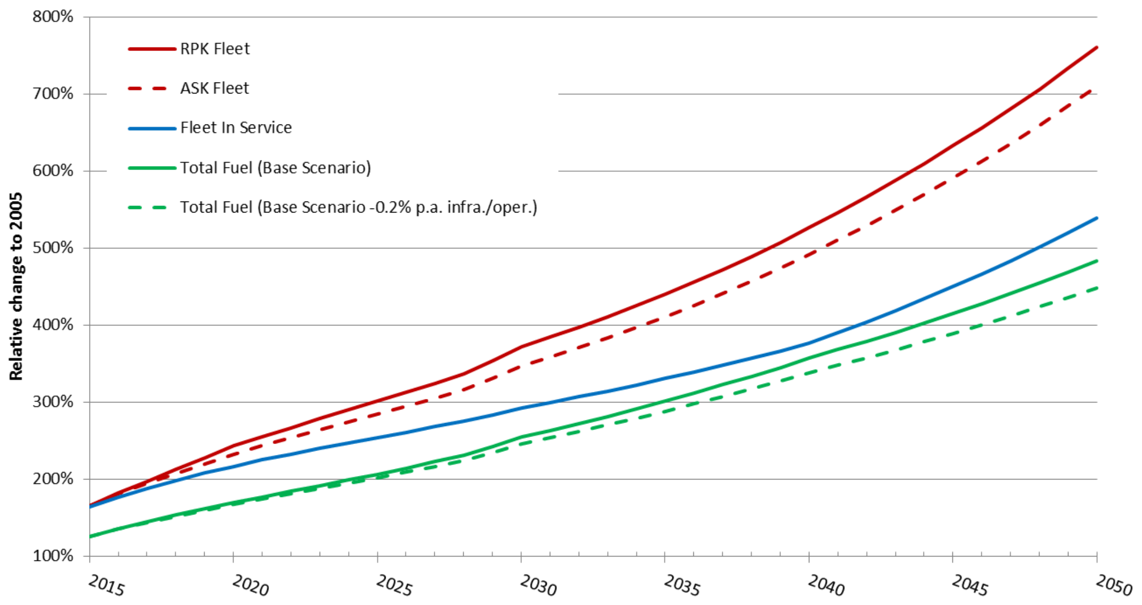

Figure 8: Basic growth scenario (2005 = 100%)

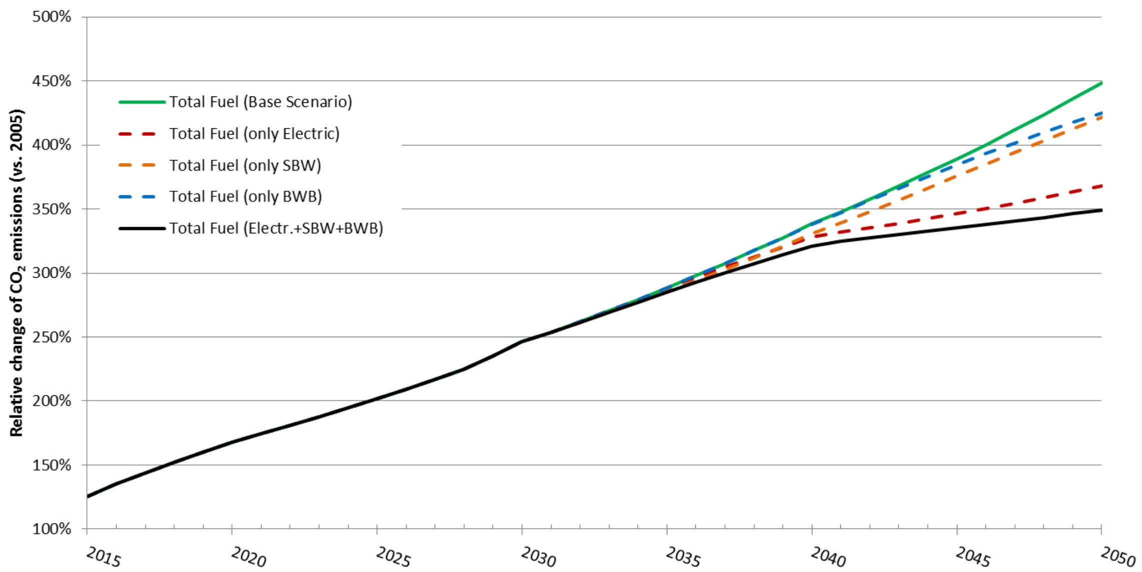

Figure 9: Contribution of presented radically new aircraft concepts to CO_2 emission reduction roadmap; including yearly operational and infrastructural improvements of 0.2% (2005 = 100%)

6. CONCLUSIONS AND RECOMMENDATIONS

6.1 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 until 2050, while keeping affordability of new products in mind.

6.2 Recommendations for further research work:

- Expand the focus of this study to further radically new technologies with high CO_2-emission reduction potential 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.
- Focus research on the improvement of production efficiencies, field demonstration and scale up capabilities of new fuels and energies (e.g. StL, 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).

ACKNOWLEDGEMENTS

This work was enabled through funding provided by IATA under their AIRCAT project. Furthermore the authors would like to thank the participants of the AIRCAT workshop in Geneva in 2015.

REFERENCES

[1] IATA, "A global approach to reducing aviation emissions, First stop: carbon-neutral growth from 2020," Geneva, 2009.

[2] IATA, "Technology Roadmap, 4th Edition," International Air Transport Association, Geneva, Switzerland, 2013.

[3] M. Hornung, A. T. Isikveren, M. Cole and A. Sizmann, "Ce-Liner - Case Study for eMobility in Air Transportation," in *AIAA Aviation Technology, Integration and Operations Conference*, Los Angeles, USA, 2013.

[4] Bauhaus Luftfahrt, "The "Ce-Liner": Air transport concept for a potentially emission-free future," 2012. [Online]. Available: http://www.bauhaus-luftfahrt.net/presse-medien/ila-2012/08-der-ce-liner/BHL_ILA2012_08_Ce-Liner.pdf.

[5] Bauhaus Luftfahrt e.V., "Bauhaus Luftfahrt," 03 March 2015. [Online]. Available: www.bauhaus-luftfahrt.net.

[6] M. K. Bradley and C. K. Droney, "Subsonic Ultra Green Aircraft Research: Phase I Final Report," National Aeronautics and Space Administration (NASA), Langley research Center, Hampton, Virginia, USA, 2011.

[7] E. Moerland, R.-G. Becker and B. Nagel, "Collaborative understanding of disciplinary correlations using a low-fidelity physics-based aerospace toolkit," *CEAS Aeronautical Journal,* 2015.

[8] M. Bradley, "NASA N+3 Subsonic Ultra Green Aircraft Research (SUGAR) Final Review," Boeing, Research and technology, 2010.

[9] M. Bradley, "Lessons from the Subsonic Ultra Green Aircraft Research (SUGAR) Study (Webinar)," 2012.

[10] G. Warwick, "Alternative View - Could liquified natrual-gas and hybrid-electric propulsion be the future of aviation?," *Aviation Week & Space Technology, June 4/11,* pp. 59-60, 2012.

[11] Airbus, "Global Market Forecast 2015-2034," France, 2015.

[12] Boeing, "Current Market Outlook," Seattle, USA, 2015.

[13] D. Marxer, P. Furler, J. Scheffe, H. Geerlings, C. Falter, V. Batteiger, A. Sizmann and A. Steinfeld, "Demonstration of the Entire production Chain to Renewable Kerosene via Solar Thermochemical Splitting of H2O and CO2," *Energy Fuels,* pp. 3241-3250, 2015.

[14] SOLAR-JET, "Sunlight to jet fuel: European collaboration SOLAR-JET for the first time demonstrates the entire production path of "solar" kerosene," 28 04 2014. [Online]. Available: www.solar-jet.aero. [Accessed 12 05 2015].

[15] P. Furler, "SOLAR-JET, Zero-carbon jet fuel from sunlight," in *AIRCAT Workshop*, Geneva, Switzerland, 2015.

[16] M. R. Withers, R. Malina, C. K. Gilmore, J. M. Gibbs, C. Trigg, P. J. Wolfe, P. Trivedi and S. R. Barrett, "Economic and environmental assessment of liquefied natural gas as a supplemental aircraft fuel," *Progress in Aerospace Sciences,* pp. 17-36, 2014.

[17] Argonne National Laboratory, "Greenhouse gases, regulated emissions, and energy use in transportation model," http://greet.es.anl.gov/, 2012.

[18] N. Carter, R. Stratton and M. Bredehoeft, "Energy and environmental viability of selected alternative jet fuel pathways," in *Proceedings of the 47th AIAA/ASME/SAE/ASEE joint propulsion conference & exhibit*, 2011.

[19] Energy Systems Argonne National Laboratory, "Argonne GREET Model," 2015. [Online]. Available: https://greet.es.anl.gov.

[20] AHEAD Project, "Advanced Hybrid Engines for Aircraft Development," Delft, 2011.

[21] R. Ghosh, T. Schilling and K. Wicke, "Theoretical framework of systems design for the air transportation system including an inherently quantitative philosophy of scenario development," *29th Congress of the International Council of the Aeronautical Sciences,* September 2014.

[22] P. Nolte, "Quantitative Assessment of Technology Impact on Aviation Fuel Efficiency," in *Air Transport Operation Symposium*, Delft, 2012.

[23] Ascend Worldwide Ltd, "Ascend Aircraft & Airline Data," [Online]. Available: www.ascendworldwide.com. [Accessed 17 10 2011].

[24] Pratt & Whitney, "Revised FESG Passenger Aircraft Retirment Methodology / Survivor Curve(s): CAEP/8 Passenger Aircraft Retirement Curves - Revision as of 1 October 2007," (unpublished), no place, 2007.

[25] ICAO, "FESG CAEP/9 Traffic and Fleet Forecasts - Methodological Paper," ICAO, Montréal, 2012.

[26] European Commission, "Energy Roadmap 2050," 2011. [Online]. Available: https://ec.europa.eu/energy/sites/ener/files/documents/sec_2011_1565_part1.pdf. [Accessed April 2016].

[27] E. S. Hendricks, J. J. Berton, W. J. Haller and M. T. Tong, "Updated Assessment of an Open Rotor Airplane using Advanced Blade Design," in *49th AIAA/ASME/SAE/ASEE Joint Propulsion Conference*, San Jose, CA, USA, 2013.

[28] G. Warwick, "Aviation Week & Space Technology," 31 March 2014. [Online]. Available: http://aviationweek.com/equipment-technology/airbus-snecma-tackle-open-rotor-integration. [Accessed July 2015].

[29] FAA, "AC 150/5300-13A - Airport Design," 2012.

[30] C. Falter, V. Batteiger and A. Sizmann, "Climate Impact and Economic Feasibility of Solar Thermochemical Jet Fuel Production," *Environmental Sceinece & Technology,* pp. 470-477, 2015.

[31] L. Carson, G. Davis and E. Versaw, "Study of methane fuel for subsonic transport aircraft," NASA contractor report 159320, 1980.

[32] Liebeck, "Design of the Blended-Wing-Body Subsonic Transport," in *AIAA 40th Aerospace and Science Meeting*, Reno, Nevada, 2002.

[33] J. C. Mankins, "Technology readniness and risk assessments: A new approach," *Acta Astronautica,* pp. 1208-1215, 17 April 2009.

[34] M. G. Möhrle and R. Isenmann, Technologie-Roadmapping, Zukunftsstrategien für Technologieunternehmen, Bremen: Springer-Verlag, 2008.

[35] CSP World, "Concentrated Solar Power," 2015. [Online]. Available: http://www.cspworld.org/cspworldmap/gemasolar. [Accessed June 2015].

[36] C. Falter, V. Batteiger and A. Sizmann, "ICAO - International Civil Aviation Organization, Green Technology Seminar," September 2014. [Online]. Available: http://www.icao.int/Meetings/EnvironmentalWorkshops/Documents/2014-GreenTechnology/6_Falter_BauhausLuftfahrt.pdf. [Accessed July 2015].

[37] International Civil Aviation Organization (ICAO), "Present and future trends in aricraft noise and emissions, Assembly - 38th Sessions, Executive Committee," 2013.

[38] International Civil Aviation Organization (ICAO), "ICAO Environmental Report," 2013.

[39] K. O. Plötner, P. C. Vratny, M. Schmidt, A. T. Isikveren and M. Hornung, "Impact of Electrically Powered Transport Aircraft on Energy and Battery Demand for Germany," in *Deutscher Luft- und Raumfahrtkongress*, Germany, 2013.

[40] EIA, "International Energy Annual 2006," 2008.

[41] FAO, " ResourceSTAT-Land 2005," 2010.

[42] Bauhaus Luftfahrt, "The Bauhaus Inventory of Energy Crops," 2010.