Hochschule für Angewandte Wissenschaften Hamburg
*Hamburg University of Applied Sciences*

## Master Thesis

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# Estimation of the global emission reduction potential of aviation technologies and their contribution to aviation's high-level emission goals

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# Estimation of the global emission reduction potential of aviation technologies and their contribution to aviation's high-level emission goals

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# Abstract

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**Title of the paper**

Estimation of the global emission reduction potential of aviation technologies and their contribution to aviation’s high-level emission goals

**Keywords**

Aircraft technologies, alternative fuels, generic aircraft, emission goals, $CO_2$ growth

**Abstract**

Global air traffic is forecasted to increase considerably over the coming years. Since the resulting impact on the environment rises accordingly, measures for mitigating aviation’s emissions have become important. The thesis identifies fuel-efficient aircraft technologies and alternative fuel types and their potential to achieve the global $CO_2$ emission reduction goals. The use of a forecast model leads to different scenarios of $CO_2$ developments until 2050. The results show that technological measures contribute to the high-level goals; however, further activities are crucial for their realisation.

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**Thema der Masterthesis**

Abschätzung des Potentials von Flugzeugtechnologien zur globalen Emissions-Reduzierung und ihr Beitrag zu den hochgesteckten Emissions-Zielen der Luftfahrt.

**Stichworte**

Flugzeugtechnologien, alternative Kraftstoffe, generische Flugzeuge, Emissions-Ziele, $CO_2$ Wachstum

**Kurzzusammenfassung**

Der weltweite Luftverkehr wird in den nächsten Jahren beträchtlich wachsen. Die damit verbundene ansteigende Wirkung auf die Umwelt verlangt nach Maßnahmen, um die Emissionen der Luftfahrtindustrie zu mildern. Die Thesis identifiziert kraftstoffsparende Flugzeugtechnologien und alternative Treibstoffe und ihr Potential zur Erreichung der hochgesteckten $CO_2$ Reduzierungs-Ziele. Die Anwendung eines Vorhersage-Modells resultiert in verschiedenen Szenarien der $CO_2$ Entwicklung bis 2050. Im Ergebnis zeigt sich, dass technologische Maßnahmen zu der Erreichung dieser Ziele beitragen, jedoch sind weitere Aktivitäten zu deren Realisierung nötig.

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## LIST OF ABBREVIATIONS

| | |
|---|---|
| ACARE | Advisory Council for Aeronautics Research in Europe |
| APMT | Aviation Portfolio Management Tool |
| APU | Auxiliary Power Unit |
| ASK | Available Seat-Kilometres |
| ASPO | Association for the Study of Peak Oil and Gas |
| ATAG | Air Transport Action Group |
| ATM | Air Traffic Management |
| BADA | Base of Aircraft Data |
| BTL | Biomass To Liquid |
| CAEP | Committee on Aviation Environmental Protection |
| CLEEN | Continuous Lower Energy, Emissions, and Noise |
| CMC | Ceramic Matrix Composite |
| $CO_2$ | Carbon Dioxide |
| DtE | Down to Earth |
| EI | Emission Index |
| ERA | Environmentally Responsible Aviation |
| FAA | Federal Aviation Administration |
| FESG | Forecasting and Economic Support Group |
| FW | Fractured World |
| GDP | Gross Domestic Product |
| GIACC | Group on International Aviation and Climate Change |
| HC | Hydrocarbon |
| HEFA | Hydroprocessed Esters and Fatty Acids |
| HLFC | Hybrid Laminar Flow Control |
| IATA | International Air Transport Association |
| ICAO | International Civil Aviation Organisation |
| IEA | International Energy Agency |
| IFAR | International Forum for Aviation Research |

| | |
|---|---|
| LNG | Liquefied Natural Gas |
| NASA | National Aeronautics and Space Administration |
| NEWAC | New Aero Engine Core Concepts |
| $NO_x$ | Nitrogen Oxides |
| RPK | Revenue Passenger-Kilometres |
| RPP | Regulatory Push & Pull |
| $SO_x$ | Sulfur Oxides |
| SRIA | Strategic Research and Innovation Agenda |
| TRL | Technology Readiness Level |
| UHB | Ultra-High Bypass |
| ULS | Unlimited Skies |

## LIST OF SYMBOLS

| | |
|---|---|
| $b_0$ to $b_5$ | Fuel function coefficients |
| g | Gramme |
| Kg | Kilogramme |
| MJ | Mega Joule |
| Mt | Mega Tonnes |
| S | Survival factor |
| x | Age of the aircraft |
| $x_1$ | Average flight distance |
| $x_2$ | Average payload |

# 1 INTRODUCTION

## 1.1 Motivation and Problem Definition

In 2050 more than 9.5 billion people will live on Earth (University of Washington, 2014). According to Boeing, a larger part of the population will have the opportunity to be mobile, since airlines will expand in emerging markets and develop innovative airline models (2014). Viewed in the context that air travel is an invaluable global asset, which entails a progressive economic and societal stability, the evolving air travel demand in expanding regions yields growing world traffic. An anticipated annual growth in airline passenger traffic by four to five per cent indicates that air travel continues to experience the fastest growth of all transport modes (Boeing, 2014; Airbus, 2015).

In spite of reduced aircraft fuel burn per passenger kilometre by nearly 70 % since 1960, the projected growth of air traffic will exceed the envisaged fuel efficiency improvements of one to two per cent yearly (ICAO, 2010; IATA, 2013). As the aviation sector is continually expanding and thus, its total fuel burn, the ecological impacts escalate significantly. Notably, the air transport's current contribution to anthropogenic Carbon Dioxide ($CO_2$) emissions represents two per cent as well as its contribution to total greenhouse emissions amounts three per cent (Intergovernmental Panel on Climate Change, 1999). Without any progress, the future share in $CO_2$ development may increase by factors of three to four over 2000 level in 2050 (Lee et al., 2010).

Hence, a responsibility of all players in the air transport industry for efficiency and sustainability is crucial. Aircraft manufacturing and airline industries, the scientific community and governmental authorities have already taken a pace forward mitigating the climate impact of aviation. In this way, strategy agendas like Flightpath 2050 or the IATA Technology Roadmap establish ambitious environmental goals for reducing aviation's emissions (European Commission, 2011; IATA, 2013).

In order to achieve the environmental goals and to offset the forecasted growth of air travel demand, it is not enough to keep up the usual rates of fuel efficiency improvement. Further profound innovations including new technological, operational approaches and alternative energy sources are therefore essential. However, the question remains if radical changes induced by new technologies are enough to achieve the environmental goals.

Thus, the question of the potential of future aircraft technologies for accomplishing the envisaged goals has motivated to propose a hypothesis being analysed in this thesis.

## 1.2 Objectives and Limitations of the Research

The primary goal of the thesis is to assess the potential of future aviation technologies and alternative energy sources to reduce fuel consumption on single aircraft level and their impact on global $CO_2$ emission growth. The assessment enables the verification or falsification of the following hypothesis: 'New aviation technologies and alternative energy sources contribute to the achievement of long-term $CO_2$ emission reduction goals on global aircraft fleet level'. In order to achieve the primary goal and evaluate the hypothesis, sub-goals are defined:

1. The identification of global $CO_2$ emission reduction goals set by international aviation institutions.
2. The constitution of a technology matrix, which indicates different characteristics like $CO_2$ emission reduction potential and availability timeframe.
3. The establishment of new generic[1] aircraft programs, which host the future technology combinations
4. The work with an existing forecast model, Fast Forward, which results in scenarios of global emitted $CO_2$ until 2050

Scenarios of more fuel-efficient future aircraft configurations over their predecessors are generated under a passenger growth rate[2]. These scenarios and the application of Fast

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[1] As the term generic occurs frequently and is essential for the further understanding, it is necessary to provide a definition within this section. 'Generic' indicates the quality of the aircraft as an abstract object and refers only to its technological prosperities, which are applicable to the whole aircraft category.

[2] Scenarios of passenger growth in terms of revenue passenger-kilometres (RPK) are explained and provided in Section 3.3.1.

Forward yield $CO_2$ development scenarios on world aircraft fleet level for different timeframes. The subsequent 'gap' assessment between the calculated $CO_2$ growth and aviation's $CO_2$ emission reduction goals supports the evaluation of the hypothesis.
As the thesis is realized within the framework of the International Forum for Aviation Research (IFAR), the work intends to establish an input for an IFAR technology roadmap[3].

Whilst Fast Forward calculates the $CO_2$ emissions from the world fleet, no detailed information for aircraft movements exists. The position of the emitted species and the atmospheric conditions, which determine the climate impact, are unknown. Thus, less attention is paid to the estimation of further aviation effects just as Non-$CO_2$ emissions or noise.

Additional opportunities for mitigating aviation's carbon footprint including improvements in operational practices, infrastructure and economic measures are just briefly mentioned.

## 1.3 State of the Art

For several years, national and international institutions, research organisations as well as manufacturers explore the influence of the aviation industry on the environment. Guided by projected long-term global emission reduction goals (introduced in Section 2.1), they consolidate their concepts in reports to consult the aviation industry and governments.
For the thematic classification and clarification of the research objectives, a study of papers and brochures of major and well-known institutions is realized respecting:

- Long-term global $CO_2$ emission reduction goals
- Future technologies including alternative energy
- Future generic aircraft types at different time horizons
- $CO_2$ reduction modelling on world fleet
- Comparison of global goals and $CO_2$ growth through a gap analysis

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[3] The term 'roadmap' is explained in Section 2.1.

These five investigation fields support the thesis' goal and clarify the research gap by rating them concerning the research depth.

The first studied institution is the International Air Transport Association (IATA). The Association published a Technology Roadmap Report in 2009 and the successor in 2013, which identify and assess the fuel reduction benefit and readiness of a large scope of technologies at different time horizons. Additionally, new aircraft types are assessed concerning an annually 1.5 % fuel efficiency improvement on world fleet level (IATA, 2009, 2013).

The International Civil Aviation Organisation (ICAO) reveals their concepts for an optimised overall performance of an aircraft in environmental reports. Chosen future technologies, the development and deployment of alternative fuels as well as improved Air Traffic Management (ATM) imply the measures inside the State Action Plan for a low carbon air transport sector (ICAO, 2010, 2013). In addition, independent experts, nominated by the ICAO, modelled two generic aircraft, a single aisle and a small twin-aisle aircraft. Technologies are assessed within three technology scenarios in order to achieve the aircraft's reduced fuel burn by up to 85 % over 2010 (ICAO, 2013).

The Beginner's Guide to Aviation Efficiency, a 2010 publication by the Air Transport Action Group (ATAG), presents more efficient concepts for technologies. These concepts follow the industry targets for reducing emissions, which are stated in the position paper The Global Flightplan from 2013 (ATAG, 2010; ATAG, 2013). Besides the aspect of improved technology, the ATAG completes its strategy by listing three more efforts: more efficient aircraft operations, infrastructure improvements and a properly- designed market based measure (ATAG, 2010). Likewise, the opportunities and challenges in developing biofuels are intensively described within the brochure Beginner's Guide to Aviation Biofuels (ATAG, 2011).

In 2000, a group of researchers establish the Advisory Council for Aeronautics Research in Europe (ACARE) in order to carry forward the Strategic Research and Innovation Agenda (SRIA). The SRIA outlines strategic actions to address key challenges in terms of noise and emission reduction requirements (ACARE, 2012). This roadmap helps to achieve the goals of its Flightpath 2050, the successor of Vision 2020. It identifies high-level goals, such as protecting the environment and the energy supply by reducing technologies' $CO_2$ emissions per passenger-kilometres (European Commission, 2011).

Three publications of the National Aeronautics and Space Administration (NASA) are examined. The Technology Roadmap's purpose is to guide the development of space technologies, but includes additionally an aeronautics chapter. In this way, general technology areas are mapped to the technology need date for the next 20 years. These technical challenges with Technology Readiness Level (TRL) are combined with 'Strategic Thrusts', such as "safe, efficient growth in global aviation" or "transition to low-carbon propulsion" (NASA, 2015).

The second treated report Aviation and the Environment by NASA from 2004 reveals a national vision for aviation and the environment. It serves as a framework for national goals and actions. For a more effective coordination, the document supplies recommendations in three different areas: communication and coordination, tools and metrics as well as technology, operations and policy (Waitz, et al., 2004).

In 2011, Ashcraft *et al.* released the paper Review of Propulsion Technologies for N+3 Subsonic Vehicle Concepts. It indicates fuel burn, noise and emission reduction goals for next generation aircraft as well as reviews chosen long-term generation aircraft concepts by the aerospace community. After studying propulsion technologies, the document creates an assessment matrix to rank these technologies by using criteria of likelihood and benefit. It evaluates them regarding their challenges to be overcome before implementation (Ashcraft et al., 2011).

On the manufacturer's side, Boeing and Airbus have a look at the climate impact of aviation within environment reports. Airbus' Sustainable Aviation-Environmental Innovations lists novel concepts of future innovations, alternative energy, ATM and recycling methods, which commit to the industry targets.

On the contrary, Boeing's Environment Report presents research activities in its company from an all-electric airliner to reducing hazardous chemicals in products and services. Both reveal their new aircraft designs for a more sustainable flight (Airbus, 2013; Boeing, 2014).

Table 1 visualise the studied papers and the rating of the investigated fields concerning their research depth.

Accordingly, thematic gaps are apparent, which are focused by the thesis.

The first field in terms of the $CO_2$ emission reduction goals is often presented within papers. The thesis takes it up and introduces global emission reduction goals of different research institutions.

A survey of new aircraft technologies and alternative fuel types is provided by the thesis. Thus, the second field is covered as it allows more space for research.

The next two fields are less studied by existing papers and roadmaps. They indicate gaps, which are filled within the thesis. It aims at the creation of future generic aircraft at different time horizons. A subsequent modelling of the $CO_2$ growth on world fleet considers the generated new aircraft types.

The last field reveals a great thematic gap and thus needs more comprehensive research. The thesis' objective is to compare the global emission reduction goals and the $CO_2$ growth. The assessment is carried out through a gap analysis.

Table 1 Rating of studied papers concerning investigation fields (own compiled table)

| | IATA Technology Roadmap 2009, 2013 | ICAO Environmental Reports 2010, 2013 | ATAG Beginner's Guide to Aviation Efficiency 2010 | Flightpath 2050 2011 | NASA Technology Roadmap 2015 | NASA Aviation and the Environment 2014 | NASA Review of Propulsion Technologies for N+3 Subsonic Vehicle Concepts 2011 | Airbus Sustainable Aviation-Environmental Innovations 2013 | Boeing Environment Report 2014 |
|---|---|---|---|---|---|---|---|---|---|
| Long-term global $CO_2$ emission reduction goals | ● | ● | ● | ● | – | ○ | ○ | ● | ○ |
| Future Technologies including alternative energy sources | ● | ◐ | ◐ | – | ● | – | ◐ | ● | ◐ |
| Future generic aircraft types at different time horizons | ◐ | ◐ | ○ | – | ○ | – | ◐ | ○ | ○ |
| $CO_2$ reduction modelling on world fleet | ○ | ○ | ○ | – | ◐ | ○ | ◐ | ◐ | ○ |
| Comparison of global goals and $CO_2$ growth through a gap analysis | ○ | – | – | – | – | – | – | – | – |

○ Incomplete Study ◐ Comprehensive Study ● Intensive Study – Non-Existent

# 2 METHODOLOGY

The theoretical fundamentals are a significant element of the methodology. The Section 2.1 firstly provides a brief overview on the interdependencies of the high increase in global air traffic demand and lastly, introduces the high-level emission reduction goals of the aviation industry. Based on the basic principles and a suitable scientific method, the approach for the study of the research objectives is expounded in Section 2.3.

## 2.1 Goals of the Aviation Industry

The forecasted strong development of the air traffic is subject to various causes. As the growth rates are expected to remain similar in the future, the aviation industry has set global goals in order to initiate the reduction of aviation's increasing emissions along with the growth of air travel.

### Air Traffic Growth

A continuous increase in air traffic demand is expected to grow by four to five per cent per year (Airbus, 2015). According to the Airbus Global Market Forecast 2015-2034, the world air traffic demand "is outperforming the GDP growth" (Airbus, 2015). The Gross Domestic Product (GDP), as a measure for the economic performance of a whole country or region, but also for the contribution of an industry sector, quantify aviation's share in global GDP to $ 2.2 trillion. In fact, the Current Market Outlook by Boeing prospects the world GDP to grow at an estimated three per cent annually over the next 20 years.

This global economic expansion is expected to rise due to a development of a global middle class. Above all, the private consumption will significantly increase through the income level rising in emerging markets (Airbus, 2015; Boeing, 2015). Table 2 demonstrates the world economy acceleration by stating the compound annual growth rate of different regions. In particular, India and China experience high economic growth (Boeing, 2015). While North America and Western Europe have mature economies, the Asia Pacific region, Latin America and other regions are foreseen to expand their markets.

Table 2 Compound annual growth rate by chosen region 2015-2025 (%) (Boeing, 2015)

| India | China | Africa | Other Asia | Middle East | Latin America | Brazil | Australia /NZ[4] | United States | European Union |
|---|---|---|---|---|---|---|---|---|---|
| 7.8 | 6.4 | 4.8 | 4.2 | 4.1 | 3.7 | 2.8 | 2.8 | 2.6 | 1.9 |

Figure 1 illustrates the greatest demand by Asia Pacific with approximately 40 % of all new airplanes, nearly as much as Europe and North America together (Boeing, 2015).

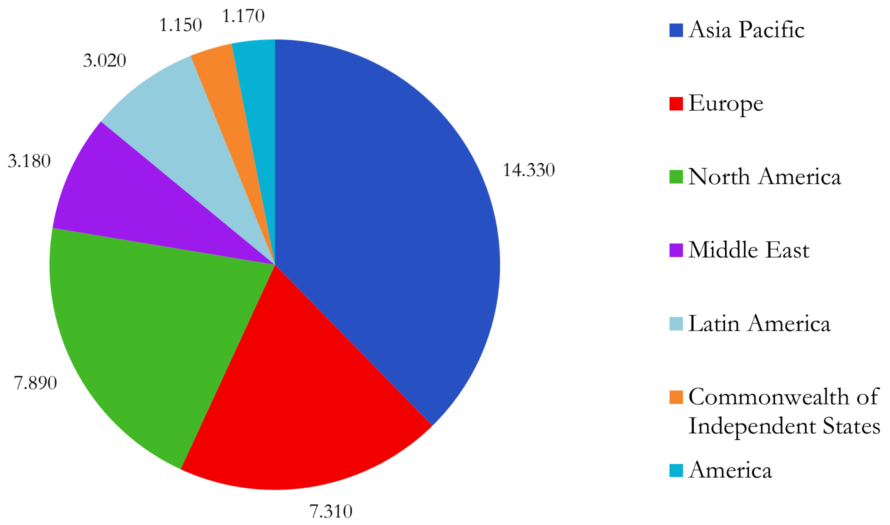

Figure 1 Demand for new airplanes by region from 2015 to 2034 (based on data from Boeing, 2015)

### A common position on global $CO_2$ emission reduction goals

In order to mitigate the growing carbon footprint caused by the steady increase in air traffic volume, aviation stakeholders create papers, roadmaps and brochures for implementing strategies and encouraging commitment. The International Energy Agency (IEA) provides a comprehensive definition of roadmaps, which "are an important strategic planning tool" (International Energy Agency, 2010). This way, governments and industry organisations

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[4] New Zealand

move forward, addressing the future difficulties, for instance energy security, and serving for the policy and public engagement (International Energy Agency, 2010).

In order to enhance the significant commitment in meeting the future challenges, efforts are already made. National and international organisations defined environmental goals in their strategy papers. Table 3 provides an overview of global emission reduction targets pursued by considered institutions.

Table 3 Selection of aviation institutions and their defined global emission reduction goals (own compiled table)

| Aviation institutions | Global emission reduction goals | References |
|---|---|---|
| IATA | 1. 1.5 % average annual improvement in fuel efficiency between 2009 and 2020<br>2. Carbon-neutral growth from 2020 onwards<br>3. Absolute Reduction of $CO_2$ emissions by 50 % in 2050, compared to 2005 | Technology Roadmap (IATA, 2013) |
| ATAG | | The Global Flightplan (ATAG, 2013) |
| Airbus | | Environmental Innovations (Airbus, 2013) |
| ICAO | 1. Annual improvement of fuel efficiency by 2 %<br>2. Stabilisation of global $CO_2$ emissions at 2020 levels | Environmental Report (ICAO, 2013) |
| ACARE | A 75 % cut in $CO_2$ emissions on aircraft level through 2050, compared to 2000 | Flightpath 2050 (European Commission, 2011) |
| Boeing | Zero absolute growth of greenhouse gas emissions, water use and solid waste to landfill from 2012 until 2017 | Environmental Report (Boeing, 2014) |
| FAA | 1. Reduction in aircraft fuel burn by 33 % from 2010 until 2018, referred to B737<br>2. Reduction in aircraft fuel burn by 50 % from 2010 until 2020, referred to B777<br>3. Reduction in aircraft fuel burn by up to 70 % until 2025 | CLEEN Program (Federal Aviation Administration, 2014) |

Especially, the first three emission reduction goals were formulated as a common position by the aviation industry[5] in 2009 (IATA, 2013). "The IATA was one of the driving forces in promoting these goals" (IATA, 2013). The shown aviation institutions either pursue or support the three defined sequential goals by individual set targets.

Accordingly, the thesis takes up the IATA emission reduction goals and integrates two of them into the study. Thus, aviation's $CO_2$ development is compared to the goals concerning the carbon-neutral growth from 2020 onwards and the reduction of $CO_2$ emissions by 50 % in 2050.

An additional effort is the 'Aeroplane Carbon Dioxide Emission Standard'. At the 37th ICAO Assembly, the Committee on Aviation Environmental Protection (CAEP) was requested to develop it. By using a metric system, it values the fuel-efficient technologies and designs and encourages aircraft and engine manufacturers to apply them (ICAO, 2013).

Besides the environment papers and technology roadmaps, outlined in Section 1.3, national and international aviation research organisations, networks and programs exist. Figure 2 provides a range of research programs in Europe and the USA. These programs explore fuel efficiency, enhanced through the use of various novel technology concepts. The European project NEWAC (New Aero Engine Core Concepts) focuses on higher thermal efficiency through investigating improved engine core components (NEWAC, 2011). On the contrary, the program CLEEN (Continuous Lower Energy, Emissions, and Noise) by the Federal Aviation Administration unites manufacturers in order to develop and demonstrate certifiable aircraft technology and evaluate possibilities for retrofit and re-engine (Federal Aviation Administration, 2015).

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[5] Participated instances: The International Coordinating Council of Aerospace Industries Associations, The International Air Transport Association, Airports Council International and The Civil Air Navigation Services Organisation (ICAO, 2010)

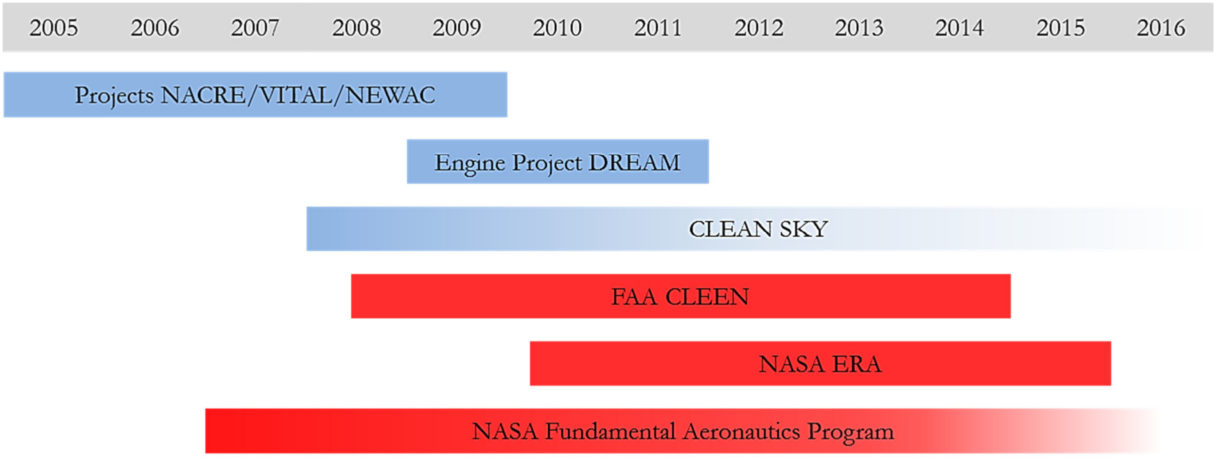

Figure 2 US and European national research programs 2005 to 2016 (based on data from ICAO, 2010)

Within these aviation research programs, national research organisations collaborate with international institutions. The network International Forum for Aviation Research (IFAR) connects research organisations worldwide and enables the identification of steps for reducing the environmental impact of aviation. Through the information exchange on research activities and the cooperation among the members, common focus areas concerning emissions, noise, security, safety and efficient operations are defined (International Forum for Aviation Research, 2010).

## 2.2 Initial Hypothesis

The thesis intends the study of the hypothesis 'New aviation technologies and alternative energy sources contribute to the achievement of long-term $CO_2$ emission reduction goals on global aircraft fleet level'. Based on previous achieved improvements and research results, the hypothesis is set by the assumption of possible reduction potentials of technologies and alternative energy sources. According to an IATA survey, fuel burn, and therefore $CO_2$, per passenger kilometre decline by 70 % over the last 50 years (2013). In addition to this, the ICAO prospects the worldwide fuel consumption to be reduced from eight litres per passenger and per 100 km in 1985 to three litres in 2025 (2010).

A hypothesis can be applied if suitable methods supply the verification of the consistency between the hypothesis and the assessment of the research data.

The Critical Rationalism takes the view that human acting is constrained by regularities, which are identified and explained by researchers in both natural and social sciences. As starting points, hypotheses presume characteristics of the reality and its regularities (Mayer, 2006). The most known method, the scientific theory, is part of the quantitative research. It describes theoretical researches on realistic questions and, while verifying or falsifying these theories, explains the abstract dependences. The application is carried out deductive; in fact, the object of inquiry is understood by concluding from general ideas to special examinations (Mayer, 2006; Oehlrich, 2015).

Conversely, the empirical method is characterised by extraction of data and based on concrete experiences. It proceeds inductively (conclusion from special assumptions to general comprehension) (Oehlrich, 2015). As an element of the social research, the applied data are used qualitative and interpret individual cases but also generalised results (Mayer, 2006; Oehlrich, 2015).

For the analysis of methods concerning research aiming at long-term statements, a comprehensive study by Hepting and co-workers is consulted.

In particular, the authors state two research types: prediction and scenarios, differing in the acquisition of their data (qualitative or quantitative). These methods are introduced for the systematic foresight of developments and the long-term assessment (a period of more than 15 years).

Predictions aim at the exact forecast of a situation in the future. By using mathematic models based on corresponding data, their conclusions are transparent and verifiable. Whereas no depiction of alternative scenarios and conjectures exist within predictions, the qualitative study of scenarios reveals potentially diverging developments. Accordingly, the application sets focus on certain key elements; thus, avoids complex interdependencies. However, it lacks the scientific character due to limited reproducibility of the results.

Compared to it, the quantitative study of scenarios, a combination of both above mentioned types, uses quantitative models for the assessment of developments.

The sensitivity analysis is associated with the quantitative study of scenarios and used for the assessment of measures (Hepting et al., 2015).

Regarding the thesis' goals, the scientific theory, serves as the suitable frame due to the deductive approach. Thereby, the present general hypothesis is verified or falsified by applying specific model data. Additionally, the described dependencies between the data support the verification or falsification of the assumed hypothesis. An inductive perspective, however, just generalises empirical results and validates the theory.

The use of the quantitative forecast model is an element of the quantitative study of scenarios and demonstrates long-term developments more comprehensive. Scenarios within the thesis describe different possible future situations. They are connected to a specific problem and create its future developments under changing conditions.

## 2.3 Approach

The theoretical interdependencies within Section 2.1, which lead to the proposal of the hypothesis, serve as starting point for the thesis' analysis. Especially the two global emission reduction goals concerning the carbon-neutral growth from 2020 onwards and the reduction of $CO_2$ emissions by 50 % in 2050 are an essential part of the analysis.

In order to analyse the stated problem, i.e. the hypothesis, an existing model is used. Chapter 3 explains the method of Fast Forward and examines the validity of its basic data. Since the model is applied to generate the $CO_2$ development scenarios, the second part of Chapter 3 identifies the influencing factors on the development. They are defined as the input data, which include the overview of scenarios of passenger traffic growth, the analysis of the future aircraft technologies and the description of two chosen alternative energy sources.

As the thesis is realized within the framework of IFAR, main emphasis is laid on studying future technologies concerning the competence fields of the IFAR's members.

Hereupon, the technology combinations for corresponding future generic aircraft of specific seat categories are provided by Chapter 4. These aircraft scenarios yield different scenarios of the $CO_2$ development on world fleet level, which are output via Fast Forward. After the scenarios are described, the findings are assessed and interpreted with reference to the above mentioned global $CO_2$ emission reduction goals. Chapter 5 concludes the thesis by verifying or falsifying the hypothesis. Additionally, it critically views the results and supplies an outlook for future research projects. Figure 3 provides the brief overview of the thesis' approach in the form of a flow chart.

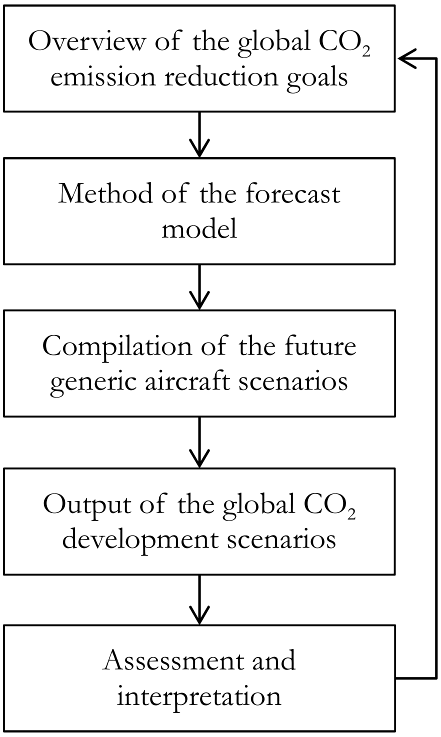

Figure 3 Schematic approach of the thesis

# 3 FORECAST MODEL

The model Fast Forward, created by the German Aerospace Centre, is used in order to forecast the global $CO_2$ emission development until 2050[6]. Based on Fast Forward's method, explained in this chapter, the basic and input data are presented. The input data, especially those from the aircraft technologies and alternative fuel types are gained through an intensive research. Additionally, the adjustments of the model, taken in order to calculate the global $CO_2$ emissions per year and the use of LNG as a substitute for kerosene, are shown within this chapter.

## 3.1 Method

### *3.1.1 Methodology Chart*

In order to assess the future overall $CO_2$ emissions of aviation, it is necessary to apply a forecast model, which analyses the theoretical carbon reducing potential of new aircraft within a global scope. It should be noted that Fast Forward considers originally no life-cycle $CO_2$ emissions, but the operating aircraft $CO_2$ emissions, which arise during the combustion. However, scenarios in Section 4.2 are generated, which additionally views the global development of emitted $CO_2$ on life-cycle level.

By means of the methodology chart, shown in Figure 4, the subsection explains the method for developing the world fleet forecast.

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[6] The present model was introduced within the TERESA project (2008-2013).

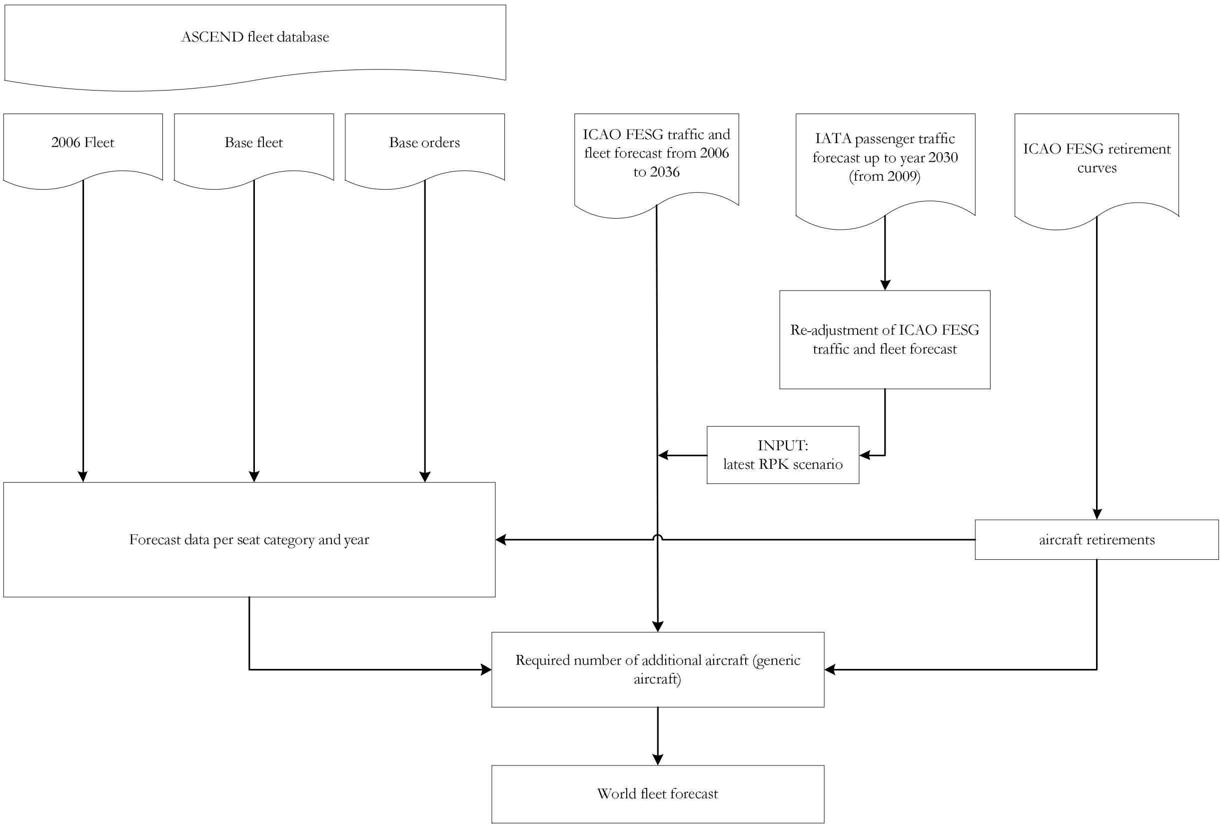

Figure 4 Methodology chart: world fleet forecast (own chart)

First of all, the size of the actual world aircraft fleet is compiled, based on the ASCEND Fleets. The ASCEND Flightglobal Consultancy provides information for over 100,000 commercial aircraft and includes details to aircraft orders, seat configurations and capacities. Hence, the data for aircraft "in service" in the 2006 fleet, the data for aircraft "in service" in the base fleet 2011 and the number of fixed orders in the forecast timeframe from 2011 serve as the database.

Secondly, a fleet forecast describes the fleet size within the considered time scope from 2006 until 2036. This fleet size forecast from 2006 was developed on a consensus-based ICAO FESG Forecast. For that purpose, the Forecasting and Economic Support Group (FESG) of the ICAO CAEP involving experts from the Member States and industries analysed among others, engine and aircraft emissions (ICAO, 2013). It is applied to estimate future traffic shares, average flight distances and load factors. Due to traffic forecast updates, the IATA Passenger Traffic Forecast from 2009 was used in order to re-adjusts the ICAO FESG

Traffic and Fleet Forecast. By including data in terms of revenue passenger-kilometres (RPK) up to year 2030, it estimated, for example, lower growth rates with respect to global economic downturns. However, in this case, the user has the opportunity to choose the latest forecast for adjustment to the actual passenger traffic development. Hence, Fast Forward provides an input box for the user's assumed air traffic forecast.

Third, retirement curves are needed to statistically estimate the survival of aircraft in the world fleet by using aircraft survival curves from the ICAO FESG 2006 fleet database. They plot the percentage of aircraft from a build-year, "still-active" at a certain year after delivery. The survival curves serve then for the calculation of future aircraft retirements from the aircraft fleet age.

There exist four curves, which are used to model the retirement of different types of passenger aircraft and for which, the retirement percentages are computed by applying the FESG provided curves. The following equation describes the survival curves, where S is the survival factor, x indicates the age of the aircraft and the coefficients A to E were calculated from the FESG 2006 fleet data.

$$S = A + B * x + C * x^2 + D * x^3 + E * x^4 \tag{1}$$

This approach, used for the retirement curves in the forecast model, is in accordance to the Aviation Portfolio Management Tool (APMT) Architecture Study (Waitz et al., 2006).

The four retirement curves are provided in Appendix A.

The final results, based on the fleet data, fixed orders and retirement estimations, calculate the number of additional aircraft needed to meet the chosen traffic growth scenario. They provide the sum of aircraft needed for replacement and growth indicating them as the next year's aircraft demand or future aircraft deliveries. The world fleet forecast, finally, is composed of the active aircraft, which are not retired yet and the future aircraft deliveries, which includes the fixed and unfixed aircraft orders. The unfixed aircraft are characterised as "generic aircraft" due to the lack of specific aircraft demand in the future.

As the basis and forecast data are clustered by eight aircraft seat categories: 51-100, 101-150, 151-210, 211-300, 301-400, 401-500, 501-600 and 601-650, the whole model is based on and works in seat categories.

The second part of Fast Forward calculates the yearly fuel consumption of each active aircraft under the influence of assumed new technologies. For existing aircraft, the EUROCONTROL Base of Aircraft Data (BADA) determines fuel functions to estimate the trip fuel in kilogrammes with a given flight distance and payload. A huge dataset over the entire operational range of an aircraft type emerge.

A polynomial equation describes the fuel function:

$$Trip\ fuel = b_0 + b_1 * x_1 + b_2 * x_2 + b_3 * x_1^2 + b_4 * x_2^2 + b_5 * x_1 * x_2 \tag{2}$$

The specific values of the fuel function coefficients $b_0$ to $b_5$ are provided in the BADA datasets for a single aircraft type powered by kerosene.

The average flight distance $x_1$ is supplied by the ICAO FESG Traffic and Fleet Forecast.

The average payload $x_2$ is calculated with the corresponding values of load factor from the ICAO FESG Traffic and Fleet Forecast, seats from the ASCEND Base Fleet and an average weight of 95 kg per passenger: Payload = Load Factor * Seats * 95.

Under technology assumptions, the user of the model has the opportunity to create technology scenarios on generic aircraft for each seat category. These assumptions concern the fuel reduction potential of new-generation aircraft projects, their expected time for an entry into service and their ramp-up time. The ramp-up time denotes the number of years, after which the production of a new aircraft is raised, i.e. at maximum capacity. The detailed consideration of the user input is given in Section 3.3. Besides that, a list of operating aircraft from the ASCEND database contributes to the calculation and includes future aircraft models, for which fixed orders exists, such as A320neo, B737max, MRJ90 or ARJ21. Their technology levels and thus, their fuel efficiency improvements over today's models were researched and added into the model. The generic aircraft, their assumed reduced fuel burn and their forecasted market share, including the fixed future aircraft models make up the calculation of the yearly average fuel consumption for each aircraft in the forecast. It is then multiplied with the average number of flights for a given seat category in order to receive the total fuel per fleet per year. Figure 5 supplies the methodology chart for the fuel burn calculation.

The second version of the forecast model is extended by the years 2030 until 2100; however, the considered timeframe for the thesis is through 2050.

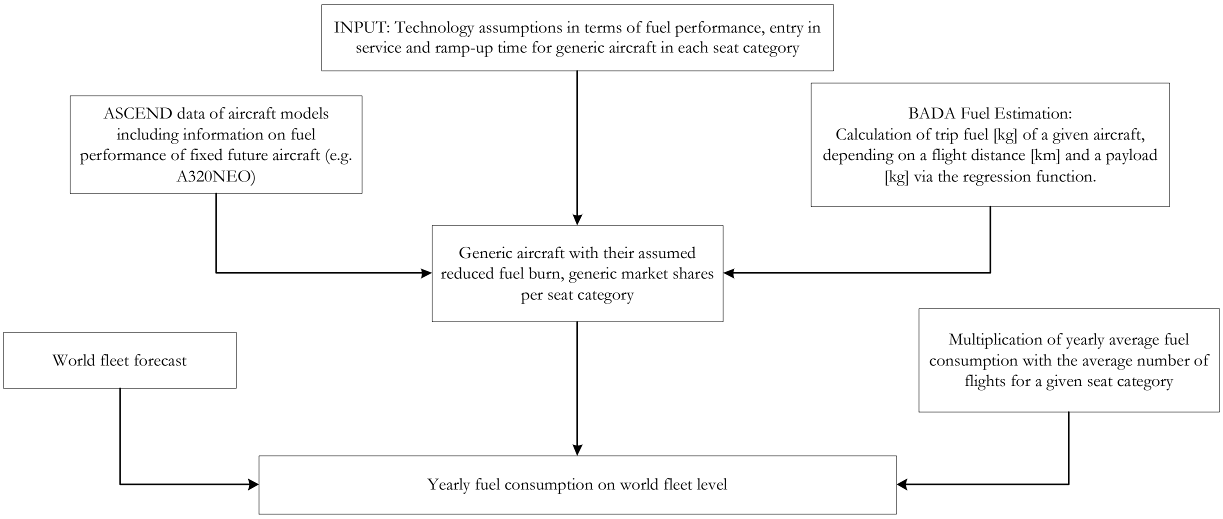

Figure 5 Methodology chart: calculation of the yearly fuel consumption (own chart)

### *3.1.2 Classification in preceded publications*

Based on an interview with the author of Fast Forward, Arno Apffelstaedt, this subsection provides information on the scientific background. The idea for the model came into being from the principle of the retirement curves of aircraft. This influencing variable and the orders, which are set by the airlines, primarily determine the development of $CO_2$ emissions. Written for the IATA, as part of the TERESA project, it was introduced in 2009 and since then, it underwent changes (Apffelstaedt, 2015). The TERESA (Technology Roadmap for Environmentally Sustainable Aviation) project used a bottom-up approach to assess the future fleet's $CO_2$ emission development. It started with the survey of a large set of technologies that could improve fuel efficiency. The results were then used to establish a technology's implementation roadmap and to calculate the fuel burn improvement per aircraft via a world fleet model (IATA, 2013). In 2009, studying on $CO_2$ reducing technologies began and the author of the model published the institute's work "Carbon Dioxide Reducing Aircraft Technologies and their Impact on Global Emissions", which came into being from an institute's paper, introduced at the German Aerospace Congress in 2008. Within, the approach for modelling the world fleet forecast was established, which is further applied by the model used in this thesis. On the contrary, the 2008 $CO_2$ emission forecast is based on the sum of the product of the daily utilization (block hours per day), the average fuel consumption (per block hour) and the fuel's specific carbon dioxide emissions for all aircraft in the world fleet through 2036. At last, the development of $CO_2$ emissions per seat-kilometres is calculated from dividing the world fleet $CO_2$ emissions by the sum of air traffic in available seat kilometres (ASK) to compare aircraft of different sizes (Apffelstaedt, 2008). In 2012, the TERESA project presented a different approach for calculating $CO_2$ emissions by using aircraft specific performance data from BADA to estimate the trip fuel until 2050, which is still valid and used in Fast Forward (IATA, 2013).

### *3.1.3 Analysis of the Basic Data*

After essential explanations to the methodology and background of Fast Forward, further inquiries respecting the validity of the model data and variables and thus, the validity of the model are carried out.

The internal and external validity, out of the psychology, are quality criteria for a study.

The internal validity exists if the change of the dependent variable is attributed to the variation of the independent variable. In addition, the results of an internal valid study are unequivocal interpretable and own no alternative explanations, which are involved in achieving the results (Sarris & Reiß, 2005; Bortz & Döring, 2006).

In order to ensure a high level of internal validity, interfering influences should be controlled and avoided by means of elimination or stabilisation (Sarris & Reiß, 2005). Without a valid connection between the dependent and independent variable, no generalisation is applied to the results, i.e. the internal validity indicates a necessary condition for the external validity. Hence, the external validity exists if the results are generalised to universality, to different places, time scopes and situations. The question concerning the generality is the fundamental of the induction, thus the two quality criteria follow the principle of the induction. The level of the external validity lowers with growing unnaturalness of the study conditions and decreasing representation of the examined variables (Bortz & Döring, 2006). Figure 6 presents the interdependency between the internal and external validity.

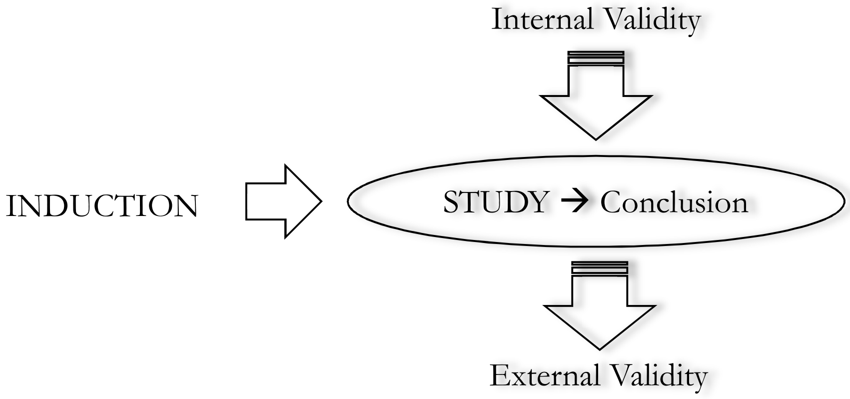

Figure 6 Schematic of the interdependency of internal and external validity (own schematic)

As already mentioned in Subsection 3.1.2, the approach of Fast Forward is based on the principle of fixed orders and retirements, set by the airlines. The $CO_2$ development is strongly dependent on both data. They are the independent variables. A variation of the independent variables implicates a change of the dependent variable, the $CO_2$ development. In addition, further independent variables are the future technologies with a better fuel performance potential, i.e. the new introduced generic aircraft in specific seat categories. Obviously, the significant global reduction of carbon is influenced by the choice of technologies with high potential. However, within this thesis, technologies are selected from five different categories (propulsion, aerodynamics, systems, materials and structural concepts); thus, from a great range and without consideration, which of them contains less risks and high potentials for $CO_2$ savings. Due to the theoretical potential, result of the intensive literature research, scenarios of the $CO_2$ development are shown. They demonstrate the range of the results depending on the range of the potentials (sensitivity analysis). Furthermore, no other influencing variables such as infrastructural improvements, enhanced operational practices or positive economic measures play a role; thus, in this case no alternative explanations for the emergence of the results are provided. In order to avoid disturbances due to varying orders and retirements applied on one study with this model, the variables need to be fix and stabile.

The external validity is characteristic for the inductive research logic. However, the thesis follows a deductive approach, i.e. the verification or falsification of an already existing general theory. Therefore, only objections against the internal validity are possible if objections against the validity of the achieved results exist.

### 3.2 Adjustments to the Forecast Model

For the thesis' goal, it is necessary to take some changes to Fast Forward. As output, it calculates the yearly fuel consumption on world fleet level. In order to obtain the overall $CO_2$ development until 2050, the amount of burnt fuel is converted into the amount of emitted $CO_2$. The mass of $CO_2$ per kilogramme of fuel burned is specific for the fuel used. For kerosene, the emission index (EI) of 3.16 is used (kg $CO_2$/kg burnt fuel). It is composed of the emission factor from the combustion 73.6 g/MJ, multiplied with the energy density of kerosene 0.043 MJ/g (Zech et al., 2014; Paschotta, 2015).

By multiplying the fuel function coefficients $b_0$ to $b_5$ with the EI of kerosene, the model directly outputs the yearly $CO_2$ emissions from the world fleet.

This calculation is also essential for the inclusion of a future generic aircraft powered by Liquefied Natural Gas[7] (LNG) into Fast Forward. Additional new technologies such as the open rotor and the strut-braced wing feature the aircraft. The corresponding fuel function is derived by generating a response surface from data points achieved by an aircraft mission performance code and then by extracting the polynomial equation and coefficients. The equation still describes the kilogrammes of fuel burned; thus, the LNG's carbon footprint

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[7] An explanation for LNG is provided by Section 3.3.3.

resulting from the combustion is calculated. The emission factor of the fuel combustion of a heavy duty truck is assumed to be equal to that of an LNG aircraft: $CO_2$ emission factor = 56.48 g/MJ. This factor is calculated based on data from the Greet model (Argonne - National Laboratory, 2015). Multiplied with the energy density of 0.0486 MJ/g and the LNG fuel function coefficients, the amount of $CO_2$ of the LNG aircraft feeds into the total mass of $CO_2$ from the world fleet. Figure 7 shows the methodology chart of the $CO_2$ emissions calculation including the adjustments (coloured in blue). Importantly, no fuel burn improvement is specified within Fast Forward due to the already calculated fuel efficiency via the fuel function coefficients.

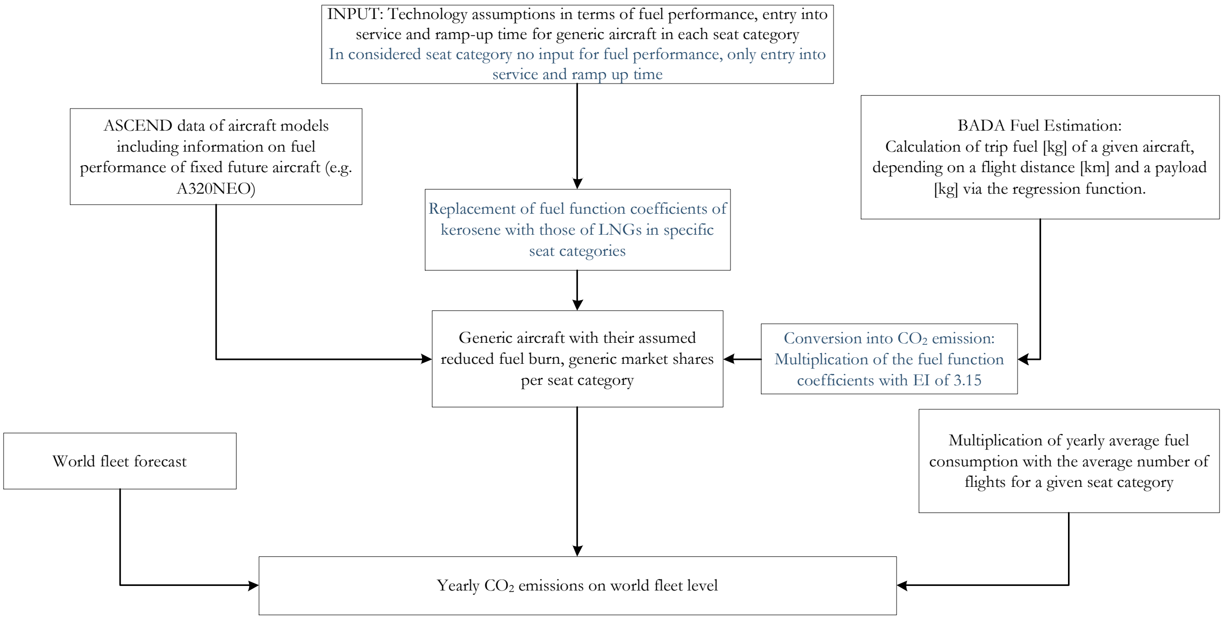

Figure 7 Methodology chart: calculation of the yearly amount of $CO_2$ emissions on world fleet level (own chart)

## 3.3 Input Data

### *3.3.1 Revenue Passenger-Kilometres Scenarios*

The following section gives an explanation for the question, why RPK forecasts serve as input for Fast Forward and subsequently, introduces studies of long-term scenarios on global air traffic development in comparison.

Passenger traffic forecast expressed in terms of revenue passenger-kilometres (RPK) is a significant factor involved in the $CO_2$ development. Since the beginning of the commercial jet evolution, global air traffic has grown strongly and continuously. The number of active aircraft in the world is dependent on the demand for air traffic. Not regarding serious economic downturns or policy changes, it is expected that air travel maintains a most likely 4.6 % growth in the future (FESG CAEP/9, 2012). Even if considering, for instance, economic crises and thus, slow down air traffic, it does not affect the orders and deliveries or retirement. However, it negatively affects orders and fleet growth in the future. Generally, RPK data is the decisive outlook, since it indicates the prospective required seats. On the contrary, ASK represent the reaction of the airlines to the demand and its meeting with the available fleet. The ICAO FESG Traffic and Fleet Forecast comprises information per seat category on:

- the Available Seat-Kilometres
- the Revenue Passenger-Kilometres
- the Fleet in Service
- the Flights per year
- the Seats in Fleet (amount of overall seats per seat category)

Based on the prospective RPK data by FESG, Fast Forward includes the adjustment to the latest RPK forecast by providing an input box for the user. The adjusted RPK are calculated by

$$RPK_{Adjusted} = \frac{RPK_{FESG}}{RPK\ World_{FESG}} \times RPK_{Input} \tag{3}$$

Assuming that the Load Factor, which assesses how efficiently airlines utilise their capacity, is exogenous (there is no dependence on the model) and calculated by the FESG Forecast data, i.e. Load Factor = $\frac{\mathrm{RPK_{FESG}}}{\mathrm{ASK_{FESG}}}$, the available seat kilometres are determined by

$$ASK_{Adjusted} = \frac{RPK_{Adjusted}}{Load\ Factor} \tag{4}$$

Thus, the RPK changes feed directly into the ASK changes.

After all, the required seats can be calculated on the basis of the underlying data by firstly estimating the total yearly distance per aircraft in kilometres and secondly, the adjusted forecasted seats in fleet.

$$Total\ yearly\ distance\ per\ aircraft = \frac{ASK_{FESG}}{Seats\ in\ Fleet_{FESG}} \tag{5}$$

$$Seats\ required = \frac{ASK_{Adjusted}}{Total\ yearly\ distance\ per\ aircraft} \tag{6}$$

The total yearly distance per aircraft, determined out of the FESG Forecast data, subjects to no change and develops identically to the FESG projection, since it is assumed that a change in $\frac{\mathrm{RPK}}{\mathrm{ASK}}$ affects all routes equally.

## CONSAVE 2050

CONSAVE 2050 from 2005 was one of the first international projects that elaborated the long-term development of air transport. As the result, four scenarios arose and were quantified by the model system AERO:

1. Unlimited Skies (ULS): infrastructure constraints
2. Regulatory Push & Pull (RPP): political regulations
3. Fractured World (FW): global fragmentation
4. Down to Earth (DtE): assumed societal value change

Behind these scenarios, alternative philosophies and specific sets of assumptions cover a broad range of possible futures and deal with one main challenge for aviation.
According to the model results, the last three constrained scenarios contain the lower passenger demand in terms of passenger-kilometres than the outcome for the first scenario. As the study includes only data for 2020 and 2050, the remaining values are interpolated under the assumption of an exponentially growth since the reference year 2000 (Berghof et al., 2005). The associated table of air traffic demand is presented in Appendix B.

### FESG CAEP/9

At the ninth Committee on Aviation Environmental Protection (CAEP) meeting in 2013, the FESG was tasked to introduce a new traffic and fleet forecast over a 30-year time horizon (from 2010 to 2040). The study results in three unconstrained scenarios for passenger traffic development, expressed in terms of average annual growth rate and revenue passenger-kilometres on global scale:

1. the high scenario (optimistic): average annual growth rate of 5.3 %
2. the most likely scenario (central forecast): average annual growth rate of 4.6 %
3. the low scenario (pessimistic): average annual growth rate of 3.9 %

The forecast has been developed for 31 major route groups, more precisely international sectors, for instance North Atlantic or Intra Europe as well as domestic sectors, among others Africa, Middle East and Japan. It includes solely the scheduled and chartered operations of commercial civil aviation aircraft. For the thesis's objective, an extension to 2050 by using a polynomial approach was necessary. A polynomial was also used by FESG to extend the base forecast (from 2010 to 2030) by an additional ten year period (until 2040). Appendix B furnishes the calculated development of passenger traffic (FESG CAEP/9, 2012).

**Air traffic prognoses from manufacturer's perspective**

In the Current Market Outlook from 2015 to 2034, Boeing prospects a world traffic growth of 4.9 % per year and state the GDP as the main driver for the increasing airline passenger traffic. Likewise, the company distinguishes the expected passenger traffic between the markets and forecasts the largest developing travel market to be within Asia. Assuming an exponential growth and with Boeing's provided global RPK data for 2014 and 2034, the calculation of anticipated passenger traffic until 2034 to the reference year 2014 is provided in Appendix B (Boeing, 2015).

Airbus predicts a world fleet growth in terms of RPK to 15,200 billion in 2034 according to its Global Market Forecast from 2015 to 2034. The manufacturer expects air travel to be doubled in the next 15 years and increased by annual 4.6 % from 2015 to 2034. Besides Boeing's passenger traffic development, the estimation of Airbus' forecast until 2034 by an exponential approach is supplied in Appendix B (Airbus, 2015).

Figure 8 reveals the air transport demand differing by the forecast studies in comparison. It is important to note that the final technical report of CONSAVE 2050 includes the past RPK from 1970 to 2000, which is extended by the value for 2010, indicated in FESG's CAEP/9 study. However, for the CONSAVE 2050 study from 2005, the 2010 data are calculated due to the constrained scenarios with different growth rates; thus, exhibit differences to FESG's value. The period 2030 to 2050 considerably indicates the great variation of conceivable developments. The most likely scenario by CAEP/9 is almost identical with the two industry prognoses; hence, the discrepancies in the increase in demand are containable. Additionally, the CONSAVE scenarios present contrasting courses due to their framework storylines. 'Fractured World', CONSAVE third scenario for instance, is expected to increase by an estimated 60 % until 2040, referred to 2010. On the contrary, the FESG study focuses on the possible range of future air traffic development without assuming specific challenges and constraints. It specifies the economic development as the main influencing factor. For example, the optimistic scenario prospects a 4.7 times growth in 2040 concerning the baseline 2010.

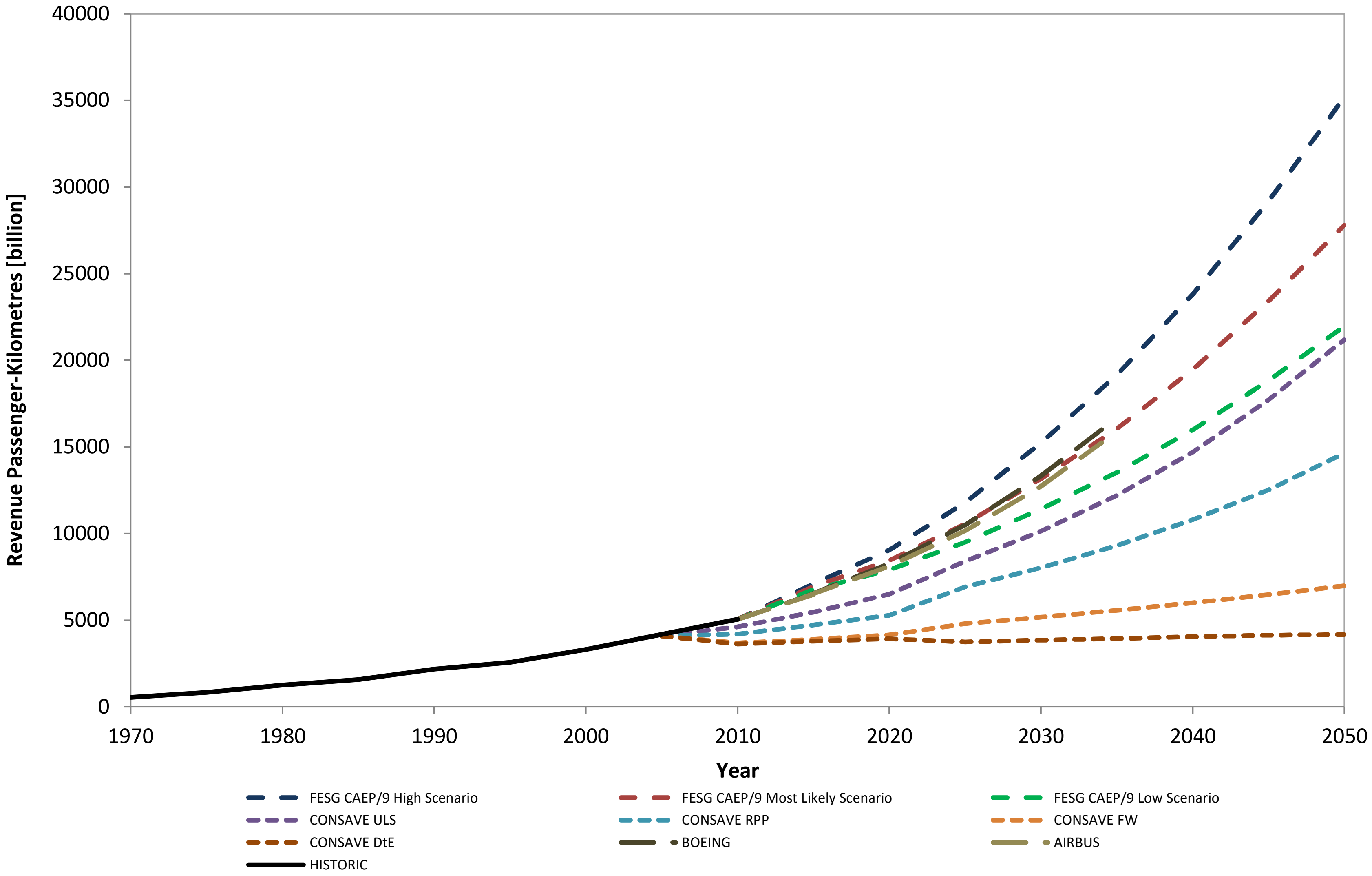

Figure 1 Air traffic demand forecast (extended from German Aerospace Centre, 2015)

### *3.3.2 Future Aircraft Technologies*

There is a group of new technologies under development that could be a strategy for reducing individual aircraft as well as global aviation $CO_2$ emissions until 2050. Carbon dioxide emissions from aircraft are a direct result of fuel burn. If the total amount of jet fuel burned is reduced, lower $CO_2$ emissions arise.

Hence, selected future technologies are surveyed in terms of their theoretical potential for mitigating aviation's impact on the environment. This investigation, based on an intensive literature study, results in a matrix of technologies, which is clustered by five technology domains:

- Propulsion
- Aerodynamics
- Systems
- Material
- Structural Concepts

The additional domain *Potential Technologies*, which includes Nanotechnologies, has been chosen due to less sufficient literature and reliable data, however indicates a valuable long-term alternative in the area of *Material.*

The future aircraft technologies are chosen accordingly as result of the study of the IFAR's member's competence fields and research activities. The International Forum comprises currently 26 aviation research organisations from all over the world, which contribute to climate and environmental challenges. Previous works, in cooperation with IFAR, yield a technology list, combining areas of airframe, propulsion, fuel and energy source that illustrates the focus domains of the members (a complete overview of all members is provided by Appendix E). Based on this list, further documents about the member's specific research topics and additionally, the review of IATA's studies, the range of novel aircraft technologies are surveyed concerning:

- the IFAR members and their competence fields
- the availability timeframe
- the possibility for retrofitting
- the theoretical potential for fuel burn reduction on aircraft level
- the reference aircraft

The first characteristic points out, on which chosen future technologies the aviation research organisation focus. It must be noted here that these institutes possess much more thematic areas than the thesis provides. The availability timeframe describes the estimated timespan for the technology's entry into service. By means of the literature study and information on the Technology Readiness Level[8] (TRL), the timeframe for the introduction of the technology is determined. The followed characteristic indicates the option for an installation of the technology as retrofit for in-service aircraft. This means that new introduced devices can fit for use in an, in this year of introduction, existing aircraft (IATA, 2013). The last two variables consider the range of the theoretical potential for fuel burn reduction on aircraft level, relative to a relevant, substituted jet transport aircraft.

Hereafter, a representative of each five domains is presented; however, the complete technology matrix is provided in Appendix D.

### (Ultra) High Bypass Advanced Turbofan (UHB Advanced Turbofan)

Advanced turbofan engines with (ultra) high bypass ratios in the range of 12 to 18 are planned for an entry into service from 2020 onwards (Ashcraft et al., 2011). The bypass ratio is one of the key indicators of engine efficiency. The higher ratio of mass flow through the bypass duct to mass flow through the engine core directly leads to an increase in thrust without burning more fuel. One path to an enhanced bypass ratio is to reduce the fan's pressure ratio, which lowers the fan's power requirement (NASA, 2014). Due to ongoing research and investment, advanced jet engines are projected to be at least ten per cent more

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[8] The TRL scale indicates the degree of maturity during the development of a technological innovation (IATA, 2013). Appendix C supplies the TRL scale.

efficient than today's engines (ATAG, 2010). In addition to improving the engine's fuel consumption, the low fan pressure ratio results also in noise reduction. The surrounding cold air lowers the noise produced by the exhaust gases (ATAG, 2010; NASA, 2014).
Likewise, this architecture is beneficial in reduced maintenance costs though incorporating further changes in jet design: active compressor, turbine clearance, flow control, advanced cooling as well as lighter and heat-resistant materials (ATAG, 2010; Nickol, 2012).

### Hybrid Laminar Flow Control (HLFC)

Flow controlled surfaces reduce the overall drag by assuring the boundary layer to remain attached; thus, laminar flow over a large section of the aircraft. Through suction in the surface airflow, HLFC allows the onset from laminar to turbulent flow moving further back along the surface. The application first on empennages, followed by the wings, leads to significant theoretical savings in fuel burn of up to 15 % compared to current designs (IATA, 2013). Research on laminar flow control started in the 1950's with series of tests on jet-propelled aircraft. However, problems such as icing and surface contamination prevented the maturing. Since 1980, further experiments had been carried out by research institutes for reducing risks, enhancing reliability and realising the anticipated entry into service in the late 2020's (IATA, 2013).

### Electrical Landing Gear Drive

The electrical taxi system is most suitable on short-range aircraft. The installation pays off by significant fuel savings in short-haul fleets, which consume up to six per cent of fuel at airports, resulting in five million tonnes per year during taxi operations (Honeywell International Inc., 2011). Either by APU or fuel cell powered, the use of the main engines is not needed until take-off. The pilot has total control over the electric motor, which is installed as a retrofit to either the nose or main landing gear. In spite of the dependence of fuel burn savings on aircraft and engine combination as well as airline's operating procedures, the forecasted maximum reduction is up to two per cent compared to an A320 with standard taxiing procedures (IATA, 2013). The technology is expected to be mature before 2020.

### Ceramic Matrix Composites (CMC)

Applied on the next generation of jet engines, the material is made of silicon carbide ceramic fibres and ceramic resin. Its promising characteristics such as light weight, durable and more heat resistant than metals allow the engine to run at higher thrust and more efficiently (GE Aviation, 2009). Today's alloys need high cooling air flows to maintain their maximum allowable operating temperatures. In contrast to CMC materials, which operate at a temperature range of 366-422 K higher than for alloys; hence, require less cooling air and increase the performance. This higher temperature and improved efficiency have potential to decrease the emissions of $CO_2$ and NOx (Halbig et al., 2013). CMC components are prospected to be introduced in the hot sections including high- and low-pressure turbine vanes and blades, turbine shrouds and combustor liners (GE Aviation, 2009). Currently, manufacturers test low-pressure turbine blades, the first non-static parts made out of CMC, for use in the next generation combat engine, but also commercial engine (GE Aviation, 2015).

### Adaptive Trailing Edge

On current flaps, gaps exist between the forward edge and sides and the wing surface. Advanced trailing edges are gapless and flexible by forming a seamless edge with the wing (NASA, 2014). The flap's adjustment of its shape depending on changes in aircraft's weight, airspeed and altitude results in improved wing aerodynamic efficiency and reduced noise during take-off, approach and landing (Robison, 2014). The advanced technology, research area of NASA's Environmentally Responsible Aviation or ERA project, cuts fuel use by an anticipated 4 to 12 % compared to an aircraft with conventional flaps. Currently tested, it promises a prospected introduction into the next commercial aircraft generation in the next six to ten years (Robison, 2014). Due to the considerable change of flight conditions of long endurance aircraft during a mission, the flap technology adjusts the flow development to the changing inflow and load conditions for a significant performance increment (Stanewsky, 2000). Nevertheless the application on short- and medium-range aircraft is additionally valuable and in the near-term achievable.

Table 4 summarises the technologies described above and illustrates the structure of the matrix with the studied characteristics. In addition, Figure 9 presents the timeline of all considered and intensively surveyed technologies, clustered by the expected timeframe for installation on next generation aircraft.

The two columns 'future generic aircraft' and 'future generic aircraft entry into service' are completed after compiling the technology combinations, which directly result in the future aircraft scenarios as input for Fast Forward. In order to conclude them, the identified estimated timespan for the technology entry into service, the reference aircraft and the range of the theoretical potential for fuel burn reduction on aircraft level serve as basis. The results are provided in Section 4.1.

Table 4 Representatives of each five technology domains

| Technology Domains | IFAR Members | Technology | Availability Timeframe | Reference Aircraft | Retrofit | Future Generic Aircraft | Future Generic Aircraft Entry into Service | Theoretical Fuel Burn Reduction |
|---|---|---|---|---|---|---|---|---|
| Propulsion[9] | For instance: DLR, Germany<br>KARI, Korea<br>NRC, Canada | (Ultra) High Bypass Advanced Turbofan | 2020-2025 | GE90-115B-powered 777-300ER | No | Aircraft of seat category 101-210,<br>211-400,<br>401-600 | 2025<br>2035 | 10 to 15 % |
| Aero-dynamics[10] | For instance:<br>DLR, Germany<br>KARI, Korea<br>INCAS, Romania | Hybrid Laminar Flow Control (HLFC) | Beyond 2020 | 2005 in-service aircraft | No | Aircraft of seat category 401-600 | 2035 | 10 to 15 % |
| Systems[11] | IAE, Brazil | Electrical Landing Gear Drive | Before 2020 | 2005 in-service aircraft | Yes | Aircraft of seat category 101-210,<br>211-400 | 2025 | 1 to 2 % |
| Material[12] | For instance:<br>DLR, Germany<br>NRC, Canada<br>JAXA, Japan: Composite turbine | Ceramic Matrix Composites | After 2020 | Current Aircraft | No | Aircraft of seat category 101-210,<br>211-400,<br>401-600 | From 2025 onwards | 6 to 8 % |
| Structural Concepts[13] | For instance:<br>DLR, Germany<br>JAXA, Japan<br>NRC, Canada | Adaptive Trailing Edge | 2020-2025 | Short-Range Aircraft<br>Long-Range Aircraft | No | Aircraft of seat category 101-210,<br>211-400 | 2025 | 4 to 12 % |

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[9] References: (IFAR, 2010; Ostrower, 2012)
[10] References: (IFAR, 2010; IATA, 2013)
[11] References: (IFAR, 2010; IATA, 2013)
[12] References: (IFAR, 2010; Inderwildi, 2010)
[13] References: (IFAR, 2010; Robison, 2014)

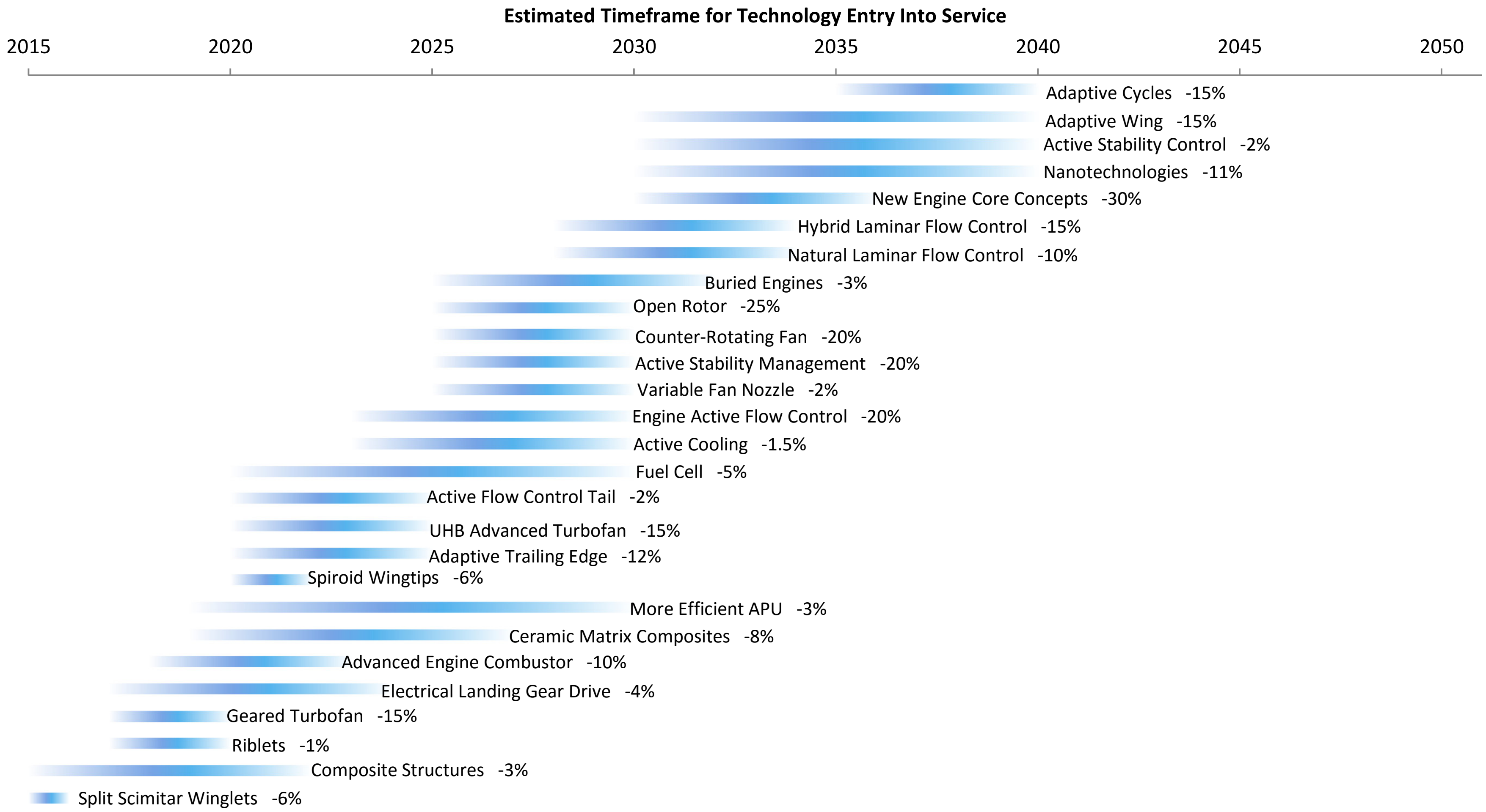

Figure 9 Maximum theoretical potential of chosen future technologies for fuel reduction relative to today's jet transport aircraft

### *3.3.3 Alternative Energy Sources*

Fuel efficiency has always driven engineers developing alternative fuels since the beginning of the aircraft revolution. The requirement for cleaner sources of energy, but also the changing costs of crude oil[14] lead to the prospective translation from conventional jet fuel to alternative energy.

Since the potential for $CO_2$ reduction of future aircraft technologies as input for the forecast model has been surveyed, the following subsection considers alternative energy sources, additionally. Thereby, the focus lies on two alternative fuels, which could power prospective aircraft types: Liquefied Natural Gas (LNG) and Biofuels. While biofuels are available in the short-term and used on both new and old aircraft, LNG promises to have high potential for $CO_2$ saving in the long-term.

#### **Biofuels**

Biofuels are produced from renewable biological resources (ATAG, 2011). They are used either directly or blended with conventional fossil fuels and have large theoretical potential to reduce aviation's carbon footprint, ready to substitute kerosene (Braun-Unkhoff, 2014). Sourced from oil plants such as algae, jatropha, halophytes and camelina, the production of this bio-derived fuel enables a near-term solution to provide a "drop-in" fuel with lower environmental impact than traditional jet fuel (ATAG, 2011).

Their production, either through directly burning or conversion by chemical processes to high-quality fuel, is not limited to locations. Characteristic of the so called second-generation feedstock is that they can be grown carbon-neutral. This $CO_2$ lifecycle starts with absorption of carbon dioxide by the energy plants. The combustion in aircraft releases the $CO_2$, which is ingested again by the regrowing biomass (Aireg e.V., 2015).

Today, biofuels are used as drop-in replacements to the conventional aircraft fuel Jet A-1, which is a type of kerosene and is most commonly used in the commercial aviation. They are blended with the petroleum-based fuel or 100 % substitute it.

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[14] The Association for the Study of Peak Oil and Gas (ASPO) Netherlands defines crude oil as liquid or semi liquid petroleum including deep-sea oil and lease condensate. The oil price decreases from 135 $ per barrel to 50 $ per barrel mid 2008 until 2009. Since then, it started to increase again (ASPO Netherlands, 2010). Moreover, it is expected that the oil production reaches its peak between 2030 and 2035 (Federal Institute for Geosciences and Natural Resources, 2009).

Since they fulfil the same qualities and characteristics of Jet A-1 such as freezing point or density, manufacturers have no need to redesign their engines and aircraft as well as fuel supplier and airports must not develop new fuel delivery systems (ATAG, 2011). Thus, a great benefit lies in their independence of the introduction of new aircraft.

Right now, certified processes allow airlines to use a blend of 50 % biofuel with Jet A-1 in commercial passenger flights. Two biofuels have received the approval for application in aviation fuel: hydroprocessed esters and fatty acids (HEFA) and biomass to liquid (BTL). During the HEFA process, the biomass is pressed in order to gain the oil inside and is then refined into jet fuel. Compared to BTL, where the biomass is firstly converted into gas and secondly, into liquid jet fuel (ATAG, 2011).

However, the production of sustainable feedstocks in required and commercial-scale quantities are necessary in order to realise the replacement of fossil fuel. Parts of the aviation industry rather see a fleet operating with a 25 % biofuel blend by 2025, increasing to 30 % in 2030 (ATAG, 2011). A study of the federal ministry of traffic and digital infrastructure assume that a demand for 80 % regenerative kerosene substitutes, i.e. biofuel blends occur in 2050 (Zech et al., 2014).

**Liquefied Natural Gas**

The potential of natural gas to meet the global demand is very promising due to its 20 % lower carbon footprint and its sufficient availability (Gibbs, 2011).

For reasons of transportation and storage, it is beneficial to enhance the density by liquefaction of natural gas through cooling to -162 °C. At LNG-Terminals, the liquefaction takes place, from where LNG can be transported over long distances by special tanker. Thus, transport via pipelines is not necessary (Paschotta, 2015).

LNG would be stored in the cargo bay, in vacuum, jacketed, lightweight, cryogenic tanks made out of aluminium. In order to use the remaining cargo space, the lighter tanks resemble existing cargo containers and include a fuel system that manages fuel distribution and tank pressure (Gibbs, 2011).

Applied to a new generation aircraft in the estimated time scope of 2030 to 2045, LNG results in performance improvements varied over the design range and aircraft type. A great advantage of LNG as jet fuel is the higher gravimetric energy density[15] of 48.6 MJ/kg, compared to that of kerosene. It results in lighter tanks, which again leads to fuel savings and increase in transport capacity (Paschotta, 2015). The amount of emitted $CO_2$ during combustion is calculated as described in Section 3.2. Specific attention should be given to the life-cycle emissions, which include the processing and supply emissions, next to the combustion emissions. Depending on the production process and delivery methods, the life-cycle emission index (EI) is typically lower than that of Jet A-1.

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[15] The energy density indicates the released energy during combustion, per kilo of fuel (ATAG, 2011).

# 4 GENERIC AIRCRAFT AND THEIR IMPACT ON GLOBAL $CO_2$ DEVELOPMENT

Based on the survey of technological innovations and future alternative fuel types, technology scenarios are compiled to assess the potential for fuel burn improvement of future generic aircraft. This chapter presents these aircraft for different seat categories and timeframes. Under changing assumptions of integrating future aircraft into the world fleet, $CO_2$ growth scenarios results from the application of Fast Forward. A followed assessment of the $CO_2$ reducing potential concludes the chapter.

## 4.1 Future Generic Aircraft

Before 2020, the world fleet will be already enlarged through an offer of new aircraft types. The single-aisle sector will bring new and more fuel-efficient aircraft like the A320neo and the 737max. Within the twin-aisle market, the A350-1000 will enter service in the second half of 2017; one year later, Boeing will deliver the 787-10, to just name a few (Evans, 2015). Experts assume that the research is currently focused on the development of already existing aircraft due to the success of re-engined types and derivatives of aircraft (Katz & Rothman, 2015). Nevertheless all-new aircraft would significantly support cutting fuel consumption since more advanced technologies are under development.

Based on the future aircraft technology survey, Figure 10 illustrates the range of the theoretical potential for fuel burn reduction on single aircraft level. It is likely achievable today ('Quick Wins'[16]), after 2020 (new design after 2020) and after 2030 (new design after 2030). Technologies of each domain and time scope were studied and, under consideration of mutually exclusive technologies, their fuel burn reduction potential summed.

Additionally, Figure 10 visualises developments until 2040, which of these new technologies can also be added to existing products. Thus, they require no new aircraft design (retrofits and modification[17]). It is important to know that despite the possible high potential of technological breakthroughs in the 2020's, the development of new technologies beyond 2030 is not constrained.

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[16] Technologies, which are available in short-term and require no new aircraft design, i.e. are either retrofits or modification, are indicated as 'Quick Wins'.

[17] Modifications term upgrades of serial production types due to a change in production specifications or an altered technology (IATA, 2013)

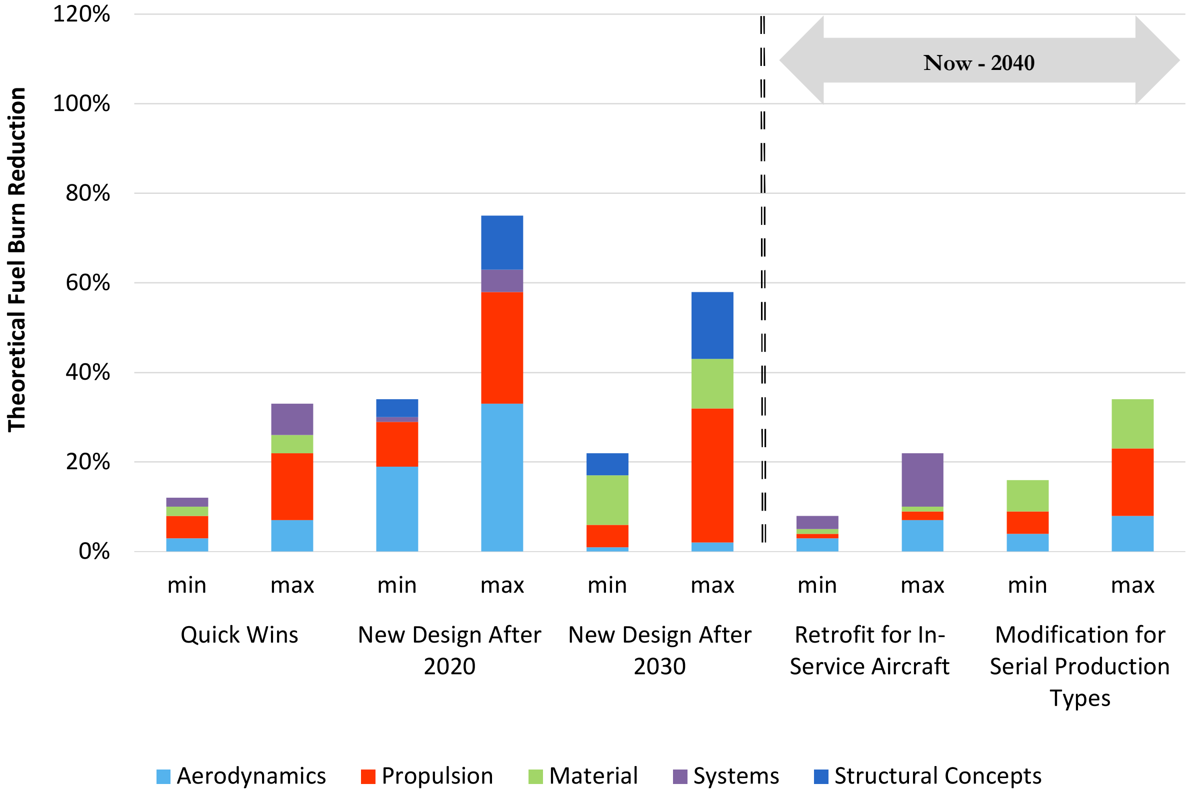

Figure 10 Range of theoretical fuel burn reduction potential of chosen future technologies for retrofits, modifications and new aircraft types (own compiled diagram)

The growth of future $CO_2$ emissions is projected for different aircraft technology scenarios. For that reason, the previously surveyed future technologies are compiled to combinations, which could be hosted by new generic aircraft classified by seat categories (the compilation is identified with regard to the technology matrix supplied by Appendix D). These generic aircraft satisfy the unfixed aircraft demand.

Aircraft of the seat categories 101-150 and 151-210, 211-300 and 301-400, 401-500 and 501-600 are chosen, as they cover the largest share in the global aircraft fleet and as these aircraft are produced by the world's leading manufacturers. The smallest (51-100 seats) and largest (601-650 seats) categories are excluded from the study.

Based on the estimated timespan of the technology's entry into service, the future aircraft's theoretical introduction is determined. Dependent on their year of introduction, they are defined as N+X generation aircraft, according to a classification by NASA (reviewed by

National Science and Technology Council, 2010). Table 5 demonstrates future generations of advanced aircraft by means of the N+1 and N+2 generation. However, the time scopes are defined by the author.

Table 5 Notation of future generation aircraft

| N | Today | Current generation aircraft |
|---|---|---|
| N+1 | 2020-2030 | Next generation aircraft |
| N+2 | 2035-2045 | Generation after N+1 |

The fuel burn reduction for the aircraft scenario is calculated from the summation of the individual technology's potential. This calculation considers no possible decrease of the potentials if technologies are combined. The improvement is indicated in comparison to a substituted reference aircraft of the same seat category. Since the future $CO_2$ development is associated with the theoretical potential of new aircraft technologies for fuel burn reduction, a sensitivity analysis provides scenarios. These scenarios meet the uncertainties regarding this theoretical potential. The low scenario marks a pessimistic assessment of the potential for fuel burn improvement, whereas the high scenario describes an optimistic assessment of the potential.

### 4.1.1 *Future Generic Aircraft of Seat Category 101-210*

Table 6 supplies the introduction of a N+1 generation aircraft in 2025, which is a substitution of an aircraft in seat category 101-210. The aircraft technologies result in a minimum fuel burn improvement of 20 % and a maximum fuel burn improvement of 55 % (the ranges result from the technology potentials shown in the technology matrix, provided in Appendix D). These two aircraft technology scenarios differ in their propulsion, each having a prospective entry into service in 2025. The ultra-high bypass advanced turbofan (UHB Advanced Turbofan) includes ceramic matrix composite (CMC) turbine blades, whereas an integration of CMC into a geared turbofan provides further potential for fuel burn improvement (General Electric, 2013).

New wingtip devices are used to reduce the aircraft's overall drag. The split scimitar winglet (also known as dual-feather winglet) is currently applied, while the spiroid wingtips can be introduced from 2020 onwards (IATA, 2013; Airliners.de, 2014). Both have an identical potential for fuel burn improvement and can be installed on aircraft of each seat category (IATA, 2013). Additional aerodynamic benefits and thus, reductions in drag and fuel consumption of an aircraft of seat category 101-210 provides the active flow control tail (Norris, 2015).

Within the domain ‘systems’, two more efficient future technologies promise to reduce fuel burn: auxiliary power unit (APU) and electrical landing gear drive. It is notable that the electrical landing gear drive is most likely beneficial on short- and medium-range aircraft. The reason is seen in the high share of taxiing time of their overall flight mission and the more frequent times on the ground (Sachs, 2015).

The adaptive trailing edge improves the wing aerodynamic efficiency resulting in fuel savings if applied on aircraft of seat category 101-210 (Robison, 2014). Advanced composites on the primary or secondary structure continue to reduce the fuel consumption and could be used in aircraft of each seat category (Nickol, 2012).

Table 6 Scenario of the fuel burn improvement of a N+1 generation aircraft in 2025

| **Seat Category 101-210<br>2025 Entry Into Service** | | |
|---|---|---|
| Propulsion | Geared Turbofan | UHB Advanced Turbofan |
| Aerodynamics | Split Scimitar Winglets | Split Scimitar Winglets |
| | Active Flow Control Tail | Active Flow Control Tail |
| Systems | Electrical Landing Gear Drive | Electrical Landing Gear Drive |
| | More Efficient APU | More Efficient APU |
| Structural Concepts | Adaptive Trailing Edge | Adaptive Trailing Edge |
| Material | Composite Primary and Secondary Structure | Composite Primary and Secondary Structure |
| | Ceramic Matrix Composite | |
| **Low Scenario** | **20 % fuel burn improvement on single aircraft level** | |
| **High Scenario** | **55 % fuel burn improvement on single aircraft level** | |

Technology scenarios of a N+1 aircraft in seat category 101-210 in 2030 are provided by Table 7. Technological innovations reduce the fuel consumption by 30 % in the low scenario and up to 70 % in the high scenario. A geared turbofan with counter-rotating fan could power a next generation aircraft. An additional propulsion technology for the 101-210 seats segment is the open rotor, seen as one of the most promising engine options in the longer term. The new design is most fuel-efficient on short-haul flights. Its characteristic lower cruise speed is not decisive on shorter flights (Gmelin et al., 2008). The propulsion system additionally integrates active cooling, which reduces cooling air and therefore decreases fuel consumption (NEWAC, 2011).

Importantly, the natural laminar flow control technology has a promising fuel burn reduction potential in the 2030-timeframe (Royal Aeronautical Society, 2005).

The future generic aircraft of seat category 101-210 hosts a fuel cell instead of the APU as fuel cells have further potential to lower fuel burn (IATA, 2013). They are applicable on aircraft of each seat segment.

Table 7 Scenario of the fuel burn improvement of a N+1 generation aircraft in 2030

| **Seat Category 101-210**<br>**2030 Entry Into Service** | | |
|---|---|---|
| Propulsion | Geared Turbofan with Counter-Rotating Fan | Open Rotor |
| | Active Cooling | Active Cooling |
| Aerodynamics | Spiroid Wingtips | Spiroid Wingtips |
| | Natural Laminar Flow Control | Natural Laminar Flow Control |
| | Active Flow Control Tail | Active Flow Control Tail |
| Systems | Fuel Cell | Fuel Cell |
| | Electrical Landing Gear Drive | Electrical Landing Gear Drive |
| Structural Concepts | Adaptive Trailing Edge | Adaptive Trailing Edge |
| Material | Composite Primary and Secondary Structure | Composite Primary and Secondary Structure |
| **Low Scenario** | **30 % fuel burn improvement on single aircraft level** | |
| **High Scenario** | **70 % fuel burn improvement on single aircraft level** | |

### *4.1.2 Future Generic Aircraft of Seat Category 211-400*

Table 8 sums up the technology scenarios of a generic aircraft of seat category 211-400. Introduced in 2025, it could have a minimum fuel burn reduction of 20 % and a maximum fuel burn reduction of 55 %.

Table 8 Scenario of the fuel burn improvement of a N+1 generation aircraft in 2025

| **Seat Category 211-400<br>2025 Entry Into Service** | | |
|---|---|---|
| Propulsion | Geared Turbofan | UHB Advanced Turbofan |
| Aerodynamics | Spiroid Wingtips | Spiroid Wingtips |
| | Active Flow Control Tail | Active Flow Control Tail |
| Systems | Electrical Landing Gear Drive | Electrical Landing Gear Drive |
| | More Efficient APU | More Efficient APU |
| Structural Concepts | Adaptive Trailing Edge | Adaptive Trailing Edge |
| Material | Composite Primary and Secondary Structure | Composite Primary and Secondary Structure |
| | Ceramic Matrix Composite | |
| **Low Scenario** | **20 % fuel burn improvement on single aircraft level** | |
| **High Scenario** | **55 % fuel burn improvement on single aircraft level** | |

The technology scenarios for a N+1 aircraft of seat category 211-400 in 2030 differ in the aircraft propulsion (Table 9). The new engine core concept possibly enters service from 2030 onwards and indicates significant potential to improve the fuel efficiency (NEWAC, 2011; IATA, 2013). The combination of the shown technologies, result in 25 % reduction in fuel burn within the low scenario and in up to 70 % reduction in fuel burn within the high scenario.

Table 9 Scenario of the fuel burn improvement of a N+1 generation aircraft in 2030

| **Seat Category 211-400<br>2030 Entry Into Service** | | |
|---|---|---|
| Propulsion | Geared Turbofan with Counter-Rotating Fan | New Engine Core Concepts |
| | Active Cooling | Active Cooling |
| Aerodynamics | Spiroid Wingtips | Spiroid Wingtips |
| | Active Flow Control Tail | Active Flow Control Tail |
| Systems | Fuel Cell | Fuel Cell |
| | Electrical Landing Gear Drive | Electrical Landing Gear Drive |
| Structural Concepts | Adaptive Trailing Edge | Adaptive Trailing Edge |
| Material | Composite Primary and Secondary Structure | Composite Primary and Secondary Structure |
| **Low Scenario** | **25 % fuel burn improvement on single aircraft level** | |
| **High Scenario** | **70 % fuel burn improvement on single aircraft level** | |

### 4.1.3 *Future Generic Aircraft of Seat Category 401-600*

A generic new aircraft, substituting its predecessor within seat category 401-600, possibly enlarge the aircraft fleet in 2035 (Table 10). Two technology scenarios have the potential to improve the fuel consumption by a minimum of 30 % and by a maximum of up to 70 %.

A N+2 generation aircraft could be powered either by buried engines (engines, which are integrated into the airframe) or the UHB advanced turbofan. The UHB advanced turbofan already includes an active controlled compressor, whereas an integration of the active stability management enhances the fuel burn potential of the first technology scenario (ATAG, 2010; Nickol, 2012).

Technological breakthroughs with expected high potential for fuel burn improvement are riblets and hybrid laminar flow control. Riblet surfaces (finely grooves attached to the skin of the aircraft) lead to reduction of turbulent flow drag. They are applied to the entire fuselage or wing or both and are most fuel-efficient on longer ranges due to a sufficient cruise flight period (IATA, 2013; Sachs, 2015). The HLFC technology is planned for an entry into service towards 2030. It is installed on the empennage and wing and reduces likely the most fuel burn on long-haul aircraft (Ostrower, 2011; IATA, 2013).

The adaptive wing adjusts its geometry to the changing flow and load requirements, which frequently occur during longer ranges (Stanewsky, 2000). Therefore, the technology achieves most efficient fuel consumption on long-range aircraft.

Table 10 Scenario of the fuel burn improvement of a N+2 generation aircraft in 2035

| **Seat Category 401-600**<br>**2035 Entry Into Service** | | |
|---|---|---|
| Propulsion | Buried Engines | UHB Advanced Turbofan |
| | Engine Active Stability Management | |
| Aerodynamics | Split Scimitar Winglets | Spiroid Wingtips |
| | Hybrid Laminar Flow Control | Hybrid Laminar Flow Control |
| | Riblets | Riblets |
| Systems | Fuel Cell | Fuel Cell |
| Structural Concepts | Adaptive Wing | Adaptive Wing |
| Material | Composite Primary and Secondary Structure | Composite Primary and Secondary Structure |
| **Low Scenario** | **30 % fuel burn improvement on single aircraft level** | |
| **High Scenario** | **70 % fuel burn improvement on single aircraft level** | |

In the 2040-timeframe, the adaptive cycle engine could be mature to drive a generic N+2 generation aircraft of the 401-600 seats segment (Table 11) (IATA, 2013). The technology scenario indicates no significant differences concerning the low and high fuel burn improvement scenario over the 2035 technology combinations. The only difference is the option of the adaptive cycle engine as propulsion. It enables the aircraft to operate under mixed flight conditions for maximum efficiency. A fuel burn reduction potential similar to the UHB advanced turbofan is achieved (IATA, 2013; Norris, 2015).

Table 11 Scenario of the fuel burn improvement of a N+2 generation aircraft in 2040

| **Seat Category 401-600<br>2040 Entry Into Service** | |
|---|---|
| Propulsion | Adaptive Cycle Engine |
| Aerodynamics | Spiroid Wingtips |
| | Hybrid Laminar Flow Control |
| | Active Stability Control |
| | Riblets |
| Systems | Fuel Cell |
| Structural Concepts | Adaptive Wing |
| Material | Composite Primary and Secondary Structure |
| **Low Scenario** | **30 % fuel burn improvement on single aircraft level** |
| **High Scenario** | **65 % fuel burn improvement on single aircraft level** |

In addition to the technology scenarios, scenarios integrating LNG and biofuel for further reducing the global $CO_2$ emissions are part of the study. Concerning the application of biofuels, scenarios consider a biofuel-kerosene blend, which is applied on the world fleet. The underlying assumptions are presented in Section 4.2.6.

In the following, the fuel burn improvement potential of these future generic aircraft serves as input for achieving different $CO_2$ emission growth scenarios on world fleet level. The "gap" analysis between the $CO_2$ growth scenarios and the global 50% $CO_2$ emission reduction goal is part of the Section 4.2.

## 4.2 Global $CO_2$ Growth until 2050

The following scenarios for the development of the $CO_2$ emissions of all aircraft are built under the FESG CAEP/9 most likely RPK growth of annual 4.6%. They are calculated by means of Fast Forward. Concerning the seat category, the fuel burn improvement, the year of entry into service and the ramp-up time of the future generic aircraft deliver the input (Table 12). The resulting diagrams with the $CO_2$ emission development are firstly described and lastly assessed in Section 4.3.

Table 12 Input variables for the forecast model

| Seat Category | Fuel Burn Improvement | Entry Into Service | Ramp-Up (7 years) |
|---|---|---|---|

### 4.2.1 *Scenario "No Action"*

The annual relative RPK development to 2011 through 2050 is supplied by . Air traffic in terms of RPK is expected to nearly increase sixfold through 2050. The corresponding relative growth of ASK to 2011 results accordingly. The relation between the RPK and the ASK is the exogenous Load Factor. Fast Forward divides the values of RPK by the Load Factor in order to attain the ASK course (see Subsection 3.3.1). The bold black coloured graph represents the development of the $CO_2$ emissions, caused by the fuel combustion of the entire world fleet until 2050, relative to 2011. If no measures for mitigating aviation's impact on the environment are implemented, this 'no action' scenario arises. It is characterised by the neglect of the integration of more fuel-efficient aircraft and additional strategies like operational improvements.

Importantly, the new developed and already ordered aircraft for short- and long- haul, like the A320neo, MRJ90, C919 or A350 are implemented within Fast Forward. They are calculated with a fuel efficiency factor[18] and affect the $CO_2$ emission growth. The visualisation of the two considered IATA emission reduction goals, concerning the carbon-

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[18] The fuel efficiency factor indicates the improvement relative to the predecessor within the seat category. It is multiplied with the BADA fuel function coefficients in order to calculate the reduced fuel consumption. For instance, the A320neo is 15% more fuel-efficient than the A320.

neutral growth from 2020 onwards and the reduction of $CO_2$ emissions by 50 % in 2050, complete the diagram.

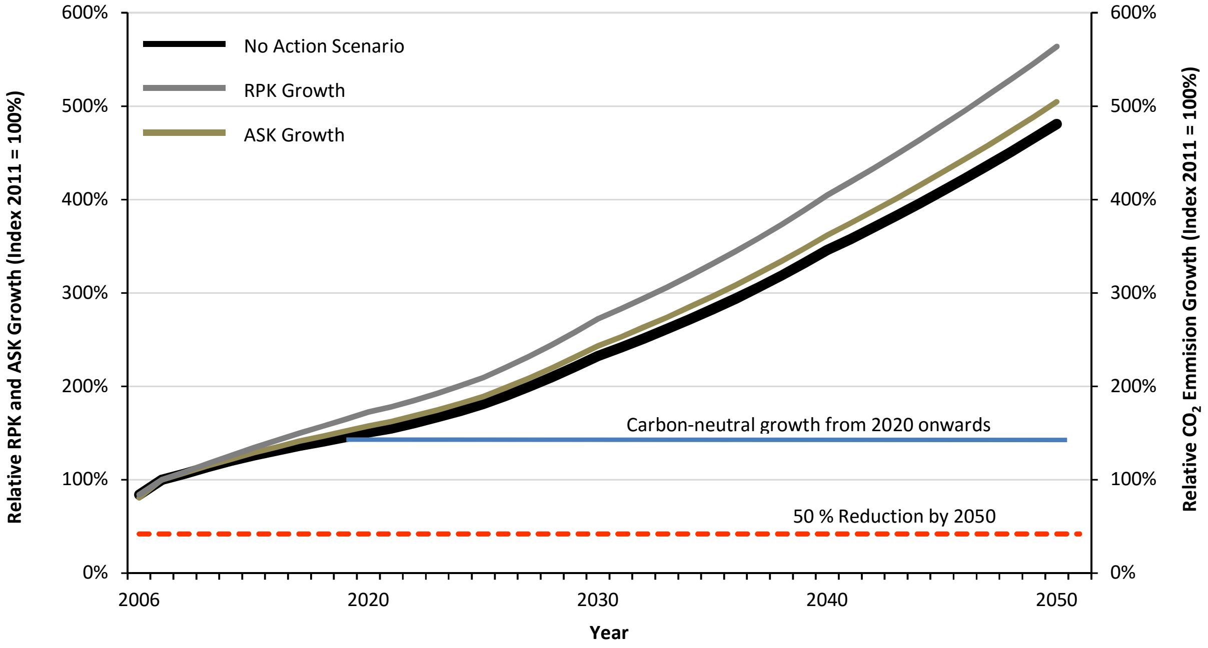

Figure 11 CO2 development (only combustion) scenario 'No Action'

### 4.2.2 *Scenario N+1 Generation Aircraft*

The course of emitted $CO_2$ from the world fleet until 2050 arises if a new generic aircraft of seat category 101-210 is introduced in 2025 (Figure 12).

The low scenario with an improvement in fuel burn of 20 % results in a 5 % reduction of $CO_2$ emissions (red graph) relative to the no action scenario in 2050. On the contrary, the 55 % fuel burn improvement on aircraft level within the high scenario could reduce the $CO_2$ growth by 14 % in 2050 (green graph).

A greater $CO_2$ reduction is apparent, when the production of the N+1 generation aircraft model is ramped-up (after seven years). This means that 100 % of the deliveries within this considered seat category comprise the N+1 generation aircraft.

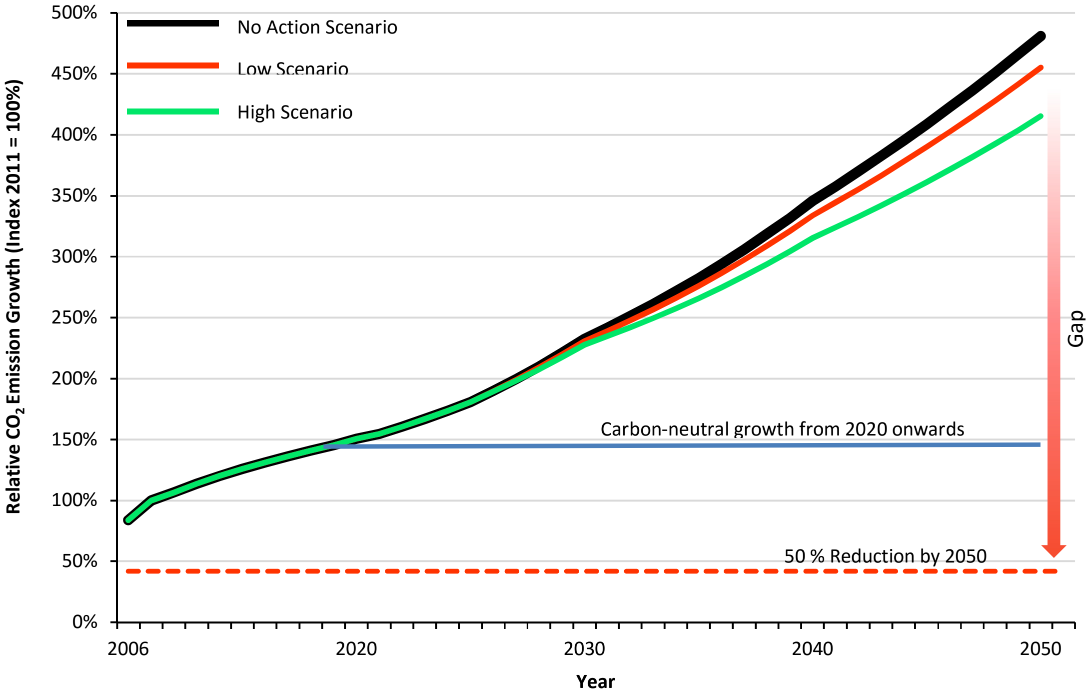

Figure 12 $CO_2$ development (only combustion) scenarios of a N+1 generation aircraft of seat category 101-210 in 2025

The following Figure 13 includes a future generic aircraft of seat category 101-210, introduced in 2030, to compare it to the N+1 generation aircraft in 2025.

The 2030-timeframe aircraft has a minimum potential of 30 % in fuel burn improvement and a maximum potential of 70 % over current aircraft of the same category.

Despite of technologies with high potential in fuel consumption reduction such as natural laminar flow control and open rotor, the N+1 aircraft in 2030 will bring similar $CO_2$ emission benefits as the future aircraft in 2025. The low scenario results in a 6 % reduction of $CO_2$ emissions and the high scenario yields a 15 % reduction in 2050.

In addition, the $CO_2$ emission reduction starts to be recognisable in 2037 and indicates no greater relative value in 2050, compared to the 2025-timeframe aircraft.

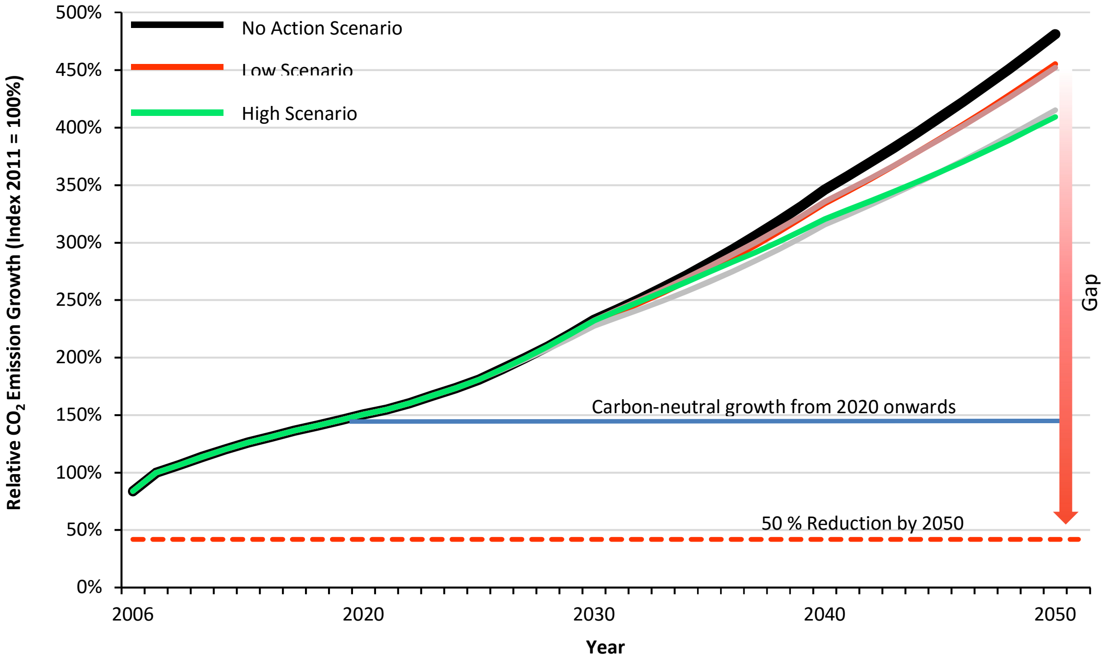

Figure 13 $CO_2$ development (only combustion) scenarios of a N+1 generation aircraft of seat category 101-210 in 2025 and 2030

Taking up the underlying assumptions similar to the scenario of a new aircraft of seat category 101-210 in 2025 and applying it to the upper seat category, further reduction of the $CO_2$ growth is achieved (Figure 14). If an aircraft in seat category 211-400 is substituted in 2025, the low scenario results in a 7 % reduction of $CO_2$ emissions in 2050 (red graph). The high scenario contributes to a 17 % reduction of $CO_2$ emissions (green graph).

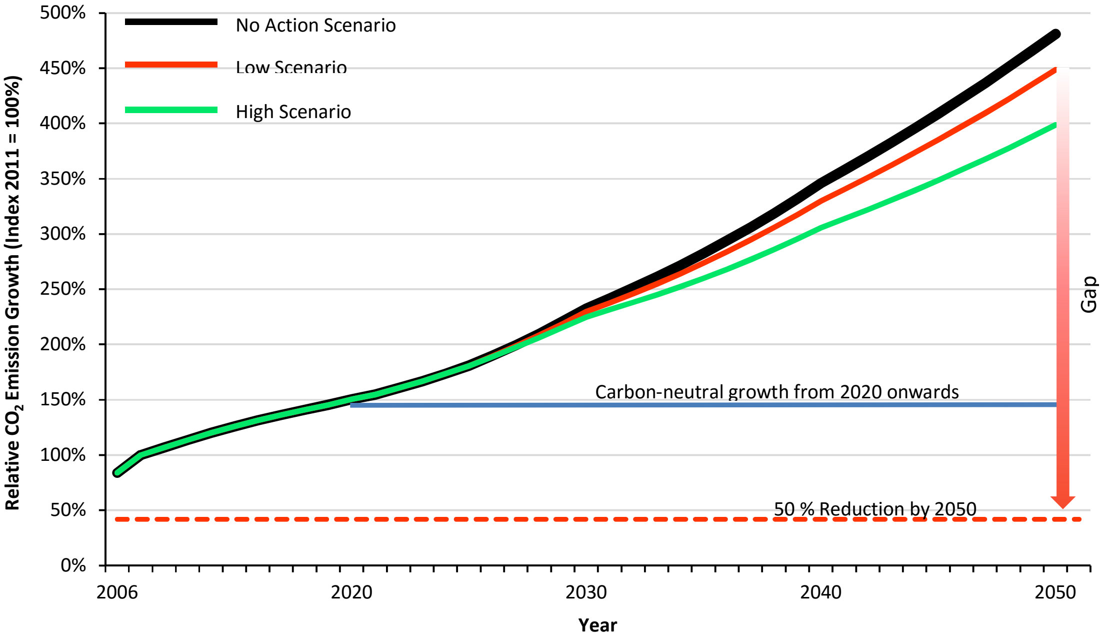

Figure 14 $CO_2$ development (only combustion) scenarios of a N+1 generation aircraft of seat category 211-400 in 2025

Figure 15 provides the course of $CO_2$ emissions until 2050, if a new aircraft of seat segment 211-400 is integrated into the world fleet in 2030. It is compared to the global $CO_2$ development under the introduction of the same aircraft category in 2025.

The N+1 generation aircraft yields a reduction of emitted $CO_2$ by up to 6 % (low scenario) and improves this development by over 17 % in 2050 (high scenario). The high scenario includes the optimistic assessment of up to 70 % fuel burn improvement due to technologies with high potentials such as new engine core concepts.

Nevertheless, the shift of the reduction of global $CO_2$ emissions takes longer due to the later entry into service. The overall $CO_2$ improvement potential however indicates the same level in 2050 as the generic aircraft in 2025.

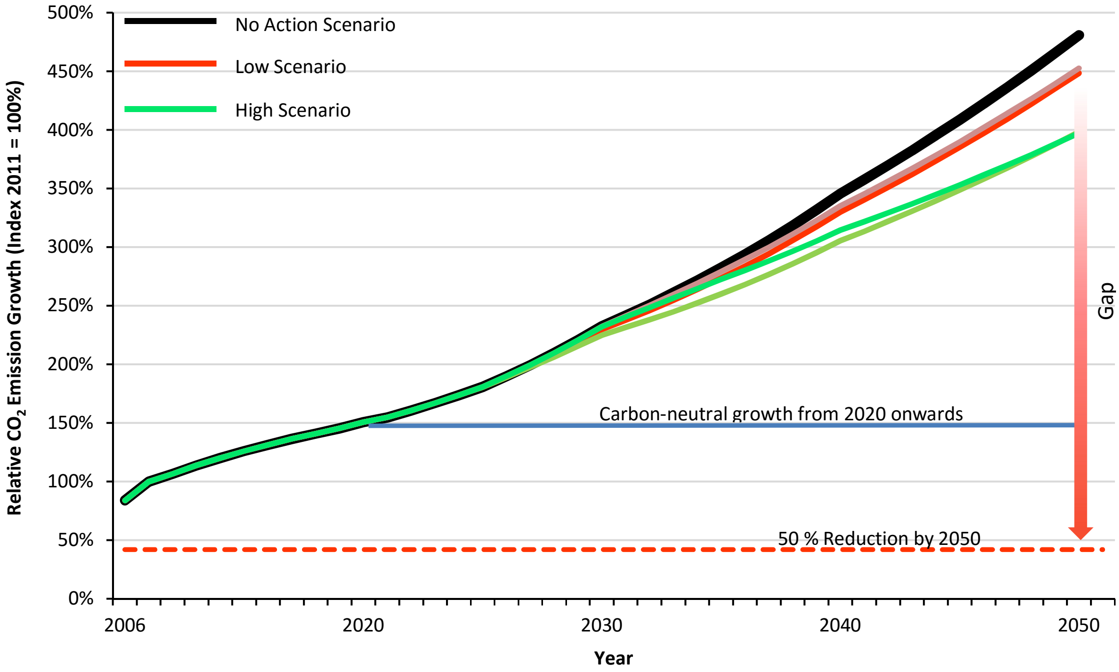

Figure 15 $CO_2$ development (only combustion) scenarios of a N+1 generation aircraft of seat category 211-400 in 2025 and 2030

### *4.2.3 Scenario N+2 Generation Aircraft*

Figure 16 presents the $CO_2$ development scenario of a N+2 generation aircraft of seat category 401-600 in 2035. It achieves a minimum reduction of $CO_2$ emissions by three per cent in 2050. In the high scenario, a reduction of seven per cent results in 2050. The $CO_2$ emission reduction starts in the 2040-timeframe and indicates no significant difference to the no action scenario in 2050.

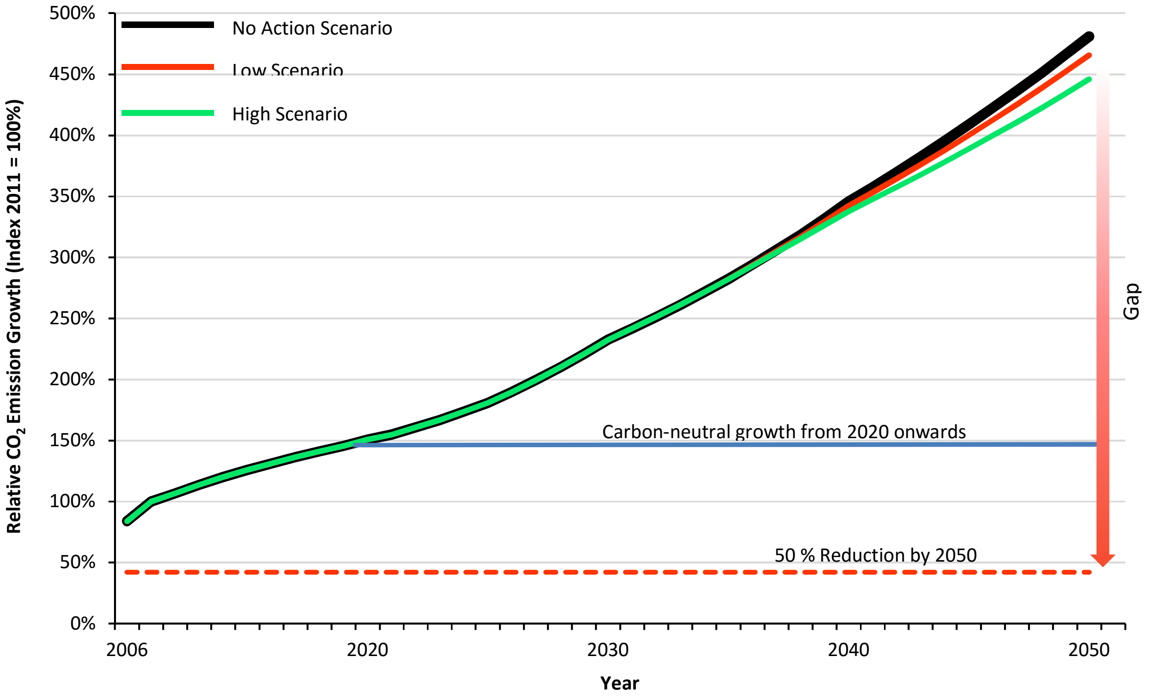

Figure 16 $CO_2$ development (only combustion) scenarios of a N+2 generation aircraft of seat category 401-600 in 2035

Figure 17 provides the scenario of the $CO_2$ growth until 2050 of a N+2 generation aircraft in 2040. Less considerable improvement of air traffic's impact on $CO_2$ in 2050 is apparent over the scenario of the same aircraft category in 2035 (pale coloured graphs).

The red graph shows the $CO_2$ emission development of almost two per cent reduction in 2050 resulting from the low scenario. The bright green coloured course of the $CO_2$ emissions indicates a four per cent reduction of air traffic's impact in 2050 emerging from the high scenario.

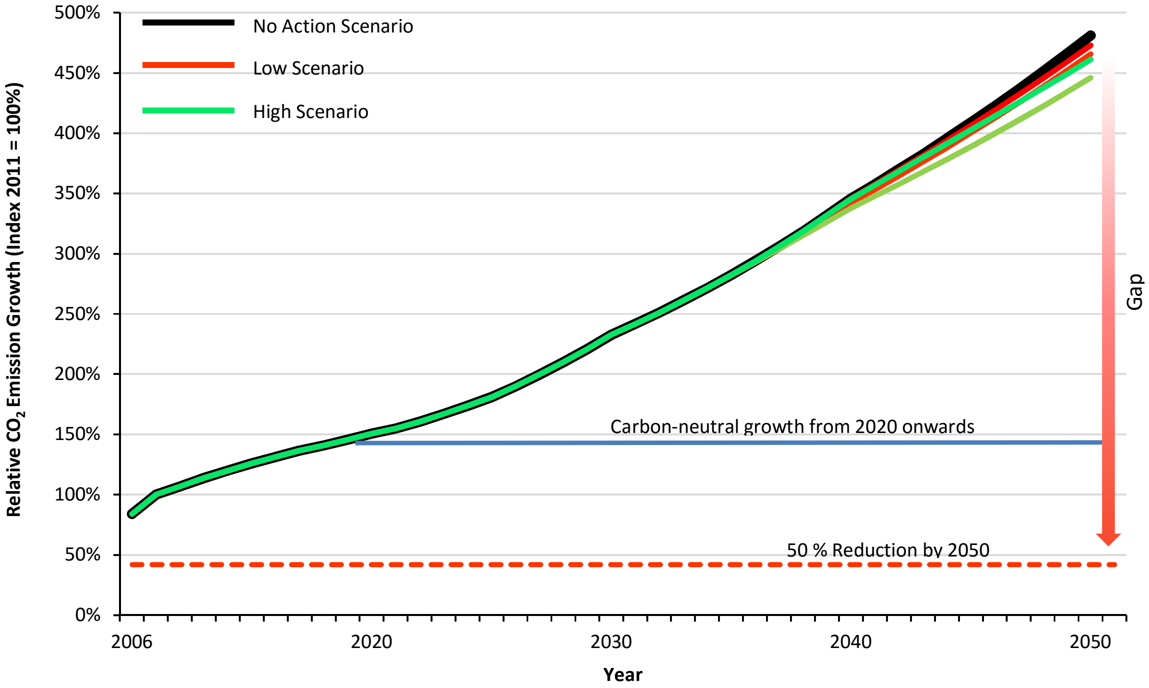

Figure 17 $CO_2$ development (only combustion) scenarios of a N+2 generation aircraft of seat category 401-600 in 2035 and 2040

Considering all modelled integrations of a sole aircraft into the world fleet, the introduction of a N+2 generation aircraft features the lowest potential for reducing $CO_2$ emissions (Worst-case scenario).

### *4.2.4 Scenario N+1 and N+2 Generation Aircraft*

Through the successively integration of two new aircraft into the world fleet higher reduced global $CO_2$ emission developments until 2050 are possible. The scenarios of the lowest and highest improvement in $CO_2$ growth of a two-step entry regarding a N+1 and N+2 generation aircraft are modelled.

The future generic aircraft of seat category 101-210 in 2025 effects an improvement of emitted $CO_2$ of five per cent in 2050. An introduction of a N+2 generation aircraft of seat category 401-600 in 2040 yields a two per cent reduction of $CO_2$ in 2050.

Figure 18 presents a minimal reduction of $CO_2$ emissions of seven per cent in 2050 if the two aircraft are introduced. This enlargement of the world fleet has no more significant reducing effect on the $CO_2$ emission development. Through the integration of a generic aircraft into the world fleet in 2040, an increase in global reduction of additional two per cent is achieved, compared to the scenario of a sole N+1 generation aircraft of seat category 101-210 in 2025. However, the optimistic assessed potentials for $CO_2$ reduction of these two aircraft yield a reduced overall $CO_2$ growth by 18 % in 2050.

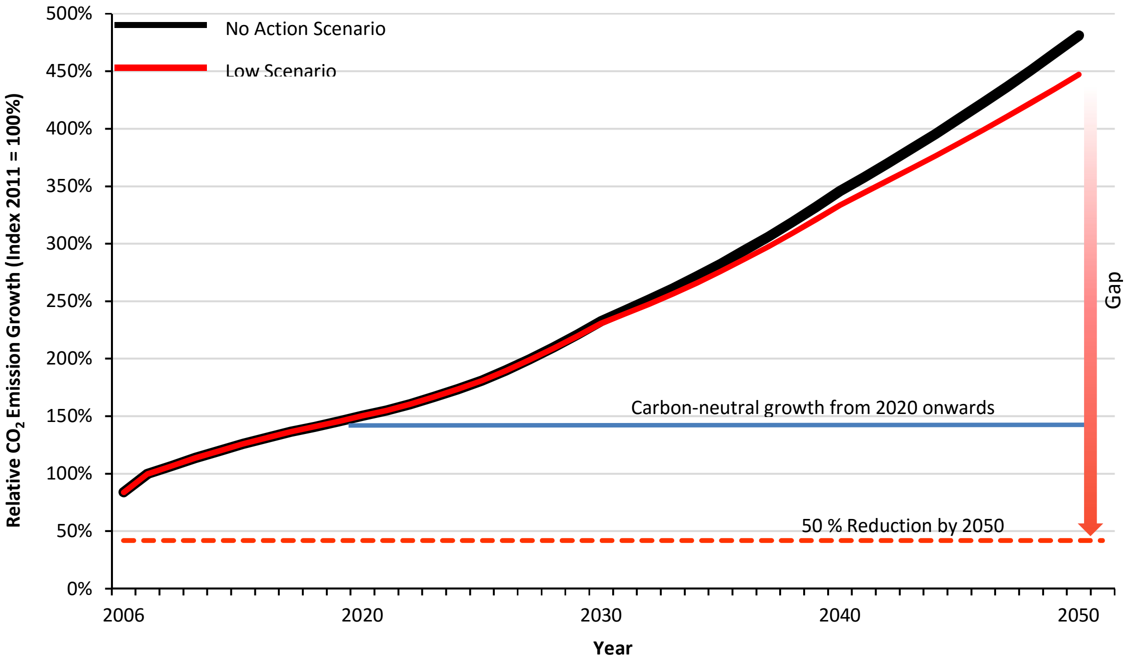

Figure 18 $CO_2$ development (only combustion) scenario of a N+1 and N+2 generation aircraft (seat categories 101-210 and 401-600)

A new aircraft with 211-400 seats in 2030 achieves a reduction in emitted $CO_2$ by 17 % until 2050. A N+2 generation aircraft of seat category 401-600 in 2035 yields a scenario, in which the global $CO_2$ emissions are reduced by seven per cent in 2050.

Figure 19 provides this scenario with an almost 25 % reduction of air traffic's carbon footprint in 2050. It results from the integration of these two aircraft due to their high percentage CO2 emission minimisation in 2050. It is the best-case scenario due to the highest achievable CO2 reduction potential, remarkable already in 2033.

The same potential has an aircraft in seat category 211-400 if it is introduced in 2025, although it has an optimistic potential of 55 %. Together with the generic aircraft of seat category 401-600, a minimisation in CO2 emissions on global level of 24 % is possible.

Considering the 101-210 seat category aircraft, it shows also high potential for a significant reduction in emitted CO2 (15 % global CO2 reduction in 2050). Its introduction in 2030, with a ten years later aircraft of highest seat category, achieves an overall CO2 improvement of 22 % in 2050.

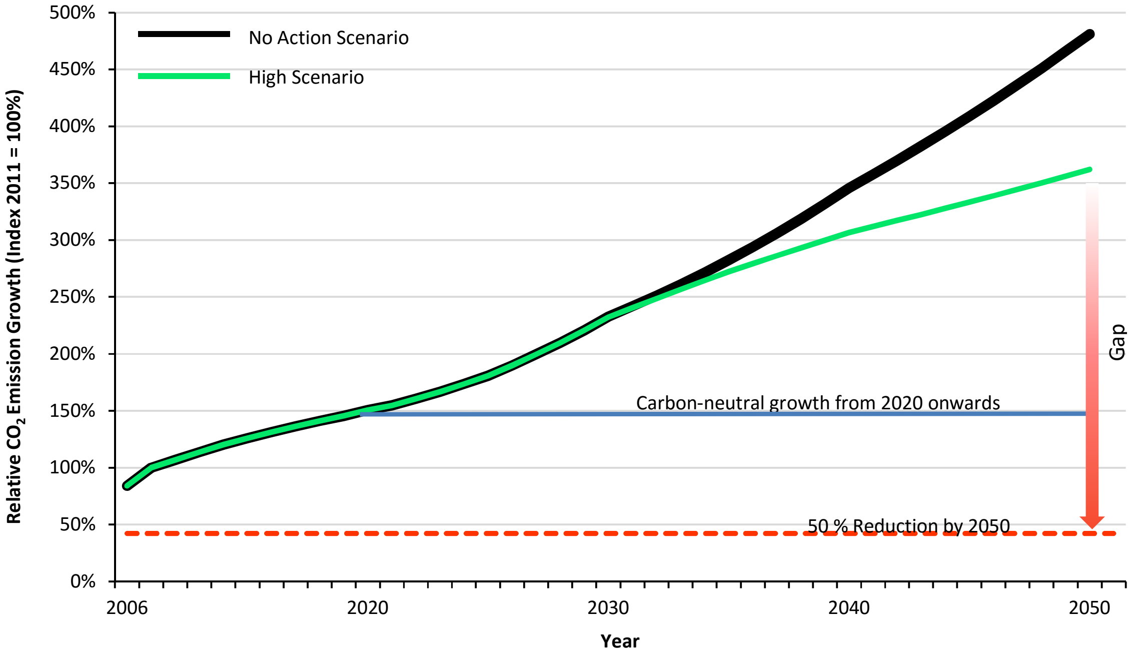

Figure 19 $CO_2$ development (only combustion) scenario of a N+1 and N+2 generation aircraft (seat categories 211-400 and 401-600)

As the red arrow within all diagrams indicates, further efforts are necessary in order to close the gap to the IATA emission reduction goals. The next scenarios include aircraft powered with alternative fuels and their potential for additional reduction of overall carbon dioxide emissions.

### 4.2.5 *Scenario Aircraft powered with Liquefied Natural Gas*

The future aircraft, which hosts technologies like the open rotor and the strut-braced wing as well as is powered by LNG, possibly enters service in 2030.

The fuel function coefficients of this specific aircraft have changed, which already contains the fuel efficiency. Thus, just the input for the two variables entry into market and ramp-up time is provided. The size of a 101-210-seater, the aircraft affects an 18 % improvement of $CO_2$ emissions in 2050 seen by Figure 20.

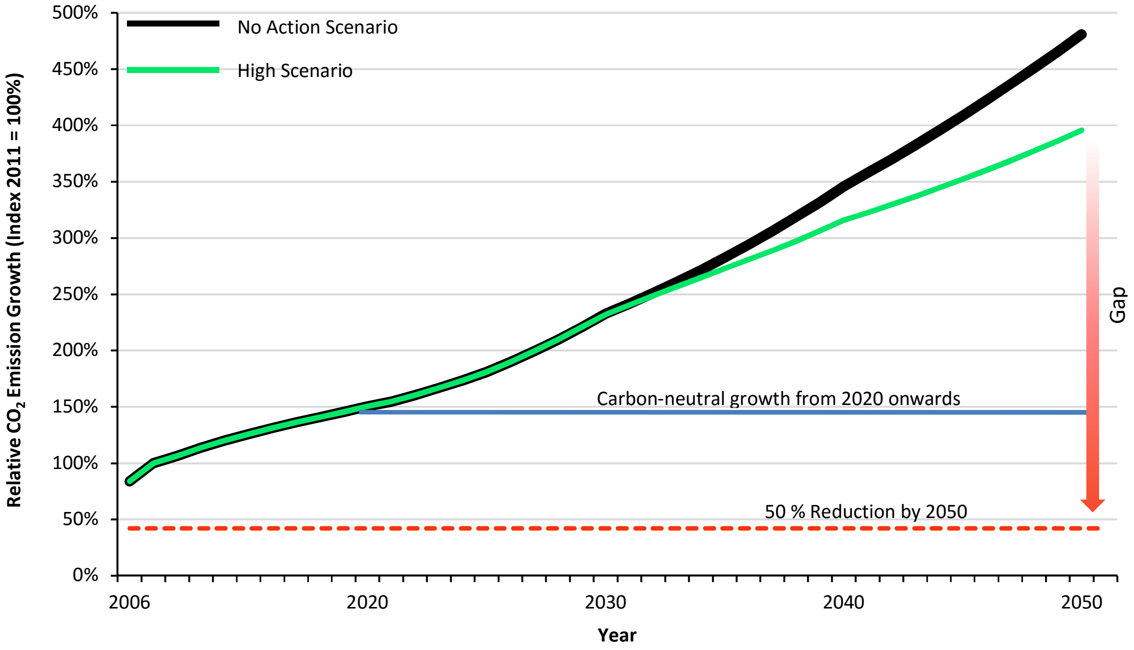

Figure 20 $CO_2$ development (only combustion) scenario of an aircraft powered with LNG in 2030

Consequently, the 18 % $CO_2$ improvement of this specific aircraft and the N+2 generation aircraft in 2035 indicates the same reduction potential as the best-case scenario. Their entries into service in 2030 and in 2035 yield an overall reduction in emitted $CO_2$ by 25 % until 2050.

LNG indicates a lower life-cycle emission EI than Jet A-1. Therefore, the reduction potential of the shown LNG aircraft concerning life-cycle $CO_2$ emissions is additional studied.

The LNG well-to-tank emission factor of 12 g/MJ features the $CO_2$ emissions occurred during the production and delivery and is added to the emission factor of the fuel combustion (see Section 3.2). Accordingly, the multiplication with the energy density of LNG results in an EI of 3.33 (for comparison, the EI, exclusive well-to-tank emissions, amounts 2.74).

As reported by a study of the Federal Ministry of Traffic and Digital Infrastructure, the well-to-tank emission factor of 14.5 g/MJ added to the emission factor from the combustion of 73.6 g/MJ supplies the life-cycle emission factor for kerosene (Zech et al., 2014). Multiplied with its energy density of 0.043 MJ/g, an EI of 3.84 is calculated (an EI of 3.16 is achieved for emissions emerged from the fuel combustion) (Paschotta, 2015).

Figure 21 clarifies that in spite of the lower LNG life-cycle EI compared to that of kerosene, no additional reduction of $CO_2$ emissions until 2050 is achieved. Equal to the result of reduced $CO_2$ growth concluded by the consideration of combustion emissions, this scenario reveals an improvement of 18 %.

This is explainable on the one hand by the less significant difference between the well-to-tank emissions of LNG and kerosene. On the other hand, LNG indicates a 13 % lower life-cycle EI compared to the life-cycle EI of kerosene. It is similar to the percentage difference of the EI's exclusive the well-to-tank emissions (less than 13 %).

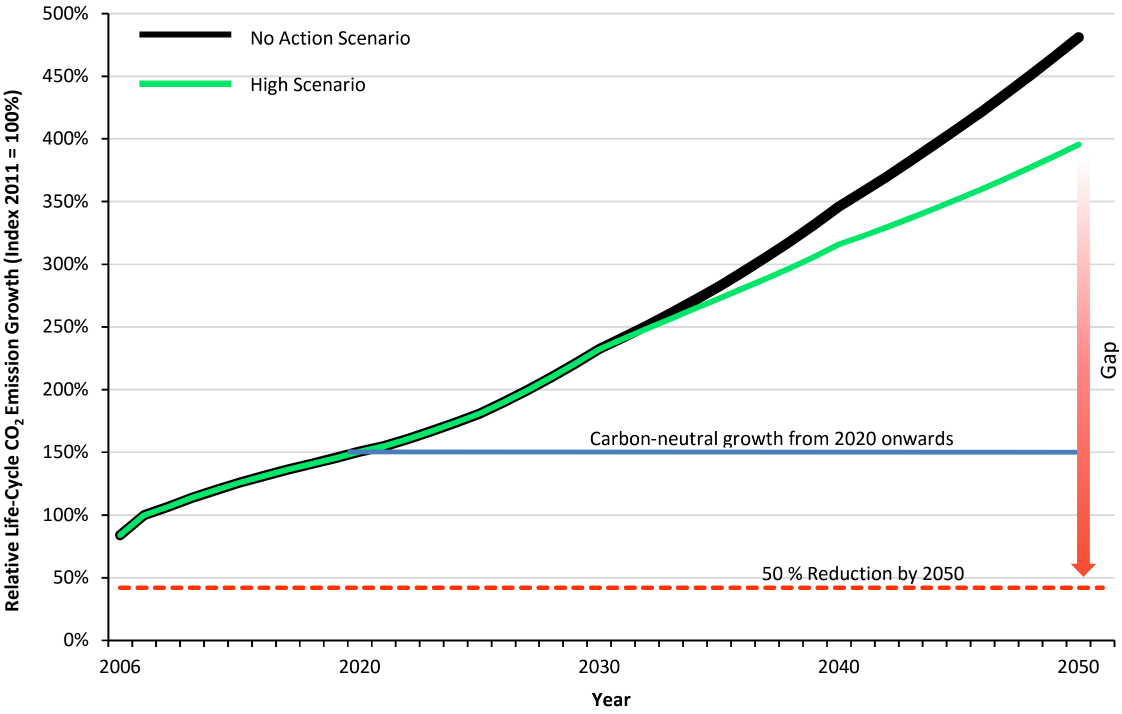

Figure 21 Life-cycle $CO_2$ development scenario of an aircraft powered with LNG in 2030

### *4.2.6 Scenarios Biofuel Blend*

Biofuels are expected to close the gap to the IATA emission reduction goals and seem to be one of the solutions for carbon-neutral growth. Since their emissions from the fuel combustion are offset through the absorption of $CO_2$ by the plants, only production caused emissions remain (well-to-tank emissions). In order to depict the $CO_2$ growth on world fleet level until 2050 if considering the remaining production emissions, a life-cycle $CO_2$ calculation for different biofuel scenarios is carried out.

Therefore, it is necessary to research the EI of biomass-based fuel. Since the two options for biofuel, HEFA and BTL are approved as drop-in fuel in today's aircraft, the EI's of both types are averaged to receive an EI of biofuels in general (ATAG, 2010). Well-to tank emissions of 41 g/MJ result from the HEFA-production, and by multiplication with the energy density of kerosene (as biofuels own the same specifications), an EI of 1.77 is calculated. It is approximately 50 % lower than the life-cycle emission index of kerosene.

Emissions in the amount of 49 g/MJ accrue during the BTL-production and delivery (Zech et al., 2014). Accordingly, an EI of 2.11 emerges if the emission factor is multiplied with the energy density. It corresponds to a reduction by more than 50 %, compared to the life-cycle EI of fossil kerosene. The resulting averaged EI of 1.94 is used for further calculations.

The following forecast scenario describes the successively increase in the share of biofuel over time. In order to calculate the influence of biofuel-kerosene blends on the global $CO_2$ emission development, new and active aircraft are assumed to use the fuel blend. As the defined best-case scenario states which maximum potential for $CO_2$ reduction is possible by introducing new technologies, kerosene is substituted by biofuel-kerosene blends in addition. The starting point of the calculation is the kerosene consumption in kilogrammes until 2050, determined within the best-case scenario (see Subsection 4.2.4). Subsequently, the share of biofuel in the fuel blend is assumed.

Today's sustainable feedstocks are not available in commercial-scale quantities, although a fuel blend with 50 % biofuel is currently certified (ATAG, 2010). Therefore, a fuel blend with 20 % biofuel powers the world fleet from 2020 onwards. As it is stated within the ATAG's brochure, in 2025 the world fleet operates with an enhanced share of biofuel by 25 % in the fuel blend. By increasing it to 30 % in 2030, they emphasise that sufficient productions of sustainable feedstocks lead to meet these targets. Through the assumption of a linear course, a share of biofuel of 50 % is expected in 2050.

Figure 22 supplies the overall $CO_2$ development until 2050 if the realisation of these industry's goals is assumed (green graph). The steps in the diagram indicate the incremental increase of the biofuel share from 2020 until 2050.

This scenario of applying biofuel-kerosene blends including two new aircraft types in 2030 and 2035 (best-case scenario) results in an additional potential of almost 25 % for $CO_2$ improvement towards the best-case technology scenario. In comparison with the no action scenario, a maximum reduction of global emitted $CO_2$ by 43 % is possible.

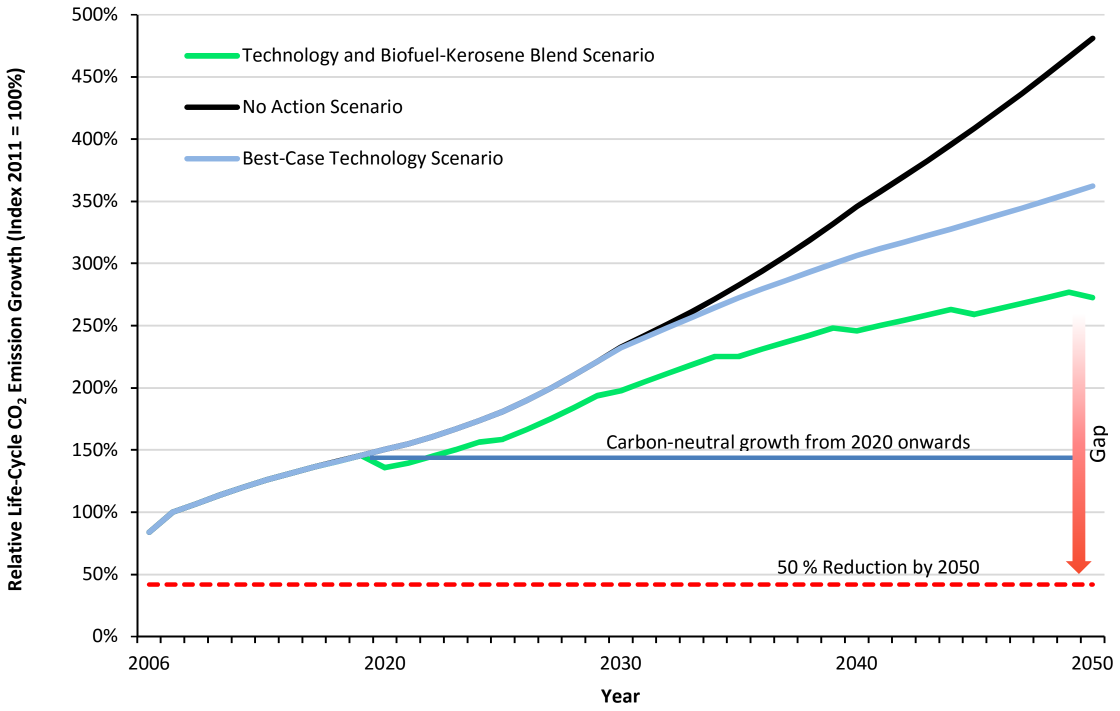

Figure 22 Life-cycle $CO_2$ development of the best-case scenario including biofuel scenario

However, in order to achieve carbon-neutral growth from 2020 onwards, the share of biofuel needs to be increased.

A backcast scenario identifies the conditions needed to obtain the carbon-neutral growth. Starting with the continuous enhancement of the biofuel percentage of the blend, the fuel should consist of 100 % biofuel from 2040 onwards to gain carbon-neutral growth.

## 4.3 Assessment of the Global $CO_2$ Reduction Potential until 2050

The IATA's aspirational goals define carbon-neutral growth from 2020 onwards and the reduction of $CO_2$ emissions from 2005 by 50 % in 2050. In order to achieve this high-level emission reduction goals, scenarios of future low-emission aircraft configurations were analysed, which lead to different $CO_2$ growth scenarios.

Table 13 provides an overview of the considered future generic aircraft scenarios, their potential for reducing $CO_2$ emissions and the resulting gap for achieving the goal respecting the reduction by 50 % in 2050. Within the table, the aircraft scenarios are briefly described once more by stating the seat category, the year of entry into service and the alternative fuel type. The scenarios' ranges of the $CO_2$ reduction potential are indicated by the low and high scenario and show their effect on the $CO_2$ development until 2050 relative to the no action scenario.

The gap to the 50 % reduction goal is calculated via the relative $CO_2$ values in 2005 and 2050 (the relative values to 2011). The goal is to reduce the $CO_2$ emissions from 2005 by half in 2050. The read $CO_2$ emissions from the diagram lead to the improvement level to be obtained. The increased $CO_2$ emissions in 2050 should be reduced by 91 % to achieve the halved $CO_2$ emissions from 2005. Accordingly, as the aircraft scenarios feature potentials for reducing $CO_2$ emissions in 2050, the remaining gaps of the low and high scenario are shown in Table 13. Figure 23 additionally clarifies the level of the improvement. The $CO_2$ reduction potential and the resulting gap result in the improvement level of 91 % in order to achieve the halved $CO_2$ emissions in 2050.

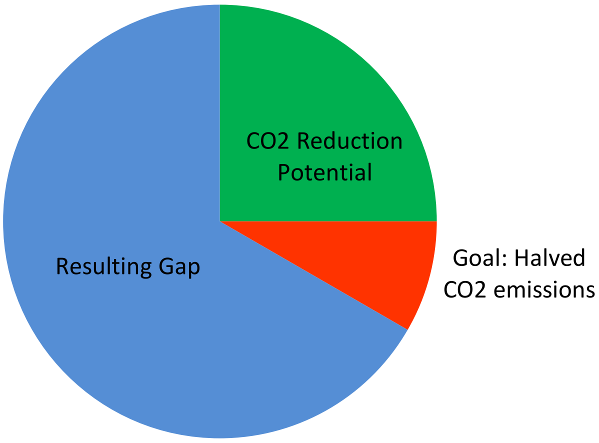

Figure 23 Approach for calculating the remaining gap (own diagram)

Table 13 Reduction of $CO_2$ emissions (only combustion) in 2050 relative to the no action scenario

| **Future Generic Aircraft Scenario** | **Low Scenario** | **Gap to the 50 % reduction goal** | **High Scenario** | **Gap to the 50 % reduction goal** |
|---|---|---|---|---|
| **N+1 Generation Aircraft** | | | | |
| 101-210, 2025 | 5 % | 86 % | 14 % | 77 % |
| 101-210, 2030 | 6 % | 85 % | 15 % | 76 % |
| 101-210, 2030, powered with LNG | | | 18 % | 73 % |
| 211-400, 2025 | 7 % | 84 % | 17 % | 74 % |
| 211-400, 2030 | 6 % | 85 % | 17 % | 74 % |
| **N+2 Generation Aircraft** | | | | |
| 401-600, 2035 | 3 % | 88 % | 7 % | 84 % |
| 401-600, 2040 (worst-case scenario) | 2 % | 89 % | 4 % | 87 % |
| **N+1 and N+2 Generation Aircraft** | | | | |
| 101-210, 2025<br>401-600, 2040 | 7 % | 84 % | 18 % | 73 % |
| Best-Case Scenario<br>211-400, 2030<br>401-600, 2035 | 9 % | 82 % | 25 % | 66 % |
| 101-210, 2030, powered with LNG<br>401-600, 2035 | 21 % | 70 % | 25 % | 66 % |

The red arrow within the above presented diagrams already indicates the gap between the determined $CO_2$ development and the IATA emission reduction goals. Additionally, Table 13 reveals the remaining improvement level in order to achieve the 50 % reduction goal.

As these different future aircraft scenarios clarify, new aircraft technologies and alternative fuel types achieve an approximation to the emission reduction goals. However, a gap still remains until the goal of the 50 % reduction is achieved in 2050.

Despite high technology potentials for lower emissions, reduced $CO_2$ growth of the world fleet is only possible on small scale. One main cause is that the world fleet still comprises a mixture of old and new aircraft in 2050. As all deliveries are covered by the new introduced aircraft of a specific seat category after seven years, its predecessor is successively substituted. However, dependent on the retirement timeframe and fleet renewal of an airline, further significant reduction is probably apparent after 2050.

An important factor is the timeframe for the entry into service. Since first upgrades (A320neo or B737max) are currently in production (thus, technologically frozen), demand for new aircraft is nearly fully saturated due to fixed orders until 2025. Hence, the replacement of current aircraft with total new designs is feasible beyond 2020. Interestingly, an aircraft of seat category 101-210, which enters service in 2030, contributes to no further reduction of emitted $CO_2$ than a new 101-210-seater in 2025, despite greater individual potential. Additionally, if a new N+1 aircraft is introduced from 2030 onwards, $CO_2$ emission reduction starts to be remarkable in 2037 (and onward) and achieves no more significant relative change in 2050. This phenomenon is explainable by the ramp-up time. After seven years, the production is ramped-up and only the new aircraft of a specific seat category is delivered.

Notably, a new integrated aircraft of seat category 211-400 has a slightly more improving effect on the global $CO_2$ development in 2050 than a new aircraft of lower seat category. Although both enter service in 2030 and have the same potential for reducing fuel burn of up to 70 %, a new aircraft of seat category 211-400 can reduce the $CO_2$ emissions by additional two per cent. This can be explained through the forecasted smaller fleet of aircraft of seat category 211-400 compared to that of seat category 101-210. In spite of larger ranges but less aircraft flight cycles[19], fuel-efficient aircraft of seat category 211-400 have more significant influence on the reduction of emitted $CO_2$.

New aircraft model of the very large seat category likely have their market entry from 2030 onwards. A slower shift of the $CO_2$ growth is apparent due to the late entry into service and the small prospective fleet size of this aircraft category.

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[19] One flight cycle of an aircraft is defined as one take-off and one landing.

Currently, the focus lies on more fuel-efficient medium-and large-sized aircraft (aircraft of seat category lower than 401-600). As the A380 just entered service, time is needed to research more fuel-efficient technological possibilities for aircraft of seat category 401-600. The largest category shows the smallest improvement, since only a few very large aircraft exist and they are introduced beyond 2030. In the scenario of introducing a N+2 generation aircraft in 2040, a greater influence on global $CO_2$ reduction would rather be conceivable from 2050 onwards. Reasons for this effect are its optimistic potential of 65 % and the retirement timeframe of the old, less efficient aircraft, which then are substituted.

Further potential to achieve the 50 % reduction goal and to close the gap is offered by the two-step entry of new aircraft (best-case scenario). An aircraft of large seat category in 2030 and of very large seat category in 2035 highly reduce the emitted $CO_2$ from the world fleet. This indicates to be the highest potential for lower $CO_2$ emissions through technological measures (by up to 25 %).

The use of an alternative energy source like LNG, applied on a future aircraft of seat category 101-210 indicates additional potential in order to close the gap (compared to a new aircraft of the same category, powered by kerosene). Optimistically introduced in 2030, it substitutes the fleet of seat category 101-210. Thus, combined with a N+2 generation aircraft in 2035, it provides the same potential as the best-case scenario.

The application of biofuel on the world fleet is expected to significantly reduce air traffic's $CO_2$ footprint and to achieve the IATA emission reduction goal. It provides further potential for lowering $CO_2$ emissions; however, on life-cycle $CO_2$ emission level (Table 14). Especially concerning the achievement of carbon-neutral growth is possible by means of biofuels, as the backcast scenario shows. If the carbon-neutral growth is achieved (which correspond to a 63 % reduction of global emitted $CO_2$ on life-cycle level), a gap to the 50 % $CO_2$ reduction goal still remains. An improvement of 28 % needs to be achieved.

Table 14 Reduction of global life-cycle $CO_2$ emissions in 2050 relative to the no action scenario

| | **Low Scenario** | **Gap to the 50 % reduction goal** | **High Scenario** | **Gap to the 50 % reduction goal** |
|---|---|---|---|---|
| **N+1 and N+2 Generation Aircraft** | | | | |
| 101-210, 2030, powered with LNG<br>401-600, 2035 | 21 % | 70 % | 25 % | 66 % |
| 211-400, 2030<br>401-600, 2035<br>Biofuel-Kerosene Blend on world fleet | 43 % | 48 % | 63 % (according to the backcast scenario) | 28 % |

# 5 CONCLUSION AND OUTLOOK

## 5.1 Conclusion

A study has been conducted to assess the influence of technological measures and alternative fuel types on world aircraft fleet $CO_2$ emissions. Under technology scenarios, i.e. different generic aircraft configurations, scenarios of future $CO_2$ development until 2050 have been generated by means of an existing forecast model.

As the thesis presents, radical aircraft technologies such as open rotor, laminar flow control or ceramic matrix composites indicate high potential for $CO_2$ emission improvement. The introduction of two low-emission aircraft indicates to reduce the $CO_2$ growth by up to 25 % in 2050 (best-case scenario). Additionally, alternative fuels such as LNG and biofuel as substitutes for Jet A-1 enable a larger step towards life-cycle $CO_2$ reduction and carbon-neutral growth - but only in combination with revolutionary fuel-efficient future aircraft technologies. A new aircraft of seat category 101-210 powered by LNG, together with a more fuel-efficient aircraft of very large seat category achieve also a reduced $CO_2$ development of 25 % through 2050. The application of biofuel on the world fleet leads to an improvement of the life-cycle $CO_2$ emissions of up to 63 % until 2050.

A corresponding gap assessment between reduced $CO_2$ emission developments and the IATA emission reduction goals showed the reducing effect of aviation technologies and alternative fuel types until 2050. However, gaps need to be filled in order to achieve the IATA goals. An integrated high fuel-efficient new aircraft of seat category 211-400 in 2030 indicates a remaining gap of 74 % and also the best-case scenario still leaves a gap of 66 %.

Finally, the results verified the hypothesis and lead to the conclusion that technological changes and alternative fuel on future aircraft contribute to the achievement of long-term $CO_2$ emission reduction goals on world fleet level.

The best-case scenario for $CO_2$ reduction is achieved through the implementation of an aircraft of seat category 211-400 in 2030 and of very large seat category in 2035. An entry into service of an aircraft with 211-400 seats would also fit in the prospected introduction of an above 300 seats aircraft. Due to a gap in seat category over 300 seats, analysed by Flightglobal, the next new aircraft type could fill in the space between the A321 and the B787-8 (Evans, 2015).

As the thesis demonstrates, two new aircraft in seat category 101-210 and seat category 211-400 have the same potential of up to 70 %. The latter achieves a slight more reducing effect on the $CO_2$ development; thus, the assessed potential of a new aircraft in seat category 101-210 should be even more increased.

Generally, more radical technological changes are crucial to highly reduce $CO_2$ emissions and to close the gap. The overall fleet efficiency through this continuous replacement of old aircraft by more efficient ones should be increased to significantly lower emitted $CO_2$. If future aircraft are introduced from 2030 onwards, a complete substitution of the world fleet is not feasible until 2050. Hence, it is of great importance to deviate from slow replacement but to introduce new low-emissions aircraft at the earliest date. Such fleet renewal can only be facilitated if research is early enough promoted to include these technologies into the new aircraft design.

Nevertheless, the long life-cycles and the development periods of aircraft set focus to further measures for limiting $CO_2$ emissions.

Incremental changes can be added to existing aircraft by technology retrofits. As results indicate, retrofits offer additional potential on already operating aircraft without requiring the development of new aircraft configurations. Higher world fleet fuel efficiency is expected through updates on existing serial production types. The possibility, to modify large existent fleets by installing an entirely more efficient engine or changes to more advanced materials, leads to considerable reduction of emitted $CO_2$. The geared turbofan for the next generation aircraft A320neo, especially, promises a 15 % higher fuel efficiency over the current engine CFM56-5B (ATAG, 2010). An engine update should also be considered for the very large aircraft categories, where a re-engined aircraft would have less impact on the environment.

As the aviation sector has already agreed on a coordinated approach, more action is needed in order to bridge the gap and to achieve a radical reduced carbon footprint. It is necessary to complete the strategy by further measures concerning infrastructure and operation. Infrastructure activities include, for instance, changes in ATM systems, which are required to manage the continuously increasing traffic density. Their limitations, resulting, for example, in inefficient routings and holdings[20], and thus in more fuel consumption, should be addressed. Operational measures for $CO_2$ reductions could feature increasing load factors by transporting more passenger or freight (Intergovernmental Panel on Climate Change, 1999). If technologies including alternative fuel, infrastructure or operational measures indicate to be not sufficient to realise the IATA emission reduction goals, economic measures need to offset the remaining gap. More stringent regulations concerning aircraft engine emissions, environmental taxes and charges as well as support for research programs could reduce emissions further (Intergovernmental Panel on Climate Change, 1999).

### 5.2 Critical Review

If future aircraft technologies are assessed, critical points should also be taken into account. New technologies are subject to strict guidelines and regulations. They must be reliable and certified in order to get installed on next generation aircraft configurations. Manufacturers develop new products, partly revolutionary devices, requiring very long lead times and investments. A high uncertainty is allocated to the manufacturers, if they are willing to implement these radical, high-risk design changes. They have to assure the reliability of the technology and thus minimise the risks. Besides, it is the airline's choice to invest large sums in completely new aircraft types, especially if the performance is reduced.

Importantly, some new technologies are most efficient in specific aircraft types; thus, their potential for fuel burn reduction is dependent on route length. This should be considered as it is an influencing factor for the $CO_2$ emission development.

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[20] Holdings describe "aircraft flying in a fixed pattern waiting for permission to land" (Intergovernmental Panel on Climate Change, 1999).

Due to soon existing fuel-efficient models fostered by high orders, an introduction of a more fuel-efficient new aircraft could possibly be realised beyond 2020. However, retrofit technologies also need to be critically examined. The manufacturers offer them if the airline's investment is offset through the reduced costs from savings in fuel burn. As a retrofit device is designed and certified for specific aircraft models, a service is commercially viable if these models feature large world fleets.

It is important to note that future technologies could interact if they are installed, which leads to a decrease of the overall potential. Through the summation of the single technology potentials, this risk is disregard.

Alternative fuel types are shown to have high potentials; however, the availability is still uncertain. Especially, in case of biofuels, the timeframe for commercial-scale quantities in order to replace kerosene is unclear. A consideration of $CO_2$ emissions caused by production is important, although the IATA emission reduction goals are referred to the emissions from the combustion. However, some alternative fuel types, for instance Hydrogen, are not beneficial due to production-caused emissions.

Concerning the applied forecast model, uncertainties result from the static assumptions of the retirement based on the age of an aircraft and the number of fixed orders approximately until 2025. As the validity of these basic data; thus, the validity of Fast Forward is given, results arise under the awareness of these assumptions. Moreover, some future technologies cause a variation of the aircraft's operation, which is not covered by Fast Forward - for instance, a lower airspeed would indicate less flown kilometres during a year.

In addition, the presented findings emerged if the FESG CAEP/9 most likely passenger growth of 4.6 % is underlay. If another, perhaps more pessimistic passenger growth of 3.9% is assumed, the growth in $CO_2$ emissions might decrease.

### 5.3 Future Research

The technological innovations should be further examined for interaction and mutual exclusion of their potentials to improve the fuel consumption. It is important to additionally study the infrastructural, operational and economic measures and their potential to significantly lower $CO_2$ emissions and close the forecasted gap. These potentials could be quantitative assessed in order to determine the necessity for more improving potential.

Due to uncertainties concerning the application of radical but highly promising technologies and manufacturer's choice to invest, a statistical assessment could consider the probabilities. Possibilities are seen in an analysis of the TRL. The scale could then indicate the probability of an installation of the technology on future aircraft until 2050. On the other hand, knowing the opinions of the airlines and manufacturers by means of interviews could capture the problem on a more reliable level.

An extension of the study to 2100 is valuable in order to estimate the potential for reducing $CO_2$ of new aircraft over a longer period. It could be interesting to determine to what extent the $CO_2$ growth caused by the global aircraft fleet is reduced. Could a possibly higher lowered $CO_2$ level be expected until 2100 or is the percentage improvement similar to the 2050 scenarios? Concerning the latter, the question of a generalization of the thesis' results to an enlarged time scope (until 2100) could be a research aspect.

If Fast Forward is adjusted within followed projects to determine $CO_2$ development scenarios, a comparison with the results derived from this thesis could be interesting. A changed model could be developed based on the fuel costs. Old aircraft are then retired if a new more efficient one is introduced, regardless of the age of the older aircraft. This rather economic approach concludes the fleet composition by estimating the costs of keeping old aircraft or purchasing the more efficient one.

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# APPENDICES

## Appendix A

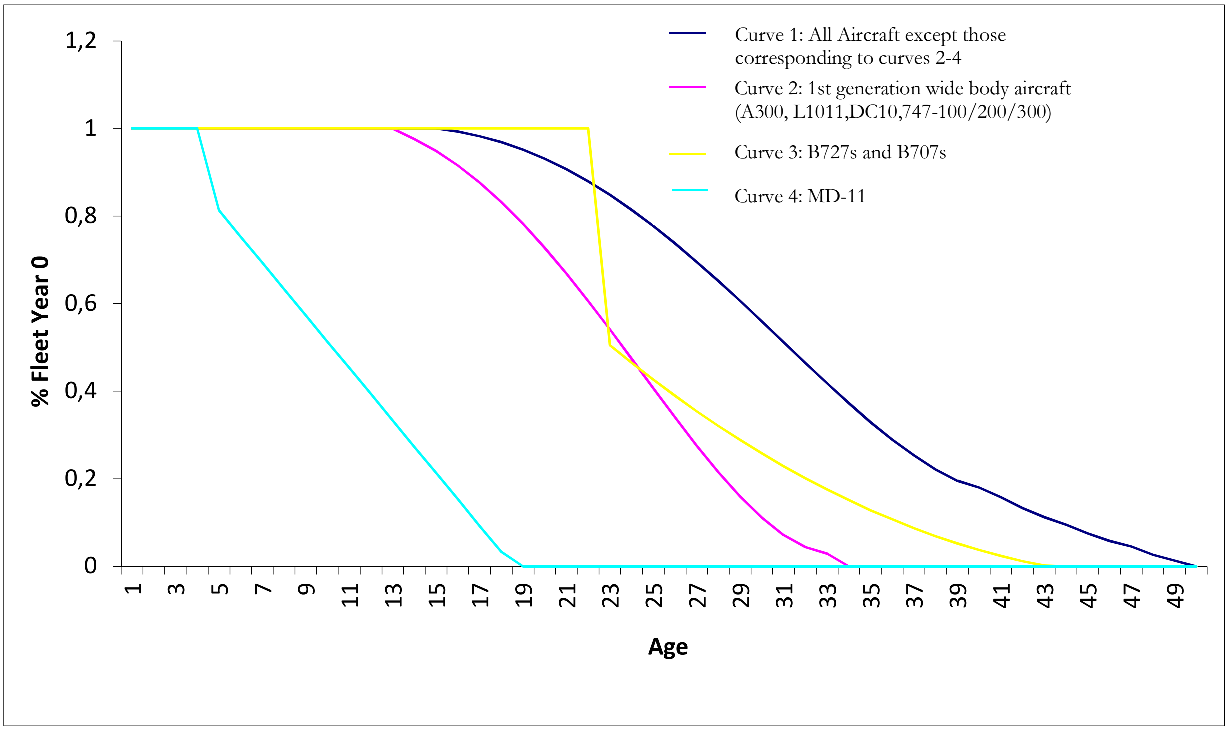

Figure 24 Retirement curves (extracted from Fast Forward)

## Appendix B

| Revenue Passenger-Kilometres [billion] | 2005 | 2010 | 2020 | 2030 | 2040 | 2050 |
|---|---|---|---|---|---|---|
| Unlimited Skies (ULS) | 4091 | 4621 | 6456 | 10127 | 14705 | 21185 |
| Regulatory Push & Pull (RPP) | 4091 | 4193 | 5284 | 8029 | 10791 | 14636 |
| Fractured World (FW) | 4091 | 3690 | 4157 | 5171 | 6001 | 6990 |
| Down to Earth (DtE) | 4091 | 3618 | 3920 | 3842 | 4038 | 4164 |

Table 15 Revenue Passenger-Kilometres scenario from CONSAVE 2050 (extended from Berghof et al., 2005)

| Revenue Passenger-Kilometres [billions] | 2010 | 2020 | 2030 | 2040 | 2050 |
|---|---|---|---|---|---|
| High Scenario (Optimistic) | 5051 | 9046 | 15223 | 23800 | 35187 |
| Most Likely Scenario (Central Forecast) | 5051 | 8453 | 13157 | 19462 | 27794 |
| Low Scenario (Pessimistic) | 5051 | 7907 | 11421 | 15987 | 21964 |

Table 16 Revenue Passenger-Kilometres scenario from FESG CAEP/9 (extended from FESG CAEP/9, 2012)

| | 2010 | 2014 | 2020 | 2030 | 2034 |
|---|---|---|---|---|---|
| Revenue passenger-kilometres [billions] | 5051 | 6.200 | 8.261 | 13.329 | 16.000 |

Table 17 Revenue Passenger-Kilometres scenario from Boeing (extended from Boeing, 2015)

| | 2010 | 2014 | 2020 | 2030 | 2034 |
|---|---|---|---|---|---|
| Revenue passenger-kilometres [billions] | 5051 | 6.200 | 8.120 | 12732,059 | 15241 |

Table 18 Revenue Passenger-Kilometres scenario from Airbus (extended from Airbus, 2015)

| | 1970 | 1975 | 1980 | 1985 | 1990 | 1995 | 2000 | 2010 |
|---|---|---|---|---|---|---|---|---|
| Revenue passenger-kilometres [billions] | 551 | 836 | 1.250 | 1573 | 2182 | 2567 | 3308 | 5051 |

Table 19 Historic Revenue Passenger-Kilometres (Berghof et al., 2005)

## Appendix C

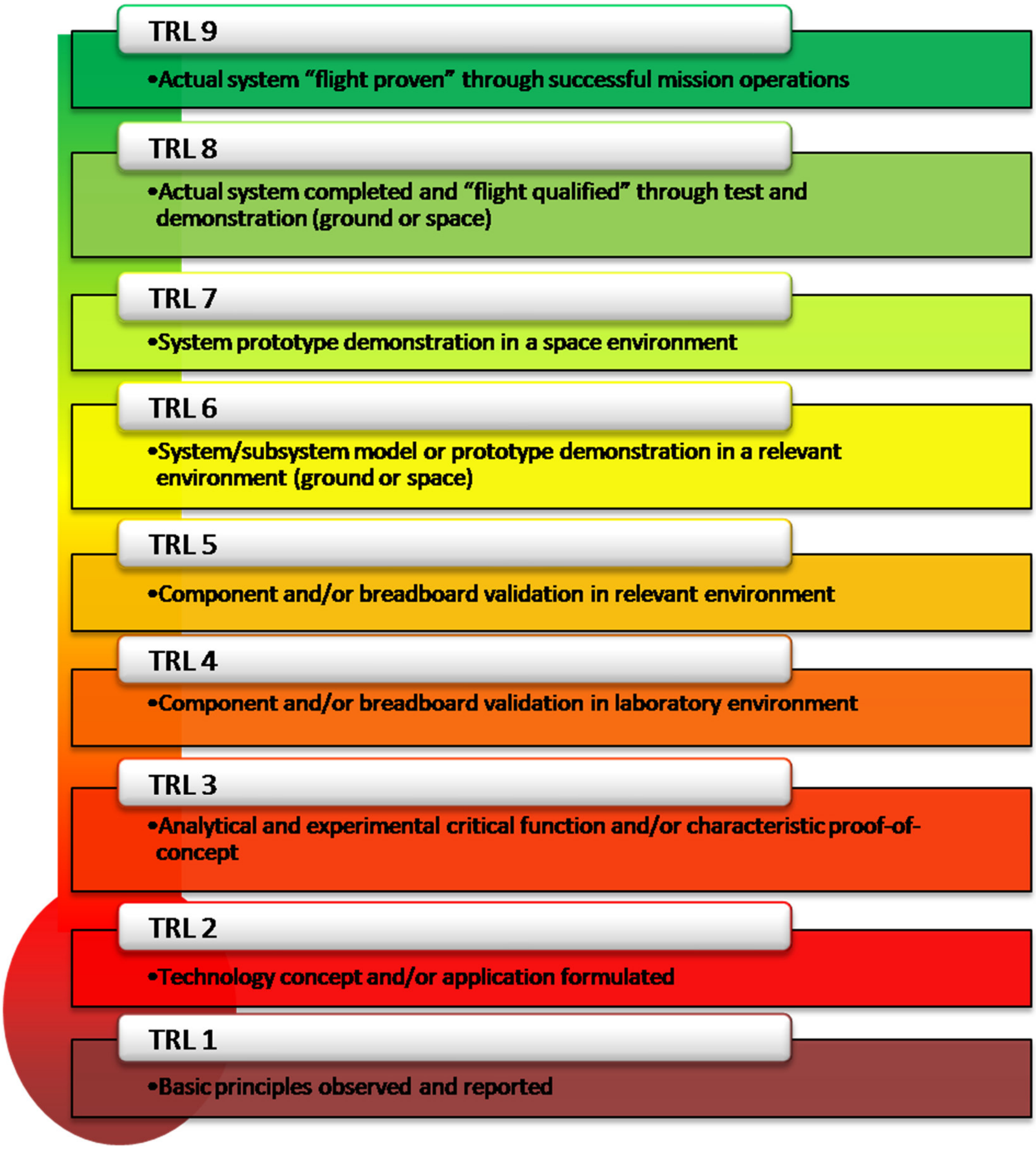

Figure 25 TRL scale (NASA, 2012)

## Appendix D

Table 20 Technology matrix (own compilation)

<table>
<tr><th>Technology Domains</th><th colspan="2">IFAR Members</th><th>Technology</th><th>Availability Timeframe</th><th>Reference Aircraft</th><th>Retrofit</th><th>Future Generic Aircraft</th><th>Future Generic Aircraft Entry into Service</th><th>Theoretical Fuel Burn Improvement</th></tr>
<tr><td rowspan="4">Propulsion</td><td rowspan="4">FOI, Sweden: New propulsion concepts (66)<br>KTN, UK: Integrated propulsion systems (67)<br>CAE, China: Further reduction of emissions (72)</td><td rowspan="2">INCAS, Romania<br>DLR, Germany<br>KARI, Korea<br>NLR, Netherlands<br>NRC, Canada<br>VKI, Belgium<br>(59)</td><td rowspan="2">Engine Active Flow Control</td><td>After 2020</td><td>2005 in-service aircraft (58)</td><td>No</td><td>Aircraft of seat category 101-210, 211-400, 401-600</td><td>2025<br>2035</td><td>10 to 20% (58)</td></tr>
<tr><td colspan="6">The application of Engine Active Flow Control to internal flow surfaces yields improved operability and lower engine noise. Benefits regarding improved fuel efficiency, lower emissions and lower operating costs are expected (34).<br>For example, Flow Control by Aspiration improves the efficiency of the compressor through the aspiration on blades (41).</td></tr>
<tr><td rowspan="2">BME, Hungary<br>DLR, Germany<br>NLR, Netherlands<br>(59)</td><td rowspan="2">Integrated Airframe-Propulsion Concepts</td><td>2025-2035</td><td>2005 in-service aircraft (58)</td><td>No</td><td>Aircraft of seat category 401-600</td><td>2035</td><td>1 to 3% (58)</td></tr>
<tr><td colspan="6">Concepts, which comprise a group of longer-term technologies such as Boundary Layer Ingesting Inlets, eventuate in significant improvements in fuel burn and noise.<br>The buried, boundary layer ingesting installation decreases the effective velocity at the face of the fan, thus engine efficiencies augment (4, 34).<br>The "Flying wing" design portrays four Rolls Royce engines which are embedded in the upper surface of the wing realizing aerodynamic efficiency and maximum noise shielding (39).</td></tr>
</table>

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | DLR, Germany<br>KARI, Korea<br>NLR, Netherlands<br>VKI, Belgium<br>(59) | Counter-Rotating Fan | After 2025 | 2005 in-service aircraft (58) | No | Aircraft of seat category 101-210, 211-400 | 2030 | 15 to 20% (58) |
| | | | | The rotating Fan in opposite direction employs a lower number of blades, which generate a high mass flow at high effectiveness (15).<br>As part of the VITAL Integrated Project addressing the objective of improvement in fuel burn, the architecture significantly increases the bypass ratio in combination with material and installation advancement (18, 34). | | | | | |
| | | DLR, Germany<br>KARI, Korea<br>NLR, Netherlands<br>VKI, Belgium<br>(59) | Open Rotor (Unducted Fan) | 2025-2030 | A320 current powerplants: CFM 56-5B4 (13, 21) | No | Aircraft of seat category 101-210, 211-400 | 2030 | 20 to 25% (13, 21) |
| | | | | The propeller-driven engine employs two counter-rotating turbines, which are directly coupled to the fan blades. Advanced aerodynamic and material technologies, for instance fan blades made out of composite, allows bypass ratios of 25 and above, lower noise levels and improved propulsive efficiency (4, 9, 34).<br>The "Unducted Fan", as the fan blades are placed outside the nacelle, is efficient at relatively low speeds (at Mach numbers less than 0.8), since the speed is limited by peripheral speed of the rotor blades and speed on the blade tips (13). | | | | | |
| | | JAXA, Japan<br>METU, Turkey<br>NRC, Canada<br>(59)<br>VZLU, Czech Republic (68) | Advanced Engine Combustor | 2020-2025 | 2005 in-service aircraft (58) | No | Aircraft of seat category 101-210, 211-400, 401-600 | 2025<br>2035 | 5 to 10% (58) |
| | | | | The lean-burn Combustor demonstrates benefits regarding enormous reduction in NOx emissions. The application of new materials allows high combustion temperatures which result in higher engine efficiency, however, similarly in higher NOx emissions.<br>Beyond 2020, further research lead to more reduction in NOx emissions, under observance of increasing fuel efficiency (34).<br>Existing Advanced Combustors are the Twin Annular Premixed Swirler (TAPS) generation II, going to be part of the LEAP engine and generation III for the GE9X (43).<br>Characteristic are Ceramic Combustors, which operate more efficient, since ceramic engines are resistant to higher temperatures enabling the combustion of fuel to be more complete. The application of such architecture yields less use of air cooling, less pollution and less fuel consumption as well as increased performance (14). | | | | | |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | VKI, Belgium(59) | Geared Turbofan | Before 2020 | Short-Range Aircraft Current powerplants (9, 21) | No | Aircraft of seat category 101-210, 211-400 | 2025 | 15 to 20% (9, 21) |
| | | | | A gear system connects the fan and the low-pressure compressor and turbine stages. While decoupling the fan section from the low-pressure compressor through gearing, both can operate at their optimal speeds. Thus, higher engine efficiency, lower fuel consumption, gaseous emissions and noise levels are the benefits of the architecture (9).<br>Engine tests for the CSeries and Mitsubishi RJ are currently carried out by Pratt & Whitney, whereas the development of larger engine types will likely require another ten years (4). | | | | | |
| | | NRC, Canada<br>NLR, Netherlands<br>DLR, Germany (59) | New Engine Core Concepts | After 2030 | 2005 in-service aircraft (58) | No | Aircraft of seat category 211-400 | 2030 | 25 to 30% (58) |
| | | | | The term Engine Core is defined by the combination of compressor, combustor and high-pressure turbine. Through the inclusion of advanced materials, advanced combustors, new thermal management systems and new aerodynamic design airfoils, the new Engine Core technologies improve fuel efficiency and lower emissions (34).<br>The Intercooled Core for a high overall pressure ratio engine concept, for instance, performs with compact and efficient intercoolers, aggressive ducting and an advanced compressor (17, 35). | | | | | |
| | | JAXA, Japan<br>KARI, Korea<br>METU, Turkey<br>NRC, Canada<br>VKI, Belgium (59) | Active Cooling (Air Cooling) | After 2020 | Short-Range Aircraft<br>2000 in service engines (4) | Yes | Aircraft of seat category 101-210, 211-400 | 2030<br>2035 | 1.5% SFC (4) |
| | | | | Cooling air is only required for the high-pressure turbine's work. A reduction of cooling air would lead to a decrease of fuel consumption.<br>An implementation of an Active Cooling System can yield efficiency gains through activation the system during take-off and climb and avoiding during cruise (41). | | | | | |
| | | no IFAR Member identified | Engine Active Stability Management | After 2025 | 120-passenger aircraft (33) | No | Aircraft of seat category 401-600 | 2035 | 10 to 20% (33) |
| | | | | Engine Active Stability Management protects the engine, specifically the compressor, against instabilities such as rotating stall and compressor surge (24). The architecture enables increasing propulsion systems performance and assures the stable flow range of the compressor. An increase of the fuel-speed surge margin and an accommodation of dynamic distortion are realized (30, 34). | | | | | |

<table>
<tr><td rowspan="6"></td><td rowspan="6"></td><td rowspan="2">DLR, Germany<br>KARI, Korea<br>NLR, Netherlands<br>NRC, Canada<br>VKI, Belgium<br>JAXA, Japan<br>(59)</td><td rowspan="2">(Ultra) High Bypass Advanced Turbofan</td><td>After 2020</td><td>GE90-115B-powered 777-300ER (51)<br>2005 in-service aircraft (58)</td><td>No</td><td>Aircraft of seat category 101-210, 211-400, 401-600</td><td>2025<br>2035</td><td>10 to 15% (51)</td></tr>
<tr><td colspan="6">Advanced Turbofan engines with (ultra) high bypass ratios in the range of 12 to 18 are planned for an entry into service from 2020 onwards (40). Their higher ratio of mass flow through the bypass duct to mass flow through the engine core directly enhance the propulsive efficiency - nearly as fuel efficient as turboprops (4, 29). Further advanced devices concerning active compressor and turbine clearance and flow control, advanced cooling, regeneration and new materials lead to lower maintenance costs and fuel consumption by up to 16% compared to current engines (9, 40). Today's manufacturers investigate ultra-efficient technologies for short-range aircraft (9).</td></tr>
<tr><td rowspan="2">JAXA, Japan<br>NRC, Canada<br>(59)</td><td rowspan="2">Adaptive Cycles</td><td>After 2035</td><td>2005 in-service aircraft (58)</td><td>No</td><td>Aircraft of seat category 401-600</td><td>2040</td><td>5 to 15% (58)</td></tr>
<tr><td colspan="6">The technology enables the aircraft to operate under mixed flight conditions for maximum efficiency (25, 42). While traditional engines run with fixed airflow, Adaptive Cycles configure their fan pressure ratio and overall pressure ratio in order to alternate between a high-thrust mode for maximum power and high-efficiency mode for optimal fuel savings (25). Such device has high potential in the short-range and military sector due to its efficiency in great range of missions (10).</td></tr>
<tr><td rowspan="2">DLR, GermanyNLR, NetherlandsNRC, CanadaVKI, Belgium(59)</td><td rowspan="2">Variable Fan Nozzle</td><td>After 2025</td><td>2005 in-service aircraft (58)</td><td>No</td><td>Aircraft of seat category 101-210, 211-400, 401-600</td><td>2025<br>2035</td><td>1 to 2% (58)</td></tr>
<tr><td colspan="6">A Variable Fan Nozzle, installed on the bypass stream of a turbofan engine, lowers the fan pressure ratio and noise, enhances the mass flows and assures a sufficient surge margin on an ultra-high bypass ratio fan. Such system realizes the variation of the fan pressure ratio independently of the fan, thus the fan operates optimally and propulsive efficiency is improved over a variety of flight conditions (34, 44).</td></tr>
</table>

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Aerodynamics | CSIR-NAL, India: Low drag aerodynamics (71)<br>CAE, China: Further reduction of drag (72) | DLR, Germany<br>JAXA, Japan<br>KARI, Korea<br>NLR, Netherlands<br>NRC, Canada (59)<br>CSIRO, Australia: Coatings (69) | Turbulent Flow Drag Coatings (Riblets) | Before 2020 | 2005 in-service aircraft (58) | Yes | Aircraft of seat category 401-600 | 2035 | 1% (58) |
| | | | | An option for coatings to reduce turbulent-flow drag is Riblets. These are finely grooves or protrusions along the air flow attached to the skin of the aircraft (34, 36). Riblets, which are applied to the entire fuselage or wing or both, achieve significant reduction in viscous drag and alteration of the turbulent boundary layer (4). | | | | | |
| | | NLR, Netherlands<br>NRC, Canada (59) | Spiroid Wingtips | 2020-2025 | 2005 in-service aircraft (58) | No | Aircraft of seat category 101-210, 211-400, 401-600 | From 2025 onwards | 2 to 6% (58) |
| | | | | The spiral-shaped wingtip eliminates wake vortices just behind the aircraft. The technology aims at a 10%-reduction in induced drag and a diminution of wingtip vortex strength (23, 34). Spiroid wingtips can have influence on aircraft spacing. A reduction would enlarge the capacity at airports and fuel savings at fleet level (34). | | | | | |
| | | no IFAR Member identified | Split Scimitar Winglets ("dual-feather" Winglets) | 2014 | 2005 in-service aircraft (58) | Yes | Aircraft of seat category 101-210, 211-400, 401-600 | current | 2 to 6% (58) |
| | | | | The Blended Winglets are retrofitted with a new aerodynamically shaped tip cap and an advanced Scimitar-tipped ventral strake (5, 32).<br>Such architecture promises improvements in fuel consumption, increase in range and payload as well as reductions in drag and weight (2). | | | | | |
| | | DLR, Germany<br>KARI, Korea<br>NLR, Netherlands<br>NRC, Canada<br>VKI, Belgium (59)<br>INCAS, Romania (70) | Hybrid Laminar Flow Control (HLFC) | From 2030 onwards | 2005 in-service aircraft (58) | No | Aircraft of seat category 401-600 | 2035 | 10 to 15% (58) |
| | | | | Such device assures laminar flow over a large section of the aircraft, specifically at first on empennages, and then followed by the wing. Through suction in the surface flow, HLFC prevents or delays the boundary layer transition (4, 34). If applied, the benefits of the technology lie in significant savings in drag by 10% and fuel burn by 15% (22, 34). | | | | | |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | DLR, Germany<br>INCAS, Romania<br>KARI, Korea<br>NRC, Netherlands<br>VKI, Belgium (59) | Active Flow Control Tail | After 2020 | B757 (11) | No | Aircraft of seat category 101-210, 211-400 | 2025 | 2% (11) |
| | | | | The air for the Active Flow Control along the vertical tail comes from the APU and is cooled by a heat exchanger system (attached below the tail).<br>The technology enables more aerodynamically designs and thus, reductions in aircraft weight, drag and fuel consumption (8, 11). | | | | | |
| | | DLR, Germany<br>NRC, Canada (59) | Active Stability Control | After 2030 | Short-Range Aircraft<br>Long-Range Aircraft (6) | No | Aircraft of seat category 401-600 | 2040 | 1 to 2% (6) |
| | | | | An aircraft, flying with a more rearward centre of gravity with active control, results in a smaller tailplane, drag and weight. The progress of such active control device is moving towards the automatic rather than manual control (6). A further and high ambitious long term future approach is the aircraft operation with reduced stability or instability in order to significantly reduce $CO_2$ emissions (34). | | | | | |
| | | DLR, Germany<br>JAXA, Japan<br>KARI, Korea<br>NLR, Netherlands<br>NRC, Canada<br>VKI, Korea (59)<br>INCAS, Romania (70) | Natural Laminar Flow Control (NLFC) | From 2030 onwards | 2005 in-service aircraft (58) | No | Aircraft of seat category 101-210 | 2030 | 5 to 10% (58) |
| | | | | The control device, specifically on the wing or nacelles, maintains the laminar boundary layers and delays the transition of the boundary to the turbulent state, thus reduces the viscous drag (4, 7). By optimisation of the shape and surface of the aircraft, the resulting overall fuel burn reduction is another benefit (34). It is limited in applicability to lower wing sweeps (7). | | | | | |
| Systems | IAE, Brazil (59) | | Electrical Landing Gear Drive | Before 2020 | 2005 in-service aircraft (58)<br>A320 compared with standard taxiing procedures (1) | Yes | Aircraft of seat category 101-210, 211-400 | 2025 | 1 to 4% (1, 58) |
| | | | | Either by APU or fuel cell powered system add-ons enable aircraft to taxi autonomously without using their primary engines (20). The electric motor that is totally controlled by the pilot has possibilities in reducing fuel consumption (1). | | | | | |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | DLR, Germany<br>KARI, Korea<br>NLR, Netherlands<br>NRC, Canada<br>VKI, Belgium<br>(59) | | More Efficient Gas Turbine APU | After 2020 | 2005 in-service aircraft (58) | Yes | Aircraft of seat category 101-210, 211-400 | 2025 | 1 to 3% (58) |
| | | | | Instead of applying the Auxiliary Power Unit for the aircraft operation on ground, many airports move on to use electrical supplies driving different systems when parked at the airport gate. With a re-design of the APU regarding advanced materials, higher thermal and aerodynamic efficiency, benefits in lower fuel use and emissions result (9).<br>In the long-term, a transition to fuel cells is considered in order to optimise the energy consumption and cut fuel use significantly (33). | | | | | |
| | Fuel Cell as substitution for APU: No IFAR Member identified | Fuel Cell as Electrical Power: DLR, Germany<br>KARI, Korea<br>(59) | Fuel Cell | After 2020 | 2005 in-service aircraft (58) | Yes | Aircraft of seat category 101-210, 211-400, 401-600 | 2030<br>2035 | 1 to 5% (58) |
| | | | | Characteristic for Fuel Cells is the electrochemical reaction of chemical energy into electricity. As they work with hydrogen and hence do not produce CO2 emissions, they have chance to replace the APU (34). Examples for such galvanic cells are the Proton Exchange Membrane Fuel Cell and the Solid Oxid Fuel Cell. While the former convert chemical energy into electricity at low temperatures and is equipped with a polymer electrolyte membrane, the latter is a high-temperature type with a solid-state, ion-conducting ceramic membrane (33). | | | | | |
| Material | CSIR-NAL, India: Advanced composites (71) | JAXA, Japan<br>DLR, Germany<br>KARI, Korea<br>NLR, Netherlands<br>NASA, USA<br>(59) | Composite Primary Structures | Before 2020 | 2005 in-service aircraft (58) | No | Aircraft of seat category 101-210, 211-400, 401-600 | From 2025 onwards | 1 to 3% (58) |
| | | | | Since the revolution of Composites in modern aircraft, continued improvements in more innovative material structures are achieved (4). These design methods are lighter and more reliable compared to traditional metallic materials, which directly result in greater economies (3, 4).<br>Advanced metallic composites (for instance GLARE) and new material systems such as stitched composites promise to provide additional weight savings (40). | | | | | |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | JAXA, Japan<br>DLR, Germany<br>KARI, Korea<br>NLR, Netherlands<br>(59) | Composite Secondary Structures | Before 2020 | 2005 in-service aircraft (58) | Yes | Aircraft of seat category 101-210, 211-400, 401-600 | From 2025 onwards | < 1% (58) |
| | | | | The first Composite Materials in aircraft were applied to secondary structures such as fairings, small doors and control surfaces (61). Their benefits lie in the high weight reduction and a large stiffness (61). Manufacturer revolutionise, for instance panels made out of composite material, regarding a superior fire persistence and higher performance in civil aircraft (60). | | | | | |
| | DLR, Germany<br>NLR, Netherlands<br>NRC, Canada<br>(59)<br>JAXA, Japan: Composite turbine (73) | | Ceramic Matrix Composites | After 2020 | Current Aircraft | No | Aircraft of seat category 101-210, 211-400, 401-600 | From 2025 onwards | 6 to 8% (62) |
| | | | | The structure of these materials is characterised by silicon carbide ceramic fibres and ceramic resin (28).<br>Ceramic Matrix Composites (CMC) can withstand higher temperatures, which are necessary for increased thermal efficiency and power output. Specifically CMC low-pressure turbine blades for next generation commercial engines are currently tested, which are lighter and thus, lowers fuel consumption (21, 27). They are also beneficial in improving the overall engine efficiency by being durable and requiring less cooling air, which allows the more efficiently operation of engines (28). | | | | | |
| Structural Concepts | KTN, UK: Use of intelligent structural designs (67)<br>CSIR-NAL, India: Adaptive structures (71) | DLR, Germany<br>JAXA, Japan<br>NLR, Netherlands<br>NRC, Canada<br>(59) | Adaptive Trailing Edge | 2020-2025 | Short-Range Aircraft<br>Medium-Range Aircraft (12) | No | Aircraft of seat category 101-210, 211-400 | 2025 | 4 to 12% (12) |
| | | | | The advanced flaps are gapless and form a seamless edge with the wing (38). They change its shape depending on changes in aircraft's weight, airspeed and altitude. The design has great potential to improve wing aerodynamic efficiency and reduce drag, noise and fuel consumption (12, 21). This near term technology is possibly applied into single aisle replacements (4). | | | | | |

<table>
<tr><td rowspan="2"></td><td rowspan="2"></td><td rowspan="2">DLR, Germany<br>KARI, Korea<br>NLR, Netherlands (59)</td><td rowspan="2">Adaptive Wing</td><td>After 2030</td><td>Medium-Range Aircraft<br>Long-Range Aircraft (53)</td><td>No</td><td>Aircraft of seat category 401-600</td><td>2035</td><td>5 to 15% (31)</td></tr>
<tr><td colspan="6">The Adaptive Wing adjusts its geometry by modification of its trailing or leading edge or both to adapt to the changing flow and load requirements. The future technology directly leads to profits in flight performances, aerodynamic efficiency gains and thus, reducing fuel consumption as well as exhaust and noise emissions (19, 31).</td></tr>
<tr><td rowspan="2">Potential Technologies</td><td rowspan="2" colspan="2">DLR, Germany; NRC, Canada; VTT, Finland: Nanotechnology in polymer composites (59)</td><td rowspan="2">Nano-technologies</td><td>After 2030</td><td></td><td>No</td><td>Not considered</td><td>Not considered</td><td>11% (50)</td></tr>
<tr><td colspan="6">Nano-manufactured materials, as integration into modern composite matrices, significantly increase the strength and lower the weight of carbon-composite materials (4, 37).<br>Carbon Nanotubes, tube-shaped carbon molecules, have the potential for stronger, lighter and more cost-effective aircraft parts, thus reducing fuel burn (16).</td></tr>
</table>

Table 21 References concerning the technology matrix

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## Appendix E

Table 22 IFAR members (research institutions)

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|---|---|
| INCAS | National Institute of Aerospace Research "Elie Carafoli" of Romania |
| KTN | Aerospace, Aviation & Defence Knowledge Transfer Network, UK |
| JAXA | Japan Aerospace Exploration Agency |
| BME | Budapest University of Technology and Economics |
| TsAGI | Central Aerohydrodynamics Institute of Russia |
| FOI | The Swedish Defence Research Agency |
| CAE | Chinese Aeronautical Establishment |
| NRC | Aerospace Portfolio, Canada |
| VZLU | Czech VZLU-Aeronautical Research and Test Institute, Czech Republic |
| DLR | German Aerospace Center |
| NLR | National Aerospace Laboratory of the Netherlands, Netherlands |
| VKI | Von Karman Institute for Fluid Dynamics, Belgium |
| CSIRO | Commonwealth Scientific and Industrial Research Organisation, Australia |
| CIRA | Centro Italiano Ricerche Aerospaziali |
| CSIR-NAL | National Aerospace Laboratories, India |
| IAE | Aeronautics and Space Institute, Brazil |
| KARI | Korea Aerospace Research Institute |
| VTT | Technical Research Centre of Finland |
| METU | Middle East Technical University Ankara, Turkey |
| NASA | U.S. National Aeronautics and Space Administration |
| ONERA | French Aerospace Lab |
| ILOT | Polish Institute of Aviation |
| INTA | National Institute of Aerospace Technology of Spain |
| TU Vienna | Vienna University of Technology |
| CEiiA | Centre for Innovation and Creative Engineering, Portugal |
| CSIR | Council for Scientific and Industrial Research, Republic of South Africa |