IATA
Technology Roadmap

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IATA TECHNOLOGY ROADMAP 2013

The IATA Technology Roadmap was prepared in collaboration with the German Aerospace Center (DLR) and the Georgia Institute of Technology

FOREWORD

Mitigating environmental impact is one of the key challenges for aviation and a main driver for research and technology in the sector. While the focus in the past was on noise and pollutant emissions, aviation greenhouse gas emissions have become the predominant environmental topic for the aviation community in the last years. Aviation contributes 2% of global man-made carbon emissions and this would rise to 3% by 2050 according to the Intergovernmental Panel on Climate Change, if no futher action were taken. Although this proportion is relatively small, a growing carbon footprint is not acceptable for any industry, and the aviation sector is taking appropriate measures to reduce it.

Aviation is the only global industrial sector which has committed to a set of ambitious emissions reduction goals: a continuous fuel efficiency improvement of 1.5% per year in the short term to 2020, carbon-neutral growth from 2020 and a 50% reduction of the world air transport's carbon footprint by 2050. IATA was one of the driving forces in promoting these goals with the relevant United Nations organizations, namely the International Civil Aviation Organization and the UN Framework Convention on Climate Change. Already in 2007, the industry adopted a four-pillar strategy to mitigate the carbon emissions from air transport. These four pillars are technology, operations, infrastructure and positive economic measures. Clearly the largest contribution to improving fuel efficiency and reducing carbon emissions comes from the introduction of new technologies, comprising more efficient airframe and engine design as well as sustainable low-carbon alternative aviation fuels.

Aviation has always been at the forefront of technological progress and has a strong track record in continuous improvement of efficiency and reduction of its environmental impact. The reduction of fuel burn, noise and smoke achieved from the beginning of the jet age to today is impressive. For the future, researchers and engineers are working on a wealth of new materials, aircraft components, engine architectures and futuristic aircraft concepts including blended wing bodies and battery-driven aircraft. This Technology Roadmap presents a selection of those technologies and evaluates their impact on fuel efficiency improvement and thus on the carbon footprint of the future world aircraft fleet.

Cooperation between all stakeholders in the aviation area is essential. The remarkable technological progress that allowed aviation to become an extremely safe and increasingly sustainable transport mode could only happen because for a long time, all members of the aviation community have been used to closely working together: airlines, manufacturers, airports and air navigation service providers, as well as research establishments, universities and other governmental institutions. As customers and operators, airlines have an important role in defining the requirements for future aircraft and advising researchers to develop technologies in a way that they are really fit for operational use. From this Technology Roadmap it can be clearly seen that the most successful aircraft programs were those that closely involved airline customers in their development process.

I wish you happy reading.

Paul Steele
Director Aviation Environment
International Air Transport Association

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"For aviation, achieving our environment targets is a key element of our licence to grow."

– TONY TYLER
DG & CEO, IATA

AVIATION'S GOAL FOR REDUCTION OF CO_2 EMISSIONS: 50% BY 2050

EXECUTIVE SUMMARY

One of the biggest challenges for today's aviation industry is the need to mitigate its contribution to climate change.

OBJECTIVE AND SCOPE

As the first industrial sector, the aviation industry has committed to a set of ambitious high-level goals to reduce its carbon emissions at a global level:

- An average improvement in fuel efficiency of 1.5% per year from 2009 to 2020
- A cap on net aviation CO_2 emissions from 2020 (carbon-neutral growth)
- A reduction in net CO_2 emissions of 50% by 2050 relative to 2005 levels

A large contribution to emissions reduction comes from the implementation of fuel-efficient airframe and engine technologies, mainly through the introduction of more modern aircraft by the continuous fleet renewal process; some technologies can also be retrofitted into in-service aircraft. The IATA Technology Roadmap is intended to help assess the potential of different technologies to improve fuel efficiency and thus to contribute to meeting the above high-level industry goals for emissions reduction.

The content of this Roadmap is based on IATA's TERESA project (TEchnology Roadmap for Environmentally Sustainable Aviation), carried out in partnership with the German Aerospace Centre (DLR) and the Georgia Institute of Technology (Georgia Tech). While in many forecasts of aviation fuel burn a top-down estimate of annual improvements is done, the TERESA project used a strict bottom-up approach to build up the future carbon footprint of aviation. It starts with estimates of the fuel efficiency improvements of single technologies obtained from industry and research experts and from literature. However, the actual mission fuel burn needs to take into account operational aspects, such as the different impact on short- and long-haul flights, and interactions between different technologies. Therefore a performance model was used to simulate mission fuel burn of aircraft equipped with selected new technologies. In order to forecast the evolution of the world fleet fuel burn over the next two decades, these results for single-aircraft improvements were applied to the current calendar of expected entry into service of coming aircraft types.

Finally, airline customers are interested in possibilities to influence the development of new aircraft programs in a way to best respond to a variety of customer requirements and thus to make the program a success. The Roadmap analyses success or failure of selected past programs and draws conclusions for coming programs.

BACKGROUND

The mitigation of man-made climate change is a major challenge to most industries and is an important issue of international policy. Aviation contributes approximately 2% of carbon dioxide emissions and an estimated 3% of all greenhouse gases, but due to the continuous increase of air traffic volume with 4 to 5% p.a. in average, this contribution is expected to grow, which is not acceptable for any industry in the longer term. Therefore strong efforts are being made by all aviation stakeholders to stabilize and reduce these emissions. IATA, together with the global associations of aerospace manufacturers, airports and air navigation service providers, has committed in 2009 to the aforementioned set of high-level emissions reduction goals, namely fuel efficiency improvement, carbon-neutral growth and halving of net emissions by 2050. Similar goals were set by the 37th ICAO Assembly in its Climate Change Resolution.

In order to meet these emissions reduction goals, IATA has established a four-pillar strategy based on:

1. Technology for airframe and engines, sustainable biofuels
2. Efficient flight operations
3. Improved airspace and airport infrastructure
4. Positive economic instruments

The present Technology Roadmap focuses on airframe and engine technologies.

In all countries with aeronautic industry, and in particular in the EU and the US, comprehensive aviation research and technology programs exist, supported by governments. They focus on technologies overcoming the big challenges for today's aviation, with the reduction of the environment footprint being one of them.

Throughout the history of aviation, fuel efficiency has always been a major driver for technology improvement, and over the last 50 years the fuel burn, and thus also the carbon emissions, per passenger kilometer has been reduced by over 70%. Fuel is the most important single cost element for airline operators; and the high and strongly volatile oil prices of the last years have even more increased their need for more fuel-efficient aircraft. In addition, an aircraft certification standard limiting carbon emissions is currently being developed under ICAO, which is intended to drive forward the development and encourage the use of more low-emissions aircraft.

RESULTS

In the first phase of the TERESA project a large scope of relevant individual technologies from the areas of aerodynamics, lightweight materials and structures, propulsion and equipment systems has been collated and their fuel efficiency improvement potential estimated by industry and research experts and compared with literature values.

The most promising of these technologies were then selected and used in a performance model that allows determining the fuel burn of a future aircraft equipped with selected new technologies for typical flight operations. Depending on the time horizon for implementation – from retrofits and design upgrades that can be applied to in-production aircraft in the short term, over technologies that need to be integrated into new aircraft designs to radically new aircraft configurations – the following efficiency improvements can be expected for suitable combinations of technologies, relative to a baseline of 2005 in-service aircraft:

- Retrofits: 5 to 12% (for aircraft without the respective technology)
- Serial Upgrades: 9 to 20%
- New aircraft designs before 2020: 10 to 21% (only short range)
- New aircraft designs after 2020: 27 to 40%
- Radical technologies (beyond 2030): up to about 50%

The following technologies were identified as most promising:

- Laminar flow control technology (natural and hybrid)
- Active load alleviation and variable camber
- Winglets and riblets
- Structural health monitoring
- Composite structures for wing and fuselage
- Engine architectures: geared turbofan, advanced turbofan and open rotor

The above improvements can of course be realized only if suitable aircraft programs are launched in the respective

Fuel efficiency improvements of 30% or more could be achievable for the aircraft generation after 2020.

Radically new aircraft and air transport concepts will be necessary to meet the ambitious emissions reduction goal for 2050.

time frame. Using the above results for single aircraft fuel efficiency, a world fleet model was subsequently established, based on the currently known calendar of entry into service of new aircraft types in the current and the following decade, to show the improvement of fuel efficiency in the different aircraft size categories of the world fleet over the coming years.

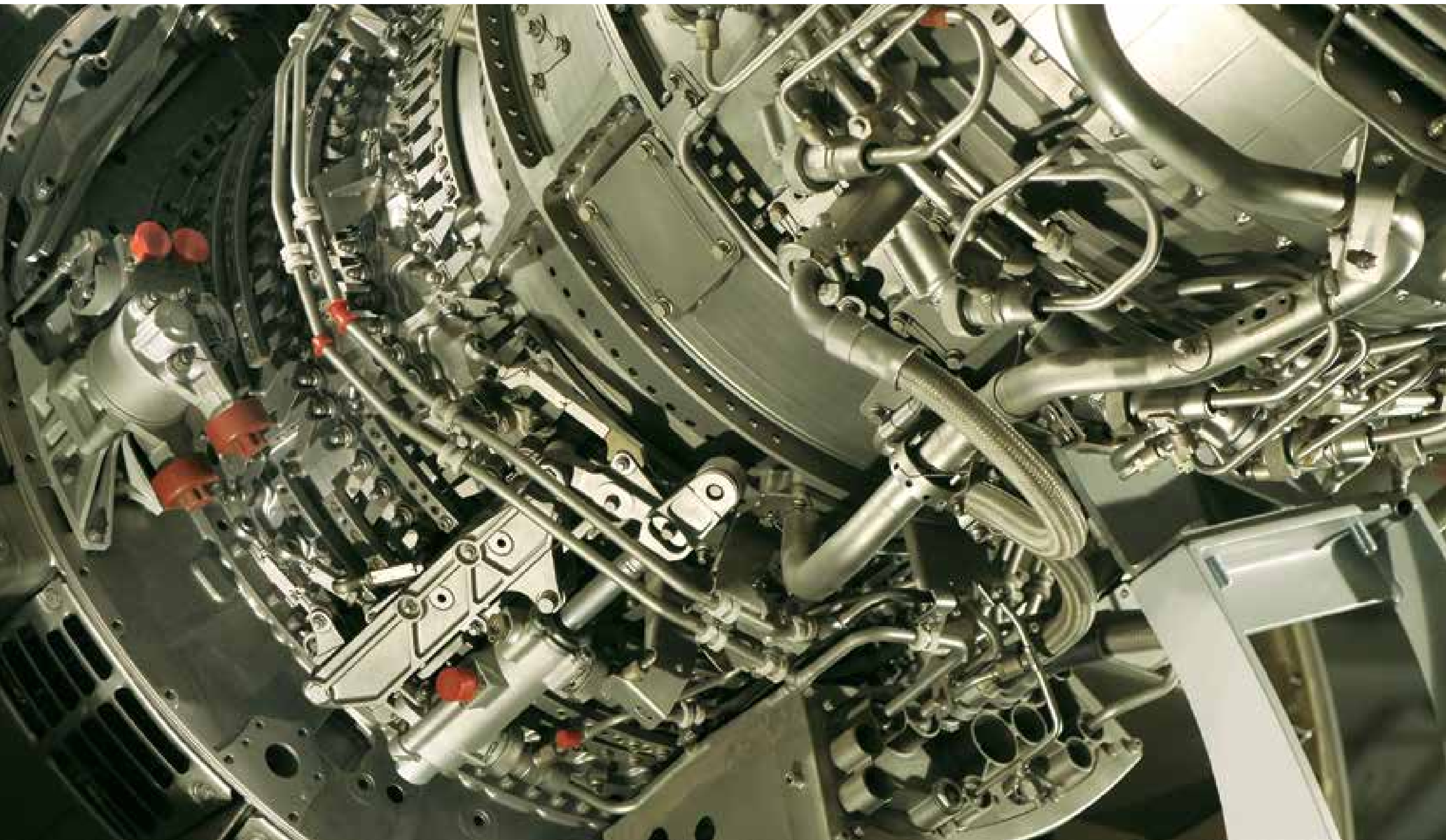
The strongest efficiency improvement of around 2% p.a. until 2030 is forecast for the regional aircraft category. Aircraft between 100 and 400 seats are expected to improve by 1.2 to 1.5% p.a.. In the category above 400 seats most aircraft are relatively new and will not be replaced in the near future; therefore the expected improvement is quite low until 2020 and in the order of 1% p.a. after 2020. Taking into account that operational and infrastructural improvements will come on top of gains from technology, this result seems promising to be in line with the industry fuel efficiency improvement goal of 1.5% p.a.

A critical factor is the time needed for new technologies to mature in order to be implemented in new aircraft programs. A set of timelines based on empirical values from past aircraft programs are shown as guideline for future estimates. Finally the possibilities for aircraft customers to take influence on the development of new aircraft types are studied, taking lessons from the success or failure of past aircraft programs.

WAY FORWARD

The identified technologies show a significant potential for emissions reduction; however, in order to benefit from this potential it is critical that manufacturers are capable of integrating them into new aircraft designs within the timeframe of aircraft development. Only technologies that have achieved the necessary maturity at critical decision points can be included in the new aircraft design; otherwise the benefit for emissions reduction might be delayed by many years. Airline customers' actively expressed interest can support this process and ensure that manufacturers put the necessary effort on driving forward technology development in order to realize a maximum out of the emissions reduction potential.

In the longer term, radically new aircraft and air transport concepts will be necessary to meet the ambitious emissions reduction goal for 2050. First assessments of emerging new technologies, such as formation flight, battery-driven aircraft and aircraft fuel from sun energy show encouraging results; these developments should thus be pursued with the necessary intensity to make them available in due time.



AVIATION'S CONTRIBUTION TO GLOBAL MAN-MADE CO_2 EMISSIONS IS 2%

1. INTRODUCTION

Throughout the history of aviation, the challenge of reducing aircraft fuel consumption has been a main driver for research and technical development, bringing with it greater fuel efficiency for airlines and better environmental performance.

1.1 THE CLIMATE CHANGE IMPACT OF AVIATION

For many years, concerns related to the impact of aviation on the local environment (noise and air quality) have received most of the attention and mitigating them remains a priority for the industry.

However, within the last twenty years global climate change has emerged as one of the big challenges of modern life, affecting a wide scope of human activities. All industries with activities generating greenhouse gas emissions, including aviation and other transport modes, are making efforts to reduce these emissions, mainly by improving energy efficiency and replacing fossil carbon-based energy sources by more sustainable solutions.

The present report focuses on the technological improvements that can contribute to addressing the impact of aviation on climate change.

Aviation contributes about 2% to global man-made CO_2 emissions (Figure 1). This value was determined by the United Nations' Intergovernmental Panel on Climate Change (IPCC) in their 4th Assessment Report in 2007[1] and has remained relatively constant since then[1]. Taking into account also other relevant exhaust emissions from aircraft engines including contrails and cirrus, the contribution of air transport to the total anthropogenic greenhouse effect has been estimated at around 3%. These numbers can be compared to the aviation industry supporting 56.6 million jobs and $2.2 trillion global GDP, while being a major driver of tourism and trade[2].

Over the past few decades, the volume of air transport has been continuously growing with an average rate of roughly 5% p.a. despite political and economic crises, and is projected to grow with a similar rate in the foreseeable future (see Figure 2). While in world regions with mature economies such as North America and Western Europe this growth tends to gradually slow, the fast-growing economies in Asia, Latin America and other regions show growth rates well above average. However, this successful growth is also a challenge in terms of its environmental impact. The IPCC forecasts that by 2050 aviation's contribution to the global anthropogenic carbon emissions could grow to 3% and it will represent 5% of total greenhouse gas emissions[1]. Although these figures are still relatively low, a growing carbon footprint is not acceptable for any industry. Effective emissions reduction measures are therefore needed to compensate for the effect of traffic growth.

1. In 2011 aviation's CO_2 emissions were 676 million tonnes compared to total anthropogenic emissions of 34 billion tonnes, i.e. 2.0%

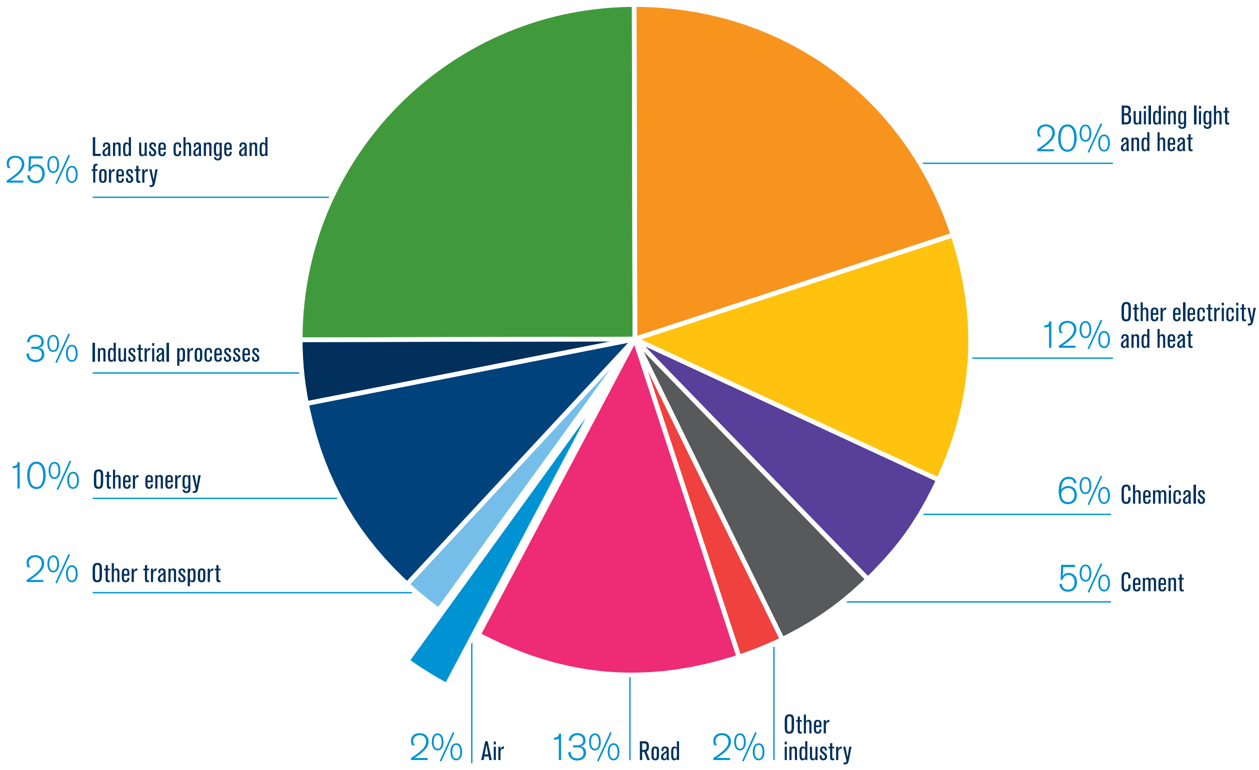


FIGURE 1: Share of different anthropogenic CO_2 emissions

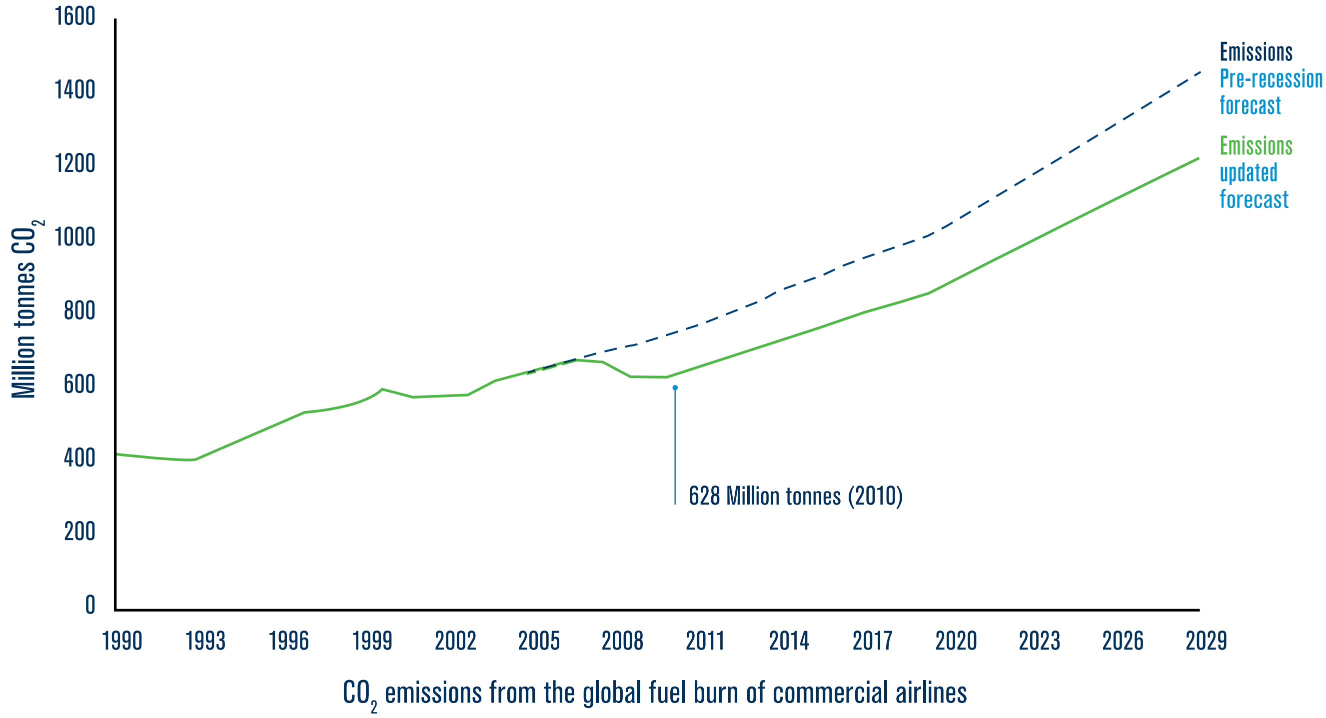


FIGURE 2: Past and forecast CO_2 emissions from the global fuel burn of commercial airlines [Source IATA]

1.2 A FOUR PILLAR STRATEGY

The aviation industry has a strong track record of addressing environmental concerns. Impressive progress has been achieved since the early jet age: perceived noise has been reduced by over 75% (20 dB); fuel consumption and the related carbon dioxide (CO_2) emissions have been reduced by well over 70% and soot emissions have virtually been eliminated. In the last 20 years alone fuel efficiency has been improved by over 35% (see Figure 3). The economic pressure from rising fuel prices reinforced the efforts for better fuel efficiency; with fuel making up over a third of the average airline's operative cost, it is fortunate that fuel savings are at the same time CO_2 emissions reductions benefiting the environment; thus economic and ecological benefits go hand in hand.

The IATA four-pillar strategy helps achieve the aviation industry's ambitious emissions reduction goals

In summer 2009, ahead of the UN Climate Conference in Copenhagen, the aviation industry announced its commitment to a global approach to mitigating aviation greenhouse gas emissions, adopting three high-level goals:

- An average improvement in fuel efficiency of 1.5% per year from 2009 to 2020
- A cap on net aviation CO_2 emissions from 2020 (carbon-neutral growth)
- A reduction in net CO_2 emissions of 50% by 2050 relative to 2005 levels

These collective goals were endorsed by the whole aviation industry (airlines, manufacturers, airports and air navigation service providers) in the joint industry submission to ICAO in September 2009 [4]. Governments meeting at ICAO in its Climate Change Resolution 17/2 at the 37th General Assembly in October 2010 [5] then set out a the fuel efficiency goal to 2% p.a. and made carbon-neutral growth an aspirational goal from 2020. Note that the 1.5% p.a. industry commitment only includes measures under industry control including basic air traffic management measures, whereas the 2% p.a. is a goal for States and includes comprehensive government-controlled measures such as air traffic management infrastructure (e.g. the Single European Sky [SES] and NextGen in the US).

These announcements succeeds IATA's 2007 vision [3] of a carbon-emission-free aviation and the availability of zero carbon-emission aircraft in a timeframe of about 50 years, which is also in line with the worldwide demand for a more environmentally friendly aviation industry.

In order to achieve the above high-level goals, the aviation industry established a four-pillar strategy [6] (see Figure 5), comprising:

1. Investment in new technology (more efficient airframe, engines and equipment, sustainable biofuels, new energy sources)
2. Efficient operations (drive for maximum efficiency and minimum weight)
3. Effective infrastructure (improve air routes, air traffic management and airport procedures)
4. Positive economic measures (carbon offsets, global emissions trading)

The first of these four pillars, i.e. new technology, contributes a large potential that is critical for achieving the desired objectives in emission reduction. Their achievement strongly depends on the development and implementation of new technologies by aircraft, engine and equipment manufacturers. The environmental benefits of these technologies (through a better fuel efficiency and thus lower carbon emissions) will become effective through airline fleet modernization and, to a minor degree, retrofits to in-service aircraft. There is an underlying challenge to select the appropriate technologies as this selection is driven by sometimes uncertain factors such as their current development status, benefits, risk and their research and development costs.

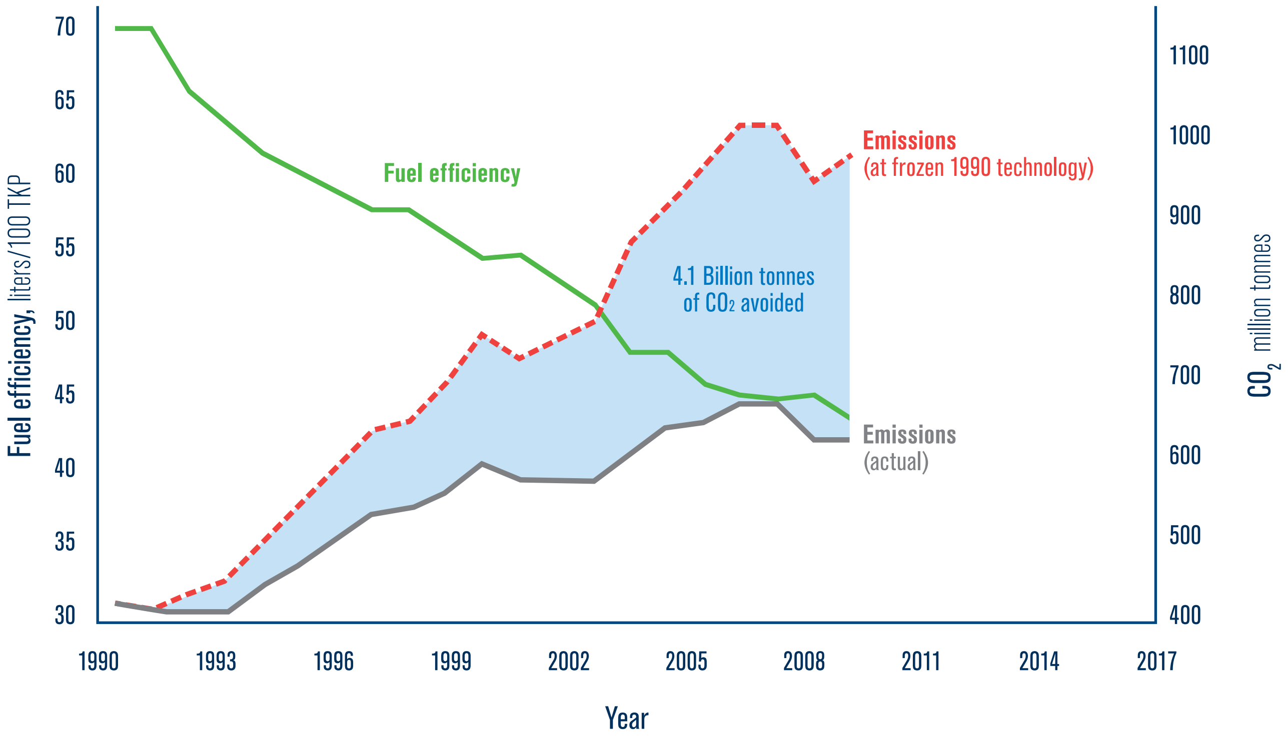


Figure 3: Fuel efficiency improvement of commercial airlines since 1990

Hypothetical CO_2 emission increase assuming no technology improvement (dotted red line), actual CO_2 emissions (solid grey line) and fuel burn in liters per 100 ton-km performed (TKP)(solid green line) [Source IATA]

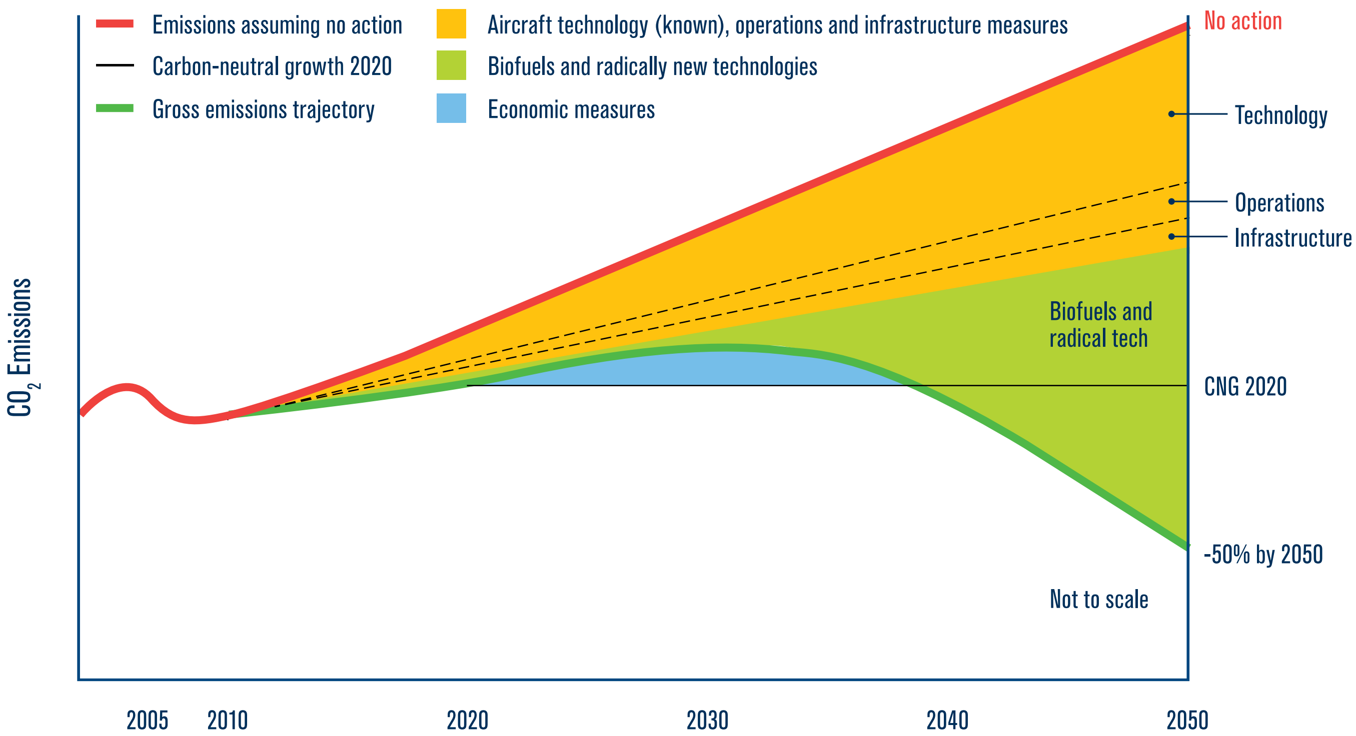


Figure 4: Schematic CO2 emissions reduction roadmap [Source IATA]

The present IATA Technology Roadmap is intended to assist airlines, and the aviation industry in general, in assessing the effect of different technologies and to monitor how technology measures help achieve the high-level industry goals for emissions reduction by providing an overview of fuel-efficient green technologies and their impacts both at single-aircraft level (Chapter 4) and at world fleet level (Chapter 6).

The work on the IATA Technology Roadmap started in 2008 by collecting an extensive amount of data on technologies from the areas of airframe, engine, air traffic management (ATM) and alternative fuels. The impact of these technologies was assessed qualitatively by a group of industry and research experts in these areas; the results have been published in the previous IATA Technology Roadmap Report (3rd edition) in 2009 [6].

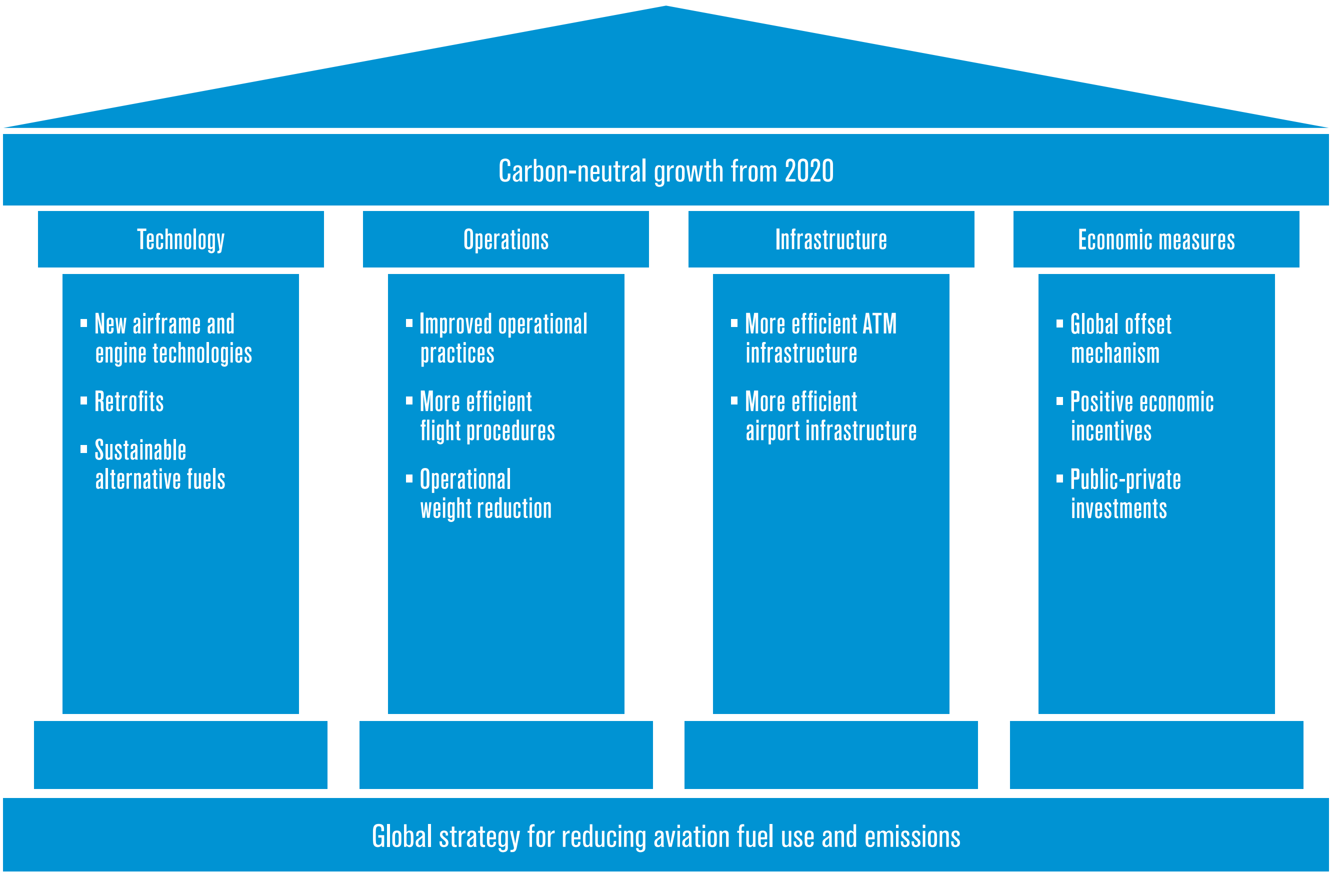


Figure 5: The IATA Four-Pillar Strategy, from [3] and [6]

For the present report, a more thorough study of the following aspects was done:

- A more detailed assessment including operational impacts and down-selection of the most promising technologies
- Determination of the efficiency benefit of new technologies using a performance model simulating a reference aircraft equipped with new technologies flying over a given flight mission.
- Evaluation of the impacts of new technologies at world fleet level, using a bottom-up fleet/CO_2 forecasting method: Based on the entry-into-service calendar and estimated deliveries of new aircraft types currently projected for the next two decades (e.g. Airbus A320 Neo, Boeing 737 Max in the late 2010s and entirely new short-range projects in the mid-2020s), world fleet fuel consumption and CO_2 emissions are then calculated from the single-aircraft performance determined before.
- Considerations about airlines' possibilities to positively influence the definition of new aircraft types and the technologies used in them, based on a review of the success or failure of past aircraft programs.

Technology contributes a very large part of emissions reduction.

The present report focuses on new technologies in the aircraft area (aerodynamics, powerplant, structure and materials, equipment systems). The very dynamically developing area of aviation biofuel technologies can be considered independently from aircraft technologies as long as only drop-in fuels are used, which is expected to be the case for the next few decades. Progress in this area is described in the IATA Reports on Alternative Fuels [7], which appear yearly.

Regarding ATM technology, IATA has published a "Blueprint for the Single European Sky" in 2012 [8]. For a further overview it is recommended to consult the comprehensive planning documents of both SES [9] and NextGen [10]. ◆

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2. STRATEGIC AVIATION TECHNOLOGY GOALS

Today's globalized world would not be possible without air transport. Airlines respond to a growing demand for air transport by adding new routes and offering more connectivity to their customers.

As a result air traffic volume is growing at average rate of about 5% per year, which is equivalent to traffic doubling in 15 years [1]. In the emerging economies in Asia, the Middle East and other world regions traffic growth is even stronger. But this impressive growth has also led to a number of big challenges that today's aviation is facing:

- Maintain and improve mobility despite more and more congested airspace and airports
- Improve competitiveness and cost-efficiency of air transport
- Address aviation's environmental footprint in terms of greenhouse gases, noise and air quality
- Maintain and improve the safety level of aviation
- Provide hassle-free security processes while maintaining at least the current security level

Overcoming these challenges is the main driving force for new technology development in aviation. To address them, strategic aviation technology programs have been created in Europe, in the US and in various other countries with existing or emerging aeronautics industry, supported by governments and often structured in partnership between industry and research establishments. Developing technologies to improve the environmental performance of aviation is one of the most important objectives of these programs.

Environment is one of the big topics in strategic aviation research programs both in Europe and in the US.

This chapter describes the current strategies and objectives of aviation technology programs in Europe and North America. These objectives will serve as a benchmark to the forecast improvements of the set of technologies investigated in further detail in this Technology Roadmap.

Moreover, the environmental impact of aviation is subject to regulatory measures. Aircraft noise and pollutant exhaust emissions (nitrogen oxides, unburned hydrocarbons, carbon monoxide and smoke) have been regulated for decades by ICAO (and similar FAA) certification rules for new aircraft types. A similar standard is being developed for CO_2 emissions.

Figure 6: ACARE, the SRAs and the Flightpath 2050 in the Framework Program environment

2.1 EUROPEAN AVIATION RESEARCH

2.1.1 STRATEGIC INDUSTRY GOALS

In 2000 the European Commission mandated a high-level group of personalities from aviation industry and research to establish "Vision 2020" as a guiding document for the EU strategy in supporting aviation research and technology. In addition to environmental goals, the Vision 2020 included four additional goals concerning quality and affordability, efficiency, safety and security of the air transportation system.

The two top-level goals of the Vision 2020 were:

1. Securing Europe's global leadership in the air transportation sector, and
2. Meeting society's needs in Europe until the year 2020.

Soon after publication of the Vision 2020 in the year 2001 the Advisory Council for Aeronautical Research in Europe (ACARE) was created, with the aim of steering the European aeronautical research policy in a way to approach the coming challenges in technology, economics, legislation and certification. The work of ACARE led to two Strategic Research Agendas (SRA's) [3][4] which contain the goals and requirements for multiple fields of aeronautical research.

In March 2011 the subsequent long-term vision document Flightpath 2050 [5] was published by a High-Level Group mandated by the European Commission. The five goals and their 23 subgoals are illustrated in Figure 7. A new Strategic Research and Innovation Agenda (SRIA) [6] giving perspectives for a time horizon 2050 has been published in September 2012. See Figure 6 for a timeline.

Table 1 shows the environmental goals as a subset of the Vision 2020/Flightpath 2050 goal set. These define (single aircraft) technology benefits over year 2000 technology for implementation on new European aircraft projects in 2020+ and 2050+, respectively.

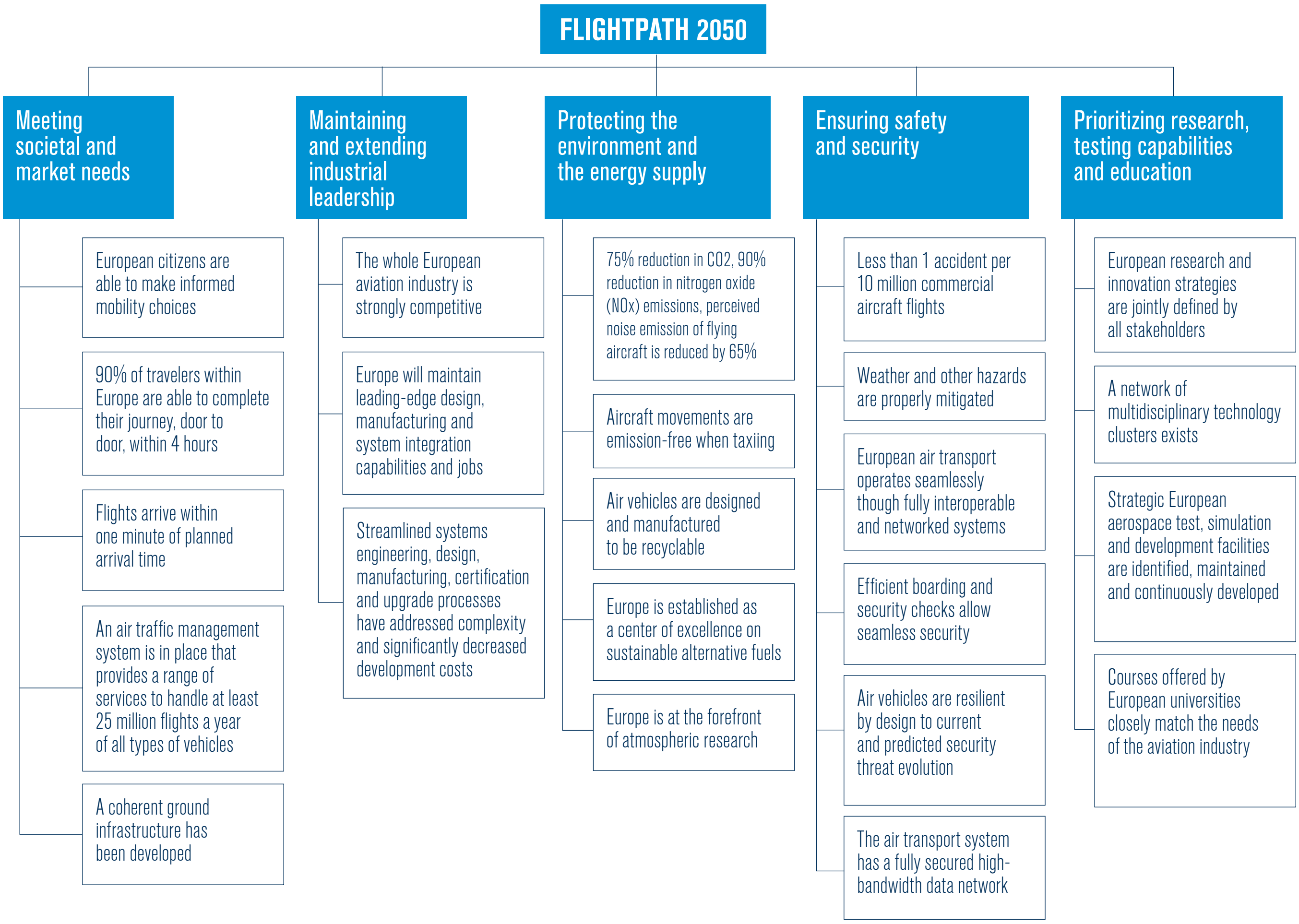

Figure 7: The five Flightpath 2050 goals and their subgoals

GOALS	TECHNOLOGY BENEFITS RELATIVE TO A YEAR 2000 REFERENCE AIRCRAFT	
	VISION 2020	**FLIGHTPATH 2050**
CO_2 reduction per passenger km	-50%	-75%
NOx reduction	-80%	-90%
Noise reduction[2]	-50%	-65%
Taxiing		Emission-free
Manufacturing and design		All aircraft recyclable
Sustainable alternative fuels		Europe established as center of excellence
Atmospheric research		Europe at the forefront

Table 1: Vision 2020 / Flightpath 2050 environmental goals. Compiled from [5]

2. Equally "Perceived" noise (EPNdB) reduction, with a reduction by 50% being equivalent to a noise level reduced by 10 dB

2.1.2 RESEARCH AND DEVELOPMENT PROGRAMS

The general EU's program for funding research, technological development and demonstration is the multi-annual Framework Program (FP). Since its inception in the early 1980s the Framework Programs have steadily increased in size and scope, and spending under FP7 (2007-2013) is now in the order of €6-7 billion per year. The next Framework Program (FP8, also called "Horizon 2020") falls under the next EU financial perspectives and will begin in 2014[3].

See Figure 8 for an illustration of the three different research levels (Level 1, 2 & 3) covered under the Framework Program and the corresponding Technology Readiness Levels (TRL)[4]. The objectives set in the Strategic Research Agendas are pursued in projects which were set up as public private partnerships. These were typically funded at a rate of 50% by the European Union. To mention are programs run and controlled by the Joint Technology Initiative (JTI) as Joint Undertakings (JU) like CleanSky or SESAR, which are a new project scale to meet the large specific multi-stakeholder challenges in aviation. Currently the administrative work for follow up programs for CleanSky2 [7] and SESAR II [8] is under way and the request for proposal procedure is being installed.

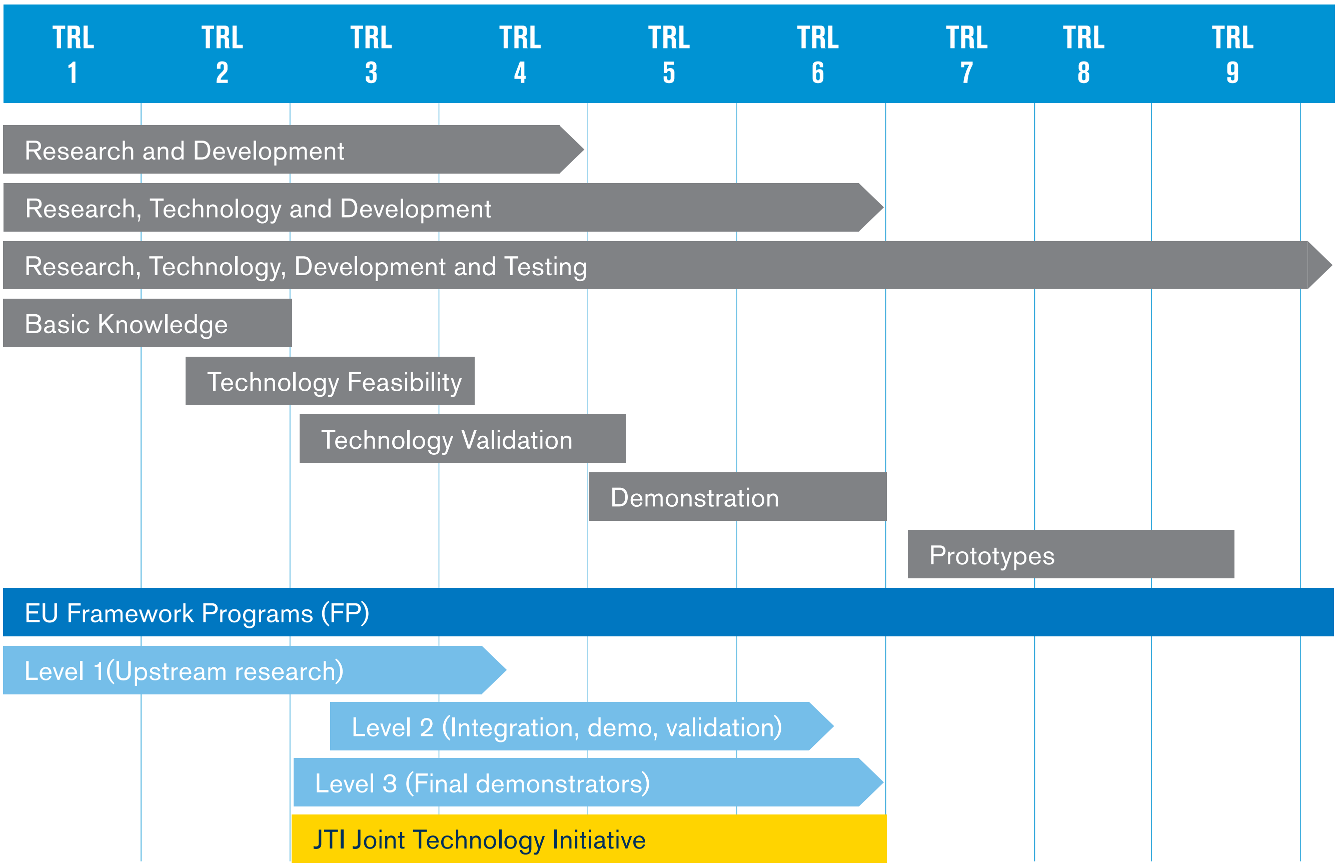

Figure 8: The EU Framework Program, with its three levels and the intended research objective

3. e.g. FP1 1984-1988 had a budget of €3.75b; FP5 1998-2002 €14.96bn; FP6 2002-2006 €17.88 bn and FP7 2007-2013 a budget of €50.5 bn; [9]
4. The Technology Readiness Level (TRL) refers to a scale from 1-9 defined by NASA and adapted by various research institutions around the world to help measuring the maturity of a technology under development. The scale tries to capture the different sequential steps in a technology evolution from "basic principles observed and reported" (TRL1) to "System/subsystem model or prototyping demonstration in a relevant end-to-end environment (ground or space)" (TRL6). An advanced introduction to NASA's Technology Readiness Levels (TRLs) can be found in Chapter 4.4.2 or in reference [14] and [15]; for an approach to translate the TRL levels into expected years of development needed see Chapter 7.1

2.2 NORTH AMERICAN AVIATION RESEARCH

Future aircraft development is currently at a pivotal point in North America regarding environmental goals. From an emissions standpoint there has been significant discussion in the past few years regarding climate change regulation and, in particular, a cap-and-trade program. The American Clean Energy and Security Act (ACES) of 2009 was proposed with language that would impose a system on the importation and production of fossil fuels which would include jet fuel. The limits within this bill were 3% lower than 2005 levels in 2012, 20% lower than 2005 in 2020, and 83% lower than 2005 in 2050. Even though the bill passed the House of Representatives on June 26 in 2009 [10], it was defeated in the US Senate in 2010 [11].

Outside of the congressional avenues there does exist a possible way for greenhouse gas (GHG) emissions to be regulated within the U.S. In 2007 the Environmental Protection Agency (EPA) was confirmed to have the authority to regulate GHGs if the organization determined they posed a threat. This determination of threat was made in 2009 and in 2010 regulations were adopted to introduce GHG emission standards. As with the cap-and-trade proposals the changing Congressional makeup introduced delays or curbs on these standards for the near term. However, it is obvious that the EPA is moving towards implementing these new specifications. Although the standards are currently only applicable for motor vehicles [12], aircraft and engine manufacturers should certainly take this into account when planning for future aircraft technologies and concepts [13].

Outside of regulation there are also specifications being enacted from other government agencies to drive technology research in certain areas. The National Aeronautics and Space Administration (NASA) has developed a 3-tiered goal structure for technology research with current aircraft at generation N; the N+1, N+2, and N+3 generations represent technologies which will be nearing maturity, i.e. roughly Technology Readiness Level 6 (TRL6) in 2015, 2020, and 2025 respectively. The goals being aimed at for these programs are shown in Table 2, relative to a 2005 baseline.

GOALS	N+1 = 2015 Technology Benefits Relative to a Single Aisle Reference Configuration	N+2 = 2020 Technology Benefits Relative to a Large Twin Aisle Reference Configuration	N+3 = 2025 Technology Benefits
Noise (cumulative below stage 4)	-32 dB	-42 dB	-71 dB
LTO NOx Emissions (below CAEP 6)	-60%	-75%	better than -75 %
Performance: Aircraft Fuel Burn	-33%	-50%	better than -70 %
Performance: Field Length	-33%	-50%	exploit metroplex concepts

Table 2: NASA N+ Goals [16]

2.3 ICAO CO_2 STANDARD

For a long time fuel costs, which usually represent the largest single item in an airline's operational costs, have been considered to be a sufficient driver for improving fuel and CO_2 efficiency and the related technology developments. Nevertheless, the need for a standard to regulate aircraft CO_2 emissions was seen at ICAO. Therefore, at its 37th session in October 2010 the ICAO Assembly decided to develop an ICAO aircraft certification standard for CO_2 emissions [17], similar to the existing standards for noise and engine emissions (nitrogen oxides, carbon monoxide, unburned hydrocarbons, smoke). The aim of the CO_2 standard is to foster the development and use of fuel-efficient technologies and designs by aircraft and engine manufacturers.

ICAO is developing a CO_2 standard for future aircraft certification.

The standard is being developed in a multi-stakeholder task group within the ICAO Committee on Aviation Environmental Protection (CAEP), with IATA participation. In July 2012 CAEP agreed upon a CO_2 metric system to be used in the certification standard [2]. This metric system is a measure of the fuel burn performance of the aircraft to be certified, which is proportional to its CO_2 emissions. Aircraft equipped with more advanced fuel-efficient technologies (structural, propulsion and aerodynamics) should be better valued under the CO_2 metric system than less advanced ones, while aircraft of comparable technology generation should also have comparable metric values. The parameters entering into the CO_2 metric system are:

- Cruise point fuel burn performance
- Aircraft size
- Aircraft weight

The metric system will have to be officially approved by the ICAO Council before publication, which is expected for late 2013.

The development of the CO_2 standard is currently ongoing with the definition of certification procedures, the scope of applicability and a regulatory limit, which will respect the criteria for ICAO environmental standards of technical feasibility, environmental benefit, cost effectiveness and the impacts of interdependencies.

In addition to the CO_2 certification standard, ICAO is working on the implementation of market-based measures to international aviation. While a single market-based measure for aviation may be necessary as a gap-filler to achieve the industry's climate change targets, including capping net emissions at 2020 levels (carbon neutral growth 2020), market-based measures are not expected to drive technological developments. ◆

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3. THE TERESA PROJECT

As mentioned in the introduction, the technology pillar is expected to yield a very large contribution to achieving the aviation industry's emissions reduction goals. A large number of individual technologies are under consideration for implementation in future aircraft and engines. In order to assess and quantify their expected benefits in an operational framework, IATA launched its TEchnology Roadmap for Environmentally Sustainable Aviation (TERESA). While many high-level forecasts of the future fuel consumption and efficiency of aviation use a top-down approach by extrapolating prior improvement rates, TERESA follows a strict bottom-up process, based on the combined effect of individual technologies and their implementation roadmap into the world fleet.

The project was carried out in close cooperation between IATA, the German Aerospace Centre (DLR) and the Aircraft System and Design Laboratory (ASDL) of the Georgia Institute of Technology (Georgia Tech). Moreover, representatives from all relevant aviation stakeholders, namely manufacturers, scientists, government agencies, infrastructure providers and airlines were involved in collecting information on a broad scope of fuel-efficient technologies and in assessing their potential for contributing to the aviation carbon emission reduction goals. The research establishments DLR and Georgia Tech evaluated the impacts on aircraft operations with the help of specifically developed models.

IATA's TERESA project follows a strict bottom-up process to evaluate future aircraft's fuel efficiency.

The TERESA project includes four phases, as illustrated in Figure 9.

Phase 1, conducted in 2008, consisted of two main activities:

1. Survey of a large set of technologies that could reduce the environmental impact of aviation, and
2. A high level qualitative assessment by representative subject matter experts from industry and research, that related the surveyed technologies to the IATA's goals.

The outcomes of this phase were used to create a strategic roadmap which was published as the IATA Technology Roadmap Report in 2009 [1].

Phase 2 of the project focused on a subset of most promising aircraft technologies selected in Phase 1. The impacts of each technology were expressed utilizing up to 14 technology factors (on airframe and engine level) which were parametrically modeled in a physics-based environment (e.g. technology X will reduce the baseline aircraft wing weight (fuselage weight, electrical weight, induced drag, friction drag, etc.) by 10%). With the help of Monte-Carlo Simulation the most effective technology combinations for either the estimated development risk or the estimated development costs were determined [2].

Phase 3 used the results of the technology modeling on aircraft level to include the calculated fuel burn improvement per aircraft into a World Fleet model to derive the fuel burn reduction potential for 8 different aircraft sizes [3].

Phase 4 is focusing on the special relationship between aircraft manufacturers and airlines. Based on a reflection of previous aircraft programs and their technology advancements, it is tried to deduct drivers which positively influenced the development programs, ranging from requirement setting over aircraft production to implementation of the new product in the airlines' fleet. ◆

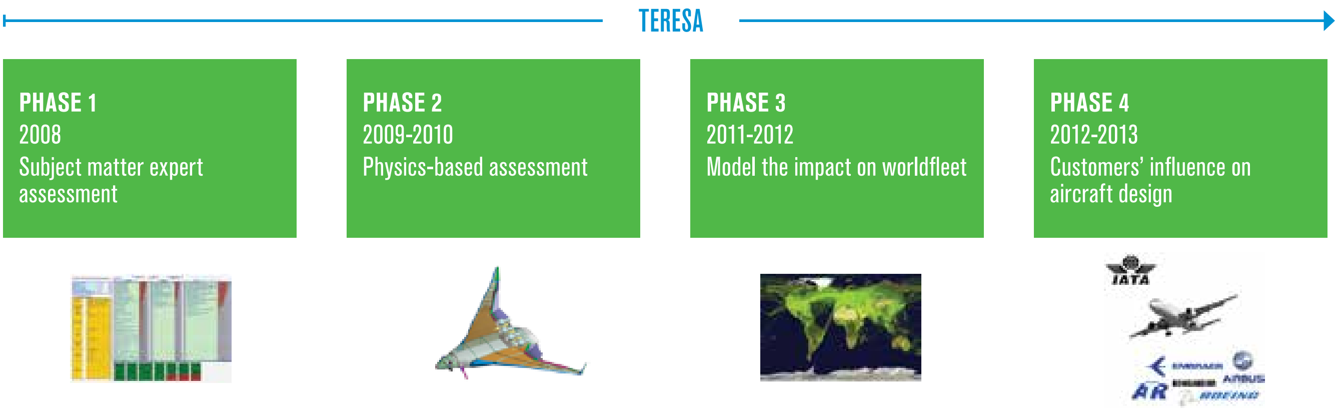

Figure 9: The phases of TERESA

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4. TECHNOLOGY EFFICIENCY

This chapter starts with an overview of individual technologies improving the fuel efficiency of an aircraft. In order to refine the estimates of fuel efficiency for real operations, aircraft equipped with combinations of selected technologies flying typical missions are simulated with a performance model. Results are shown for future aircraft that are representative for various time horizons (retrofits of current in-service aircraft only, upgrades of serial production types, new aircraft families before and after 2020). While this chapter deals with single-aircraft efficiency, the technology impact on the future world fleet's fuel burn will be investigated in Chapter 6.

4.1 TECHNOLOGY OVERVIEW

A broad scope of different technologies contributes to aircraft fuel efficiency improvement and emissions reduction, mainly from the areas:

- Airframe (aerodynamics, lightweight materials and structures, equipment systems, new configurations)
- Engines

Numerous relevant technologies have been identified at the beginning of the TERESA project. In preparation of the 2009 IATA Technology Roadmap a workshop with engineering experts was held where estimates of their respective fuel efficiency improvements were collated [1], which were later cross-checked with literature values. Table 3 and Table 4 show a recent update of the technology lists. More detailed descriptions of all these technologies and their fuel efficiency potential, including their effect on other environmental impacts (noise, pollutant emissions) and on aircraft operations (such as cruise speed limitations, increased maintenance etc.) can be found in the Technical Annex.

While the 2009 roadmap contained technologies from the four areas of airframe, engine, air traffic management and alternative fuels, the present report comprises only airframe and engine technologies. Effects from these two technology fields can be modeled utilizing higher fidelity aircraft design tools; also emissions reductions due to improvements in air traffic management and to the use of drop-in low-carbon fuels are largely decoupled from the aircraft fuel efficiency. The following tables (Table 3 and Table 4) just contain information on the current TRL level of the technologies; the indicated years of introduction were calculated using the typical times needed for achieving the different TRL levels as described in Chapter 7.1. Compared to the 2009 Technology Roadmap Report, a number of recent technologies have been added, which are indicated in bold characters.

The reader should be aware that the time horizons in the column "availability" in Table 3 and Table 4 (and introduced in more detail in Chapter 4.3.2) indicate the year when a technology could reach the maturity necessary for entry into service of an aircraft equipped with this technology (TRL8), assuming a normal pace of development and the availability of a target aircraft.

These time horizons were introduced at the beginning of the TERESA project in 2008, in view of the expected new aircraft introduction timetable "valid" at that time, in particular with completely new single-aisle aircraft from both big manufacturers before 2020, which was seen as a target aircraft for many new technologies. Due to changes in the market and a large shift to re-engined aircraft models instead of new developments the availability of technologies currently under development is now often decoupled from the availability of aircraft programs which can host the new technologies.

Furthermore one has to bear in mind that a lot of technologies require a whole new aircraft design to be applicable; as a result a technology or a concept might be ready at some point in the future with no aircraft program hosting their potential and making the calculated fuel burn reductions available to the world fleet. Therefore one cannot automatically assume that a technology will be implemented at the time indicated in Table 3 and Table 4 and contribute its benefits to reducing the emissions of the world fleet. A potential delay to the entry into service of the next relevant target aircraft must be taken into account.

A broad scope of fuel-efficient airframe and engine technologies and concepts has been assessed.

Group	Concept	Technology	Applicability to aircraft program	Fuel Reduction Benefits	Current development status (TRL #)	Availability of technology (calculated)
Aircraft Configuration	Truss-Braced Wing / Strut-Braced Wing		after 2020	10 to 15%	2	2028
	Hybrid-Wing-Body		after 2020	10 to 25%	4	2026
	Cruise-Efficient STOL		after 2020	< 1%	3	2027
	Morphing Airframe		after 2020	5 to 10%	3	2027
	Flying without landing gear		after 2030	10 to 20%	1	2032
Aerodynamics	Advanced Wingtip Devices	Wingtip Fence	retrofit	1 to 3%	9	2012
		Blended Winglet / Sharklets	retrofit	3 to 6%	9	2012
		Raked Wingtip	retrofit	3 to 6%	9	2012
		Split Winglets with scimitar tips	retrofit	2 to 6%	7	2022
		Spiroid Wingtip	after 2020	2 to 6%	7	2022
	High Lift Devices	High-Lift / Low-Noise Devices	after 2020	1 to 3%	4	2026
		Variable Camber Trailing Edge	before 2020	1 to 2%	9	2012
		Dropped Spoiler	before 2020	1 to 2%	9	2012
		Hinge-less Flap	after 2030	1 to 2%	3	2027
	Drag Reduction Coatings	Drag reduction coatings	retrofit	< 1%	9	2012
		Turbulent Flow Drag Coatings (Riblets)	retrofit	1%	8	2015
		Aircraft Graphic Films	retrofit	1%	9	2012
	Natural Laminar Flow		after 2020	5 to 10%	7	2022
	Hybrid Laminar Flow		after 2020	10 to 15%	7	2022
	Variable Camber with existing control surfaces		before 2020	1 to 3%	8	2015
	Variable Camber with new control surfaces		after 2020	1 to 5%	5	2024
Structural	Active Load Alleviation		before 2020	1 to 5%	9	2012
	Composite Primary Structures		before 2020	1 to 3%	9	2012
	Composite Secondary Structures		before 2020	< 1%	9	2012
	Smart wing technologies, smart actuators		after 2020	1 to 5%	6	2023
	Morphing Wing		after 2030	2 to 8%	5	2024
Cabin	High power LEDs for cabin lighting		retrofit	< 0.5%	9	2012
	Wireless/Optical connections for Inflight-Entertainment		retrofit	< 0.5%	9	2012
	Light weight cabin interiors		retrofit	1 to 5%	9	2012
	Windowless Design		after 2020	5 to 7%	4	2026
System	APU	Lithium Batteries for secondary power	after 2020	< 1%	5	2024
		More efficient gas turbine APU	after 2020	1 to 3%	7	2022
		PEMFC (Proton Exchange Membrane Fuel Cells)	after 2020	1 to 5%	6	2023
		SOFC (Solid Oxide Fuel Cell)	after 2020	1 to 5%	5	2024
		SAFC (Solid Acids as Fuel Cell)	after 2030	1 to 5%	2	2028
	Landing Gear	Landing Gear Drive (Wheel Tug)	before 2020	1 to 2%	8	2015
		Taxi Bot	retrofit	1 to 4%	7	2022
		Adjustable Landing Gear	before 2020	1 to 3%	8	2015
	Flight Control System	Advanced Fly-by-Wire	before 2020	1 to 3%	8	2015
		Fly-by-Light	after 2020	1 to 3%	6	2023
		WFCS (Wireless Flight Control System)	after 2020	1 to 3%	5	2024
	More electric aircraft (mea) architecture		before 2020	1 to 5%	8	2015
	Zonal dryer		retrofit	< 1%	9	2012
	Energy harvesting device for wingtip sensors		after 2020	< 1%	5	2024
	Energy harvesting device for cabin switches		after 2020	< 1%	5	2024
	System Health Monitoring - diagnostic and prognostic		before 2020	1 to 4%	8	2015

Table 3: Overview of airframe technologies, their current TRL level and their estimated time for introduction, continued on next page

Group	Concept	Technology	Applicability to aircraft program	Fuel Reduction Benefits	Current development status (TRL #)	Availability of technology (calculated)
Material	Glare		before 2020	1 to 3%	9	2012
	CentrAl		before 2020	1 to 3%	7	2022
	Fluoropolymers		after 2020	< 1%	6	2023
	High Strength Glass Microspheres		after 2020	< 1%	6	2023
	Morphing Material (Group)		after 2020	1 to 5%	3	2027
	Advanced Alloys (Group)		before 2020	1 to 3%	8	2015
Processes	Laser Beam Welding		before 2020	< 1%	9	2012
	Friction Stir Welding		after 2020	< 1%	7	2022

Table 3: Overview of airframe technologies, their current TRL level and their estimated time for introduction

For completely new aircraft configurations and concepts (first group) the calculated years of introduction for the concepts of the group "aircraft configuration" in Table 3 are solely based on statistics from previous aircraft programs (for a further introduction see Chapter 7.1). To establish such a concept the development should have reached at least TRL 6 at that time an aircraft manufacturer shows the first signs of launching a new program.

Group	Concept	Technology	Applicability to aircraft program	Fuel Reduction Benefits	Current development status (TRL#)	Availability of technology (calculated)
New Engine Architecture	Geared Turbofan (system arch)		before 2020	10 to 15%	7	2016
	Advanced Turbofan (system arch)		before 2020	10 to 15%	7	2016
	Counter Rotating fan (system arch)		after 2020	15 to 20%	3	2023
	Open Rotor/Unducted Fan (system arch)		after 2020	15 to 20%	5	2019
	New engine core concepts (2nd GEN)		after 2030	25 to 30%	2	2026
	Embedded Distributed Multi-Fan (2nd GEN System)		after 2030	< 1%	2	2026
Advanced Engine Concepts	Fan	Component Improvements	before 2020	2 to 6%	8	2013
		Zero Hub Fan	before 2020	2 to 4%	7	2016
		Very High BPR Fan	before 2020	2 to 6%	7	2016
		Variable Fan Nozzle	after 2020	1 to 2%	7	2016
	Combustor	Variable Flow Splits	after 2020	1 to 2%	5	2020
		Ultra compact low-emission combustor	after 2020	1 to 2%	5	2020
		Advanced Combustor	before 2020	5 to 10%	8	2013
	Compressor	Bling-concept	after 2030	1 to 3%	3	2023
		Blisk-concept	after 2020	1 to 3%	7	2016
	Variable Geometry Chevron		after 2020	< 1%	5	2020
Nacelles and Installation	Buried engines		after 2020	1 to 3%	5	2020
	Reduced nacelle weight		before 2020	1 to 3%	7	2016
Engine Cycles	Adaptive Cycles		after 2030	5 to 15%	2	2030
	Pulse Detonation		after 2030	5 to 15%	2	2030
	Boundary Layer Ingestion Inlet		after 2020	1 to 3%	3	2023
	Ubiquitous composites (2nd GEN)		after 2020	10 to 15%	3	2023
	Adaptive/Active flow control		after 2020	10 to 20%	2	2026

Table 4: Overview of engine technologies, their current TRL level and their estimated time for introduction

4.2 FUTURE CONCEPTS AND TECHNOLOGIES

The quantitative modeling simulation described in Chapter 4.3 focuses on the most promising technologies applicable on today's tube-and-wing aircraft configuration, which are expected to be mature for the new aircraft generation entering into service around 2025. In addition, more advanced technologies including novel aircraft configurations are under development. This chapter gives a number of relevant examples expected to be implemented in the 2030 – 2040+ timeframe.

Within NASA's Subsonic Fixed Wing (SFW) program there are a number of initiatives to look at technology and aircraft concepts for the N+2 and N+3 timeframes (see Chapter 2.2). The majority of the concepts discussed here will be from the N+3 programs, which comprise the most innovative concepts and are aiming at a timeframe of technology introduction between 2030 and 2040 [2].

The European counterpart can be seen in the New Aircraft Concepts Research (NACRE) initiative which was carried out in the years 2004 – 2010. Under this project three different configurations were defined and researched, namely the Pro Green Aircraft, the Payload Driven Aircraft and the Simple Flying Bus [3]. Nevertheless it was decided not to aim at one specific type of aircraft, but instead to develop generic solutions at component level ensuring that the results can be applied to a wide range of new aircraft. For each of the major aircraft components (cabin, wing, propulsion system, and fuselage), aspects such as aerodynamics, materials, structure, engines and systems were investigated to see how they would affect the quality, affordability and environmental performance of air transport in general [4].

4.2.1 FUTURE AIRCRAFT CONFIGURATIONS

STRUT BRACED OR TRUSS BRACED WING

A concept which is again under current attention by research entities [5] and aircraft manufacturers [6] is the strut braced wing (SBW) or truss braced wing (TBW). The concept utilizes a structural support to allow for large span wings without as large an increase in structural weight. By increasing the span the lift is increased and the engine size can be reduced. Recent studies suggest that a SBW configuration can reduce the fuel weight by 15% and a TBW configuration is expected to reduce the fuel weight by almost 20% [6].

ELECTRICALLY PROPELLED AIRCRAFT

A recent preliminary design study intended to fulfill the Flightpath 2050 goals was performed by Bauhaus Luftfahrt [7]. The so called Ce-Liner shall be a 180 – 200 seater with a design range of 600nm, 900nm or 1400nm depending on the desired Entry into Service (EIS) of 2030, 2035 or 2040 and the corresponding technological evolution, mainly regarding batteries. The concept combines multiple new developments considering a C-shaped wing design and an electric propulsion system, see Figure 10. The concept is intended to fulfill the requirements for an emission-free aircraft.

HYBRID WING BODY

The Hybrid Wing Body (HWB) (Figure 11) concept has been existing for decades but has had a recent resurgence [8]. As a mix between the traditional tube-and-wing and a flying wing, the HWB seeks to obtain increased fuel efficiencies through the elimination of the tail section and increased structural efficiency. This is probably the most radical departure from the conventional aircraft that is seriously under consideration by aircraft manufacturers but several negatives have prevented it from being more accepted.

The advantages of the HWB have made it very appealing in answering some of the challenges laid out in the NASA N+3 Goals. In particular the community noise aspect is one in which it particularly excels. Due to the large expanse of structure the body provides a much greater barrier to noise from upper surface engines than what could be accomplished with a tube and wing. While the engine noise itself would be comparable, it would be shielded from the ground and reduce community interference. In a NASA

Figure 10: "Ce-Liner": Air transport concept for a potentially emission-free future [7]

study the HWB was found to have a cumulative -37 dB difference from a 2005 reference tube and wing aircraft [9].

The difficulties with the HWB concept stem among others from the fact that it does not have a circular cross section like the conventional tube and wing. When pressurized at altitude this can put uneven stress on the fuselage and the ability to address this in a lightweight and economical fashion is an issue under current research [8]. Other challenges are e.g. the vertical acceleration on passengers sitting far off the centerline, gate space at airports, evacuation regulations, and the option to apply a family concept onto the design.

Figure 11: Blended Wing Body, as envisioned by DLR

4.2.2 FUTURE ENGINE CONFIGURATIONS AND ARCHITECTURES

In North America and in Europe various propulsion technology development programs are being considered for application in future engine concepts. Many of these engine concepts are being considered by Boeing for the Subsonic Ultra Green Aircraft Research (SUGAR) program and by Airbus for its equivalent NSR (new short-range) aircraft concept. This falls within the NASA N+3 timeframe described above. In particular research is aimed at the areas engine cycle, combustion, materials, and acoustic.

Radically new aircraft configurations are being developed for the time beyond 2030, including electric propulsion.

The future engine technologies are expected to have a significant impact on the reduction of greenhouse gas emissions. This section will introduce six different future engine architectures that can be expected to have in some cases more than 50% reduction in fuel burn after 2030 [10].

OPEN ROTOR

The Open Rotor (Figure 12) is a concept that has been investigated for a long time and was already introduced on technology demonstrators (Boeing B7J7 and McDonnell Douglas MD 94x) at the end of the 1980s. Back then it did not make its way into production, as is often cited, due to noise and reliability issues and the decrease in oil price. But now it is looking to buy its way back into future aircraft designs [11]. With several propeller shafts the thrust to weight ratio of the engine can be significantly increased over a similar turbofan. There is some weight penalty due to the gearbox necessary to drive the propellers as well as controllers to modify the pitch of the blades. The other

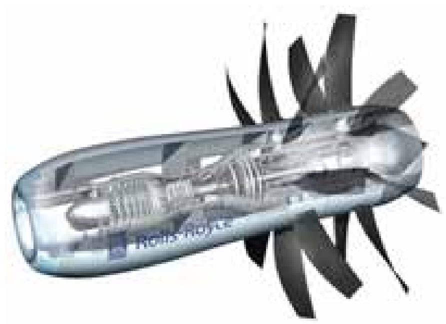


Figure 12: Innovative Engine Demonstrator Flying, A340-600 CROR test bed (above) [13]; counter rotating open rotor (CROR) as envisioned by Rolls-Royce (below) [14]

major deficiency in this configuration is the noise and safety (blade-off) penalty which will result from the external rotors. Airframe shielding could be used to moderate this impact [12].

ELECTRIC PROPULSION

The propulsion systems utilized on the N+3 concepts generally fall into 2 different classes. The first is a small electric motor which is connected to the fan through a gearbox. The batteries required are housed in nacelles which allow for easy replacement between flights due to the long recharge times required. The sizes of the fans are much larger than they would be necessary for a standard gas turbine engine in order to offset the increased weight of the battery packs which must be hauled throughout the flight [15].

The second type of motor is a hybrid fuel cell gas turbine which utilizes a single spool gas turbine for takeoff and climb and the fuel cell for cruise [16]. It is believed that in this configuration a 70% thermal efficiency is possible. Both systems are connected to the same fan with the gas turbine utilizing a gearbox. Due to the complexity of this design there is still much study and work to be done to bring it to a usable state.

DISTRIBUTED PROPULSION

Distributed propulsion (Figure 13) is an engine configuration which separates the propulsion systems out to several small systems which are spread out across the aircraft. This concept allows for the required thrust but without having large, heavy, drag inducing pieces and can even allow for the fans to be integrated into the structure. Typically distributed propulsion is accomplished through the use of several large propulsion units which are buried in the fuselage and drive a distributed set of smaller fans. In addition, if the fans are distributed along the span of the wings like on a HWB then the potential using them as controls by varying the thrust exists [18].

PULSED DETONATION

In a normal combustor compressed air is continuously heated to cause a temperature rise with a small decrease in pressure. However, in a pulsed detonation engine the air is allowed to fill a vessel and then a discontinuous (pulsed) detonation occurs which raises the pressure and the temperature. This can allow for large fuel burn improvements but is a technology which requires significant extra weight to be added to the combustor and the increased flame temperatures can lead to an increase in NOx emissions [16] and [17].

BOUNDARY LAYER INGESTION (BLI)

Boundary layer ingestion is the ability of an engine to have the boundary layer coming off another surface such as the aircraft fuselage to contact the fan and not cause disruptive interference. If this can be accomplished then the propulsion units can be moved closer to the wings or fuselage which would decrease structural weight and drag associated with large pylons. For HWB aircraft having the engines as incorporated into the airframe as possible is essential which makes BLI almost an enabling technology [18].

ENGINE COOLING TECHNOLOGIES

Cooling the engine at various points has been an area of technology research for some time. One concept is to have the air coming through the compressor be cooled prior to combustion. Using a heat sink approach will allow for heat to be removed from the flow with a pressure loss as well. Current research is focused around understanding the performance implications for this type of technology. Using an endothermic fuel [20] has also been discussed to allow for a heat sink effect as well as low NOx production [15].

4.2.3 FUTURE TECHNOLOGIES

The Technical Annex contains a wealth of information on future aircraft technologies. Therefore the interested reader is advised to have a more thorough look at the Technical Annex for a more detailed description of the technologies which are currently under observation.

Figure 13: Distributed Propulsion in a HWB (NASA [19])

4.3 TECHNOLOGY PERFORMANCE MODEL

To improve fuel efficiency forecasts for the present Roadmap, an aircraft performance modeling tool[5] was used to determine the fuel efficiency of future aircraft equipped with different meaningful combinations of selected technologies when operating on typical flight routes. The most relevant technologies from Table 3 and Table 4 were selected to be included in this model as described in Section 4.3.2. The main elements of the technology performance model are described hereafter.

4.3.1 REFERENCE VEHICLES AND MISSIONS

Technologies required to minimize emissions might differ for varying commercial missions. Thus, a short and a long-range aircraft on a respective typical mission will be used as reference configurations to assess the technologies. The reference configurations are described in Table 5. Figure 14 shows the two reference aircraft as well as their respective cabin layout. Note that a flight length of 1000 nm was selected as reference mission for the short-range aircraft; this corresponds e.g. to a trip from Frankfurt to Istanbul, which is an average flight length in this category – although relatively long at a European scale, it is shorter than many "short-range" routes in North America or Asia. The long-range reference mission, corresponding to a range of 3500 nm, represents a trip from Frankfurt to New York. Both reference missions are illustrated in Figure 15.

Configuration	Reference aircraft	Passengers	Mission length	Max range	Cruise speed	Take-off field length
Short-range	A320-200	150	1000 nm	5000 km (2700 nm)	Ma 0.78	2000 m
Long-range	A330-300	300	3500 nm	15000 km (8100 nm)	Ma 0.84	3500 m

Table 5: Specification of the reference configuration

Figure 14: The short-range and long-range reference vehicles and their seating layout

5. In this study the preliminary aircraft design tool PrADO (Preliminary Aircraft Design and Optimization tool), which was originally introduced at the Technical University of Braunschweig, was used [21][22].

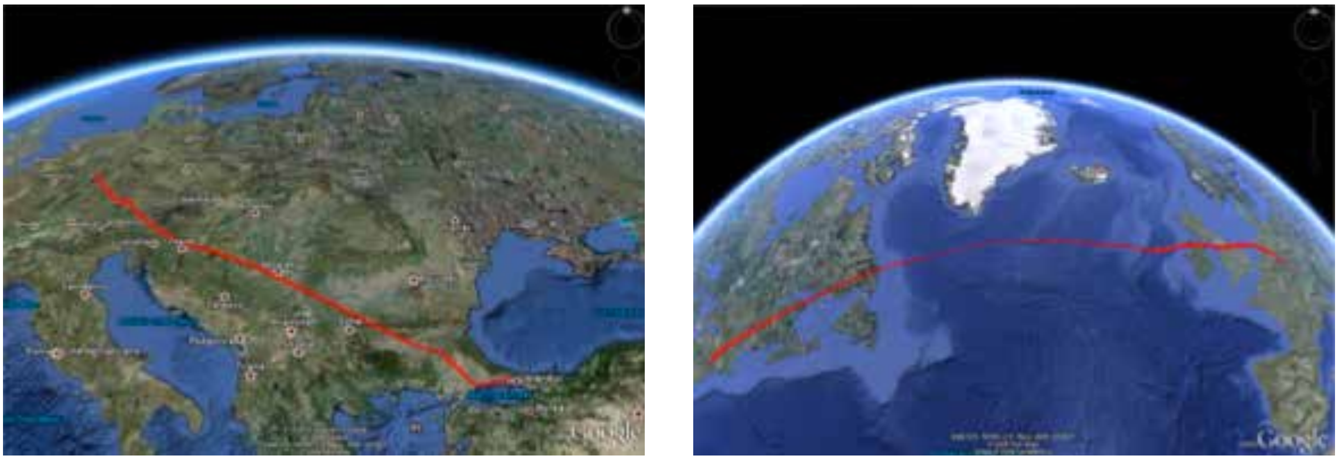


Figure 15: The reference missions for short-range (left) and long-range (right)

4.3.2 TECHNOLOGY SELECTION AND TIME HORIZONS

Sixteen technologies were selected as the most relevant and robust against various scenarios in the short to mid-term and used for the calculation of the CO_2 emission reduction potential. See Figure 16 for a listing. Note that lightweight material technologies are counted independently for application to wing, fuselage and empennage because of the significant impact on the weight breakdown of the aircraft. Since modeling of "extreme" configurations is not possible without massive changes to the existing aircraft template files (A320 and A330) and moreover no reference models for the calibration and assessment of these "extreme" configuration exist, it was decided to simulate only classical tube-and-wing aircraft configurations with wing-mounted engines, neither open-rotor engines nor more radical aircraft concepts such as the blended wing body are modeled and are therefore not included in the scope of selected technologies, although they are expected to be of high importance in the long term.

Aircraft equipped with new technologies were modeled on typical flight operations.

	General Technologies
T1	Natural Laminar Flow Control
T2	Hybrid Laminar Flow Control
T3	Active Load Alleviation
T4	Variable center
T5	Fuel Cells for Secondary Power
T6	Lightweight Cabin Interiors
T7	Riblets
T8	Laminar Flow Drag Coatings
	Wing
T9	Central
T10	Composite Primary Structures
T11	Advanced Aluminum Aerostructures
T12	Al-LI Alloys
	Fuselage
T13	Central
T14	Composite Primary Structures
T15	Advanced Aluminum Aerostructures
T16	Al-LI Alloys
	Empennage
T17	Central
T18	Composite Primary Structures
T19	Advanced Aluminum Aerostructures
T20	Al-LI Alloys
	Engine
T21	Advanced Turbofan
T22	Geared Turbofan
	Additional Technologies
T23	Winglet
T24	Structural Health Monitoring

Figure 16: Technologies considered for quantitative analysis

Similar to the previous edition of the IATA Technology Roadmap [1], these technologies are grouped into various categories related to different time horizons (see Figure 17):

1. technologies that can be retrofitted to current in-service aircraft,
2. technologies that can be integrated to current production aircraft,
3. technologies that can be integrated to new design before 2020,
4. technologies that can be integrated to new design after 2020,

The shift of the new short range replacements well beyond 2025 by aircraft manufacturers, made it necessary to include a fifth group for the technology clustering , which reads,

5. breakthrough technologies after 2030.

Since the publication of the 2009 Technology Roadmap, both major airframe manufacturers have announced a shift of their fully new single-aisle programs well beyond 2025 [11] (the Airbus A320 successor, currently named A30X, and the Boeing 737 successor, also called Y1). This shift has a significant influence on the penetration of new fuel-efficient aircraft into the world fleet and thus on the evolution of the global carbon footprint of aviation over the next 15 to 20 years. Also the research and development programs of aircraft, engine and system manufacturers might be slowed down or reduced if the target aircraft time scale is delayed.

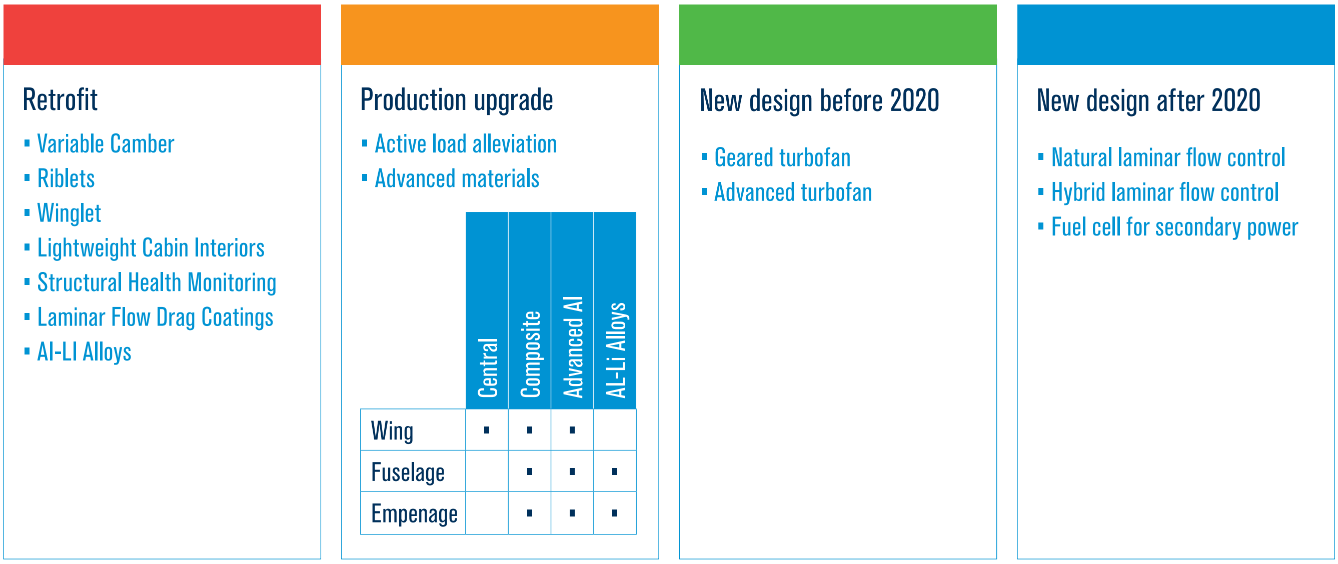
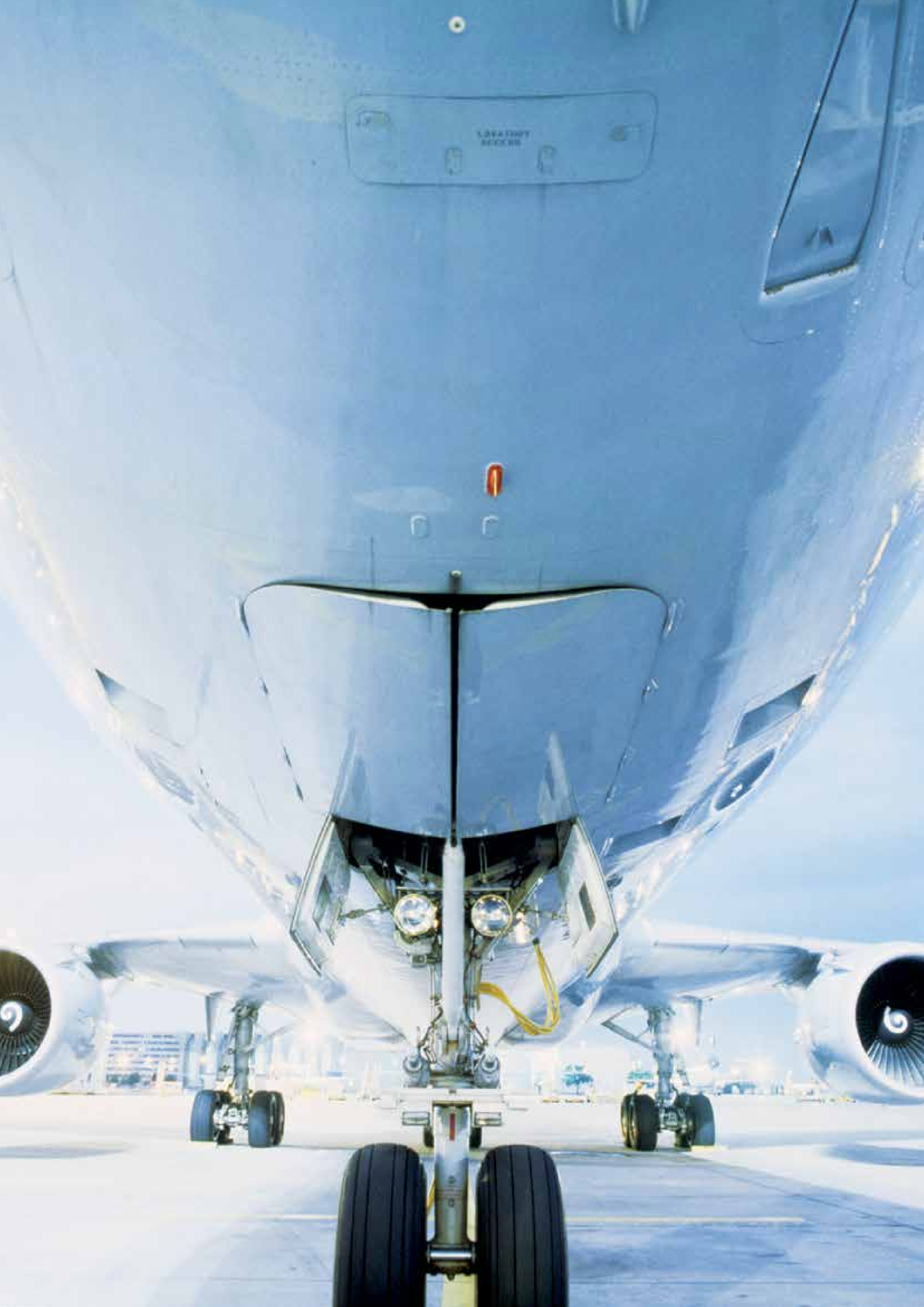


Figure 17: Technology groupings per integration categories



4.4 RESULTS

4.4.1 COMPARISON OF QUALITATIVE AND QUANTITATIVE RESULTS

The results obtained with the technology performance modeling described above were compared with the earlier qualitative assessment in terms of the fuel reduction potential per aircraft given in percent compared to the 2005 baseline aircraft.

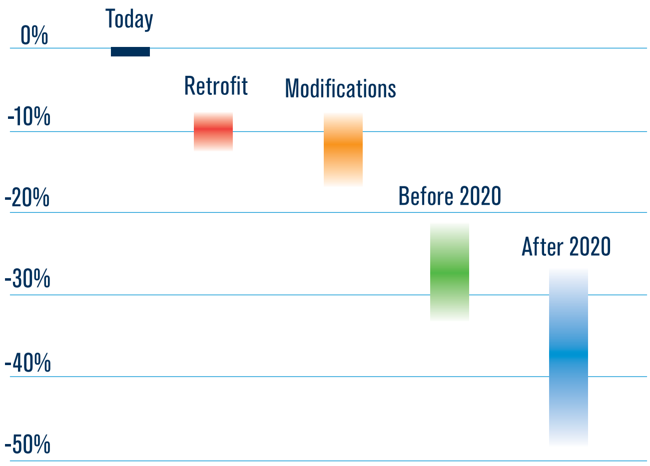


Figure 18: Results of the qualitative assessment (see first Roadmap report [1])

Since the publication of the previous IATA Technology Roadmap in 2009, both major airframe manufacturers have shifted their new single-aisle programs well beyond 2025 [11]. Therefore two calculations have been made, one based on the currently valid new aircraft model delivery schedule (solid bars in Figure 19) and another one, purely for comparison purposes, based on the schedule valid in 2009 (dashed bars in Figure 19). The usefulness of the latter result is mainly to show the good agreement of the qualitative engineering estimates (Figure 18) with a more refined quantitative analysis (Figure 19). Chapter 5 will show that also other technology assessments by various groups yield similar results, and in Chapter 6 an assessment of the impact of fuel-efficient technologies on the currently valid timeline of new aircraft programs will be given.

The agreement between qualitative and quantitative assessment is particularly good for the first three time phases until 2020, for which the forecast is already relatively accurate. In general the qualitative analysis slightly overestimates the quantitative results (see Table 6), mainly because integration effects are accounted for more accurately and only a limited number of selected technologies is taken into account for the quantitative assessment. Furthermore the performance model could only describe classical tube-and-wing designs with wing-mounted engines. This prevented modeling more radical configurations such as open rotor or blended wing body. The CO_2 reduction potential of radical technologies is shown in Table 6 as a rough estimate based on the inputs from 2009, which are still seen as valid.

SHORT RANGE QUANTITATIVE ASSESSMENT **LONG RANGE QUANTITATIVE ASSESSMENT**

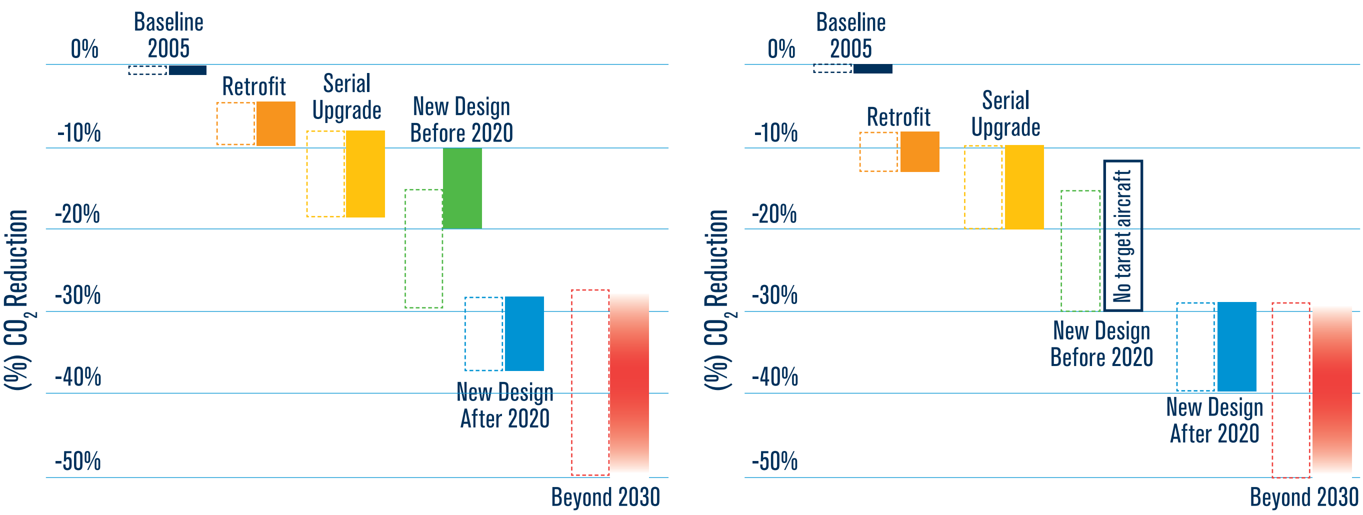


Figure 19: Quantitative assessment for short-range and long-range aircraft (solid bars: results based on the current 2013 new aircraft model EIS outlook; dashed bars: results based on the EIS outlook valid in 2009, for comparison with the 2009 IATA Technology Roadmap)(see [23])

	Qualitative		Quantitative SR		Quantitative LR	
	Min	Max	Min	Max	Min	Max
Retrofit*	-7%	-13%	-5%	-10%	-6%	-12%
Serial upgrade	-7%	-18%	-9%	-18%	-10%	-20%
New design before 2020 (2009 forecast)**	-20%	-35%	-16%	-29%	-17%	-31%
New design before 2020 (current forecast)			-10%	-21%	no target aircraft	
New design after 2020	-25%	-50%***	-27%	-38%****	-29%	-40%****

* for aircraft without the respective technologies ** for comparison with earlier studies *** including revolutionary technologies
**** not including revolutionary technologies

Table 6: Minimum and maximum gains through technology introduction

4.4.2 TECHNOLOGY MATURITY AND COSTS

The degree of maturity achieved so far for the technologies considered is very different, and so are their development costs. Estimates of:

- the current Technology Readiness Level (TRL)* [24] for each technology (Figure 20)
- a rough order of magnitude of research and development (R&D) investment needed until the technology would be in operation
- the time horizon when the technology would be introduced

were collected from technical experts; the results can be found in Section 4.1 and in more detail in the Technical Annex.

In order to identify meaningful technology combinations within the TERESA project, a correlation was established between the fuel efficiency potential of the new technologies, their estimated development costs (R&D costs) and the risk related to the introduction of a combination of new technologies. To measure the inherent development risk related to a specific technology, the number of development stages missing on the TRL scale from the current technology status up to reach TRL 9 were used. For a combination of technologies, the risk is expressed by the sum of the stages missing up to reach TRL 9 for all technologies within this portfolio. Figure 21 shows a set of different combinations of technologies leading each to a different total risk. In other words one is

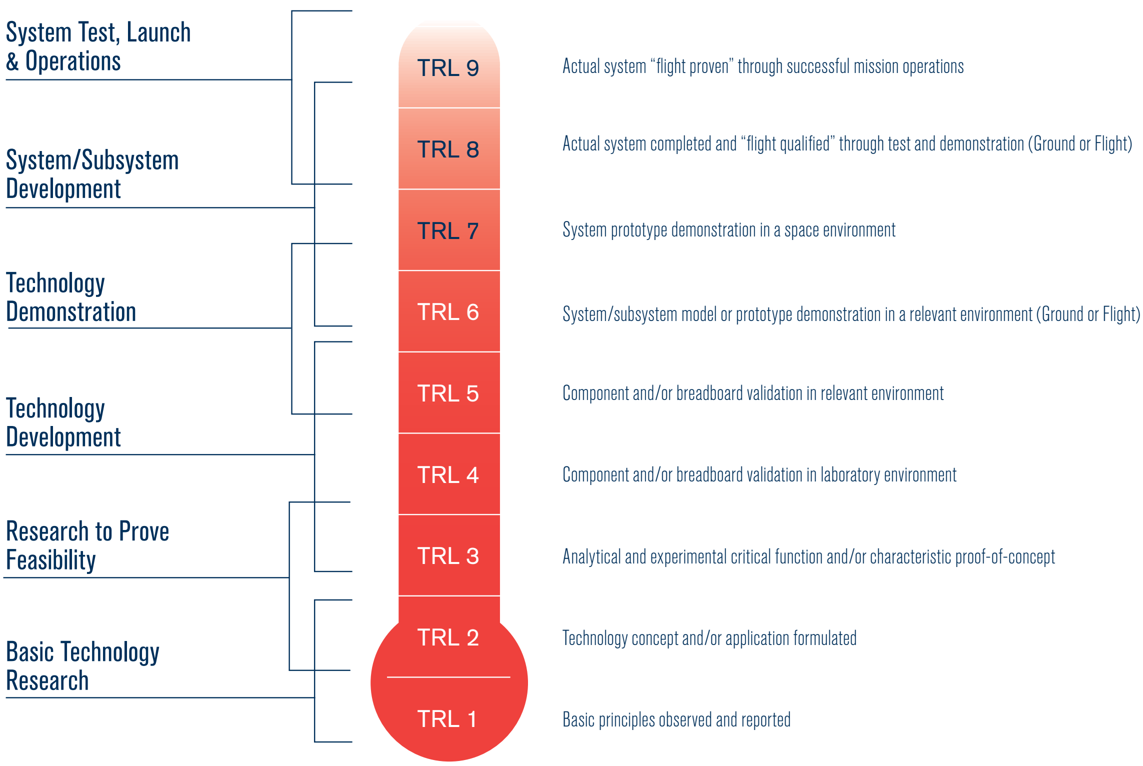


Figure 20: The NASA TRL Meter

searching for the technology combination with the highest gain in CO_2 reduction potential combined with the lowest risk in this context.

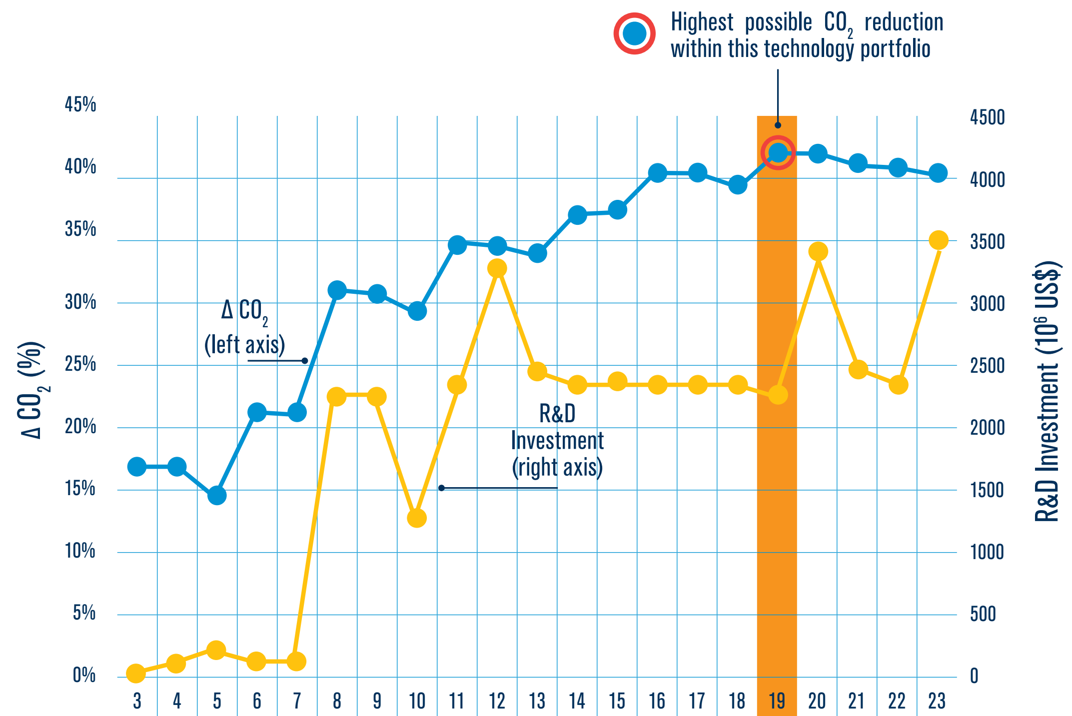
It can be seen in Figure 21 that with the set of technologies considered for the investigated long-range configuration a maximum reduction of 40% CO_2 can be achieved (blue curve). The development risk for the respective technology combination corresponds to a cumulative ΔTRL of 19 to 20. Other combinations of technologies with a higher cumulative risk, do not further increase the CO_2 reduction potential. Using only more mature technologies, i.e. with lower Δ TRL, allows achieving only a smaller reduction potential. Figure 21 also shows the R&D investment required as a function of Δ TRL (yellow curve). It must be noted that it is extremely difficult to forecast development costs of individual technologies for several reasons:

- the risk of unforeseen complications,
- the difficulty of basing estimates on historic cost data, because the efforts for developing a single technology and implementing it into an aircraft design cannot be easily segregated from total aircraft development costs,
- finally an understandable reluctance of manufacturers to publish commercially sensitive data.

Therefore only rough orders of magnitude (US$ 1M, 10M, 100M, 1B) are used in this work, which imply that real costs can differ from the data shown by a factor of 2, 3 or sometimes more. However, qualitative trends and relative cost ranges are reflected.

The figure shows sudden changes in R&D costs when single technologies with high R&D expenses are introduced, e.g. the peaks in R&D effort at Δ TRL of 12, 20 and 23 are all caused by selecting hybrid laminar flow technology instead of the much cheaper natural laminar flow technology.

A detailed listing of technology sets that are most effective with respect to CO_2 reduction is shown in Figure 21. Comparing the most fuel and CO_2 effective technology sets with Δ TRL = 19 and 20 it turns out that both sets differ only in two choices: natural laminar flow technology and composite material for empennage (Δ TRL = 19 technology set) vs. hybrid laminar flow technology and advanced aluminum structure for empennage (Δ TRL = 20). Using the less mature technology set (Δ TRL = 20 instead of Δ TRL = 19) provides a gain in max Δ CO_2 reduction of less than 1% but causes a steep increase of R&D expenses (of very roughly 50%, caused by adding a technology whose development costs are in the order of $ 1bn). The highlighted technology combination therefore appears to be particularly promising in terms of a trade-off between maximum CO_2 reduction potential and R&D expenses. This finding is even clearer considering the fact that the R&D costs for all technology sets from Δ TRL = 11 to 19 are all of the same order or even higher compared to Δ TRL = 19, while the CO_2 savings follow a more or less gradually increasing trend with increasing development risk factor.



			3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Aerodynamics	T1	Natural Laminar Flow Control								■	■		■	■	■	■	■	■	■		■	■	
	T2	Hybrid Laminar Flow Control						■	■			■								■			■
	T3	Active Load Alleviation	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
	T4	Variable Chamber				■	■							■	■				■	■	■	■	■
	T5	Fuel Cells									■	■	■	■	■	■	■	■	■	■	■	■	■
	T6	Lightweight Cabin Interiors	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
	T7	Riblets				■	■							■	■				■	■	■	■	■
	T8	Laminar Flow Drag Coatings						■	■	■	■	■	■			■	■	■					
Wing	T9	CentrAL								■								■				■	■
	T10	Composite Primary	■	■	■	■	■	■	■		■	■	■	■	■	■	■		■	■	■		
	T11	Advanced Aluminum																					
	T12	Al-Li Alloys																					
	T13	CentrAL																					
Fuselage	T14	Composite Primary	■	■		■	■	■	■	■	■	■		■	■	■	■	■	■	■		■	
	T15	Advanced Aluminum			■								■								■		■
	T16	Al-Li Alloys																					
Empennage	T17	CentrAL																					
	T18	Composite Primary	■																■				
	T19	Advanced Aluminum		■	■		■		■			■	■		■		■			■	■	■	■
	T20	Al-Li Alloys				■		■		■	■			■		■		■					
Engine	T21	Advanced Turbofan														■	■	■	■	■	■	■	■
	T22	Geared Turbofan						■	■	■	■	■	■	■	■								
	T23	Winglet	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
	T24	Structural Health Monitoring	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
			3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23

Figure 21: Maximum CO_2 and fuel burn reduction for technology sets with specific cumulative development risk (ΔTRL, blue curve) and related rough order of magnitude R&D costs (orange curve) (upper graph); Most effective technology sets with specific cumulative ΔTRL for Long-range Configuration

If the technology combinations are grouped by their entry-into-service (EIS) time horizon, some clearly distinguished clusters can be observed, as shown in Figure 22 as a function of Δ TRL and in Figure 23 as a function of R&D expenses. Overall, CO_2 reduction potential expectedly increases with EIS being further in the future. A study of fuel efficiency improvement through introduction of future aircraft equipped with new technologies and their impact on the world fleet's CO_2 footprint, taking into account the current EIS calendar of future aircraft types and a forecast of future world fleet and movements, is described in Chapter 6.

High emissions reductions can only be achieved if sufficient efforts are made for new technologies to mature.

Comparing the fuel and CO_2 reduction potential for different aircraft ranges, it is observed that the maximum obtainable reduction for the short-range configuration (38% of reference fuel burn) is around 6% less compared to the long-range configuration (40% of reference fuel burn). This result is consistent, since fuel burn in cruise fully benefits from all fuel-efficient technologies, whereas climb and acceleration require additional energy that is less dependent on these technologies; block fuel reduction can thus best be reduced by technology in long cruise flight. However, the overall distributions of CO_2 reduction potential are almost identical for short and long-range.

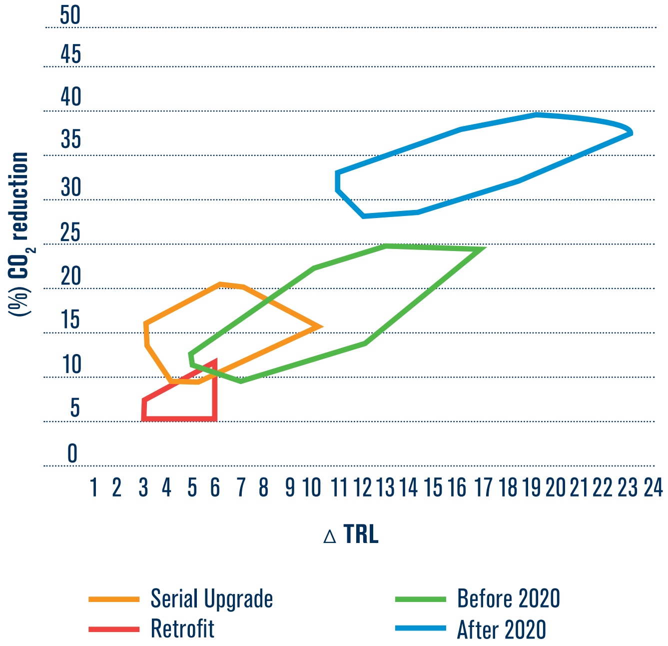


Figure 22: Range of CO_2 reduction potential as a function of ΔTRL for relevant technology combinations at different time horizons.

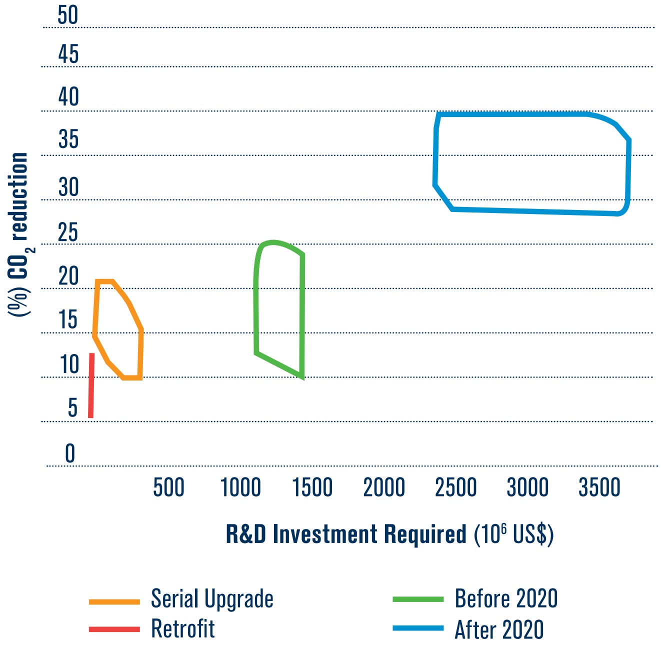


Figure 23: Range of CO_2 reduction potential as a function of R&D investments for relevant technology combinations at different time horizons.

4.5 RECOMMENDATIONS

To summarize, the investigation allowed for a clear identification of robust and promising technologies and revealed only minor differences between short and long-range. All designs should be equipped with winglets and employ structural health monitoring. The identified technology options are, starting with the most mature ones:

- Wing and fuselage should be designed with composite structures.
- Active load alleviation is mandatory on all designs; if technically feasible the option for variable camber should be included.
- Turbulent drag reduction on fuselage should be done with riblets on current production aircraft and all future designs.
- Drag reduction on wing, nacelle and empennage should be realized with laminar flow technology for all designs after 2020, no preference between natural or hybrid option could be identified. Taking into account the R&D investment required the preference would be natural laminar flow technology, wherever feasible in stable flow conditions.[6]
- The preferred engine option before 2020 is geared turbofan, followed by various kinds of advanced turbofans including counter-rotating fans for all designs after 2020. The open rotor could not be analyzed in the model used here. Provided the expected fuel saving potential is realized and the current challenges (in particular noise reduction) are solved, the open rotor should be applied as soon as it is available.
- No clear preference between composite, advanced aluminum or Al-Li alloys for the empennage emerges from the analysis.
- It should be noted that the application of laminar flow control as well as the open rotor might impose a cruise speed limit between Mach 0.7 and Mach 0.75. These operational limitations might restrict the usability of these concepts to short-to-medium haul aircraft.

6. This statement has to be qualified with the hint that there is currently no profound database about natural as well as hybrid laminar flow in daily aircraft operation available. Further research focusing especially on laminar flow and its implications on aircraft operation are necessary. Also, the decision to introduce hybrid laminar technologies or no laminar technologies in unstable areas has to be based on case studies taking into account the information about weight of a hybrid laminar technology system versus the gain in drag reduction.

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AROUND 30-35% PROJECTED REDUCTION IN AIRCRAFT CO2 EMISSIONS FOR THE NEXT DECADE.

5. COMPARISON WITH OTHER ASSESSMENTS

In this section the findings from the TERESA project are compared and benchmarked with existing technology assessments from other research institutions. In particular the work from the ACARE Goals Progress Evaluation (AGAPE), the UK Committee on Climate Change (CCC) and the Independent Expert Study within ICAOs Committee on Aviation Environmental Protection (CAEP) were taken into consideration.

5.1 ACARE GOALS PROGRESS EVALUATION (AGAPE)

An assessment similar to TERESA was conducted with broad participation from the European aviation R&D community in order to assess the technological progress achieved towards fulfillment of the goals laid down in the Vision2020 [1] and the ACARE Strategic Research Agenda (SRA). For the half-term of the 20-year period covered by the SRA (2000 to 2020), the European project AGAPE (ACARE Goals Progress Evaluation) was granted in order to evaluate technologies developed with European funding contributing towards achieving the ACARE goals. A good summary of the AGAPE environmental goals assessment can be found in the final project report [2]. The performance assessment was done by collecting subject matter expert estimates of the capability delivered by the technologies being developed. The subject matter experts were drawn from across the Air Transport stakeholder community.

The analysis was specifically structured in order to answer the following questions:

1. What are the results achieved from 2000 to today?
2. What are the results foreseen from on-going research projects?
3. What are the corresponding gaps for goal completion?

The TERESA results are broadly in line with other independent evaluations

The final AGAPE report is confidential; however, cumulative results have been presented e.g. at the 49th AIAA Aerospace Sciences Meeting (AIAA/ASME) 2011 in Orlando [3] or at the 2011 Aerodays in Madrid [4]. Figure 24 shows the replicated AGAPE results for the environmental ACARE goals: 50% reduction of CO_2, 80% reduction of NOx and reduction of noise by 50%.

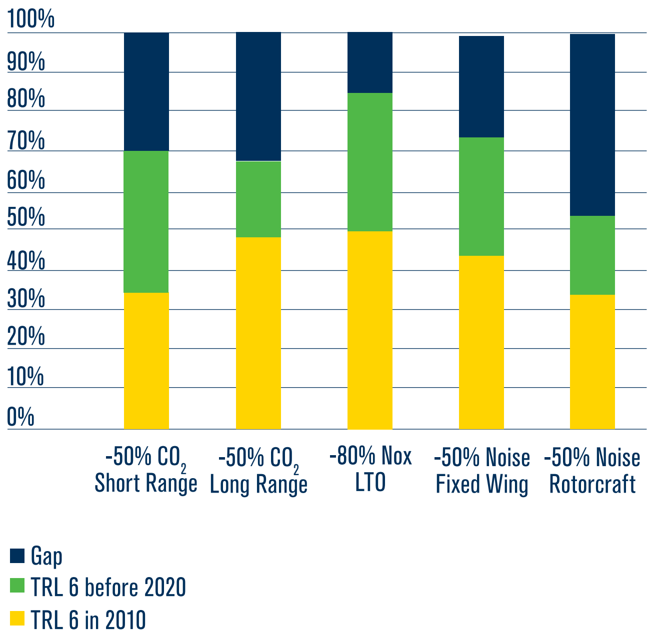

Figure 24: Replicated AGAPE Outcome – Degree of achievement of ACARE environmental goals

The findings relevant to the CO_2 reduction goal can be summarized as follows: For short-range aircraft a 17% reduction of CO_2 has already been validated to TRL 6 (excluding operational measures). If on-going projects are successful as planned, this reduction would increase to around 35% (again without operational measures). For long-range aircraft almost half of the reduction goal has already been secured and a reduction between 30 and 35% is expected to be achievable before 2020.

5.2 UK COMMITTEE ON CLIMATE CHANGE (CCC)

The CCC is an independent body established under the UK Climate Change Act (2008) that advises the UK Government on setting and meeting carbon budgets and on preparing for the impacts of climate change. Within the "UK Aviation Report" from 2009 [5] options are set out for how the UK can meet the 2050 aviation target to reduce emissions to 2005 levels in 2050 and it includes analysis of UK aviation demand and emissions and methods to improve the carbon efficiency of planes. Due to evolutionary improvements on the aircraft such as geared turbo-fan, weight reduction (e.g. greater use of composite materials) or improved aerodynamic features (e.g. winglets) a 40% reduction potential is forecast for the 2020s compared to 2005 level. The fleet average improvement between 2005 and 2050 is forecast to be in the range of 0.7% to 1.2% p.a. per seat-km (without considering operational measures).

5.3 ICAO INDEPENDENT EXPERT STUDY

The seventh meeting of the International Civil Aviation Organization (ICAO) Committee on Aviation Environmental Protection (CAEP/7) held in February 2007 requested advice from Independent Experts (IEs) on the prospects for reduced aviation fuel burn from technology advances over the medium term (ten years, 2020) and long term (twenty years, 2030) [6].

The mandated assessment by the IEs of the reduction in aviation fuel burn from technology advances followed a two-step process: an industry led Fuel Burn Reduction Technology Workshop held in London in March 2009 and then a formal Fuel Burn Reduction Technology Goals Review, held in Atlanta in May 2010 led by the Independent Experts [9]. It was under this second meeting in Atlanta that the results for four different technology scenarios were presented (see Table 7). Due to time and resource constraints it was agreed to only calculate the fuel burn reduction potential on single aisle 110 to 210 seater (like B737-800 and A320-200) and small twin aisle 211 to 400 seater (like B777-200ER and A330) aircraft. Also the operational parameters of the reference aircraft like range, payload, cruise speed, wing span etc. were adopted. Under the two time horizons of 2020 and 2030 three different technology scenarios were introduced (a higher scenario count meaning a more challenging set of technologies being introduced into the reference aircraft).

The results in Table 7, which were determined by universities and research establishments such as Stanford University [7] and the German Aerospace Center (DLR) [8], presented a fuel burn reduction potential for new aircraft between 23% to 41% depending on the aircraft category, timeframe and technology scenario selected.

5.4 COMPARISON AND DISCUSSION

Table 8 shows a comparison of the cumulative results of TERESA with AGAPE, the CCC and the ICAO CAEP investigation. A good agreement is seen for the comparison of the CAEP results with TERESA. The research under the AGAPE and the CCC framework does not cover the exact time horizon (AGAPE baseline is 2000 and CCC target is later than 2020) and therefore does not match the given TERESA timeframe. However, the number of technologies taken into account in AGAPE is higher since all technologies investigated in EU projects in framework programs 5 and 6 are considered. The comparison of the TERESA result for the time period after 2020 with the CCC investigation shows good correlation.

The publicly available documentation for the CAEP, AGAPE and CCC investigations lack detailed technology listings. Thus, a one-on-one comparison of identified CO_2 reduction potential for single technologies is not feasible. The same applies for a comprehensive update of the existing 2008 TERESA technology listing [10]. ◆

	2020		2030	
	Single Aisle	Small Twin Aisle	Single Aisle	Small Twin Aisle
Technology Scenario 1	23%	19%	29%	26%
Technology Scenario 2	29%	25%	34%	35%
Technology Scenario 3			41%	41%
Technology Scenario 3 plus open rotor			48%	

Table 7: The findings of ICAOs Independent Experts study for CAEP [9]

	BEFORE 2020				AFTER 2020			
	Short Range		Long Range		Short Range		Long Range	
	Min	Max	Min	Max	Min	Max	Min	Max
TERESA (2009 forecast)	-23%	-29%	-24%	-29%	-27%	-38%	-29%	-40%
TERESA (2013 forecast)	10%	21%			-27%	-38%	-29%	-40%
AGAPE (Baseline 2000)	-35%		-34%					
CCC					-40%		-40%	
CAEP/IEs	-23%	-29%	-19%	-25%	-29%	-41%	-26%	-41%

Table 8: Comparison of TERESA findings with other investigations

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6. WORLD FLEET MODELING

In this section it is assessed how the introduction of new aircraft equipped with fuel-efficient technologies into the world fleet over time impacts global CO_2 emissions of air transport.

A methodology newly developed by DLR [1] was used for this purpose (see Figure 25). It consists of two separate working blocks:

1. Evolution of the world fleet of commercial passenger aircraft (fleet forecast: steps 1-4).
2. Fuel consumption and performance information of each aircraft model (steps 5-6) → global CO_2 emissions and traffic calculated by aggregating the single aircraft estimates → forecast the evolution of fuel and CO_2 efficiency thanks to new technology.

6.1 WORKING BLOCK 1 – FLEET FORECAST

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

- The first step is to identify today's fleet of aircraft from the ASCEND Fleet Database[7]
- From the detailed information provided by ASCEND, the following year's retirements are then projected for each make and model in the world fleet, based on the specific age of each active aircraft. The retirement process is driven by so-called 'retirement curves', which have been estimated through a survival analysis from historical data for the ICAO Committee on Aviation Environmental Protection (CAEP) [2].
- The next step is estimating the number of additional aircraft needed to satisfy the selected traffic growth scenario (with the help of information on traffic shares in the latest ICAO FESG forecast) [3].
- The sum of aircraft needed for replacement and growth constitutes the next year's aircraft demand = new aircraft deliveries. The original aircraft that are forecast to remain active (i.e. are not retired) plus the new aircraft deliveries (including yet unfixed make and model) make up the new world fleet. This process of simulating yearly fleet changes is repeated until the final year of the forecast period is reached.

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

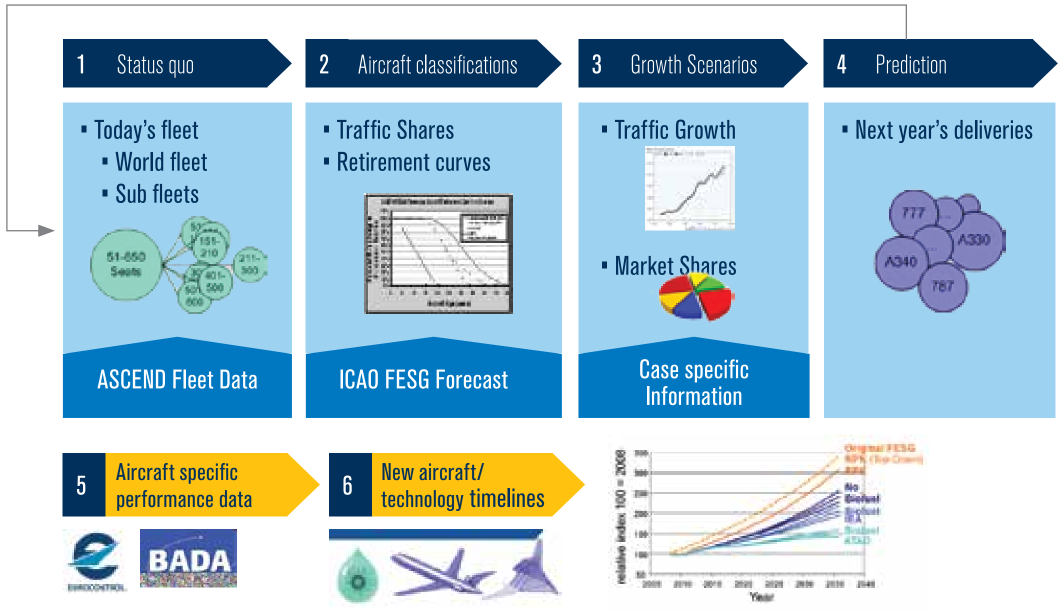

Figure 25: General CO_2 Forecast Schematic: Bottom-up Forecast based on Year-to-Year Dynamics

For the current forecast some additional specific assumptions were made (see Figure 28). The most important assumption concerns future aircraft deliveries (see Table 9). It is assumed that all aircraft that are currently on fix order (i.e. excluding options and statements of interest) are being delivered according to schedule. Very detailed information (e.g. size, make, model, and delivery date) on these aircraft is obtained from the ASCEND database. Further, it is assumed that the current IATA traffic forecast holds in the long-run (see Figure 2). Further aircraft are needed in addition to the aircraft on order to satisfy projected traffic growth over the forecast period up to the year 2030.

Traffic growth in the model is modeled separately for eight different aircraft size categories according to the ICAO CAEP/8 Forecast [3], see Figure 27.

	Year	Manufacturer	Model	Variant
2010 - 2020	2014	Airbus	A350	A350-900
	2014	Bombardier	C-Series	CS-100
	2014	Comac/ACAC	ARJ21	
	2015	Bombardier	C-Series	CS-300
	2016	Airbus	A350	A350-800
	2016	Airbus	A320neo	
	2016	Comac	C919	
	2017	Airbus	A350	A350-1000
	2017	Boeing	A737max	
	2017	Mitsubishi	MRJ	
	2019	Boeing	B777-8	
2020 - 2030	2025	Airbus	A30X	NSR
	2025	Boeing	Y1	NSR
	2030	Boeing	B777 Successor	NLR
	2030	Airbus	A330 Successor	NLR

Table 9: Entry into service timeline for future aircraft

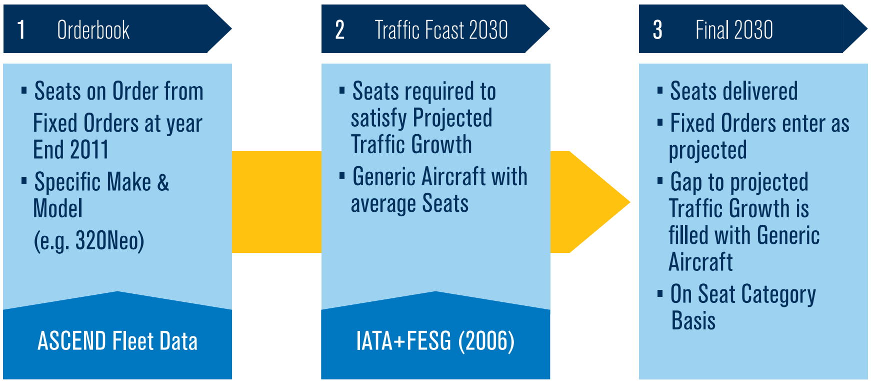

Figure 26: Major Case-Specific Forecast Assumptions for TERESA-Phase III

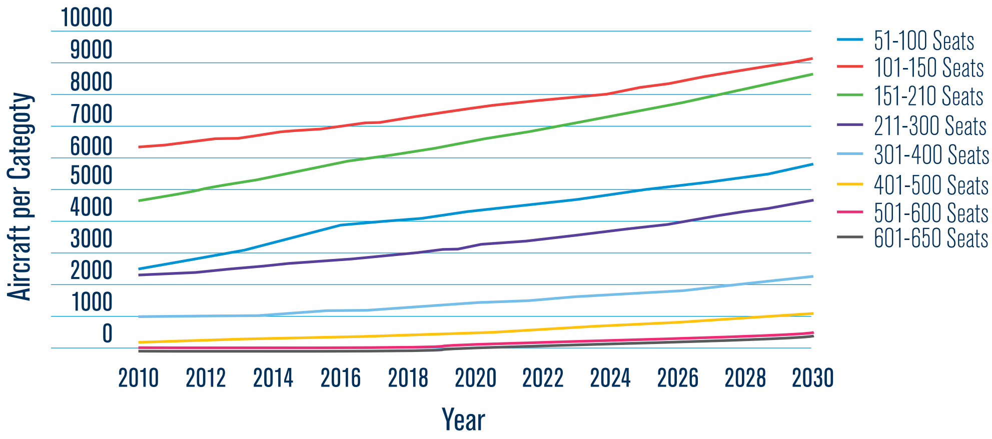

Figure 27: World Fleet Forecast per Seat Category (2010-2030)

After assigning fixed orders (according to the ASCEND information on seat count) to this demand, "unfixed aircraft demand" is left in each seat category. Specific aircraft models are not assigned to this demand, but a "generic aircraft" (i.e. a virtual average aircraft) is used for each seat category.

Figure 28 and Figure 29 show two major results of the fleet forecast done with this approach. Figure 28 shows the forecast size of the global aircraft fleet, while Figure 29 shows projected deliveries per year. In both figures aircraft were grouped into four different categories:

- "Old Technology": out-of-production aircraft such as the MD-80
- "Current Technology": all aircraft that are currently in serial production (e.g. A320, B777 etc.)
- "New Technology": all aircraft models not yet in service that are expected to introduce new, CO_2-relevant technology into the world fleet[8], thus, from a technological perspective, are more advanced than the "Current Technology" group
- "Unfixed Demand" (generic technology): eight generic aircraft (one per each seat category)

The first three groups capture all aircraft with fixed make and model, i.e. aircraft that have been in service or on fix order at the end of year 2011, while the latter group consists of generic aircraft.

8. These include, for example, A320neo, A350, 737max, 787, CSeries, and Mitsubishi MRJ.

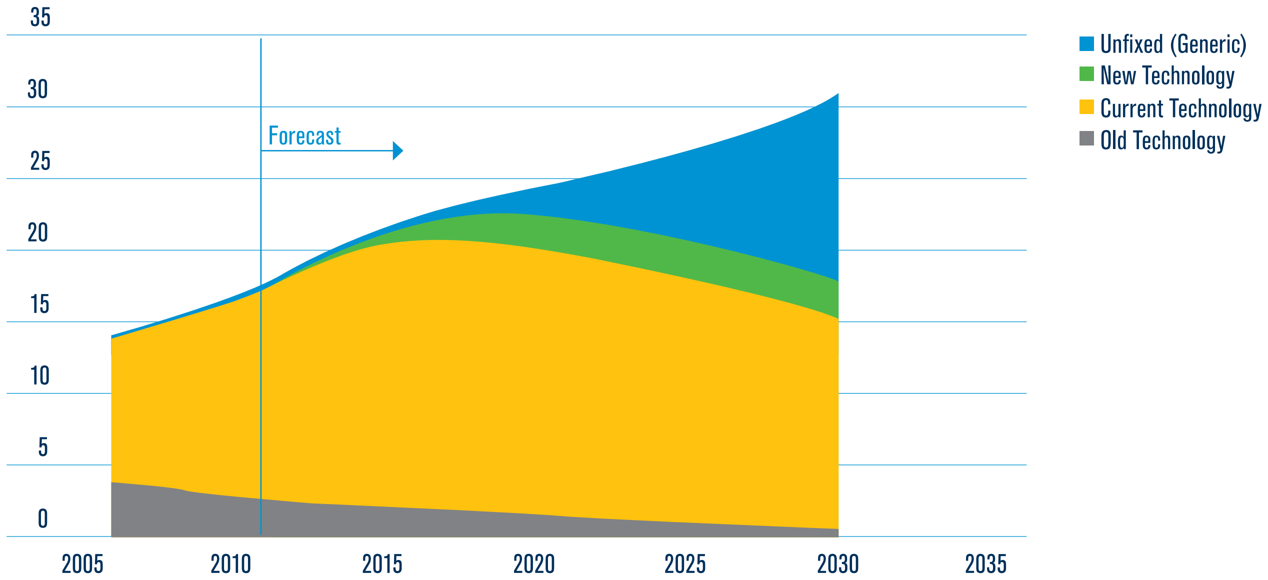

Figure 28: Fleet in Service per Technology Group 2006-2030 (Forecast)

Two important conclusions are immediately obvious from Figures 28 and 29:

- Current technology keeps dominating the active world fleet (Figure 28) over the entire forecast horizon,
- As today's fixed orders take up most of the projected aircraft demand up to the year 2020 (Figure 29), technological uncertainty is relatively small in the next decade.

On the other hand, only a few fixed orders stand at the moment for 2021-2030. It is this "open" demand, which constitutes the "free" technological lever for influencing global CO_2 emissions through new aircraft projects. In Figure 29, it is also shown how this "open" demand is allocated to the different aircraft size categories. Clearly, technological uncertainty is small for the size categories 151-400 seats, where fixed orders satisfy projected demand until or beyond 2020. There is more room for speculation in the smaller (51-150 seats) and very large (401-650 seats) categories. For better accessibility of the results, market shares (shares of total yearly deliveries per technology group and size category) are displayed in Figure 30.

In 2030 half of the world fleet will be new-technology aircraft .

6.2 WORKING BLOCK 2 – TECHNOLOGY AND GLOBAL CO_2 EMISSIONS

To assess the influence of new technology (fleet renewal) on global CO_2 emissions, yearly fuel consumption and traffic is assigned to each active aircraft. For existing aircraft of given make and model, the EUROCONTROL Base of Aircraft Data (BADA) Aircraft Performance Model (APM) is used[9]. In particular, the block fuel consumption is estimated using BADA Datasets[10] a given flight distance and a given payload, to generate a huge dataset over the entire operational range of an aircraft type. For distance, load factor, and flights we take the average values of the corresponding size categories (different for each year) from the ICAO CAEP/8 forecast.[12]

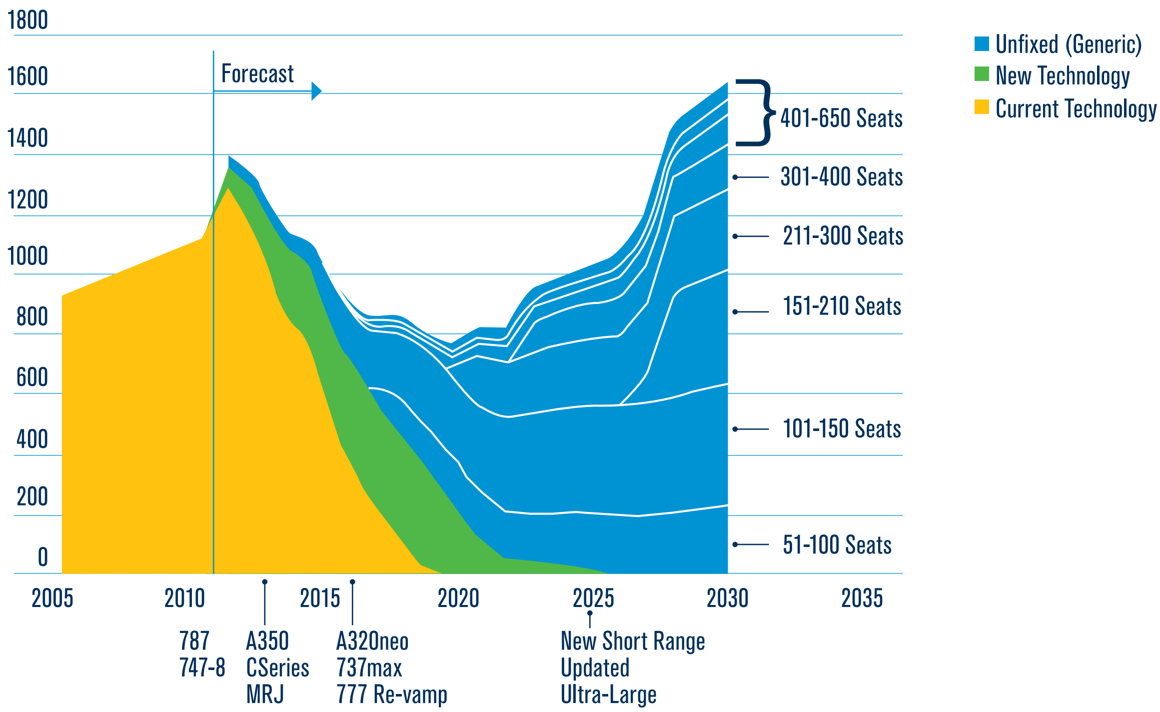

Figure 29: Yearly Deliveries per Technology Group and Seat Category 2006-2030 (Forecast)

On the BADA dataset we estimate, for each aircraft model i, a "fuel function" of the form:

$$\textbf{blockfuel}_i = \beta_{io} + \beta_{i1} \times \textbf{distance} + \beta_{i2} \times \textbf{payload} + \beta_{i3} \times \textbf{distance}^2 + \beta_{i4} \times \textbf{payload}^2 + \beta_{i5} \times \textbf{distance} \times \textbf{payload}$$

These fuel functions represent the original calculation very well, with an average coefficient of determination $R_2 > 0.99$.[11]
Yearly fuel consumption is then estimated as $yearlyfuel_i = flights_i \times blockfuel_i$. Payload is calculated as $loadfactor_i \times seats_i \times 95$ kg.[13]
Corresponding traffic (in RPK) is $flights_i \times distance_i \times seats_i \times loadfactor_i$.

9. *http://www.eurocontrol.int/products/bada*
10. BADA datasets contain the specific values of the coefficients present in the model specification that particularize the BADA model for a specific aircraft type.
11. Unfortunately, due to EUROCONTROL policy, we cannot publish the independent _β-results.
12. Load factors are adjusted downwards for the years 2011-2019 on the basis of IATA-internal estimates to account for post-crisis effects.
13. This number, which slightly deviates from the ICAO standard value of 100 kg, originates from a NLR study (Peeters_2005_Fuel_efficiency_of_commercial_aircraft_NLR-CR-2005-669, *http://www.transportenvironment.org/sites/default/files/docs/Publications/2005pubs/2005-12_nlr_aviation_fuel_efficiency.pdf*, *http://www.transportenvironment.org/sites/default/files//docs/Publications/2005pubs/2005-12_nlr_aviation_fuel_efficiency.pdf*)

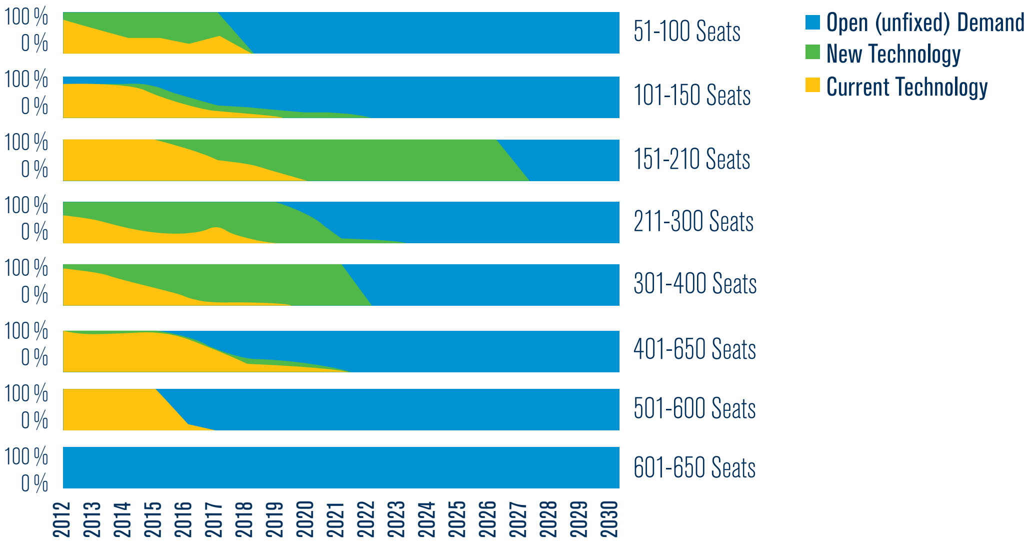

Figure 30: Market Shares (Delivery Shares) per Technology and Seat Category 2012-2030 (Forecast)

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

New technology enters the world fleet through projected deliveries of "New Technology" and "Unfixed Demand" (future generic aircraft).

For new aircraft models of fixed make and model (included in fixed orders, group "New Technology"), technology levels are mostly fixed and assumptions about fuel/CO_2 efficiency improvements over today's models can be made with high certainty. Reference aircraft and relative fuel burn compared to the reference aircraft for these aircraft are presented in Table 10. The assumptions are in broad accordance with publicly available industry and research data.

More uncertainty surrounds unfixed demand. The assumptions used here are based on the findings in Chapter 4 (see Table 3 and Table 4) and are combined with knowledge about market entry and fuel reduction potential of new aircraft projects with fixed make and model (the "New Technology" group) and an analysis of the probability of further new aircraft projects being realized by aircraft manufacturers in the timeframe 2013-2030.

As explained in the fleet forecast chapter above, it is not aimed to detail the realization of unfixed demand by forecasting market shares for specific makes and models. Instead, the demand in each seat category is represented by a "generic aircraft". This generic aircraft stands for the average delivered aircraft of a specific forecast year. A higher share of more efficient aircraft is represented by an improving performance over the years, as shown in Figure 31 for the different seat categories. It thus accounts for the combined impact of a fleet of multiple aircraft models. All assumptions regarding the impact of new aircraft projects, market shares, ramp-up times and technology on aircraft fuel efficiency in a specific size category can be reflected by adjusting a single parameter: the technology factor (fuel function multiplier) of the generic aircraft in the respective size category.

New Technology	Technology Factor	Reference
A320neo / 737max / CSeries	0.85	A320 / 737 / CRJ
A350 / 787	0.8	767 / 777
747-8	0.85	747-400
MRJ90	0.87	CRJ-900
SU95 / ARJ21	1	CRJ-900
MS21 / C919	0.9	A320

Table 10: Assumptions Concerning Fuel Efficiency Improvement of New (fixed) Aircraft Models

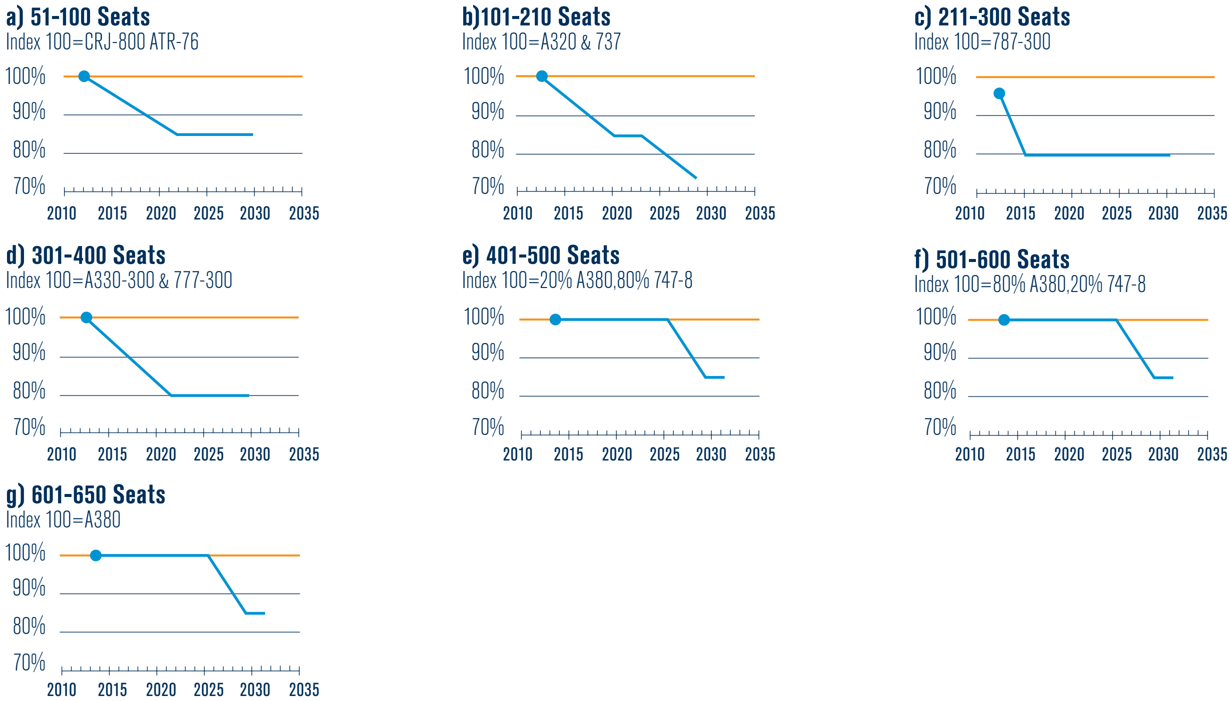

Figure 31: Technology Scenarios: Assumptions on Yearly Fuel Consumption of Generic Aircraft
(Representing Assumptions on Market Shares, Fuel Reduction Potential, New Aircraft Projects and Ramp-Up Times)

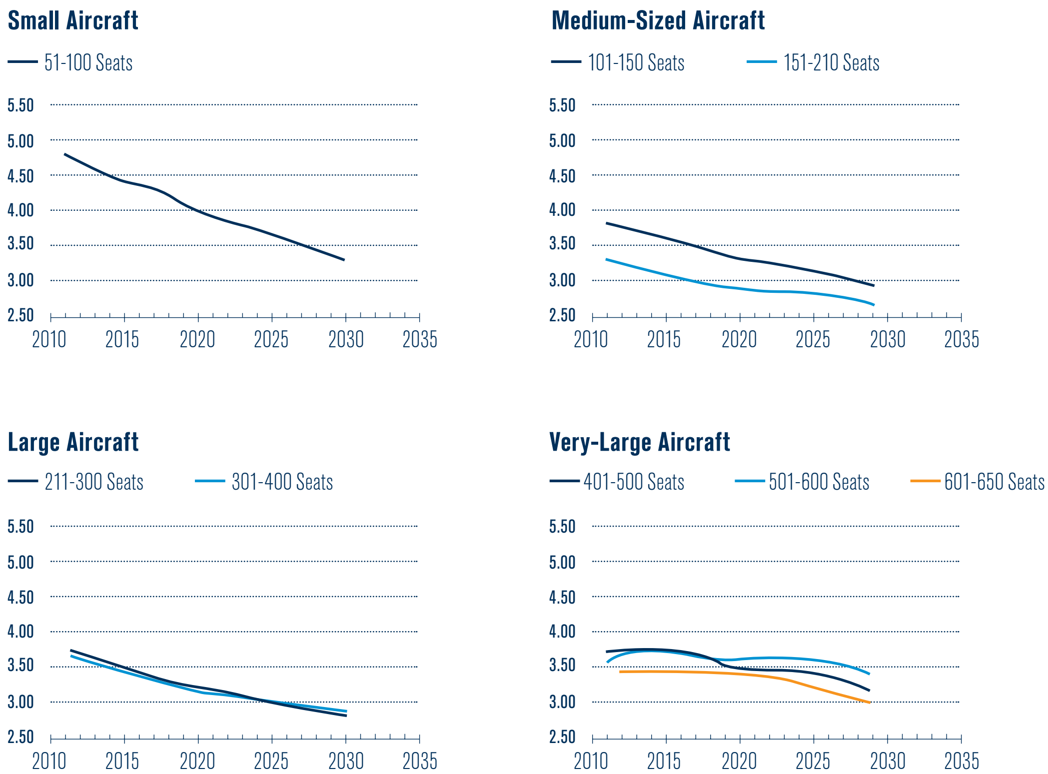

Figure 32: Average Fuel Efficiency of the Entire World Fleet (Forecast)

The intuition behind the curves in Figure 31 is as follows:

- In the 51-100 seats category (Diagram a), the baseline is the current state-of-the-art aircraft CRJ-900 and ATR 72-600. There are many new entrants currently pushing into the regional jet market (Sukhoi SSJ, ARJ21, etc.). However, amongst these, only the Mitsubishi MRJ holds a real fuel burn potential over current aircraft. It is assumed that all market share will slowly move to similar next-generation aircraft (with performance comparable to e.g. the MRJ), as the newcomers (Embraer, Bombardier) develop similarly capable aircraft to retain market share. This point is reached in 2022.
- In the 101-150 and 151-210 seats categories (Diagram b), today's dominating aircraft are the A320 and 737, which constitute our baseline (with equal weight). A two-step entry of new aircraft in these size categories is modeled. Firstly, a shift to aircraft with roughly 15% fuel reduction potential over current aircraft is seen, beginning in 2014 with the entry of the CSeries and ending in 2021, 4 years after the market entry of the re-engined A320neo and 737max. Secondly, following current marketing policy of Airbus and Boeing, the entry into service of newly designed narrow-body aircraft in the mid-2020s is modeled. These aircraft are assumed to entail technology improvements that lead to roughly 30% fuel reduction over the current aircraft (see Figure 19).
- The technology factors in the 211-300 and 301-400 seats categories (Diagrams c and d) are mainly influenced by the market entry of the 787 and A350. Both hold an efficiency improvement of about 20% over the baseline aircraft 767, A330 and 777. Furthermore, Boeing announced plans for a "re-vamped" 777 later this decade [4], which is assumed to bring similar fuel benefits. In the smaller size category (211-300 seats) there is a relatively near shift to 100% market share of the new aircraft: 787-8 deliveries have already begun and market entry of the A350-900 is projected for 2014. The shift takes longer in the 301-400 seats category, because the larger aircraft of the A350 and 787 series, as well as the 777 re-vamp, have a later market entry. Historically, new aircraft have been in production without a successor for about 20 years. Because of the high development cost that Airbus and

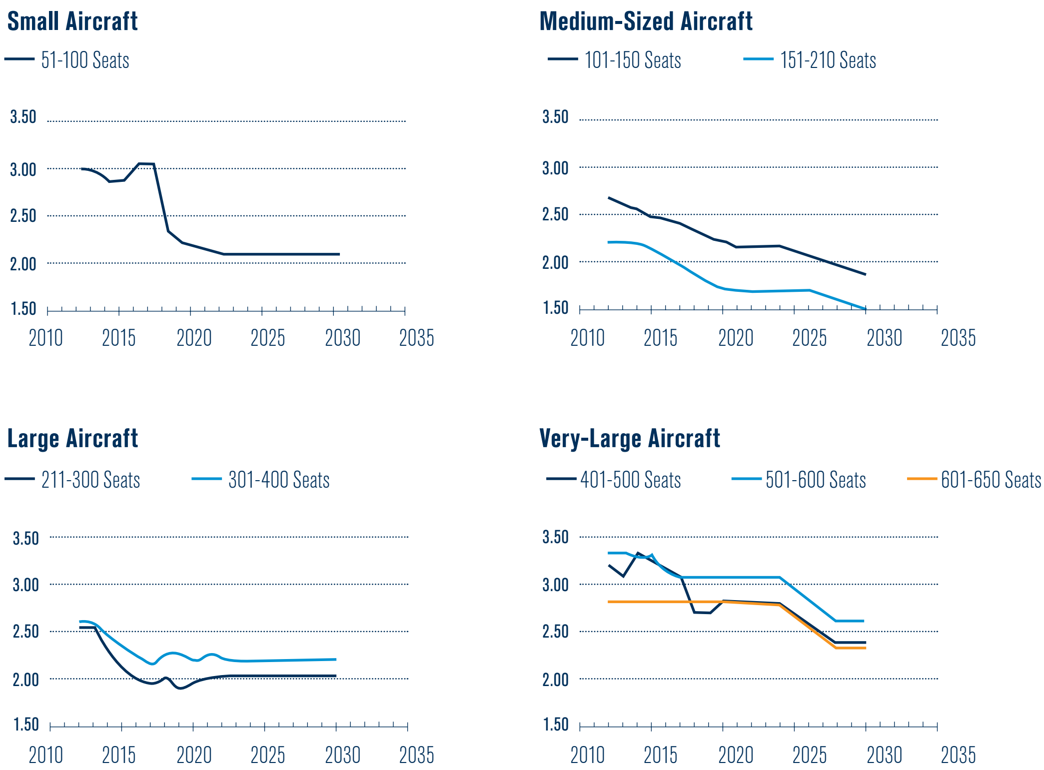

Figure 33: Technology Frontier: Fuel Efficiency of Aircraft Entering (Being Delivered to) the World Fleet (Forecast)

Boeing incurred when realizing the A350 and 787, additional new aircraft designs (or serious updates) are not believed to appear in later years in the forecast period: the curves thus remain flat.

- Finally, in the "very-large" size categories (401-650 seats, Diagrams e to g), the baseline aircraft are the A380 and 747-8. These aircraft are relatively new to the market and no changes are expected before the mid-2020s. At that time, the A380 will have seen a production lifetime of about 20 years and a technological upgrade is believed to be inside the bounds of realism. However, according to current market outlooks, Airbus and Boeing aim at bringing new narrow body aircraft to the market at the same point in time. As, in contrast, there is no indication of new development efforts for the very large aircraft category, and as the simultaneous realization of two entirely new aircraft projects seems unrealistic (due to financial and engineering capability constraints), "only" a moderate step is modeled: a design update, which is capable of pushing fuel consumption to around 85% of the reference aircraft.

Combining the fleet forecast of working block 1 with the estimates of fuel consumption and traffic of the individual aircraft according to Chapter 4 and with the assumptions concerning technology development throughout the forecast horizon from working block 2, an estimate of the impact of technology for new aircraft projects on global fuel and CO_2 efficiency can be derived. We restrict here to presenting two major results.

- First, Figure 32 shows the development of fuel efficiency of aircraft entering the global aircraft fleet. This parameter is called here the "technology frontier". It is given by the fuel consumption per seat-km (i.e. fuel/ASK in liters per 100 km) for the most efficient aircraft in a given category at a given time. The curves show the combined fuel efficiency of all aircraft being delivered in a specific year of the forecast. These include fixed orders of aircraft with given make and model ("Current Technology" and "New Technology") and "Unfixed Demand", which is modeled by the generic aircraft as defined in Figure 13, and the shares of each as given in Figure 10. In early years of the forecast, the development is mainly set by the deliveries of fixed aircraft models. In later years, the assumptions on generic aircraft play the major role. Clearly, the smaller aircraft categories show the highest technological impact; the "two-step approach" in the 101-210 seats category of first upgrading (A320 neo, 737 max) and later replacing the current technology with totally new designs is shown to yield continuous improvement over the years.
- As a second result, Figure 33 shows the yearly development in fuel efficiency of the entire active world fleet per seat category. The fuel efficiency metric used is the average fuel consumption per passenger-km (i.e. fuel/ASK in liters per 100 km). Here, the main driver is the basic fleet build-up for each year, as presented in Figure 30. On a world fleet level, influences other than the fuel efficiency of new aircraft being delivered play major roles: most importantly, the retirement of old, less efficient aircraft and the development of load factors. The smallest size category (51-100 seats) shows the biggest improvement in relative terms (about 2% p.a. between today and 2030). The fuel efficiency in the 101-400 seat categories improves between 1.2 and 1.5% p.a., while the largest category shows the smallest (very low before 2020 and then increasing to about 1% p.a.). The reason for the latter effect is that currently only a few very large aircraft exist and the largest seat categories are effectively only building up over the forecast period. Naturally then, fuel efficiency cannot improve largely from the retirement of older aircraft as it is the case in all other size categories. The most efficient aircraft are clearly found in the large narrow-body segment. Average fuel consumption per passenger in the 151-200 seats class drops below 3 liters/100 km before 2020.
- These results appear promising to meet the high-level industry goal for 1.5% p.a. fuel efficiency improvement, if one takes into account that further benefits from operations and infrastructure come on top of technology. Further studies and information about the future routes and aircraft utilization are necessary to fully quantify the impact on future world fleet emissions.

Continuous fleet renewal will improve fuel efficiency by 15 to 30% in all seat categories by 2030.

6.3 CONCLUSIONS

From the point of view of CO_2 reduction, what conclusions can be drawn from the world fleet forecast in terms of recommendations for future technology research?

Regarding technologies that can only be implemented in entirely new aircraft designs; the first advice is to promote research early enough so that these new technologies can be considered in the planning process of new aircraft projects. With the next generation aircraft projects (787, A350, A320neo, B737max [5][6] and the like) being already technologically frozen and demand for the next decade being nearly fully saturated due to fixed orders, the focus can thus only be on aircraft projects with market entry dates beyond 2020.

The second conclusion is that realistic constraints regarding the most likely time frame of new aircraft projects need to be taken into account in research and technology development planning. As said in the chapter above, the authors believe that no (entirely) new aircraft model with market entry in the 2020s is likely in the large and very-large size categories, while both Airbus and Boeing have promised successors to the A320 and 737 in that decade. Accordingly, research should focus on technologies adequate for regional and narrow-body seat categories that can be market-ready in the mid-2020s (e.g. open rotor technologies). At the same time, research into technologies to improve CO_2 efficiency in the large and very-large classes should prepare for a market entry after 2030. If started now, the long preparation time might finally allow truly revolutionary aircraft concepts to be realized (see Chapter 4.2).

In a broader sense, another main conclusion to be drawn from the fleet analysis is that it is necessary to also pursue research into technologies that can bring benefits without requiring an entirely new aircraft model, i.e. retrofits and minor or major design upgrades. The contribution of such shorter-term innovation is strongly needed to realize high-level emission reduction goals such as carbon-neutral growth. The examples of the A320neo, 737max and 777re-vamp show that design upgrades, which can be realized more frequently by aircraft manufacturers than entirely new aircraft models (because of lower development cost, see Table 11 and 12), can bring remarkably high benefits. This possibility should be brought into the focus also for the large and very large aircraft categories, where an engine upgrade may be possible (and environmentally required) in the 2020s. ◆

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IT TYPICALLY TAKES AROUND 20 YEARS FROM THE BASIC PRINCIPLES OF A NEW TECHNOLOGY UNTIL ACHIEVING OPERATIONAL MATURITY.

7. TIMELINE AND SCENARIO FOR NEW AIRCRAFT PROGRAMS

Technology development in aeronautics is normally planned and carried out in a way correlating with the introduction of a specific new aircraft model. However, the introduction of new aircraft programs is often shifted due to reasons not necessarily linked to new technologies, which leads to decoupling the forecasted technology availability from the introduction of new aircraft programs.

DLR established an empirical metric that allows an estimate of the time needed to bring the technology from the current development status to being ready for market introduction. It is apparent that aeronautical technology development can rarely be seen as a process being independent from aircraft programs and the respective introductory timelines. The external pressure on a technology to progress and the assigned amount of labor and financial backup to it certainly influence the speed of the technology advancement. The approach described here aims at obtaining representative average times needed for technology development and is solely based on historical data. Furthermore this section has a closer look on former commercial aircraft programs and their accumulated development costs. The collected data will be used as an indicator for future activities of the existing aircraft manufacturers, i.e. the introduction of new aircraft programs, on the commercial aircraft market.

7.1 FROM TECHNOLOGY READINESS LEVEL TO A TIMELINE

The present approach establishes an approximate relation between the given qualitative TRL and the years it will take to introduce the technology into service (the "Years to Maturity" for a current TRL) as depicted in Figure 34.

So far this estimate is solely based on historical data and does not account for the influences of e.g. financial incentives, administrative restrictions or supports, availability of resources and so forth.

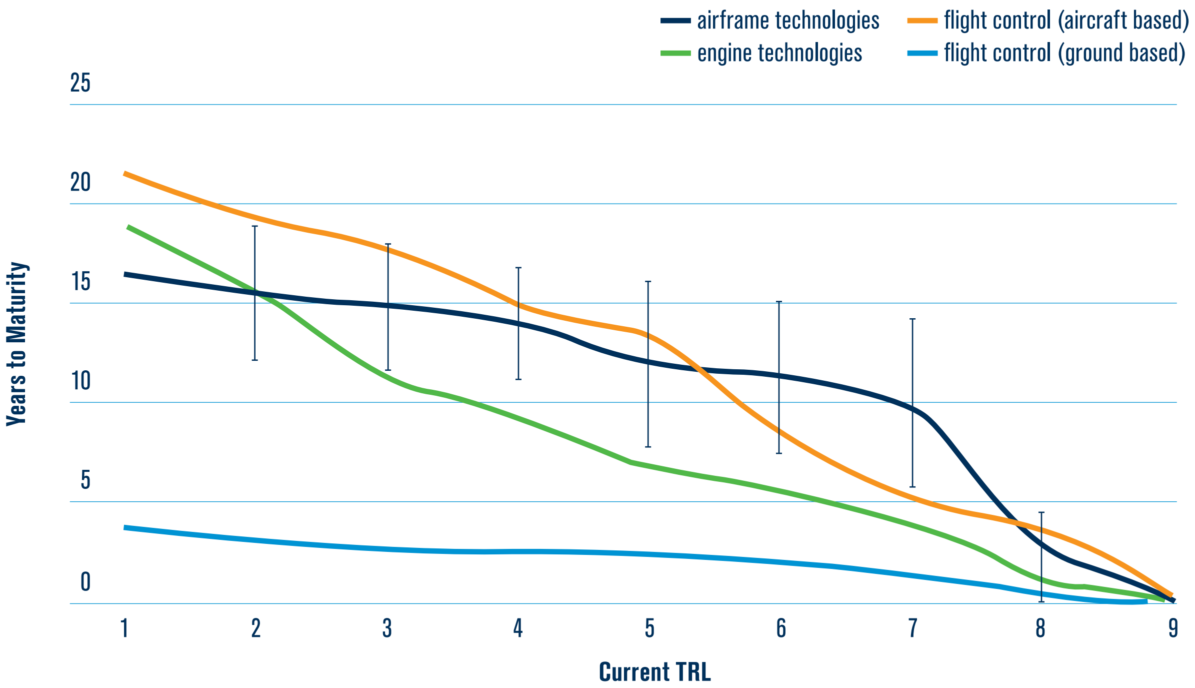


Figure 34: Maturation Timeline for Technology Readiness Level

Four different timelines were developed, as shown in Figure 34, namely for:

- airframe technologies
- engine technologies
- flight control systems employed on board
- flight control systems employed on ground.

Note that the times for system development and approval differ considerably between flight control systems on board and on ground; therefore two different timelines were considered necessary.

The general procedure contained the identification of a technology followed by a thorough description of its subsequent stages from the patenting phase to its common aeronautical application. The underlying dataset contains various co-existing development paths for the same technology. Therefore Figure 34 contains the plotted standard deviation per data point in years to Maturity for the airframe technologies as an example.[14]

Individually selected results for the engine and airframe areas from Figure 34 are explained as follows. In the field of engine technologies the turbofan technology shall serve as an example. [See example on page 62]

14. Research was enabled utilizing online available data bases from the German Patent and Trademark Office (DPMA) (http://www.dpma.de/), Free Patents online (*http://www.freepatentsonline.com/*), NASA Technical Reports Server (NTRS) (*http://ntrs.nasa.gov/search.jsp*), among others

The patent submission for a turbofan engine by Hans von Ohain [1] was chosen as the starting point for TRL 1. The patent was filed on 12th September 1939. Then it took until 1954 that a civil aircraft, the Avro 706 Ashton, was equipped with a turbofan engine. In this case the Rolls Royce Conway, had its maiden flight and the technology had its introduction into a commercial test bed, at this point the TRL 7 level was reached. It took the turbofan technology 15 years to overcome those seven technology levels. Another four years were needed to bring the technology to TRL 9 and introduce it into commercial aircraft service on the Boeing 707 with the Pratt & Whitney turbofan JT3. In the field of airframe technologies the rather important step from TRL 7 to TRL 9 with its 10 years to maturity in between can be explained using for example the A380 introduction into service (EIS). After the maiden flight was executed in 2005 the EIS of the A380 already happened only two years later in 2007. But from today's point of view one has to state that the first delivered aircraft were more likely in the condition of TRL 8 than TRL 9, as only the location of minor fatigue cracks in the wing will entail maintenance work and production process adaptation which will result in an A380 delivered without any rework needed most likely in the years 2013-15 [2].

New aircraft development costs have considerably increased over the time – re-design and re-engining are a low-cost alternative.

7.2 RATIONALE FOR INTRODUCTION OF NEW AIRCRAFT PROGRAMS

To give a rationale for the likelihood of a new aircraft program being introduced by an airframe manufacturer, the development costs and times of former aircraft programs were considered. Table 11 shows the development costs for selected new aircraft programs and Table 12 respectively for selected retrofitted/re-engined aircraft programs over the last 70 years of aeronautical history [9]. The aircraft programs are ranked by the accumulated development costs per aircraft seat. Interestingly the development time needed for a new program could hardly be reduced since the 1960s when it took 6-7 years to develop[15] the B707 or the DC-8 to nowadays 7 years of development time needed for the B787 or the A350. It is furthermore visible that the development costs rose in general. While the development of a "cutting edge" supersonic aircraft like the Concorde consumed "only" approximately 11.5 billion US$ (normalized 2012 value) in the 1970s, the development of an "ordinary" aircraft like the Boeing 787 consumed up to 32 billion US$. Without trying to look at the reasons about the rise of development costs in greater depth, it is supposed that the development costs can be used as an indicator for the scale (re-engined or newly developed aircraft) and the likelihood of an upcoming aircraft program under the 2020+ timeframe.

15. The time between "go ahead" until to entry into service is meant by the term development time

Aircraft Model	Number built/ ordered as of 2012	Development Time in Years	Year Entered Service	Development Costs	Development Costs/Seats	Development Cost/Seat Built
					(in constant 2012 US$)	
DC-3	607	2	1936	4.8M	0.23M	3770
DC-6	704	3	1947	161M	2.88M	4084
B707	1010	6	1958	1453M	10.38M	10,276
B747	521	4	1970	5500M	12.17M	23,355
DC-8	556	7	1959	1011M	12.64M	227,299
B777	400	6	1995	7800M	19.50M	14,265
A380	253	7	2007	16,100M	30.67M	121,212
A350	555	7	2013	15,200M	55.07M	99,229
Concorde	20	9	1976	11,495M	114.95M	5,750,000
B787	873	7	2011	32,000M	121.21M	138,845

Table 11: Development Costs of selected past and current Aircraft Programs - New Designs[16]

The comparison of results between e.g. the B707 (see Table 10) and the A320neo (see Table 12) give some valuable insight into developments in the aeronautical industry. While Airbus, with its A320 neo, is the manufacturer to achieve a development cost of under 10.000$ per seat built for the first time since the development of the B707, they still just "re-engined" an existing design. And while the development cost for the B707 equalled Boeing's market value at that time, it was backed up by the US government through ordering the model in its KC-135 version. In the case of the A320neo, Airbus, nowadays a private company, has to provide the R&D funds for design upgrades while still fulfilling its shareholders' interests.

In Figure 35 the development costs per seat for different aircraft programs in the last 70 years of aeronautical history are mapped. The development costs per seat are plotted in a logarithmic scale over the years of introduction of the respective aircraft program. The costs per seat for new aircraft programs are 5 to 10 times higher compared to the ones for retrofitted or re-engined programs.

Aircraft Model	Number built/ ordered as of 2012	Development Time in Years	Year Entered Service	Development Costs	Development Costs/Seats	Development Cost/Seat Built
					(in constant 2012 US$)	
A320neo	1196	6	2016	1300M	7.93M	6628
B747-8	106	6	2012	4000M	8.57M	80,805
A340-500	131	5	2002	4100M	11.42M	87,180
B737max	451	6	2017	3000M	18.29M	40,560

Table 12: Development Costs of Aircraft Programs – Redesigned

16. It was tried to account for the numbers of aircraft built under the same development level / production batch as far as possible. The development costs for subsequent stretched or re-engined versions were accumulated. For example in the case of the B747 only the development costs of the first development phase could be found, therefore just the 205 aircraft of the B747-100 and the 316 aircraft of the B747-200 production line (before a major design upgrade was performed) were taken into account. Due to this fact the number of aircraft built, which was taken into account for this study, can differ from the total number of aircraft built in the program by the manufacturer.

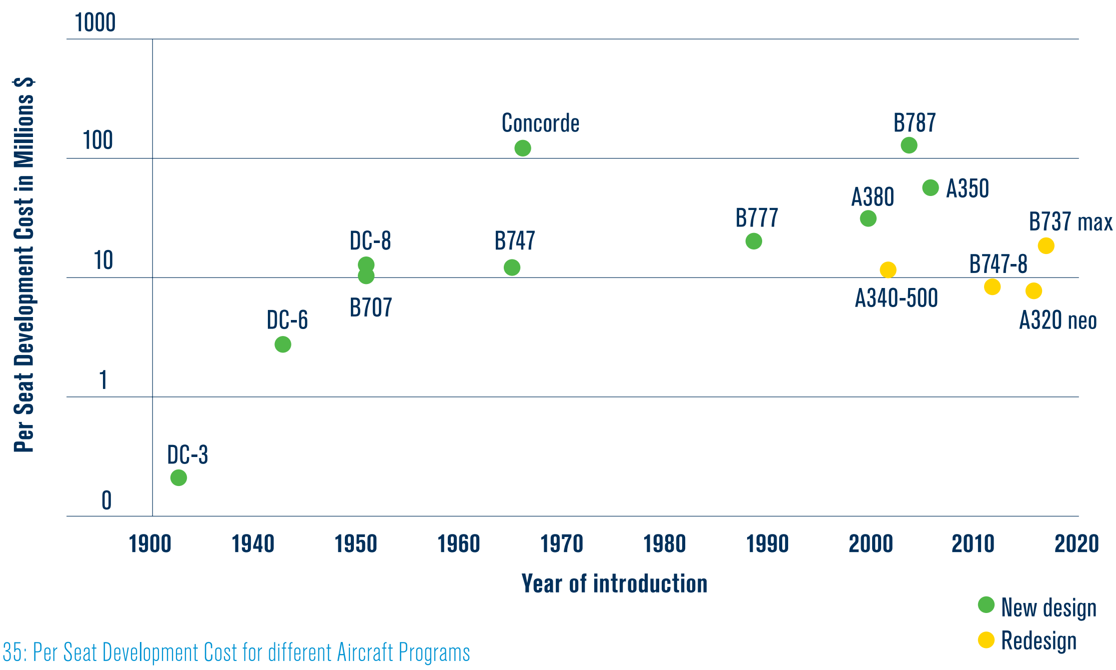


Figure 35: Per Seat Development Cost for different Aircraft Programs

Figure 36 illustrates the development costs per aircraft seat built of different aircraft programs. While the A380, B787 and A350 all accumulated costs per seat of approximately 100.000$ - 130.000$ per aircraft seat built. The development of the Concorde consumed up to 5.000.000$ per aircraft seat built. If one compares the B787 and the Concorde as an example for the introduction of pioneering aeronautical technology at that time, it becomes clear how much pressure aircraft manufacturers are facing nowadays for their programs to be successful; because they are no longer covered by guarantees from national governments in case of a detrimental project. The need to secure development cost simply through aircraft sales gives an idea why manufacturers seem to prefer the choice for the re-engined aircraft variants over the fully new developments.

To achieve the often cited quantum leap and foster the introduction of really innovative designs for the time after 2020, the upkeep and extension of substantial public funding for aeronautical research and guarantees for production run up time seem likely to be necessary. The significance of this financial support lies in the needed decoupling of the short-term shareholder demands for a high return on investment from the required financial buffer to overcome the possible cash flow problems during the run up time of a new program [3].

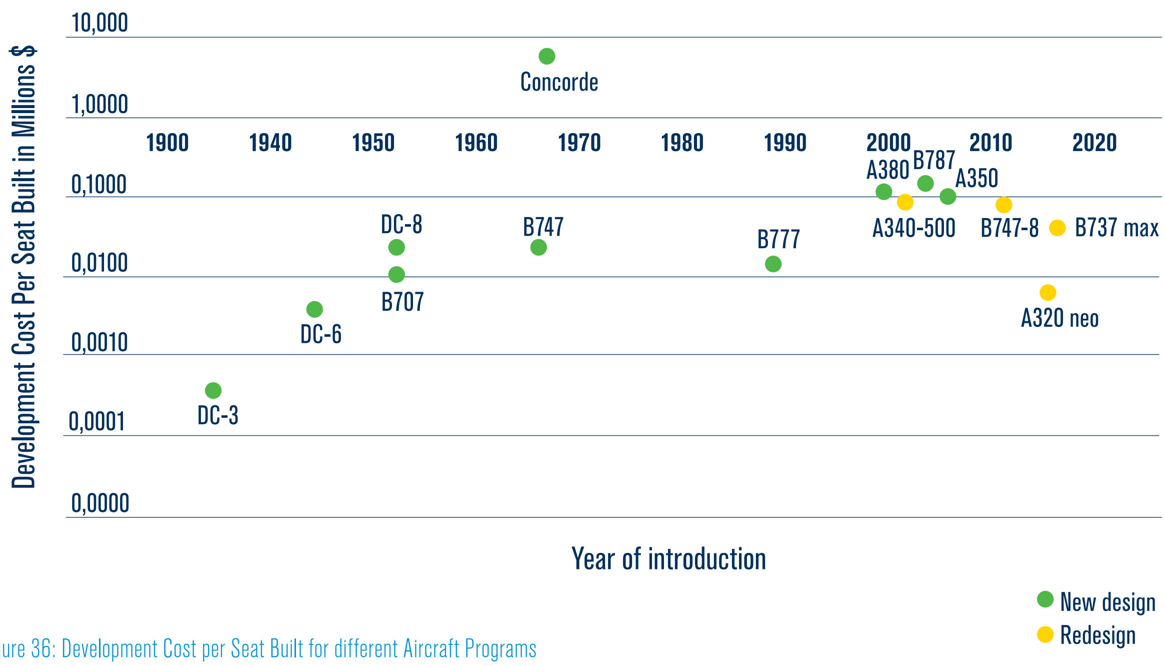


Figure 36: Development Cost per Seat Built for different Aircraft Programs

7.3 AIRLINES AND AIRCRAFT MANUFACTURERS – A SYMBIOTIC RELATIONSHIP

Generally speaking air travel is following a global trend where the demand has constantly grown over the last 60 years. Periodically it is exposed to cyclical shifts where periods of high growth are followed by moderate or even negative growth. Therefore one could regard the market for aircraft manufacturers and airlines being exposed to change continuously. Whereas airlines are considered to be able to respond more flexibly to changes in demand by for example altering their route network, the aircraft manufacturers with their long research and development cycles for new products await more difficulties to deal with fluctuating demand.

This might help to better understand the special relationship between aircraft manufacturers and airlines. One answer might lie in the very specific producer-customer relationship with a few suppliers which produce highly valued and highly complex products for a very limited and restricted market. The periods from the first market studies to the delivery and in-service support for an aircraft program can easily span a period of up to twenty years and more.[17] Moreover the number of manufacturers which could bear the vastly rising development costs for a new product shrunk over the last 60 years, leading to just a dozen companies left worldwide being capable of developing aircraft meeting today's safety and reliability standards. Logically the choice to go ahead with a particular aircraft program by a manufacturer, its success or failure, is closely connected to cautious and farsighted albeit risky decisions being made on the side of the operator.

In the following we will have a short look at noteworthy events exemplifying the special relationship between manufacturer and aircraft operator during the last decades.

It started in the 1950s with a period of new planes being introduced into the fast growing market every other year. The manufacturers were in a permanent competition between each other to build aircraft designed to fulfill the exact requirements of the airlines. The introduction of the highly productive and reliable jet aircraft like the B707 and the Douglas DC-8 in the late 1950s and the early 1960s changed the industry [4]. Manufacturers who were not prepared to meet this technology evolution with an adequate product either in size or design speed found themselves close to bankruptcy or as an object for merger and acquisition under the course of a few years. Quite likely motivated by the general arms race of the cold war and the "Sky is the limit" attitude the B747 was built as the biggest passenger aircraft [5] in the end of the 1960s and supersonic passenger transport became possible with the Concorde in the 1970s [6]. Supported by the rising environmental awareness and determined European countries, a new aircraft manufacturer, Airbus, was led on stage in the 1970s and started to grow by introduction of its first full product family with the A320 in the 1980s [7]. An always growing demand for short-haul travel with jet aircraft was covered successfully by Embraer and Bombardier in the 1990s. Even more growing environmental awareness and safety issues led to a termination of supersonic transport at the beginning of the new millennium, while the A380 replaced the B747 as the biggest passenger aircraft in 2005.

17. For example, the Very Large Commercial Transport (VLCT) program started approximately in 1990 within the Airbus company; after a first market study, it took seventeen years and the consultation of up to twenty airlines, airports and suppliers to share the risk, until the aircraft A380 was finally introduced into commercial service in the year 2007.

7.3.1 MARKET DECISIONS OF AIRCRAFT MANUFACTURERS AND AIRLINES

During the last sixty years different aircraft manufacturers have envisioned, designed and built aircraft in many different specifications; differing e.g. in their capacity, range, flight speed or the propulsion system. Figure 37 gives a short and coarse overview for different manufacturers and when they entered the market with an aircraft in one of the four designated seat categories. An arrow behind a company name indicates that the manufacturer carried on serving that seat capacity with its product. If just the manufacturer's name is indicated, the company withdrew from the market after that initial production. It becomes visible that after a time of high diversity in the fifties and sixties the variety of manufacturers was reduced due to mergers and bankruptcies. Only now after the millennium it happens that "new" players enter the market. While in the 1950s it could occur that a manufacturer built an aircraft solely for the requirements of just one airline as a launch customer, today the requirement setting process includes among a variety of airlines also other stakeholders of the air transportation system, such as airports or air navigation service providers. The idea of incorporating more parties into the market studies and requirement setting process shall augment the aircraft's robustness whereby possibly the variety of aircraft being tailored to specific customer needs is sacrificed.

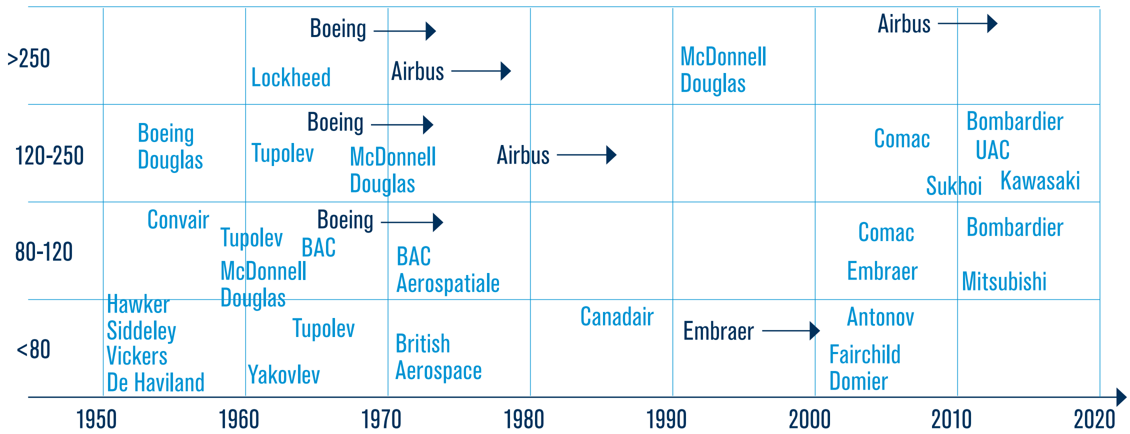


Figure 37: Aircraft Manufacturers launching programs in different seat categories over time

Despite the need for an economical viable product today's airlines are no longer in the comfortable position to negotiate their technical product requirements explicitly with the aircraft manufacturer.

The question of an appropriate design range for an aircraft is ubiquitous. Most aircraft are operated well below their equipped design range for the largest amount of time. This conclusion led various stakeholders to postulate the need for short range aircraft with lower design ranges. A review of the aircraft history shows that products with a too short design range have not been successful in the world-wide market.[18] This is for several reasons: Airlines look for a product which contains some range reserve to allow for operational flexibility. At a daily level, this allows them to ensure flying a route with a given aircraft type even in adverse wind conditions and including diversions without unscheduled technical stops. It also ensures their capability to be able to serve a growing route network without the need of growing the fleet, which is a main argument especially for smaller airlines. Furthermore the interest of leasing companies is substantial. Their range requirement aims for a product which can be marketed globally.

18. The Dassault Mercure and the VFW 614 shall serve as an example here, while the authors are well aware that also others problems caused these programs to stall.

7.3.2 THE WORLD FLEET OF CIVIL AVIATION

A closer look at the last 60 years of civil aviation shows the expected trend for a cyclical industry, an oscillating aircraft delivery curve. Years with a high aircraft production output alternate with years of a lower output (see Figure 38). Within the first ten years from 1950 to 1960 many groundbreaking products were incorporated, namely:

- the Vickers Viscount as the first turboprop aircraft (introduction in 1950)
- the De Havilland Comet as the first jet engine propelled aircraft in civil service and produced in series (1952)
- the Boeing B707 (1958) and the Douglas DC-8 (1959) as the first commercially successful civil jet aircraft

After these years the world-wide production output for "new age"[19] aircraft never fell short of 600 units after it crossed this threshold in 1964. The aircraft production/delivery curve reflects global events like the oil crisis, market deregulation, and so forth, as well as growth being propelled by new aircraft introduced, like the B737 and B747 in the 1960, B757/B767 and A320 in the 1980, and the B777 and A330/A340 in the 1990s.

Furthermore Figure 38 depicts the number of manufacturers operating in the market, the number of models (A320-200, B757-300) and their variants (different engine options) available and produced every year. The number of manufacturers continuously declined over the years, leaving 10-12 in today's market. Available aircraft models oscillated between 30-40 models, while it seems to become transient now at 30. In the middle of the nineties the available variants reached their peak at 95, after that they decreased to 74 being available today.

The last sixty years of civil aviation (aircraft>30 seats)

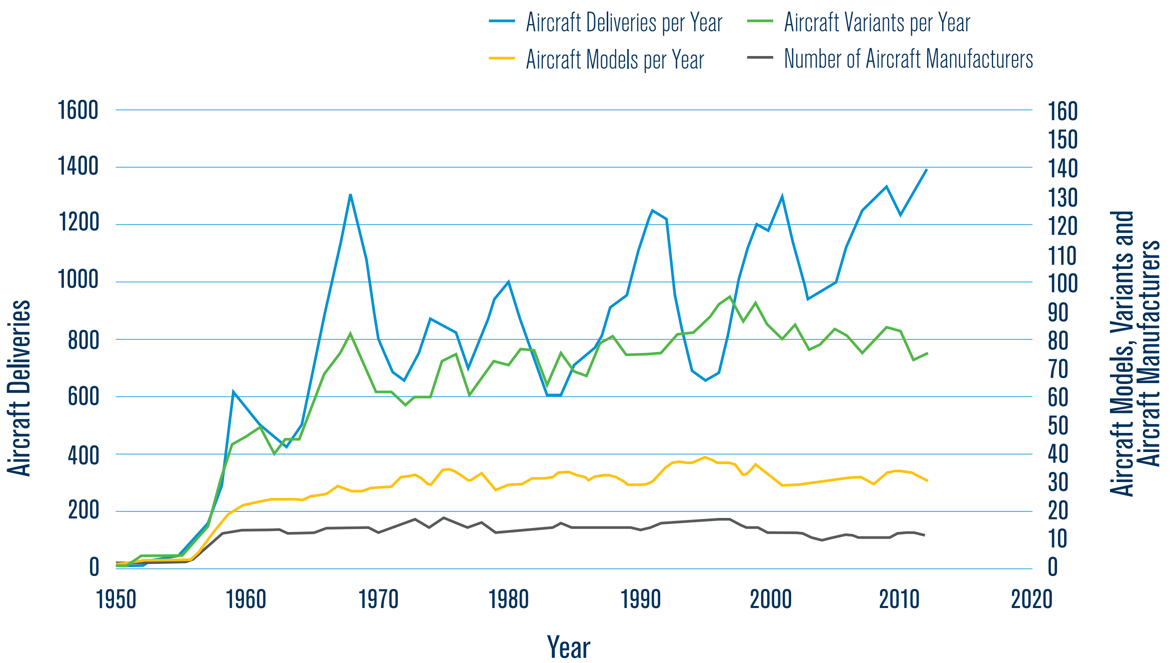


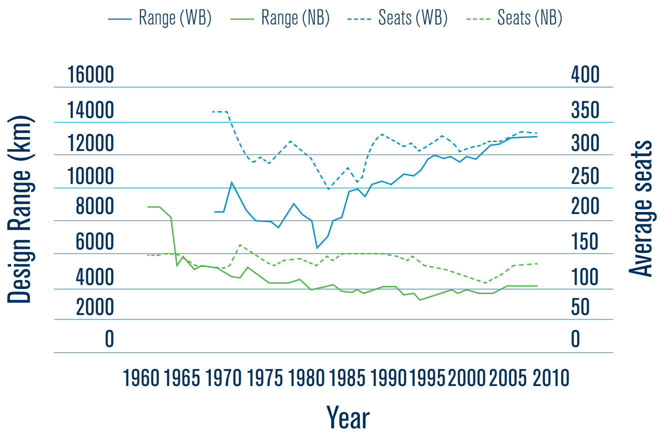
Figure 38: Civil Aircraft Delivery; Number of Models, Variants and Manufacturers. For this study we considered only turboprop, jet and turbofan propelled aircraft. Piston engines were excluded

19. Turboprop, jet and turbofan propelled aircraft

7.3.3 REQUIREMENTS OVER TIME

The aircraft requirements have changed over the last 50 years. In Figure 39 we compare the design range and the aircraft capacity over the course of time for narrow-body and wide-body aircraft as the average of the world fleet sales. While the average installed range for wide body aircraft is rising and asymptotically approaches a value around 13500km the value for the narrow body aircraft decreased over time and is drawing near 4000km. The average seat capacity for the wide body models started with the introduction of the first B747 at around 350 seats and decreased over time while it now nears a value of 330 seats on average per aircraft. The value for narrow body aircraft is oscillating between 120 and 150 seats. The maximum payload evolution curves are following the average seat counts even though it is apparent that the early wide body aircraft seem to have a higher extra cargo payload capacity than nowadays models as the curves show more difference.

It seems that wide-body aircraft within their class as well as narrow-body aircraft within their class become more and more alike regarding the range they are designed for.



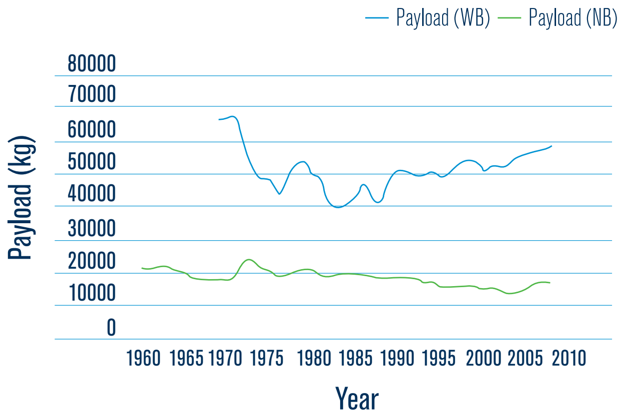


Figure 39: The Evolution of Requirements over the course of time: Design Range and Number of Seats (left); Maximum Payload (right)

7.3.4 AIRCRAFT OWNERSHIP

Aircraft leasing becomes more and more important for airlines to answer more flexible to a changing market environment and to be able to renew their fleets without the massive up-front costs which buying new aircraft normally entails (see Figure 40). From the first leased aircraft in the end of the 1960 the percentage rate grew up to nearly 35% of the world fleet being owned by leasing companies (see Table 13).

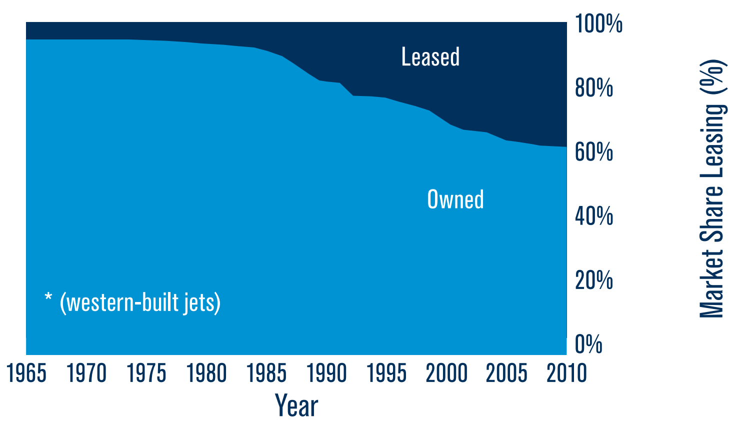


Figure 40: Market Share of Owned to Leased Aircraft in the world-fleet

This ratio of leased aircraft within a fleet or within a special aircraft model shall be used as an indicator for the growing importance of leasing companies in the requirement setting process for aircraft manufacturers. Based on the assumption that leasing companies operate globally it seems likely that the ordered aircraft shall be able to fulfill varying customer demands. Therefore being equipped with a design range much higher than the average flown range within the respective airline network is expected to be a high selling point for an aircraft to a leasing company. ◆

	Jets (Western Built)	Jets (Eastern Built)	Turboprops (Western Built)	Turboprops (Eastern Built)	Business Jets
Total Aircraft	24138	1858	8741	2773	18621
Total Operating Lease	8301	79	700	42	65
Percent Operating Lease	34,39%	4,25%	8,01%	1,51%	0,35%

Table 13: Percentage of leased aircraft per class

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NEW TECHNOLOGY SHOULD HELP THAT AVIATION'S GLOBAL CARBON FOOTPRINT WILL NOT CONTINUE GROWING IN THE LONG TERM, DESPITE THE EXPECTED ONGOING INCREASE OF AIR TRANSPORT VOLUME BY 4 TO 5% PER YEAR.

8. CONCLUSIONS AND OUTLOOK

The continuous improvement of air transport's environmental performance, and in particular the mitigation of its impact on climate change, is one of the big challenges for today's aviation industry and research, together with improving safety and security, capacity and comfort. More concretely, new technology should help that aviation's global carbon footprint will not continue growing in the long term, despite the expected ongoing increase of air transport volume by 4 to 5% p.a.

8.1 CONCLUSIONS

Improving fuel efficiency has been a strong driver for technological development throughout the history of aviation. All large airframe and engine manufacturers make significant efforts to improve the environmental footprint of their products and in particular their fuel efficiency and consequently carbon emissions. Environmentally-friendly technology is at the top of the agenda of aerospace research establishments, often supported by governmental R&T programs such as the EU Framework Programs, driven by ACARE's Strategic Research and Innovation Agenda, and the NASA programs for future aircraft generations.

Thanks to these research and development efforts, a broad scope of engine, aerodynamic, materials and equipment technologies is currently available for implementation or under development at different technology readiness levels (TRL). A description of these technologies and a first qualitative assessment of their efficiencies had already been published in the previous IATA Technology Roadmap (3rd edition, 2009).

For the present report a more detailed evaluation of emissions reduction was made by DLR and Georgia Tech, using a performance model that allows an easy determination of fuel consumption of aircraft equipped with a selection of future technologies for specific flight operations. The results of this evaluation, show that a significant potential for fuel burn reductions can be expected, depending on the time horizon for technology implementation, as shown in the following table:

	Short-range		Long-range	
	Min	Max	Min	Max
Retrofit	5%	10%	6%	12%
Serial upgrades	9%	18%	10%	20%
New types before 2020	10%	21%	no target aircraft	
New types after 2020 (excluding open rotor)	27%	38%	29%	40%

These figures are in good agreement with previous qualitative assessments and also with similar studies by other groups (AGAPE, ICAO, UK-CCC).

Of course the actual implementation of technologies into future aircraft types depends on many factors. An analysis of the development risk (development steps on the TRL scale still to be made in order to achieve full maturity) and of the related rough order-of-magnitude development costs shows that there is quite some potential from relatively low-cost retrofits and serial upgrades. Technology combinations that achieve 30% or more fuel burn reduction compared to a today's reference aircraft include combinations of at least two different technologies requiring development costs in the order of billions of dollars.

A realistic assumption of the time that is necessary to achieve maturity is also essential; the empirical values presented in Chapter 7 help to estimate these times. Often the opportunity for implementing a new technology in a new aircraft program is missed because the TRL required for a positive program decision is not reached at a critical milestone. Therefore it is particularly important to drive progress in the earlier phases of technology development.

The largest contributions to fuel efficiency come from new engine architectures (geared and advanced turbofans), composite structures and natural or hybrid laminar flow control. In the longer term the open rotor is seen as the most efficient engine option, provided solutions are found for the remaining technical issues (mainly the noise level).

It needs however to be kept in mind that both the open rotor and natural laminar flow control may require a lower cruise speed than for current aircraft, which might limit their application to short- to mid-range aircraft. Plans for radically new aircraft configurations and forms of propulsion (including electric) are emerging. It is important to give reasonable room to pursuing such research to lay the basis for achieving maturity of these concepts in the decades beyond 2030.

On a world fleet level, the continuous fleet renewal will offer a significant potential for fuel efficiency improvement over the next two decades. With the currently known entry-into-service calendar for new aircraft types a continuous improvement of average fuel efficiency is expected in all aircraft size categories. In particular the single-aisle category will benefit from the two-step introduction of the re-engined A320 and B737 families in the second half of the current decade and the following entry into service of fully new aircraft families by both big manufacturers in the 2020s. Also in the regional category a continuous strong improvement thanks to various new models is expected.

The annual fuel efficiency improvements per seat category of roughly 1 to 2% found in the present model calculations look promising to meet the high-level industry goals on fuel efficiency, but more detailed investigations on the future utilization of the different aircraft categories are needed to give a more reliable projection.

Re-engined narrow bodies in this decade and fully new designs after 2020, as well as continuous improvement in the regional aircraft category will strongly contribute to the world fleet's fuel efficiency.

8.2 OUTLOOK

Intense research and technology development work on emissions-reducing technologies in all fields of aviation is ongoing at research establishments and manufacturing companies all over the world. A broad scope of fuel-efficient technologies is currently under development and expected to become available in the near future, with a very promising emissions reduction potential as described in the chapters above.

However, it is important not to underestimate the gap between the pure technology development and implementation into flying aircraft. As described in Chapter 7, the step from prototype demonstration (TRL6) to full qualification in an operational aircraft environment (TRL8) can take up to eight years for complex technologies. A technology envisaged for use on a new aircraft type must have reached the necessary maturity at relevant decision points in the aircraft design process. Otherwise it would miss the chance for integration into the respective aircraft type, which may mean that the efficiency benefits from this technology might be delayed for many more years. Therefore there should be sufficient momentum during all phases along the technology development process to ensure that full benefit can be taken from it.

Airline customers can have an important role in this process. By showing their interest and support for new technologies and by participating in their evaluation, they make it easier for manufacturers and research establishment to drive forward the necessary developments and justify the related funding. Regarding the very high development costs for a new aircraft program, it must be ensured that it fits the needs of a broad variety of customers including their requirements for operational flexibility.

The organizations in charge of defining aviation research and technology policy and strategy, such as ACARE in Europe, are giving special emphasis on the innovation and integration aspect, with stronger participation of end-users, namely airlines, airports and air navigation service providers; this is also reflected in ACARE's name change from "Advisory Council for Aeronautic Research in Europe" to "Advisory Council for Aviation Research and Innovation in Europe".

Moreover, these strategic organizations have extended their goal-setting timeframe further into the future, with ACARE's vision document "Flightpath 2050" and NASA's strategic planning including an additional generation of long-term future ultra-green aircraft concepts ("N+4"). More room is thus given to radically new ideas for the air vehicles and air transport concepts of the future, which rely on out-of-the-box thinking and leaving the classical concepts of tube-and-wing aircraft as well as today's forms of airports and airspace organization.

Intense research and technology development work on emissions-reducing technologies in all fields of aviation is ongoing at research establishments and manufacturing companies all over the world.

Only with such concepts will the remaining gap towards a radical reduction of aviation's carbon footprint be overcome. Formation flight, battery-driven aircraft and production of aircraft fuel from sun energy and carbon dioxide (sun-to-liquid) are examples of such radical concepts which will be put in practice several decades from now. Early assessments of these technologies show a considerable emissions reduction potential, which is encouraging for achieving the 2050 high-level goal of 50% global aviation carbon footprint reduction. These and other long-term studies should therefore be intensified, and all aviation stakeholders should work together to prepare in time the green and efficient air transport system of the future.

The annual fuel efficiency improvements per seat category of roughly 1 to 2% found in the present model calculations look promising to meet the high-level industry goals on fuel efficiency, but more detailed investigations on the future utilization of the different aircraft categories are needed to give a more reliable projection.

ACRONYMS

ACARE	Advisory Council for Aviation Research in Europe
ACES	American Clean Energy and Security Act
AGAPE	ACARE Goals Progress Evaluation
Al-Li	Aluminium-Lithium
APU	Auxiliary Power Unit
ASDL	Aircraft System and Design Laboratory
ATM	Air Traffic Management
BADA	Base of Aircraft Data
BPR	Bypass Ratio
CAEP	Committee on Aviation Environmental Protection
CCC	UK Climate Change Committee
CO2	Carbon dioxide
CROR	Counter-rotating Open Rotor
DLR	Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Center)
EIS	Entry into Service
EPA	US Environmental Protection Agency
FAA	US Federal Aviation Administration
FESG	Forecasting and Economic Support Group
FP	EU Framework Program
GDP	Gross Domestic Product
Georgia Tech	Georgia Institute of Technology
GHG	Greenhouse gas
HWB	Hybrid Wing Body
IATA	International Air Transport Association
ICAO	International Civil Aviation Organisation
IPCC	Intergovernmental Panel on Climate Change
JTI	Joint Technology Initiative
JU	Joint Undertaking
LR	Long-range
LTO	Landing/Take-off Cycle
NASA	National Aeronautics and Space Administration
NextGen	Next Generation Air Transportation System
NSR	New Short-range
R&D	Research and Development
R&T	Research and Technology
RPK	Revenue Passenger Kilometer
SBW	Strut-braced Wing
SES	Single European Sky
SESAR	Single European Sky ATM Research
SFW	Subsonic fixed wing
SR	Short-range
SRA	Strategic Research Agenda
SRIA	Strategic Research and Innovation Agenda
SUGAR	Subsonic Ultra Green Aircraft Research
TERESA	Technology Roadmap for Environmentally Sustainable Aviation
TKP	Tonne-kilometers performed
TBW	Truss-braced Wing
TRL	Technology Readiness Level

TABLES

FIGURES

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