



Aircraft Technology Roadmap to 2050



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Senior Vice President
Member & External Relations
International Air Transport Association
33, Route de l'Aéroport
1215 Geneva 15 Airport
Switzerland

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Abbreviations

ACARE	Advisory Council for Aviation Research and Innovation in Europe
APU	Auxiliary Power Unit
ASK	Available Seat Kilometer
ATRU	Auto Transformer Rectifier Unit
BLADE	Breakthrough Laminar Aircraft Demonstrator in Europe
BLI	Boundary-Layer Ingestion
BPR	Bypass Ratio
BWB	Blended Wing Body
CENTRELINE	C oncept validation s tudy for fuselage wakefilling propulsion i ntegration
CLEEN	Continuous Lower Energy, Emissions and Noise
CO₂	Carbon Dioxide
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
DC	Direct Current
DLR	German Aerospace Center (Deutsches Zentrum für Luft- und Raumfahrt)
DOC	Direct Operating Costs
EGTS	Electric Green Taxiing System
EIS	Entry into Service
ERA	Environmentally Responsible Aviation
GARDN	Green Aviation Research and Development Network
HLFC	Hybrid Laminar Flow Control
HWB	Hybrid Wing Body
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
InP	In-production
LUC	Land-Use Change
MIT	Massachusetts Institute of Technology
NASA	National Aeronautics and Space Agency
NLF	Natural Laminar Flow
NMA	New Midsize Aircraft
NT	New Type
PFC	Propulsive Fuselage Concept
RPK	Revenue Passenger Kilometer
R&T	Research and Technology
SAF	Sustainable Aviation Fuel
SAW	Spanwise Adaptive Wing
SMA	Shape Memory Alloy
SUGAR	Subsonic Ultra Green Aircraft Research
TRL	Technology Readiness Level
VTOL	Vertical Take-Off and Landing

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Executive Summary

Goals and timeline

In 2009, all stakeholders of the aviation industry committed to a set of ambitious climate action goals, namely:

- improving fuel efficiency by 1.5% per annum between 2009 and 2020;
- reaching net carbon neutral growth from 2020;
- reducing global net aviation carbon emissions by 50% by the year 2050 relative to 2005.

Meeting these goals is one of the major challenges for today's aviation sector. The industry is well on track for the short-term fuel efficiency goal, and ICAO has put in place the CORSIA system (Carbon Offset and Reduction Scheme for International Aviation) to achieve the mid-term carbon-neutral growth goal. The long-term 50% carbon reduction goal requires the combined efforts of all aviation stakeholders (aircraft and engine manufacturers, airlines, airports, air navigation service providers and governments).

Since the aviation industry committed to this set of goals in 2009, an impressive number of technological solutions contributing to the 2050 goal have been proposed and many related projects have been initiated. These consist of numerous aircraft (airframe and engine) technologies as well as sustainable aviation fuels, operational and infrastructural measures.

This roadmap focuses on technologies and design of future aircraft. In the short-to-mid-term, i.e. until about 2035, new commercial aircraft will still be "evolutionary" developments with a traditional tube-and-wing configuration and turbofan engines powered by conventional jet fuel (or a sustainable drop-in equivalent). From 2035 onwards, one can expect "revolutionary" new aircraft configurations and propulsion systems to be ready for entry into service, provided the economic framework conditions are favourable to their implementation. These radically new aircraft designs include, among others, blended wing bodies, strut-braced wings, and hybrid and battery-electric aircraft.

Current and planned new aircraft models

Numerous new aircraft models in most seat categories have recently entered commercial service or are imminent in the next few years. Under favorable conditions, their fuel burn per available seat-km is typically 15 to 25% less than that of the aircraft models they replace. When considering everyday operational conditions, improvements are usually a few percent lower. Typically, a new aircraft generation

replaces older models in the same seat category every 15 to 20 years or so. With the introduction of many new models in the current period (2014 – 2020), this might result in an innovation gap in the second half of the 2020s, before demand for a follow-on of the current new aircraft generation will arise. This could lead to a noticeable slowdown in the average fuel efficiency improvement.

Evolutionary aircraft technologies

Continuous progress is being achieved in all areas of evolutionary technologies, namely aerodynamics, materials and structures, propulsion and aircraft equipment systems. Some examples of technologies which have recently made noticeable progress are: natural and hybrid laminar flow control, new high-bypass engine architectures as well as aircraft systems such as electric landing gear drives and fuel cells for onboard power generation. By applying combinations of evolutionary technologies, fuel efficiency improvements of roughly 25 to 30% compared to today's aircraft still appear possible. However, further improvements of the tube-and-wing configuration powered by turbofans are becoming more and more difficult to conceive around 2035.

Revolutionary aircraft technologies

In the longer term towards 2050, radically new aircraft configurations will be required to reduce fuel burn and carbon intensity significantly. The novel airframe configurations that are currently seen as most promising are the strut-braced wing, the blended wing body, the double-bubble fuselage and the box-wing aircraft. While for a long time blended wing bodies were thought to be a solution optimized for very large aircraft of several hundred seats, it has recently become realistic to design small blended wing bodies of 100 to 200 seats. On the one hand, they do not have the same drawbacks as their large counterparts in terms of airport compatibility and passenger acceptance. On the other hand, they allow improved boarding time and passenger comfort.

The most promising propulsion technologies are open rotors, boundary layer ingestion and electric aircraft propulsion. Due to their large weight per unit of stored energy, batteries as primary energy storage for aircraft propulsion place limitations on the size and range of fully battery-powered aircraft. Various categories of hybrid-electric aircraft propulsion exist as well, which use liquid fuel as a primary energy source. They benefit from the high energy efficiency of electric motors and use batteries as an additional energy source for peak loads. Today, several electrically-powered general aviation aircraft types are

already in operation. Specialized start-up companies work on 15 to 20-seaters for the next decade and 50 to 100-seater regional aircraft, announced for entry into service around 2035. Even though this time scale seems optimistic, it shows the stepwise scalability of electric aircraft technology, which helps reduce its development risk. While today about 65% of electricity generation comes from fossil sources and produces significant amounts of CO₂, it is likely that the share of renewable electricity will increase noticeably in the next decades, thanks to governments' and industries' current focus on climate action throughout all sectors.

Operational aspects

Most radically new aircraft configurations yield additional benefits beyond fuel efficiency, such as lower maintenance costs for electric motors compared to combustion engines, or better aircraft utilization over a day thanks to shorter airport turnaround time for small blended wing bodies. However, new challenges arise for the implementation and operation of these aircraft. Such challenges could be the required adaptation of the airport infrastructure for large blended wing bodies, the need for high-power electricity supply for recharging electric aircraft, and issues with higher noise levels and lower flight speeds for open rotors.

Economic aspects

The additional operational benefits and potential challenges have to be considered together with fuel savings when establishing a business case for radically new aircraft. If the direct operating costs (DOC) for a new aircraft type are significantly lower than for comparable models, a higher purchase price can be justified. However, a very high aircraft price, even if linked to high DOC savings, may present a prohibitive risk for airlines as customers. Manufacturers need to consider these aspects when setting their prices and determining the number of aircraft to be sold to reach the break-even point.

The development of a radically new aircraft type represents a very high investment for aircraft manufacturers, which may be considered too risky as long as incremental developments building upon existing aircraft concepts could offer a similar degree of improvement. On the other hand, radically new aircraft are a good opportunity for newcomers in the aerospace market with specialized skills.

Estimated carbon reductions

The impact of new technologies on future CO₂ emissions of the global aviation fleet is modelled for different scenarios describing various degrees of air traffic growth and technology implementation. Three air traffic growth scenarios, which were developed in the IATA 20-year passenger forecast, were combined with five technology implementation scenarios. Compared to the reference case with no new aircraft models introduced after the imminent ones, the most optimistic scenario with the introduction of electric aircraft over 150 seats before 2050 achieves a reduction of typically 25% of CO₂ emissions. After a peak in the current years with annual fuel efficiency improvements well above 1.5% until shortly after 2020, a slowdown of improvement below 1.0% p.a. in the late 2020s is observed (which does not consider entry into service of a fully new 210–300-seater in the mid-2020s, as its development has not yet been announced officially). After 2035, the improvement rate strongly depends on the scenario chosen and reaches values in the order of 3% p.a. for the most optimistic electrification scenario.

Disruptive technologies

Finally, a short outlook is given on two disruptive transport types that might partially replace subsonic commercial flight in the near future: For short-haul traffic, Hyperloop is a ground-based passenger and cargo transport system currently in the test phase, reaching similar travel speeds as commercial aircraft. For long-haul connections, new supersonic aircraft, which are currently under development, are expected to see a revival in the 2020s, first for business and later for commercial travel. However, the environmental challenges related to supersonic aircraft are higher than for subsonic aircraft.

Recommendations

Recommendations for a seamless implementation of radically new aircraft are given. In particular, close cooperation between all aviation stakeholders, including newcomers specialized in single categories of novel aircraft, is required with sufficient lead time to prepare adaptations of airport and airspace infrastructure and to develop necessary standards and regulations. Airlines should proactively show their interest in new fuel-efficient aircraft contributing to the Industry's climate action goals, to give manufacturers more certainty about the expected demand, which is needed to launch a new aircraft program.

1. Introduction

1.1. Background

Since the Wright brothers' first flight in 1903, air transport has been constantly growing and modernizing. Within a century, tremendous progress has been achieved in aircraft design and flight operations, revolutionizing transport for people and goods and making it a truly global industry. Aviation has always been strongly dependent on economic and political factors and, despite experiencing crises, is now well established throughout the world as an indispensable means of transport ensuring global connectivity.

Since the early jet age, the volume of air transport has doubled about every fifteen to twenty years, which makes it the fastest growing transport sector. With growth in tourism and trade, aviation is expected to continue expanding in the future at a similar rate as today. Recent forecasts show that by 2036, air passenger traffic is expected to grow at an average rate of 3.7% per annum, respectively, reaching almost 14 trillion revenue passenger-kilometers (RPK) more than the double compared to 2016 [1].

Aviation has long been the focus of public attention for its environmental impact, such as noise, pollutant emissions and, more recently, carbon dioxide (CO₂) emissions. While aviation emissions have consistently grown in absolute terms over the past, the global share that they represent among all man-made CO₂ emissions has been fairly constant with 2% (see Figure 2, from data by the Carbon Dioxide Information Analysis Center [2]. This means that the emissions of aviation [3], despite being one of the most

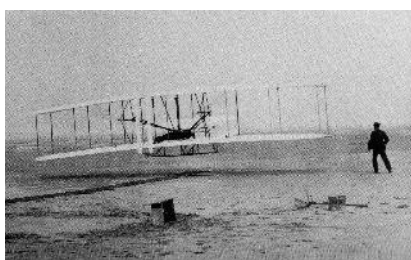
strongly growing sectors with a continuous growth rate between 4 and 5% p.a., have not been growing faster than the average of all man-made CO₂ emissions.

In 2009, the entire aviation industry (comprising airlines, aerospace manufacturers, airports, air navigation service providers and business aviation) committed to high-level climate action goals [4], which are:

- improving fuel efficiency by 1.5% per annum between 2009 and 2020;
- achieving net carbon neutral growth from 2020;
- reducing global net aviation carbon emissions by 50% by the year 2050 relatively to 2005.

In order to meet these goals, aviation stakeholders have adopted a multi-faceted strategy [4], which is based on: technology (including more fuel-efficient aircraft as well as sustainable alternative fuels [SAF]), efficient flight operations, improved airspace and airport infrastructure, and positive economic measures.

Achieving these goals is a highly challenging task. In particular, the 2050 goal of 50% reduction of aviation's global carbon footprint requires the combination of all possible contributions from all stakeholders (aircraft and engine manufacturers, airlines, airports and air navigation service providers [ANSPs]) and all of the four pillars (technology for aircraft and engines as well as sustainable fuels, operations, infrastructure and market-based measures).



The Wright Flyer, 1903



DH 106 Comet, 1959



Airbus A350-XWB-1000, 2018

Figure 1: Evolution of Aircraft Technology

Achieving aviation's climate goals is a highly challenging task and requires the combination of all possible contributions from all stakeholders and all pillars of the IATA strategy.

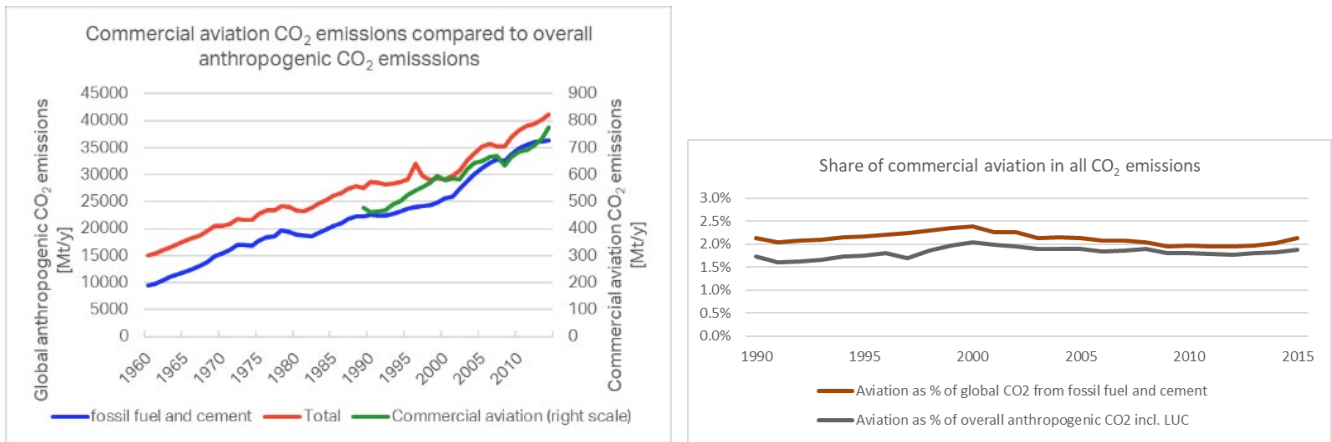


Figure 2: (Left) Commercial aviation CO₂ emissions (right scale) compared to overall anthropogenic CO₂ emissions (left scale), broken down into industrial emissions (fossil fuel and cement) and land use change (LUC) (from [2]); (Right) Commercial aviation CO₂ emissions compared to overall anthropogenic CO₂ emissions

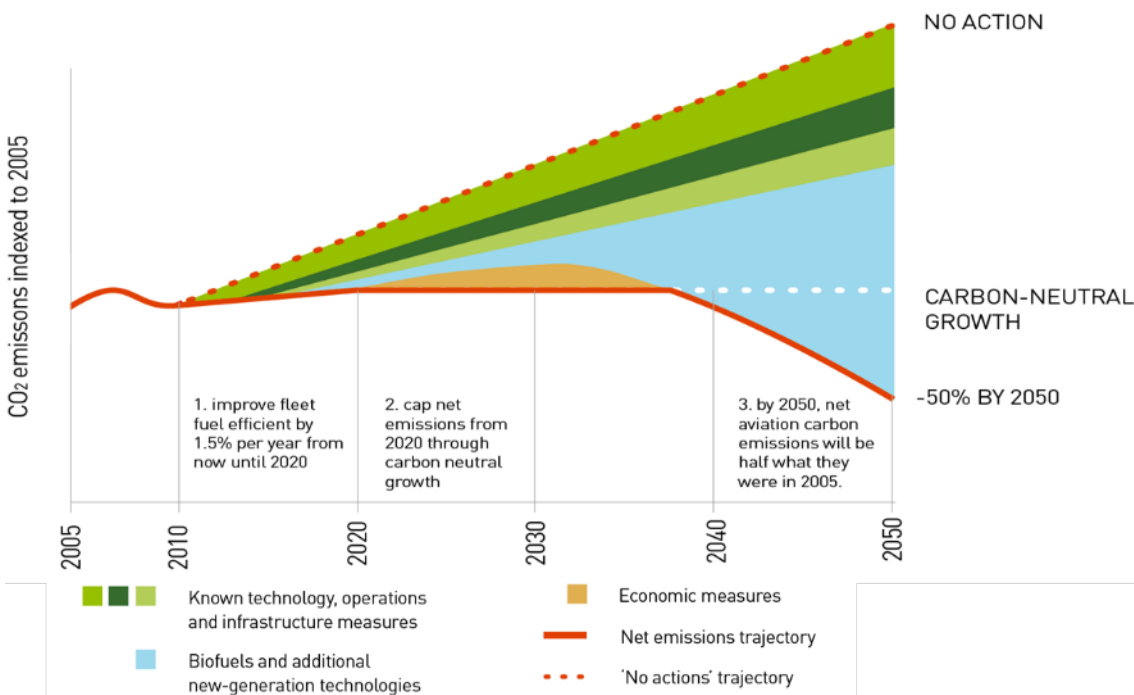


Figure 3: Schematic CO₂ emissions reduction roadmap

- The focus of this roadmap is on **green aircraft technology**. Continuous improvement of aircraft fuel efficiency plays a crucial role in working towards the 2050 carbon reduction goal. In fact, since the beginning of the jet age, technological innovations such as lighter materials, higher engine performance and aerodynamic improvements have reduced fuel consumption per passenger-km or ton-km of aircraft by over 70%. Further substantial reductions from new technologies are expected in future. However, when new, more efficient aircraft are introduced, it takes several years after entry into service (EIS) until they penetrate the market in sufficient number and their benefits are noticeable at a world fleet fuel efficiency level.
- **Sustainable aviation fuels (SAF)** produce typically up to 80% lower CO₂ emissions on a lifecycle basis than conventional (fossil) jet fuel. Currently, a variety of pathways from biogenic sources are certified for aviation use, and more are under development, including non-biogenic fuels such as Power-to-liquid. All SAF types considered today are drop-in fuels, i.e. they have very similar physical and chemical properties to conventional jet fuel and can be blended with it over

a wide percentage range. The main obstacle to wide implementation of SAF is not technical, but economic, as SAF is not yet produced at competitive cost compared to conventional jet fuel.

- **Operational improvements** include measures taken by airlines, airports and ANSPs in their day-to-day operations, such as reducing the weight of onboard equipment, selecting most fuel-efficient routes or flight profiles and using fixed ground power supply instead of the aircraft's auxiliary power unit (APU) during airport turnaround.
- Airport and airspace **infrastructure improvements** include creation and installation of new flight routes, airport runways, procedures or equipment that allow more fuel-efficient operations.

- Finally, **market-based measures** do not reduce physical emissions within the aviation sector but help achieve emissions reductions in other sectors where they are more cost-effective.

Driven by the current momentum towards renewable energy and States' commitments under the Paris agreement, it is likely that other industry sectors will move to decarbonize in the coming decades. One example is replacing fossil fuel powered cars by electric ones. Aviation needs to make strong efforts to reduce its CO₂ emissions at a similar pace. The IATA four-pillar strategy helps to achieve this goal.



1.2. Scope of this Report

In its role to represent, lead, and serve the aviation industry, IATA is bringing together manufacturers, researchers, infrastructure providers, government agencies as well as airlines to ensure that all stakeholders work together to achieve the best results in reaching the aviation industry's climate goals through the commitment to improving technology for the future air fleet.

This report aims to show a possible timeline of future technological innovations and their effect in reducing CO₂ emissions from the global aircraft fleet and the likelihood of their implementation. Some can be retrofitted to aircraft in service, others can be implemented as serial upgrades in existing models, and some require new aircraft designs. From 2035 onwards, radical technological innovations with higher fuel efficiencies including aircraft configurations other than classical tube and wing and new forms of propulsion, such as battery or hybrid electric power, could become possible. They are expected to allow a substantial

contribution to the 2050 carbon reduction goal. However, it must be considered that not all innovations that are technologically feasible will be implemented if they are not sufficiently supported by economic and business considerations.

1.3. Technology Objectives

Aviation has always been a high-tech industry, and continuous progress in the development of new technologies is vital for a sustainable growth of the aviation industry. They are not only the basis for a more fuel-efficient fleet, but also a key factor for improvements in flight and ground operations, for a pleasant passenger experience and for reducing as much as possible the impacts of air transport growth on the environment.

Responding to the aviation industry's need for advances in research and technology (R&T), government-funded programs in various countries are an effective means to support R&T activities in aviation. Reducing the

From 2035 onwards, radical technological innovations with higher fuel efficiencies including aircraft configurations other than classical tube and wing and new forms of propulsion, such as battery or hybrid electric power, could become possible.

New technologies are a key factor for improvements in flight and ground operations, for a pleasant passenger experience and for reducing as much as possible the impacts of air transport growth on the environment.

environmental impact of air transport is one of the most important goals of these programs, alongside with improving mobility and passenger satisfaction, cost efficiency, safety and security [5].

- In Europe, Flightpath 2050 [6] sets a vision for aviation to respond with research and technology development to its main challenges, including environment. One of its goals is: *“In 2050 technologies and procedures available allow a 75% reduction in CO₂ emissions per passenger kilometer.... relative to the capabilities of typical new aircraft in 2000”*. The Advisory Council for Aviation Research and Innovation in Europe (ACARE) has established a strategic research and innovation agenda as a route towards those targets [5].
- NASA, in the framework of its Environmentally Responsible Aviation (ERA) program, has set goals for the development of new technologies for future aircraft generations (“N+1/N+2/N+3”) regarding the reduction of fuel consumption, noise and NO_x emissions. These refer to the availability of technologies at a relative early technology readiness level (TRL) of 4 to 6 (see definition in Section 2.2). The following goals are set for fuel or energy consumption reduction [7]:
 - N+2: by 2020, 50% relative to 777-200 (entry into service: 2030 – 2035)
 - N+3: by 2025, 60% relative to 737-800 (entry into service: 2035 – 2040)

In order to achieve these and similar goals, various technology programs focusing on the environment have been established, such as the following:

- Since 2010, FAA has been conducting the *Continuous Lower Energy, Emissions, and Noise (CLEEN)* program, with substantial participation from the US aerospace industry. After a successful initial program (CLEEN I), CLEEN II is running from 2015 to 2020. Its goals “include developing and demonstrating certifiable aircraft technology that reduces aircraft fuel burn”, with a target of 40% [8].
- The Canadian *Green Aviation Research and Development Network (GARDN)*, jointly funded by the Canadian Government’s Business-Led Network of Centres of Excellence (BL-NCE) and the Canadian aerospace industry, supports research and development projects in the areas of “clean, sustainable and silent flying” [9].

- The EU’s *Clean Sky 2 Joint Technology Initiative* was set up to develop and demonstrate innovative technologies contributing to the “Ultra Green” and “Highly Cost-Efficient Air Transport System” target concepts. One of its objectives is to *“increase aircraft fuel efficiency, thus reducing CO₂ emissions by 20% (2025) to 30% (2035) compared to ‘state of the art’ aircraft entering into service as from 2014”*. The *Clean Sky 2* program includes tests on full-scale demonstrators, representative for future aircraft configurations and their operational environment, to ease the implementation of the new technologies into future aircraft design and operations (Clean Sky, 2018).

In addition to goals for R&T programs, regulatory measures and operational goals have also been set to ensure lower CO₂ emissions of future aircraft.

Aviation is the first sector that has agreed on a globally recognized CO₂ emissions standard. The UN International Civil Aviation Organization (ICAO) has developed, in collaboration between governments and industry, the new *Aeroplane CO₂ Emissions Certification Standard* [10]. It was adopted by the ICAO Council in 2017 as part of the ICAO environmental standards, which include, for instance, aircraft noise certification. The CO₂ standard has been developed to assess the technology level of the aircraft design, considering propulsion, aerodynamics and weight, but excluding operational aspects. It encourages aircraft design including more fuel-efficient technologies, which lead to higher margins to the certification limits. The CO₂ standard will apply to subsonic jet and turboprop aircraft that are new type (NT) designs from 2020, as well as to those aircraft type designs that are in-production (InP) in 2023 and undergo a change. InP aircraft that do not meet the standard can no longer be produced from 2028, unless the designs are modified to comply with the standard.

An example of an operational goal supporting the implementation of new aircraft technologies relates to the plans of electrifying aviation in Norway. Avinor, the public operator of most Norwegian airports, in conjunction with the Norwegian government, aims at operating all short-haul flights (up to 90 minutes on domestic routes and those to neighboring Scandinavian airports) with electric aircraft by 2040 [11].

Regulatory measures and operational goals can support the implementation of new aircraft technologies.

Government-funded programs in various countries are an effective means to support R&T activities in aviation.

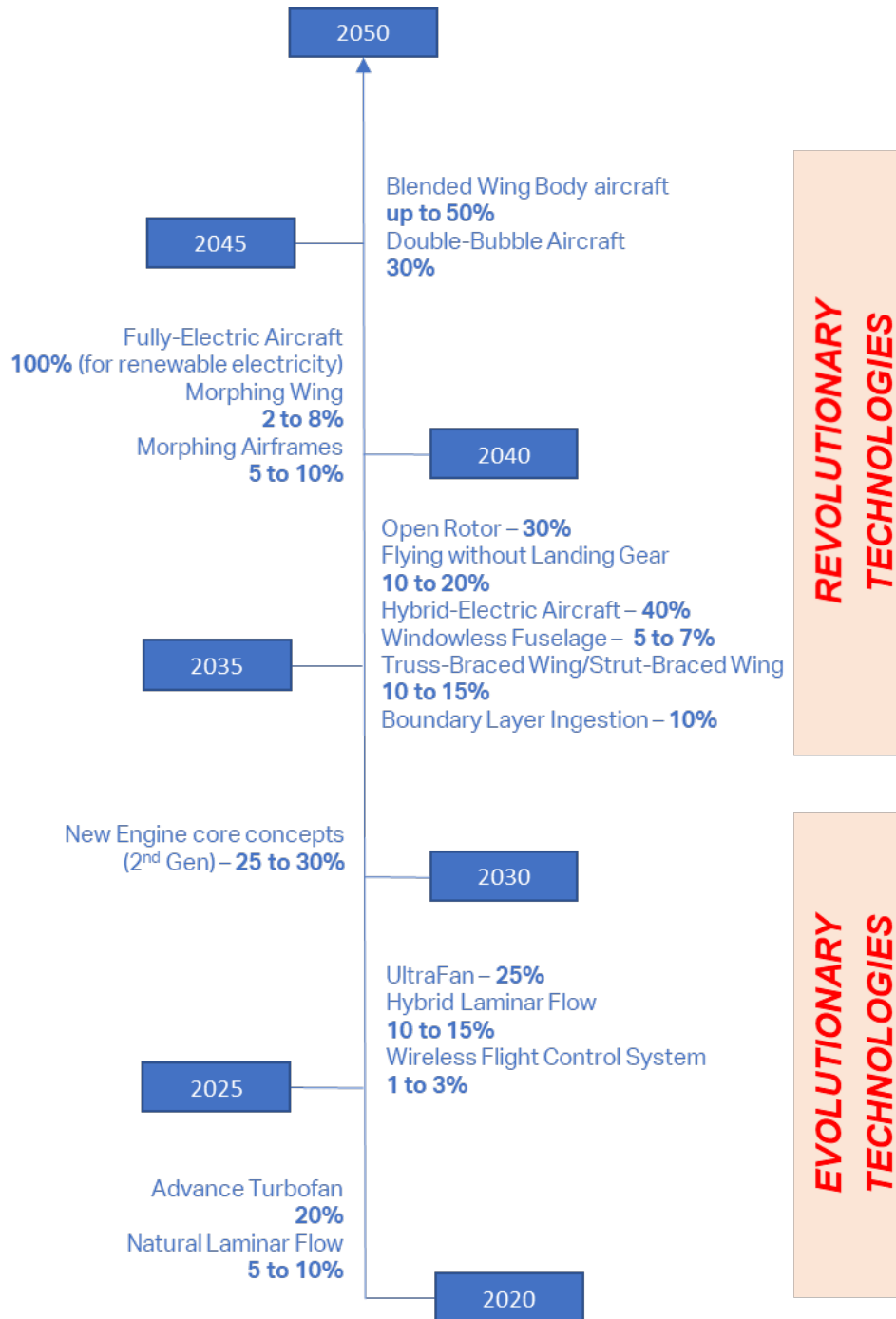


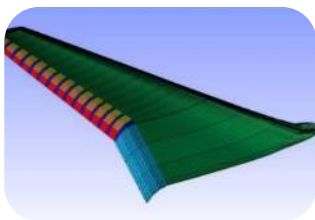
Figure 4: Timeline of expected future fuel efficiency improvements compared to predecessor aircraft or engine of the same category, details are given in Chapters 2 and 3

2. Evolutionary Aircraft Technologies

Evolutionary aircraft technologies are those that can be fixed on a classical tube-and-wing aircraft configuration with jet fuel-powered turbofan engines. Within the next 15 to 20 years, all new technologies for commercial aircraft will still be evolutionary, as radically new configurations will require more time to reach technical maturity. The current progress of evolutionary technologies allows the short-term carbon reduction goal to be met until 2020 (1.5%

average annual fuel efficiency improvement). They have a potential to improve fuel efficiency in the order of 30% by around 2030 compared to 2005. However, beyond around 2035, further fuel efficiency potential from evolutionary technologies may slow down [12].

Evolutionary technologies can be classified into several categories, depending on their way of implementation:



Retrofits



Production Upgrades



New Aircraft Designs

2.1. Baseline Fleet and Imminent Aircraft

The aircraft fleet in service in 2017 constitutes the baseline for this roadmap, see Table 1.

A range of new aircraft in various seat categories is planned to enter service in the next few years ("Imminent aircraft"). Each aircraft model replaces older generation models of similar size and range. Typically, the new models are 15% to 25% more fuel efficient than their predecessors. The design of the imminent aircraft is already well defined and their entry into service is fixed. Fuel-efficiency characteristics of imminent aircraft are known with a reasonably high degree of confidence, allowing a reliable forecast of their impact upon global fleet efficiency.

After the entry into service of the new aircraft models shown in Table 1, major new aircraft programs have not yet been officially announced. However, towards the end of

2018, plans for new "middle-of-the-market" aircraft in the 210-300 seat category have become more concrete. Boeing is studying concepts for a clean-sheet New Midsize Aircraft (NMA, unofficially named "797"), initially envisaging a market entry around 2025 [13], although the project has recently got lower priority [14]. Its first version would seat 225 passengers at 5000 nm range, to be followed two years later with a version for 265 passengers at 4500 nm. As the main innovative features, the proposed design could include an ovoid fuselage and a fuel-efficient shorter engine inlet design [15].

Airbus is envisaging an A321XLR with 4500 nm range, as a longer-haul version of the 4000-nm-range A321LR with a maximum capacity of 244 passengers. Recent news indicate that Airbus is considering a new clean-sheet narrow-body jet as well as a re-engined A350neo wide-body, for entry into service in the middle of the next decade [16]. In the highest seat categories, a potential A380 upgrade was envisaged before the announcement of stopping the A380 production.

Evolutionary technologies have a potential to improve fuel efficiency in the order of 30% by around 2030 compared to 2005, well beyond 2030 however, their potential may slow down.

The typical time between aircraft generations succeeding each other is around 15 to 20 years, sometimes longer.

Aircraft Category	Aircraft	Type	Range	Fuel Efficiency Benefits per ASK (compared to predecessor)	EIS	Maximum Seat Capacity	Reference Aircraft
Regional Jet	Airbus A220-100	Single Aisle	5741 km	20% [17]	2015	125	
	Airbus A220-300	Single Aisle	6112 km	20% [17]	2016	160	
	Embraer E175-E2	Single Aisle	3815 km	6% [18]	2021	90	Embraer E175
	Embraer E190-E2	Single Aisle	5278 km	17% [18]	2018	114	Embraer E190
	Embraer E195-E2	Single Aisle	4815 km	24% [18]	2019	146	Embraer E195
Narrow-body	Boeing 737 MAX 7	Single Aisle	7130 km	20% [19]	2021	172	Boeing NG 737-700
	Boeing 737 MAX 8	Single Aisle	6570 km	20% [19]	2017	210	Boeing NG 737-800
	Boeing 737 MAX 9	Single Aisle	6570 km	20% [19]	2018	220	Boeing NG 737-900
	Boeing 737 MAX 10	Single Aisle	6110 km	20% [19]	2020	230	
	Boeing 737 MAX 200	Single Aisle	6570 km	16% [19]	2019	200	
	Airbus A319 neo*	Single Aisle	6950 km	15% [20]	2017	160	Airbus A319 ceo
	Airbus A320 neo*	Single Aisle	6500 km	15% [20]	2016	194	Airbus A320 ceo
	Airbus A321 neo*	Single Aisle	7400 km	15% [20]	2017	244	Airbus A321 ceo
	Airbus A321 LR	Single Aisle	7400 km	20% [20]	2018	240	Boeing 757-200W
Wide-body	Airbus A330-800 neo	Twin Aisle	13900 km	14% [21]	2019	406	Airbus A330-200
	Airbus A330-900 neo	Twin Aisle	12130 km	14% [21]	2018	440	Airbus A330-300
	Boeing 787-9	Twin Aisle	13620 km	20% [19]	2014	242	Boeing 767-300ER
	Boeing 787-10	Twin Aisle	11910 km	25% [19]	2018	330	Boeing 767-400ER
	Airbus A350 XWB-900	Twin Aisle	15000 km	25% [20]	2015	400	
	Airbus A350 XWB-1000	Twin Aisle	14750 km	25% [20]	2018	440	
	Boeing 777X-8	Twin Aisle	16110 km	20% [19]	2023	375	Boeing 777-200LR
	Boeing 777X-9	Twin Aisle	14075 km	20% [19]	2020	425	Boeing 777-300ER

*Airbus announced 20% saving in fuel burn per seat for the A320neo family by 2020 [20]

Table 1: List of recent and imminent aircraft (green: recently entered into service – blue: imminent)

The typical time between aircraft generations replacing each other is in the order of 20 years, sometimes longer. With new aircraft models currently being introduced in almost all seat categories, it is uncertain if the next generation of aircraft will arrive before the 2030s except in the 211 – 300 seat category, as seen in Figure 5. The “middle of the market” aircraft might therefore be the only new aircraft model between the early 2020s and the early 2030s offering significant fuel efficiency improvement relative to

its predecessor. This may lead to a discernible slowdown of the annual fuel efficiency improvement rate of the world fleet during this time. On the other hand, this situation may offer the chance of engineering workforces being available to develop radically new aircraft designs for the following generation of commercial aircraft, which from the 2030s would replace the generation of today’s new and imminent aircraft (see Chapter 3).

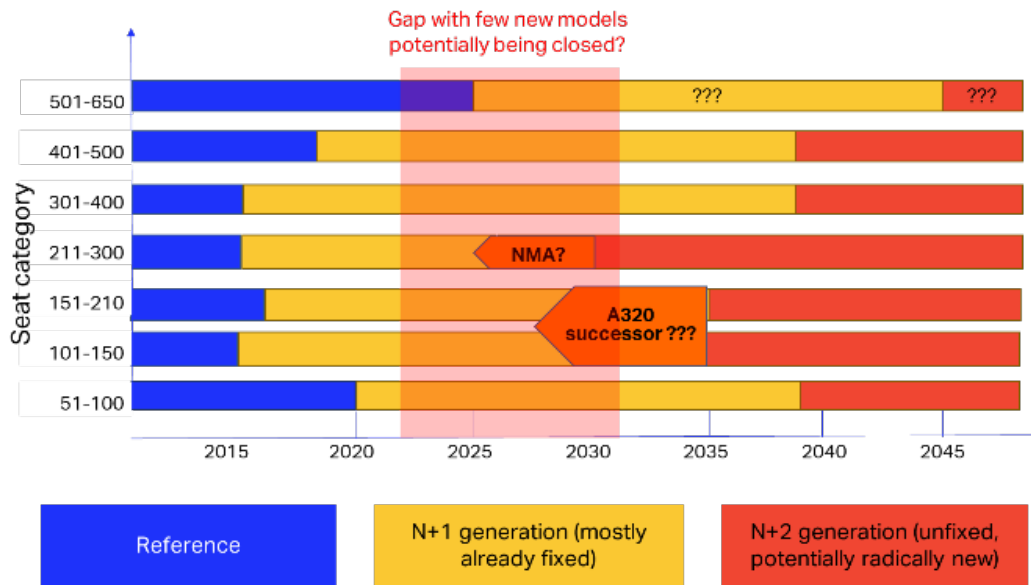


Figure 5: Expected sequence of future aircraft generations in different seat categories, including recent indications on new developments (based on [22])

2.2. Future Technologies

Aircraft entering service in the next few years have the same overall configuration as their predecessors. However, they are equipped with retrofits, serial upgrades and newly designed components and systems, which allow them to have a higher fuel efficiency performance. Table 2 shows a list of the most fuel-efficient retrofits and upgrades installed on the imminent fleet.

Another group of new fuel-efficient technologies are under development and planned to be used in new aircraft types in the near future and do not require radically new aircraft configurations. Table 3 contains a list of the most significant future evolutionary aircraft technologies with their Technology Readiness Level (TRL) as defined by NASA [23], which consists of a scale of progressing levels of maturity defined as shown in Figure 6:

Group	Concept	Type of Technology	Fuel Reduction Benefits
Aerodynamics	Variable Camber	Retrofit	1 to 2%
	Riblets	Retrofit	1%
	Raked Wingtip	Retrofit	3 to 6%
	Winglets	Retrofit	3 to 6%
Cabin	Lightweight Cabin Interior	Retrofit	1 to 5%
Material & Structure	Advanced Materials	Production Upgrade	1 to 3%
	Active Load Alleviation	Production Upgrade	1 to 5%
	Composite Primary Structures	Production Upgrade	1 to 3%
	Composite Secondary Structures	Production Upgrade	<1%
System	Adjustable Landing Gear	Production Upgrade	1 to 3%
	Taxi Bot	Retrofit	1 to 4%
	Advanced Fly-by-Wire	Production Upgrade	1 to 3%
	Structural Health Monitoring	Retrofit	1 to 4%
Advanced Engine Components	Fan Component Improvement	Production Upgrade	2 to 6%
	Very High BPR Fan	Production Upgrade	2 to 6%
	Advanced Combustor	Production Upgrade	5 to 10%

The numbers mentioned above are based on the IATA Technology Roadmap 2013 [22].

Table 2: List of retrofits and upgrades available for aircraft before 2030

Group	Concept	EIS	TRL	Fuel Efficiency Benefits)
New Engine Architecture (Ultra-High Bypass Ratio: UHBR)	Advance Turbofan [24]	2020	8	20% (Trent 700)
	Ultrafan [24]	2025	7	25% (Trent 700)
	GE9X [25]	2020	8	10% (GE90-115B)
	Counter Rotating Fan [22]	after 2020	3	15 to 20%
	Ultra-High Bypass Ratio Engine [26]	2025	5	20 to 25% (5 to 10% re LEAP)
Advanced Engine Concepts	Zero Hub Fan [22]	2020	7	2 to 4%
Engine Cycle	Adaptive/Active Flow Control [22]	after 2020	2	10 to 20%
	Ubiquitous Composites (2nd Gen) [22]	after 2020	3	10 to 15%
Aerodynamics	Natural Laminar Flow [27]	after 2020	8	5 to 10%
	Hybrid Laminar Flow [28]	after 2020	7	10 to 15%
	Variable Camber with New Control Surfaces [22]	after 2020	5	5 to 10%
	Spiroid Wingtip [22]	after 2020	7	2 to 6%
Systems	Electric taxiing system with Auto Transformer Rectifier Unit [29]	2021	8	3%
	Fuel Cells [30]	2020	8	1 to 5%

Table 3: List of new technology concepts (2020-2035)

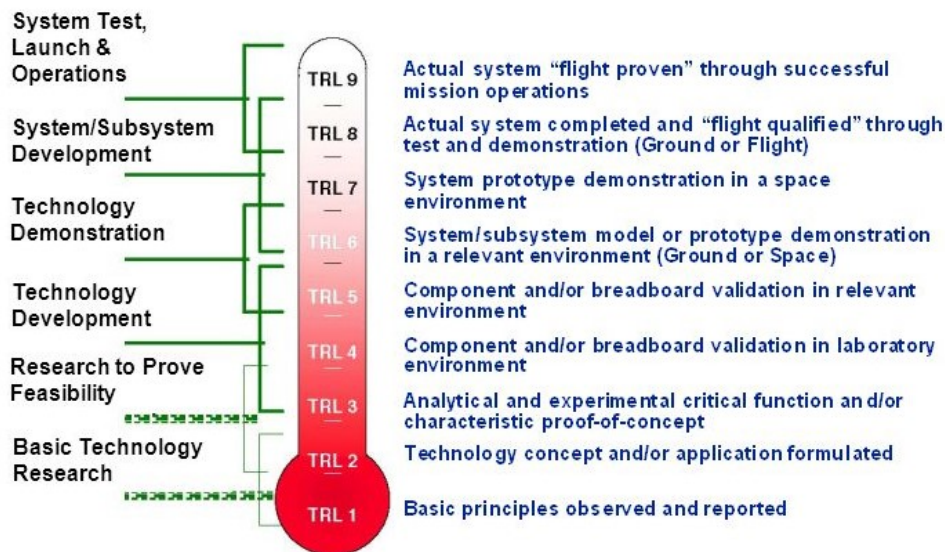


Figure 6: The NASA TRL Meter [23]

2.3. Individual Technologies

As can be seen from Table 2, the main contributions to fuel efficiency in evolutionary aircraft design are in the areas of aerodynamics, new engine architecture and systems.

Aerodynamics

Aerodynamic technology has been progressing continuously throughout the past decades to produce new designs with significantly reduced drag. An aerodynamic technology that has been pursued over many years and has recently made new progress in development is *Laminar Flow Control*. This technology allows considerable drag reduction by preventing turbulences in the airflow over the surface of the aircraft.

Natural Laminar Flow (NLF) Control achieves laminar flow only by designing the surfaces of the wings and other aircraft parts with a suitable shape. This technology is studied for example in the project BLADE (Breakthrough Laminar Aircraft Demonstrator in Europe). Since September 2017, flight tests have been conducted with an A340 test aircraft, on which the outer wing sections, of about 10 meters width, were replaced by laminar profiles. The size of the laminar sections is representative for the wing dimensions of typical narrow-body aircraft, which are likely to apply the laminar flow technology first. From the test flight results, the fuel saving potential of NLF for an 800-nautical mile flight would be around 4.6% [27].

Another way to create laminar flow conditions is *Hybrid Laminar Flow Control (HLFC)*, which uses boundary-layer suction to maintain laminar flow over the aircraft surface. This technology is particularly suited for swept wings and

fins. NASA, in the framework of its Environmentally Responsible Aviation (ERA) research program, carried out a series of test flights on a B757 equipped with a HLFC system to evaluate the dependence of laminar conditions on factors such as surface manufacturing, suction devices and surface coatings to prevent contamination [28].



Figure 7: A340 Laminar Flow BLADE demonstrator first flight

New Engine Architecture

In recent and imminent new aircraft models, the most significant contribution to fuel burn reduction comes from new engine technologies. Some of these engines have already entered service and others are expected to be installed on new aircraft in the near future. These engines have higher by-pass-ratios (BPRs) than previous engine models. In the case of regional jets and single-aisle aircraft such as the MRJ, the Embraer E2 family, A220 (formerly C series), A320neo and 737MAX, new engines operating on these aircraft have a BPR of 9 to 12, which allow fuel burn

reduction of about 15% compared to earlier engines with a BPR of typically 5 to 6. New engines for wide-body aircraft including A330neo and 777-9 reduce fuel burn by 10% compared to previous engines [28].

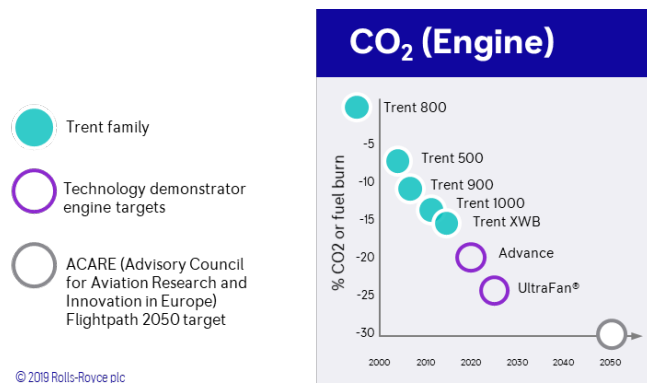


Figure 8: Improved efficiency levels of Rolls-Royce Trent engine generations from the Trent 800 onwards

In Europe, within the Clean Sky 2 program, new engine architectures are developed and going to enter production in the near-term.

- As an example, Rolls-Royce is working on two new efficient designs planned for launch in 2020 and 2025, respectively: the *Advance* and the *UltraFan* engines. The *Advance* engine presents a three-shaft architecture with a new high-pressure core. The *UltraFan* is a step further using the *Advance* core but with a two-shaft configuration coupled to a geared turbofan [31].
 - The *Advance Engine* is expected to have at least 20% reduction in fuel burn and CO₂ emissions relative to the Trent 800.
 - The *Ultrafan Engine* is a further development of the *Advance Engine*, with an expected minimum 25% improvement in fuel burn and CO₂ emissions relative to the Trent 800.
- Safran is working on *Ultra-High-Bypass Ratio (UHBR)* turbofan engines with a bypass ratio of at least 15 [32]. The design makes extensive use of lightweight composite materials. The UHBR is expected to have a 5 to 10% fuel efficiency relative to the LEAP engine, used e.g. in the A320neo family, or 20 to 25% to conventional engines in the narrow-body category [26].

In the USA, new engine designs are being produced under the CLEEN II national research program.

- The GE9X engine, which will power Boeing's new 777X aircraft, is considered to improve fuel efficiency by 10% relative to the GE90-115B engine. Its certification is expected in 2019 [25].



Figure 9: Ultra-High Bypass Ratio engine design (Safran UHBR Clean Sky project)



Figure 10: GE9X engine design

Aircraft Systems

Advances in aircraft systems can reduce fuel consumption considerably in current aircraft configurations. Some examples:

- Aircraft taxiing offers high fuel saving potential through new aircraft systems. Safran has developed an *electric taxiing system* (Electric Green Taxiing System, EGTS) consisting of electric motors mounted in the main landing gear wheels, which allow taxiing without using the main engines or a towing tractor [33].
- An *Auto Transformer Rectifier Unit (ATRU)* is envisaged as a low-weight power supply for the EGTS, which converts 115 V AC produced by the aircraft's auxiliary power unit (APU) to 540 V DC required by the EGTS motors [33].



Figure 11: Aircraft landing gear with Safran Electric Green Taxiing System

- Fuel cells produce electric energy from oxygen from ambient air and gaseous hydrogen. They are environmentally friendly as they generate neither noise nor pollutant emissions, only clean water. Fuel cells could replace the APU and power various onboard systems such as engine start-up, ventilation, flight controls, lighting, ovens for meals and in-flight entertainment. They can robustly operate over the duration of a long-haul flight in all flight conditions. Safran is currently working on the development of this technology, which is expected to be ready for commercial flight applications by 2019-2020. Depending on operational conditions, fuel savings are

predicted to be between 1 and 5% [30]. It has to be considered, however, that fuel cells require a regular supply of hydrogen as a fuel. Therefore, the implementation of fuel cells for onboard power supply in future aircraft will be likely only once a worldwide hydrogen supply structure is being built up as a clean energy source for various industry sectors. With the current progress in renewable energies, this may well happen within the next decade.

Evolutionary Technologies – Outlook

The fuel efficiency improvement potential of conventional tube-and-wing plus turbofan aircraft configurations is likely to significantly reduce in the coming decades. Nevertheless, the improvement estimated to be achievable by the cumulation of various different technologies is still considerable. A study by NASA in the framework of their Environmentally Responsible Aviation (ERA) [34] shows that tube-and-wing configurations equipped with technologies such as active laminar flow, riblets, adaptive trailing edge and ultra-high bypass or geared turbofan engines, reach over 40% improvement compared to a 2005 best-in-class baseline aircraft. The fuel efficiency difference between the best evolutionary and the first generation of revolutionary aircraft configurations (see Chapter 3) would be in the order of only 5%. However, it must be considered that the revolutionary configurations have further development potential well beyond 2050.

3. Revolutionary Aircraft Technologies

As seen in the previous chapter, evolutionary technologies based on conventional tube-and-wing design powered with turbofan engines only have a limited potential for further fuel efficiency improvement. Achieving the long-term industry climate goal (reducing global net aviation CO₂ emissions by 50% by the year 2050 relative to 2005) would require further CO₂ emissions reductions of over 80% by 2050. A large part of this reduction will likely have to be covered by the use of sustainable aviation fuels (SAF). However, meeting this highly increasing demand for SAF could be challenging. With strong improvements in fuel efficiency, resulting in a more moderate increase in global fuel demand, this challenge could be alleviated. Thus, even with a strong SAF deployment in future, there is high interest for substantial fuel efficiency improvements in future aircraft including radically new technologies and design concepts. The same considerations are valid in relation to carbon offsets, which are also not available in unlimited quantities. Strong efforts to reduce aviation fuel consumption thus help to better match demand and availability for carbon offsets.

Traditional aircraft manufacturers such as Airbus and Boeing, as well as specialized start-up companies such as Zunum Aero and DZYNE, research institutions and academia (DLR, NASA, ONERA, Bauhaus Luftfahrt, among others) are working on a variety of novel aircraft concepts. The major trends in the development of future more efficient aircraft are in novel aircraft configurations as well as revolutionary propulsion technologies, materials and structures. Their development and implementation, including necessary adaptations of the air transport system, require considerable lead times. The first radically new larger commercial aircraft are therefore expected to be able to enter service from about 2035 under optimal framework conditions (Figure 12). This chapter provides a description and an assessment of radically new technology concepts with high fuel efficiency benefits.

While it is very likely that the technical development of these new aircraft concepts could be achieved within the next two to three decades, there are economic and commercial constraints that might delay or even prevent their implementation.

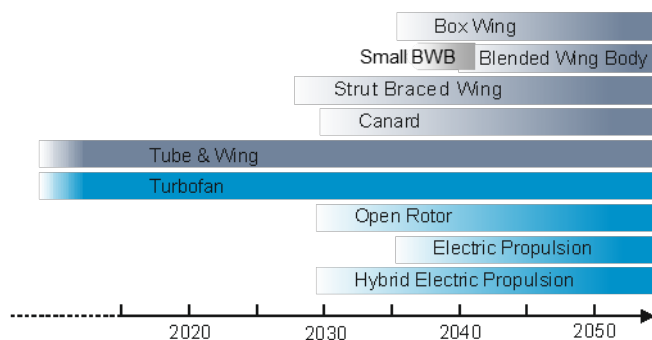


Figure 12: Potential timeframes for the availability of analyzed aircraft and engine concepts for airliners

3.1. Novel Airframe Configurations

While all current commercial aircraft have a conventional tube-and-wing configuration, novel configurations with higher fuel efficiency benefits are also considered for future airframes. Design concepts currently seen as most promising by research establishments include: strut-braced wing, blended wing body, double-bubble and box-/joined-wing aircraft. All these designs are significantly more environmentally friendly than conventional aircraft designs, not only more fuel-efficient, but also quieter. The descriptions below indicate for each concept the preferred applicability to either short or long-haul, the degree of fuel-efficiency benefit and the point in time when technical maturity can be reached under optimal conditions.

Strut-braced Wing

The strut-braced wing design (SBW) concept utilizes a structural wing support to allow for larger wing spans without increasing structural weight. By increasing the span, the induced drag is reduced and therefore less thrust is needed, which allows installing smaller and lighter engines. Folding wingtips avoid the aircraft exceeding the maximum wingspan of the airport category standard of comparable present aircraft. An additional advantage is that the high wing arrangement allows bigger engine sizes, such as open rotors. Within the "Subsonic Ultra Green Aircraft Research" (SUGAR) studies conducted by Boeing, a 154-seat high aspect-ratio, low induced-drag SBW aircraft was designed. A first configuration was designed with advanced turbo-fan engines for an entry into service in 2030-35 [35].

This configuration is about 29% more fuel-efficient over a 900 nm mission (design range of 3,500nm) than a Boeing 737-800 with CFM56 engines. Additional wing-weight optimizations of this design combined with an open rotor could potentially lead to a block fuel saving of up to 53% [36] compared to the evolutionary baseline fleet. Its EIS could be feasible around 2040.



Figure 13: Strut-braced Wing with Open Rotor designed by NASA/Boeing

Blended Wing Body

The blended wing body (BWB), also called hybrid wing body (HWB), is mainly a large flying wing, which contains a payload area (passenger cabin or cargo storage area) within its center section. The shape of the center body and the outer wings are smoothly blended. In the past, the flying wing design was mainly used for military aircraft, such as the Northrop B-2 bomber. In civil aviation, the BWB is seen as a typical example of a “futuristic” new aircraft category which could potentially enter into service in civil aviation in the next decades. Its aerodynamic shape allows generating lift by the entire aircraft, which is thus significantly higher than for conventional tube-and-wing configurations.

So far, in BWB concepts for civil aviation applications, very large long-range configurations have been favoured, as the aerodynamic benefits are highest in cruise flight and for a large center body area. However, it has recently become possible to also optimize smaller versions of BWBs designed for around 100 passengers on short-haul routes, see below. Out of various BWB concepts, a typical example is the 500-seat design developed at the German Aerospace Center (DLR) with an estimated EIS at the earliest in 2040 [37]. Fuel efficiency forecasts for various large BWB designs typically vary between 27% [38] and around 50% [34] lower than current aircraft of similar size and range. For the new small BWB design, fuel efficiency estimates are around 30% below current reference aircraft [39].

Other examples of BWB concepts are designs developed as part of NASA’s X-plane project [40] [41] [42], where several manufacturers have developed different design ideas for a BWB aircraft. The Boeing design is based on

experience with the unmanned subscale X-48 experimental aircraft. The BWB aircraft design displays a wing blended with the main hull, with two engines and a pair of small vertical fins installed on top of the rear edge of the aircraft.



Figure 14: Blended Wing Body designed by DLR



Figure 15: NASA X-plane: Blended Wing Body designed by Boeing

Small BWB concept

DZYNE Technologies, in cooperation with NASA, have developed a small BWB aircraft concept, with a basic design capacity of 120 seats. It shares some of the same features as the large BWB designs described above, however the vertical stabilizer fins on this vehicle are part of the wing tips, appearing as oversized winglets. Optimizing the layout also for a smaller BWB has become possible thanks to a landing gear storage mechanism that needs less height and allows a flatter design of the entire aircraft [39], [41]. This design allows benefits from the advantages of the BWB concept in a market segment with much higher volume than the 400+ seater range targeted by BWBs so far. In particular, the short twin-aisle cabin configuration and the large overhead bins allow easier and shorter passenger boarding and disembarking than in comparable single-aisle aircraft (in average 5 rows to the nearest exit vs 22 for the

737-700 [39]. Existing airport passenger bridges could be used without the need for adaptation. This is expected to shorten airport turnaround time significantly and thus allow increased utilization of the aircraft. Whereas earlier passenger acceptance studies of very large BWBs showed that passengers felt uncomfortable in cabins with several hundred seats, reminiscent of a cinema hall, with very few window seats, there is no negative impact on passenger acceptance with the small BWB. On the contrary, with easier boarding, it alleviates a frequent item of passenger dissatisfaction [43]. Emergency evacuation, which was identified as an issue for large BWBs, is enhanced as well compared to single-aisle aircraft.



Figure 16: NASA X-plane: Blended Wing Body designed by DZYNE

In previous studies, one challenge identified for the BWB concept was the difficulty of designing aircraft families with high commonality between the members. In tube-and-wing aircraft, cabin size can easily be increased or reduced by inserting or removing cylindrical sections of the fuselage.

In the framework of the small BWB concept, a T-shaped “plug” design is proposed to obtain a series of aircraft models derived from a basic one, with passenger capacities varying from 120 to 200 [39].

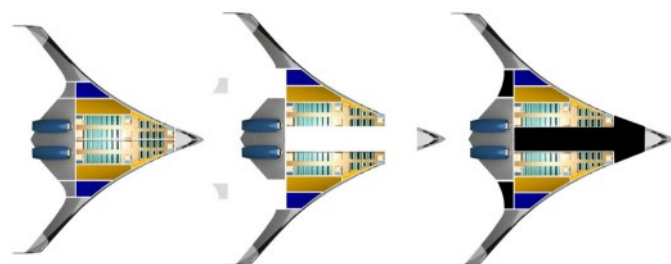


Figure 17: Insertion of a T-plug to grow the capacity of a BWB (from [39])

It is even thought of offering the smallest BWB version in a business jet configuration, which may open an additional market niche and might possibly enter service already around 2025 [44].

Cargo BWB

Another promising application for BWBs is cargo transport. Contrary to passenger aircraft, dedicated cargo aircraft do not need the entire cabin to be pressurized. Making the irregularly shaped BWB structure resistant to the pressure differential between cabin and outside air at cruise altitude is a major design challenge. Cargo aircraft would not have this constraint, as only the cockpit would have to be pressurized. Also, moving and storing cargo containers would be easier in a broad BWB than in a narrow tube-and-wing aircraft. For these reasons, it is not unlikely that the first BWB design will be for cargo transport.



Figure 18: Flying-V aircraft concept developed by TU Delft in collaboration with KLM

“Flying-V”

Another promising flying wing-type concept that has recently attracted considerable attention is the “Flying-V” [45], a V-shaped highly-swept double wing configuration designed for a similar passenger number (314) and range as the A350. The two wings accommodate the passenger cabin, the cargo hold and the fuel tanks. With the same wingspan as the A350, it can use the same airport infrastructure. Similar to the BWB configuration, the Flying-V has lower aerodynamic drag and is 20% more fuel-efficient than a comparable tube-and-wing aircraft. Based on an initial idea developed at Airbus, the Technical University of Delft in the Netherlands is now developing the concept further. The project is supported by KLM, which presented it at the 2019 IATA Annual General Meeting in Seoul [46].

Double-bubble fuselage

As part of NASA’s X-plane project, Aurora Flight Sciences designed the D8 aircraft concept, whose main feature is a “double-bubble” fuselage that can be thought of consisting

of two blended side-by-side tubes. The wide flattened fuselage body generates additional lift. Therefore, the wings can be designed smaller and lighter to carry the aircraft weight, which leads to a significant fuel burn reduction relative to comparable conventional configurations. In addition, the engines attached at the rear of the fuselage allow the air to flow over the top of the aircraft and move through the engines which in return helps reducing the overall drag. This concept is known as boundary layer ingestion (see below). The D8 configuration has the potential of achieving up to 20% compared to the A320neo [41] [47].



Figure 19: NASA X-plane: Double-bubble designed by Aurora Flight Sciences



Figure 20: Parsifal Box-wing design

Box-/Joined-Wing

The box-wing configuration, which was proposed first by Ludwig Prandtl in 1924, connects the tips of two offset horizontal wings. For a given lift and wingspan, this configuration assures minimum induced drag and offers savings in fuel consumption compared to conventional aircraft. Parsifal, a research project coordinated by the University of Pisa, aims at designing an aircraft with the same wingspan as an Airbus A320 or Boeing B737 that has

the same capacity as an aircraft of a larger category, such as an Airbus A330 or a Boeing 767, and the fuel consumption of the smaller aircraft [48].

3.2. Revolutionary Structure and Materials

While a considerable amount of weight reduction has been achieved through the use of composite materials and light metal alloys, researchers are looking into revolutionary materials that would offer even better weight efficiency and increased aircraft performance. In its Spanwise Adaptive Wing (SAW) project, NASA is currently investigating aircraft wings that can adapt to each flight phase by modifying the shape of different parts of the wings, with the aim of reducing weight and drag, and thus improving fuel efficiency. A revolutionary material is instrumental in reaching this goal, the *shape memory alloy* (SMA), a nickel-titanium alloy that can be “trained” to return to its initial shape after a deformation when heated [49] [50].

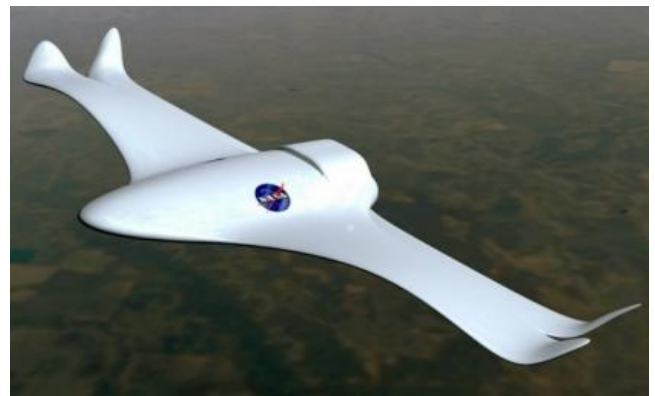


Figure 21: Shape Memory Alloy technology designed by NASA

Another promising technology is the morphing wing that is under study by NASA and MIT. This new wing architecture could greatly simplify the manufacturing process and reduce fuel consumption by 2-8% by improving the wing’s aerodynamics, as well as improving its maneuvering capabilities. The morphing mechanism would comprise the whole wing, which would be covered by a skin made of overlapping pieces reminiscent of scales or feathers. The ability to deform a wing shape to do pure lift and roll would increase flight efficiency and thus reduce fuel burn. In addition, wind-tunnel tests of this structure showed that it matches the aerodynamic properties of a conventional wing at about one-tenth of its weight [51].

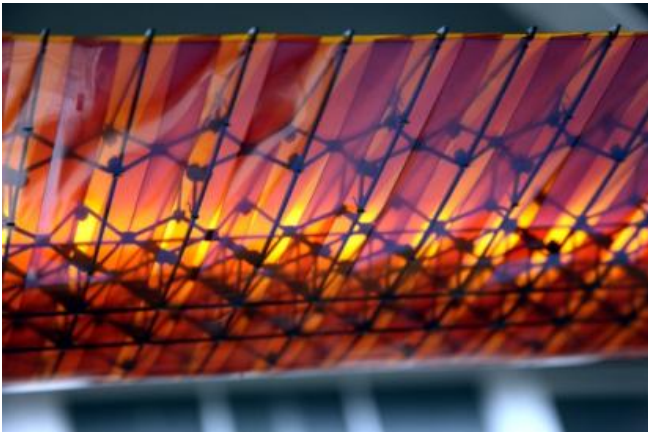


Figure 22: Morphing Wing technology designed by NASA/MIT

3.3. Revolutionary Propulsion Technology

Radically new propulsive designs are expected to have considerable impact on fuel reduction for the future fleet. The implementation of revolutionary engines and electric aircraft is expected to allow very significant fuel and emissions savings in the coming decades. Currently, the open-rotor design, boundary-layer ingestion and electric aircraft are the most prominent innovations when it comes to aircraft propulsion technologies.



Figure 23: Safran Counter-Rotating Open Rotor developed in Clean Sky

Open Rotor

The open rotor is a fuel-saving engine architecture that is a hybrid between a propeller and a turbofan engine, characterized by two counter-rotating, unshrouded fans. It allows a reduction of fuel burn and CO₂ emissions of typically 30% compared to conventional turbofan engines,

such as the CFM56. While the open rotor concept itself is several decades old, its development was slowed down mainly by challenges to reduce its noise levels, which are higher than from comparable turbofan engines. Manufacturers envisage the open rotor engine to enter service around the year 2030 [26] [52].

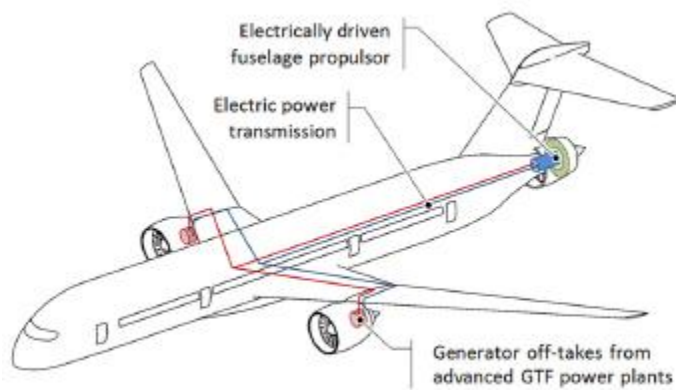
Boundary Layer Ingestion

With the aim of reducing the weight and drag of high propulsive efficiencies generated by conventional systems integrated in the aircraft, a promising approach of distributing the propulsive thrust on the main structures of the airframe is considered. This idea is referred to as the "Propulsive Fuselage Concept" (PFC), which allows the whole fuselage to act as a propulsive thrust. The most straightforward way to implement this concept is by full annular boundary layer ingestion (BLI). The concept of wake-filling through BLI has been thoroughly investigated in various projects. Some of those include NASA's "FuseFan", the Bauhaus Luftfahrt "Claire Liner", the MIT "D8" concept and the NASA "STRAC-ABL" [53]. With the BLI technology, engines are located near the rear of the aircraft so that air flowing over the fuselage becomes part of the mix of air going into the engine air inlet and is then accelerated backwards. According to NASA, analytical studies have shown that BLI technology is capable of reducing the aircraft fuel burn by as much as 8.5% compared to aircraft operating today [54].



Figure 24: Propulsive Fuselage concept by Bauhaus Luftfahrt, integrating boundary layer ingestion and airframe wake filling

As part of the Horizon 2020 Framework Programme, the European Union is funding a project that is dedicated to proving the validation of the PFC concept, called CENTRELINE (ConcEpt validation sTudy foR fuselagE wakefillng propulsioN integration). This project explores a turbo-electric, twin engine PFC systems design with an aft-fuselage BLI propulsor [53].



H2020 CENTRELINE (turbo-electrically driven fuselage wake-filling)

Figure 25: CENTRELINE technology concept for fuselage wake-filling propulsion integration

CENTRELINE aims at maximizing the benefits of aft-fuselage wake filling under real systems design and operating conditions. Its objectives are to achieve a TRL of 3 to 4 for the PFC concept at the end of the project and to reach 11% reduction of both CO₂ and NO_x emissions reduction in reference to current advanced conventional aircraft that are equipped with power plant, aerodynamic, structural and systems technologies suitable for an EIS year of 2035.

Electric Aircraft

Plans to use electricity as a clean propulsive energy for aircraft have recently made strong advancements. Electric motors do not produce any emissions during their operations, this makes them a crucial technology element in reaching the environmental goal for 2050. Electric power generation is obviously not emissions-free today, but it can be expected that the related emissions will go down considerably between now and 2050, thanks to the strong trend towards renewable energies across all sectors of the global economy ([55], see Figure 25).

Aircraft manufacturers in conjunction with electric equipment providers or specialized niche companies (see below) are currently developing electric technologies to serve as a propulsive energy and to provide energy on-board the aircraft.

Amongst the different electric propulsion architectures considered for future aircraft, six main categories can be distinguished, which rely on different technologies [56]. The levels of CO₂ reduction associated with the different

technologies are a function of the component performances, the configuration, and missions.

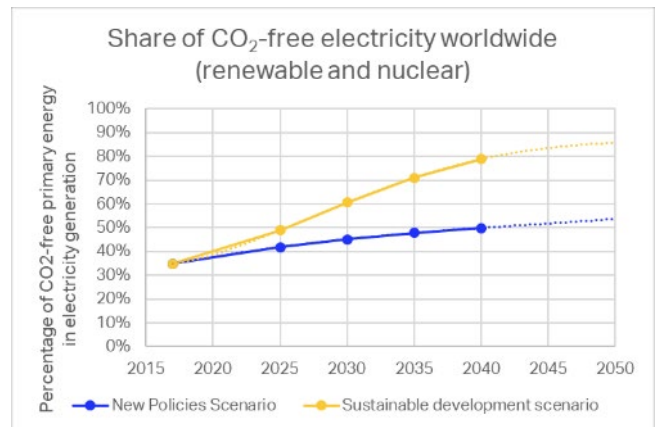


Figure 26: Share of electricity from CO₂-free primary energies (renewable plus nuclear) for two policy-driven scenarios (from [55])

All-electric systems rely on batteries as the only propulsive power source on the aircraft.

Hybrid-electric systems rely on gas turbine engines for propulsion power generation and for charging batteries. Also, the batteries provide energy needed for propulsion during several phases of flight.

- **Parallel-hybrid:** with this system, a turbine engine and a battery-powered motor are both mounted on a shaft which drives a fan, so that either or both components can provide propulsion at any time given.
- **Series-hybrid:** with this technology, only the electric motors are connected to the fans mechanically. The function of the gas turbine is to drive an electric generator, which in turn drives the motors and/or charges the batteries. Series-hybrid systems are compatible with distributed propulsion concepts that use multiple small motors and fans.
- **Series/Parallel partial hybrid:** this system has one or more fans which can be driven directly by a gas turbine while other fans can be driven by electric motors exclusively, these motors can be powered by a turbine-driven generator or by a battery.

Electric motors do not produce any emissions during their operations. This makes them a crucial technology element in reaching the environmental goals for 2050.

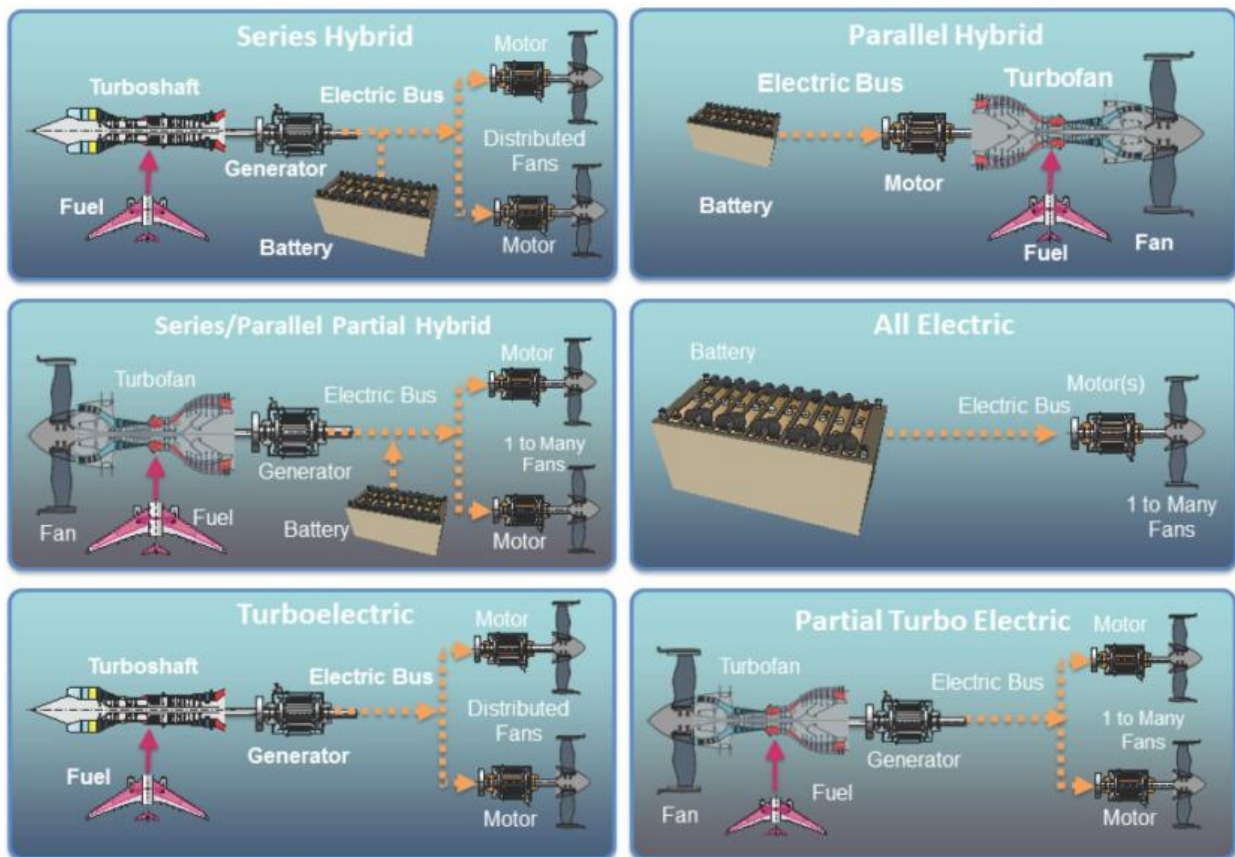


Figure 27: Electric propulsion architectures [56]

Turbo-electric systems do not rely on batteries as propulsive power source during any phase of flight, they rather use gas turbines.

- Full turbo-electric: in this configuration, turboshaft engines are used to drive electric generators that power inverters and consequently individual direct current (DC) motors which drive the individual distributed electric fans.
- Partial turbo-electric: this system is a variant of the full turbo-electric system which uses electric propulsion to provide some of the propulsive power, the rest is generated by a turbofan driven by a gas turbine. Consequently, the electrical components for a partial turbo-electric configuration can be developed with smaller advances beyond the state of the art than are needed for a full turbo-electric configuration.

It is relatively easy to transmit electric power to multiple widely spaced motors. Also, electric motors require much less maintenance than combustion engines. Therefore, a larger number of separate electric engines installed on an aircraft does not lead to much higher maintenance costs. This situation is different from the case of jet aircraft, where high maintenance costs are a strong penalty for four-engine aircraft compared to twins. Thus, electric propulsion

concepts are well-suited for application to distributed propulsion architectures. This includes design options for boundary layer ingestion (BLI).

The introduction of electric propulsion for aircraft is a revolutionary step in the aviation industry. It is made easier by the fact that it is a scalable technology, which allows a step-by-step implementation starting with 1- and 2-seater aircraft, which operate already today, and including several smaller-scale innovation steps that would be introduced before reaching a battery-powered commercial aircraft with about 100 seats.

Electric air taxis

Electric air taxis are becoming a reality with many start-ups and aircraft manufacturers involved in finding solutions to urban air mobility. As examples of the current progress in electric flight, two German start-ups have developed two vehicles that could transport passengers from one place to another inside and between cities without producing any emissions.

Volocopter ran its first manned flight in 2016 and acquired German and international safety certificates on its 2X

vehicle that can accommodate up to two people on-board and fly for up to 27 km at 70 km/h [57].

Lilium, a Munich-based start-up, is developing a fully-electric VTOL (vertical take-off and landing) aircraft that can accommodate up to two people and fly up to 300 km in one hour. An unmanned prototype has already had its first flight

in 2017, a larger 5-seater version flew for the first time in May 2019 [58]. A manned prototype will be used later for certification flights [59]. According to Lilium, passengers would be able to book their own VTOL in 2025. However, air traffic management restrictions for these aircraft must be resolved before commercial services can start [58].

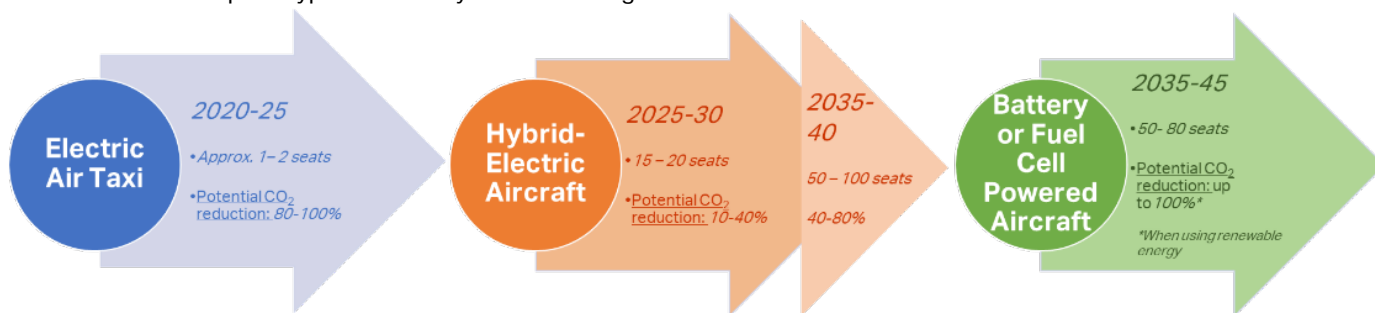


Figure 28: Step-by-step approach in the penetration of electrically-powered aircraft into the market

Hybrid-electric aircraft

Hybrid-electric aircraft are considered a very effective substitute for conventional short- and medium-range aircraft in the near future. Many large companies in the aerospace and electrical equipment sectors are investing in this technology such as Airbus, Siemens, Rolls-Royce, Boeing and others. Different principles of hybrid-electric aircraft combining innovative electric motors and combustion engines have been described in the previous section. In addition, heavy-weight batteries could be replaced by hydrogen fuel cells, provided a reliable worldwide hydrogen supply network is in place (see also Section 2.3 – Aircraft Systems). These aircraft are being designed to replace conventional aircraft powered by combustion engines on regional routes. According to DLR studies, it will be perfectly possible to replace 60 to 70% of all conventional regional aircraft with hybrid aircraft [60].



Figure 29: E-Fan X Technology designed by Airbus

In November 2017, Airbus, Rolls-Royce and Siemens formed a partnership with the objective to develop and build a hybrid-electric demonstrator aircraft, the E-Fan X, planned to fly in 2020. It uses serial hybrid-electric technology to power a 2-megawatt electric motor, mounted on a BAe 146 flying testbed replacing one of the four gas turbine engines. The longer-term goal is to build a commercial aircraft equipped with the E-Fan X technology that can accommodate 50-100 passengers on board and fly regional and short-range routes, with an envisaged entry into service around the year 2035 [61] [62]. In May 2019, SAS and Airbus signed a Memorandum of Understanding for research on operational and infrastructural bnn requirements for the introduction of hybrid and electric aircraft into commercial service. SAS has a goal of 25% emissions reduction by 2030.

In the US, Boeing and a US airline have invested in a start-up based in Washington State, Zunum Aero, which aims to develop the world's first commercial hybrid electric-powered passenger aircraft. Zunum planned to fly a demonstrator aircraft by 2019 for its initial hybrid aircraft that can accommodate 15 passengers and fly up to 600 nm. This aircraft was expected to enter service in 2023. However, the company is currently in financial difficulties. Zunum's further plans include introducing a short-range hybrid aircraft in 2027 that would be able to accommodate 50 passengers and fly up to 1000 nm. In addition, there are development plans for a 100-seater aircraft that would be able to fly up to 1500 nm. The aircraft would be able to cut 80% of local CO₂ emissions and is expected to enter service in the early 2030s [63].

The introduction of electric propulsion for aircraft is a revolutionary step in the aviation industry. It is made easier by the fact that it is a scalable technology.



Figure 30: Hybrid-Electric Aircraft designed by Zunum

NASA's STARC-ABL, one of NASA's X-plane project designs, is a **turbo-electric aircraft**. The STARC-ABL is a single-aisle turboelectric aircraft with an aft boundary-layer propulsor. This design relies significantly on electric power, not only for propulsion, but also to operate electrical onboard systems

such as flight controls, avionics and de-icing. The STARC-ABL would accommodate up to 150 passengers and is envisaged to enter service between 2035 and 2040, with a 10% emissions reduction benefits [64].



Figure 31: NASA X-plane: STARC-ABL design

Electric Aircraft Design	Electrical Power (MW)	Electric Aircraft Type	EIS	CO ₂ Reduction Benefits	Range	Aircraft Configuration	Number of Passengers
Zunum Aero	4-5	Series-hybrid	2027	80%	Regional	Tube & wing	50
Zunum Aero	15	Series-hybrid	2030-35	80%	Regional	Tube & wing	100
E-Fan X	8 to 16 [62]	Series-hybrid	2030-35		Regional	Tube & wing	50-100
STARC-ABL	2 to 3	Partial turbo-electric	2035-40	10%	Regional	Tube & wing	150

Table 4: List of Hybrid-Electric Aircraft Concepts

Battery-powered aircraft

Battery-powered aircraft achieve the highest possible CO₂ emissions reduction and environmental benefit in general. They generate neither CO₂ nor pollutant emissions affecting local air quality during operations, and their noise generation is much lower than that of aircraft powered by combustion engines. Question marks remain over the CO₂ emitted by electrical power generation. While today's electric power generation produces roughly 0.6 kg CO₂/kWh in world average (2009 value, [65]), it can be expected that with the progress in renewable energy development and States' commitments under the Paris agreement (some States planning an 80 to 90% reduction of their CO₂ emissions by 2050), CO₂ emissions from electricity will be significantly lower in the next decades. The most optimistic scenario in IEA's World Energy Outlook foresees over 80% of CO₂-free electricity after 2040 (see Figure 25).

Some companies are currently working on the design and development of battery-powered aircraft, these are however likely to need more time until entry into service than comparable hybrid-electric aircraft. Wright Electric, a startup company based in Los Angeles, aims at providing zero-emissions short-haul flights with battery-powered aircraft. The company has a partnership with low-cost carrier easyJet [66]. Wright Electric's design is based on distributed propulsion with a large number of electric fans integrated in the wings, and on batteries that can be easily exchanged during airport turnaround. Wright Electric is targeting an aircraft model that would accommodate 150 passengers and be able to fly up to 290 nm. They announced plans to enter the market by 2035 [67].



Figure 32: Wright Electric battery-powered aircraft concept with distributed propulsion

From academia, Bauhaus Luftfahrt designed a battery-powered concept aircraft in 2012, the Ce-Liner, with a C-wing configuration that substantially improves its aerodynamic efficiency compared to a conventional airframe design, in order to minimize energy consumption and thus battery weight. The Ce-Liner concept study made assumptions about progress in battery energy density continuing as currently observed, without however exceeding any physical limitations. Under these assumptions, a Ce-liner with a maximum seat capacity of 189 passengers in a single class version and a range of 900 nm was found to be able to enter service by 2035 [68] [69], however, more recent feasibility estimates are significantly more cautious.



Figure 33: Ce-Liner Aircraft designed by Bauhaus Luftfahrt

Electric blended wing body

There are even plans to combine the benefits of electric propulsion and the blended wing body airframe design. NASA has been studying BWB concepts with distributed turboelectric propulsion systems over the last decade [70]

[71] and predicted fuel savings in the order of 70%. The recent progress in small BWB design, as described in Section 3.1, could lead to new opportunities in this area. Small BWBs typically cover the 100-to-150 seat category, which is much better adapted to various concepts of hybrid, and potentially battery, electric propulsion than very large aircraft. Furthermore, the market potential in this seat category is large and it can be expected that development costs will be shared among a high number of units to be produced. An electric BWB could build upon the combined progress in airframe and propulsion design, which are expected to occur in parallel in the next decades.



Figure 34: NASA Turboelectric Blended Wing Body

The timeline for the market introduction of electric aircraft is still subject to strong uncertainties, the most critical aspect for full-battery as well as for hybrid propulsion being the necessary progress in battery technology. On one hand, one can find a strongly marketing-oriented view with startup companies forecasting entry into service of 15-to-20-seat electric aircraft around 2023, going up to 100-seat aircraft in the early 2030s. This includes an optimistic view on the availability of battery technology, with the need for capital to build up a production being seen as the main challenge.

On the other hand, more conservative views see an entry into service of electric aircraft in the 15-20 seat category around 2030. As for regional hybrid aircraft of 50-100 passengers, entry into service dates would rather be around 2050. This view is mainly influenced by an expected longer time needed for battery technology development.

A recent survey among aerospace professionals [72] indicates broad agreement that a hybrid-electric aircraft

It can be expected that with the progress in renewable energy development and States' commitments under the Paris agreement, CO₂ emissions from electricity will be significantly lower in the next decades.

could enter commercial service by the early 2030s, while views on when battery-electric aircraft could become available are more divergent. In average, the experts see an entry into service around 2043 as realistic.

Recently, public funding bodies have focused more strongly on electric aviation as part of future sustainable transport

(e.g. in the UK [73] and in the EU [74]). This may contribute to accelerating the development and maturation of electric aircraft propulsion. The planned stronger efforts to fund electric aircraft technology development publicly are not only motivated by the expected climate impact, but also by the benefits for noise and air quality.

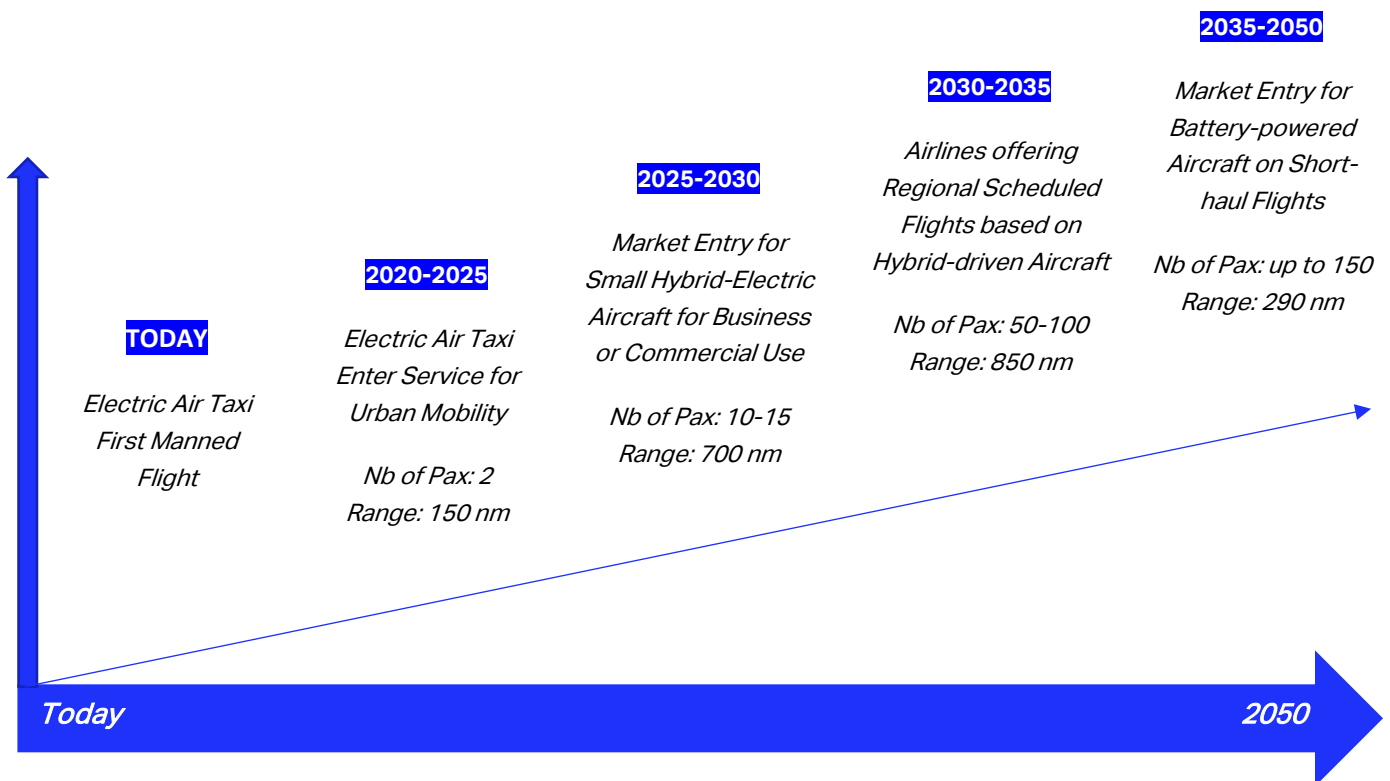


Figure 35: Outlook for Electric Propulsion Market (optimistic view)

3.4. Assessment of Revolutionary Technology Concepts and Deployment Challenges

Compared to today's aircraft, all revolutionary technology concepts and aircraft configurations have a considerable impact on various aspects of operations. Most of them have been designed with the aim of reducing fuel burn and CO₂

emissions. However, further benefits may come along with them, whereas other properties may present challenges for implementing the technology or for day-to-day operations. This can affect various areas of operations, such as:

- Environment (noise, local air quality)
- Ground operations and infrastructure
- Flight performance
- Passenger and cargo aspects
- Maintenance
- Industrial aspects (development, manufacturing)
- Certification

The following paragraphs give an overview of the main challenges and benefits of the revolutionary concepts studied in this report. More details are described below (see also [12]).

Open Rotor

	Benefits	Challenges
Environment	Fuel burn	Higher noise levels
Flight performance		Lower cruise speed (longer flight times, less utilization)
Passengers		Higher cabin noise

- Open rotor engines have a cruise speed of around Mach 0.7, lower than current short-to-mid-range aircraft cruise speeds of Mach 0.75 to 0.79. As a result, flight times are slightly longer than with current aircraft (in the order of 10 min for a 1000 nm flight), which can result in lower utilization. Also, air traffic management needs to take measures in time on ensuring the integration of a strongly increasing number of aircraft with lower than current typical cruise speeds into the flight network.
- Open rotor engines generate high exterior (environmental) and interior (cabin) noise. Despite progress achieved in the recent past, manufacturers need to find solutions to further reduce the noise to

become comparable to future turbofan aircraft that will enter into service in a similar time horizon.

- Weight penalties resulting from ensuring open rotor blade-off safety requirements must be kept to a minimum to avoid trade-off against the benefits from reducing fuel consumption.

Recommendations for Seamless Market Penetration

- Expand efforts in network and air traffic management research, focusing on an increasing range of aircraft with different cruise flight speeds and other operational characteristics.
- Further reduce noise emissions by open rotors through continued research and development efforts.

Strut-braced Wing

	Benefits	Challenges
Environment	Fuel burn	
Ground operations		Folding wing
Flight performance	High wings -> space for large engines (UHBR, open rotor)	

- The high-mounted wings provide enough space for very high-bypass or open-rotor engines.
- Large wing spans of SBW aircraft push them into higher aircraft design groups for airport compatibility than other aircraft in a comparable seat category, which leads to restrictions in operations on smaller airports and higher airport charges. To avoid this, wing tips may

need to be foldable. This feature already exists on the Boeing 777X [75].

Recommendations for Seamless Market Penetration

- Work on redefining current aircraft design group classifications to enable different handling characteristics at airports for revolutionary aircraft configurations.

Blended Wing Body

	Benefits	Challenges
Environment	Lower fuel burn Less noise (engine shielding)	
Ground operations & infrastructure	Easier boarding & disembarking – shorter turnaround time, more comfortable	Ground service infrastructure may need adaptation*
Passenger / Cargo	Large available cargo volume	Passenger acceptance for very large cabin*
Industrial	With the small BWB design, the concept is now scalable	Unconventional design processes needed, with high uncertainties Family concepts more complex to implement* High investments
Certification		Emergency evacuation*

* Challenge applies essentially or only to large BWBs, not to small ones

- BWB design is subject to high uncertainties since today's standard design methods are directly applicable only to tube-and-wing aircraft configurations. Consequently, high investments need to be made in new design methods and tools as well as in investigating handling qualities, which is crucial to reduce uncertainties. Further research is also important to get a clear identification of overall benefits.
- The aerodynamic shape of BWBs is more complex than that of a tube and wing configuration, thus it is challenging to design modular aircraft family concepts for fuselage and equipment systems. As a result, the development of a family concept for BWBs requires a completely new design for each family member.
- The payload-weight distribution and loading procedures of the BWB design presents certain operational challenges when it comes to the

accessibility of ground services and maintenance for airports and airlines. This issue is expected to be less severe for small BWBs such as the DZYNE design.

- Large multi-aisle cabin spaces inside the BWB imply the need of new operational processes and procedures that must be defined to comply with cabin safety requirements including evacuation.

Recommendations for Seamless Market Penetration

- Focus research and technology activities on the reduction of uncertainties in the aircraft design procedure for BWBs and other non-tube-and-wing configurations by expanding design capabilities.
- Strengthen concepts and strategies for production, assembly, supply and logistics of heavy and complex structures.

Electric aircraft (hybrid and battery)

	Benefits	Challenges
Environment	Energy efficiency Low noise No pollutant emissions from electric propulsion	
Ground operations and infrastructure		Electricity supply at airports (installation and commercial arrangements) Battery recharging and storage facilities
Flight performance		Battery energy/power capacity and performance are critical
Maintenance	Less frequent and costly for electric motors than for combustion engines	
Industrial	Synergies with automotive sector Scalability starting from already existing very small aircraft	
Certification		New certification processes Battery safety

- Successful market introduction of electric aircraft requires sufficient battery performance for the intended propulsion concept (hybrid or full-battery) and payload-range combination.
- For the implementation of a large fleet of commercial electric aircraft, reliable supply concepts for the increasing electric power demand at airports are necessary. In that case, electricity companies could become new industry stakeholders by introducing new market concepts and energy supply chains.
- The standardization of batteries (in terms of size, shape, voltage, connectors etc.) to be used as a propulsive energy source allows quick battery exchange during aircraft turnaround at airports and the maximization of economies of scale for battery production and availability.
- Full-battery electric aircraft do not generate any exhaust emissions, those of hybrid aircraft are significantly lower than for those with combustion engines. This is a considerable benefit for the local air quality around airports. According to current scientific understanding, both NOx emissions and contrails, whose formation is enhanced by particulate matter emissions, contribute to net global warming. This would mean an additional climate benefit thanks to the reduced exhaust emissions.
- Hybrid and, even more, full battery-electric aircraft are considerably quieter than turbofan-powered ones. They could use noise-restricted city airports and thus benefit from additional airport slots.

Recommendations for Seamless Market Penetration

- Focus research and development efforts on high performance batteries with high energy density, taking benefit from.
- Support novel battery and battery production technologies.
- Support the development of strategies for building up worldwide battery supply networks and airport infrastructure.
- For all the above actions to be effective, strengthen the collaboration links between the aviation and the energy technology sector and take benefit from synergies between both sectors.

3.5. Economic Aspects of Revolutionary Aircraft Development Programs

General aspects

The development of radically new aircraft represents a very high and risky investment for the manufacturer, which will be made only if there is sufficient commitment from potential airline customers.

Airlines will only be interested in purchasing a new aircraft type if it has overall advantages compared to other aircraft of comparable size and range, and if it is sold at a price that allows the airline to make profit with its operation, which is a function of its direct operation costs (DOC). Fortunately, fuel burn reduction as the main environmental consideration is well aligned with the need to keep DOC down. The operational benefits described in Section 3.4 allow additional DOC improvements beyond fuel savings.

Economic drivers for new technology development

Fuel costs have always been a strong driver for new fuel-efficient aircraft technologies. While in the long-term average, fuel prices follow a continuous upwards trend, the strong volatility of oil prices in the last years makes it difficult for an airline to reasonably estimate the savings from new aircraft with improved fuel efficiency. Fluctuating exchange rates and geo-political uncertainties add to the risks affecting a commitment to purchasing new aircraft.

With the introduction of market-based measures for aviation's climate impact (ICAO's CORSIA system for international aviation), the cost of carbon adds to the cost of fuel. The development of carbon prices is still highly uncertain, however, a cost of 100 USD per tonne of CO₂ may become realistic after 2030. This makes fuel-efficient and CO₂ emissions reducing technologies economically more attractive.

Many radically new aircraft configurations have other DOC benefits beyond fuel and emissions savings. Section 3.4 lists a number of examples, such as lower maintenance costs for electric aircraft and better aircraft utilization thanks to shorter airport turnaround times for small blended wing bodies. It is important to include these benefits, which are often less uncertain than fuel savings, in airlines' business case calculations.

Many radically new aircraft are also much quieter than current configurations. This gives them advantages at airports with noise-related operating restrictions, which are no longer an essentially European phenomenon, as show the examples of Hong Kong, Delhi and Shanghai. Operational or financial advantages for electric aircraft are another potential driver to push developments in this area.

Development costs

It is very difficult to obtain reliable indications about the costs of development and production of different future technologies, as costs are commercially sensitive information. However, lessons learned from past developments such as the A380 and Boeing 787 indicate that the development costs for a new aircraft program are essentially driven by the complexity of a modern aircraft. This suggests that the costs for developing a revolutionary large commercial aircraft program may lie in a similar order of magnitude as for recent advanced wide-body aircraft, i.e. in the order of 10 to 15 billion USD. For comparison, the development costs for the first car with hybrid propulsion were in the order of 6 billion USD. Compared to wide-body aircraft, the narrow-body and regional market segment is much larger and allows to reach the break-even number of aircraft in a shorter time. The small BWB and strut-braced wing are intended for the narrow-body segment, whereas the electric aircraft is aiming at the regional segment.

Very high investment costs for new aircraft programs are a great risk to manufacturers. However, new technologies become more affordable over time with broader technology progress. This was the case e.g. for carbon-fiber material that has replaced more and more metal aircraft components. Synergies with other industries support this trend. An example is the progress in battery technology in the automotive sector that aviation can benefit from. As a general rule, efficiency improves at a stronger rate than investment cost increases.

Market and industry aspects

The development of a radically new aircraft type represents a very high investment for aircraft manufacturers, which may be considered too risky if incremental developments building upon existing aircraft concepts could offer a similar degree of improvement.

The development of electric aircraft is currently starting in the general aviation category and is planned to go on with business and regional aircraft. Large aircraft manufacturers such as Airbus and Boeing have engaged in partnerships for electric aircraft development (e.g. E-Fan, Zunum), which cover a market segment that can be complementary to their own.

The scalability of electric aircraft concepts is an essential aspect reducing the development risk for larger aircraft and allowing start-up companies to enter the aviation sector without excessive barriers. Their main challenge is attracting capital, hiring appropriately skilled engineers, especially for aircraft design and certification, and building up a suitable supplier network.

Generally speaking, the barriers for a new manufacturer to enter the commercial aviation market are very high, in particular due to strict safety and reliability requirements and high costs of certification. Developing a radically new product requiring different design skills and certification processes is a chance for newcomers to enter the market through a specialized niche [39].

Technology funding

As mentioned in Section 1.3, public funding programs for aviation research and technology exist in various countries, which help overcome a part of the economic challenges of developing new technologies. Improving the environmental impact of aviation is one of the key areas of public R&T funding. Recently, funding organizations such as the EU Horizon 2020 program [74] have focused on electric aircraft technologies. This measure could indeed contribute to accelerating their development. However, public technology programs also need to consider that a broad variety of technologies instead of single solutions is required to respond to the challenge of sustainable aviation.

For a radically new aircraft to have realistic market chances, it is important to offer other operational advantages than reduced fuel burn only.

4. Modelling Future Aircraft Emissions

In this chapter, a modelling methodology developed by DLR [76] is used to model the potential CO₂ savings for a number of technology implementation scenarios for evolutionary and radically new aircraft types, combined with a number of air traffic growth scenarios. Section 4.1 describes the choice of technologies used to build the related scenarios, and Section 4.2 describes the air traffic growth scenarios, which are based upon the 2018 IATA 20-year passenger forecast [1].

4.1. Selection of Technology Scenarios

Each technology scenario consists of a set of aircraft configurations for all future-generation aircraft that are expected to enter the world fleet in the different seat categories (see Figure 5 for the timing of the generations in each seat category). These aircraft configurations need to be selected amongst those that are expected to be available at the planned EIS date. The following technology scenarios were modelled:

- Technology scenario 1 (T1): hypothetical reference
 - Only imminent aircraft, then no introduction of new aircraft programs (hypothetical)
- Technology scenario 2 (T2): conservative
 - Turbofan engines
 - No radically new configuration
- Technology scenario 3 (T3): radical configurations
 - Turbofan and open-rotor engines
 - Additional improvement by new aircraft configurations
- Technology scenario 4 (T4): towards electrification
 - Additional improvement by new configurations, same as in T3
 - Hybrid and battery-electric propulsion electricity assumed 100% renewable

Figure 35 shows the combinations of aircraft and engine configurations selected for each seat category in all four scenarios.

Technology Scenario 1 (T1): Only Fixed Aircraft Programs (hypothetical baseline)

Technology scenario T1 models a world fleet developing under the selected growth scenario, if only the imminent aircraft programs in Table 1 were introduced. This is equivalent to the introduction of only an N+1 generation in all seat categories, with no further generation following until 2050. T1 represents a hypothetical “reference” or “no

change” scenario. It is not expected in reality that no next aircraft generation will be introduced between 2020 and 2050. Figure 35 illustrates the aircraft program matrix associated with the T1 scenario.

Seat Category	Aircraft Generation	Tech. Scenario	Total fuel saving [%]		
			min	mean	max
51-100	N+2	2,3	27%	36%	48%
51-100	N+2 (hybrid)	4a	80%	80%	80%
51-100	N+2 (elec.)	4b	100%	100%	100%
101-150	N+2 (cons.)	2	26%	34%	46%
101-150	N+2	3	27%	38%	48%
101-150	N+2 (elec.)	4b	100%	100%	100%
151-210	N+2 (cons.)	2	26%	34%	46%
151-210	N+2	3	27%	38%	48%
210-300	N+2	2,3,4	24%	30%	40%
210-300	N+3 (cons.)	2	28%	38%	52%
210-300	N+3	3	31%	43%	57%
301-400	N+2	2,3,4	28%	38%	50%
401-500	N+2	2,3,4	28%	38%	50%
501-600	N+2 (cons.)	2	27%	36%	51%
501-600	N+2	3	31%	42%	57%
601-650	N+2 (cons.)	2	27%	36%	51%
601-650	N+2	3	31%	42%	57%

Table 5: Total fuel burn improvement of unfixed aircraft programs

Technology Scenario 2 (T2): Conservative

T2 describes the development of the world fleet under a conservative technology and aircraft design scenario, i.e. all unfixed aircraft programs rely on a standard tube and wing configuration with turbofan engines.

Technology Scenario 3 (T3): New Configurations

T3 introduces new aircraft and engine configurations in generations N+2 and N+3. In generation N+2, small blended wing bodies or strut-braced wing aircraft are selected for the 101-150 and 151-210 seat categories, for the seat

categories above 500 seats large blended wing bodies are included into the fleet.

Technology Scenario 4 (T4): Towards Electrification

In scenario T4, the same aircraft and engine configurations are selected as for scenario T3. In addition, hybrid or battery-electric propulsion is introduced, in analogy to current trends in the automotive industry. Two variants are considered: The first one (T4a, medium optimistic) is inspired by Zunum’s forecast, assuming hybrid-electric

propulsion in the generation N+2 for the 51-100 seat category. The second one (T4b, most optimistic) reflects Wright Electric’s forecast with battery-electric propulsion (100% CO₂ reduction) for the 51-100 and the 101-150 seat categories. No improvement for electric propulsion is considered for any of the higher seat categories.

Table 5 shows the assumed fuel burn reductions of all future generation aircraft programs selected for the four technology scenarios.

Technology scenario T1 (hypothetical baseline)

	51-100	101-150	151-210	211-200	301-400	401-500	501-600	601-650
Ref.	T&W/TF	T&W/TF	T&W/TF	T&W/TF	T&W/TF	T&W/TF	T&W/TF	T&W/TF
N+1	T&W/TF	T&W/TF	T&W/TF	T&W/TF	T&W/TF	T&W/TF	T&W/TF	T&W/TF

Technology scenario T2 (conservative)

	51-100	101-150	151-210	211-200	301-400	401-500	501-600	601-650
Ref.	T&W/TF	T&W/TF	T&W/TF	T&W/TF	T&W/TF	T&W/TF	T&W/TF	T&W/TF
N+1	T&W/TF	T&W/TF	T&W/TF	T&W/TF	T&W/TF	T&W/TF	T&W/TF	T&W/TF
N+2	T&W/TF	T&W/TF	T&W/TF	T&W/TF	T&W/TF	T&W/TF	T&W/TF	T&W/TF
N+3				T&W/TF				

Technology scenario T3 (new configurations)

	51-100	101-150	151-210	211-200	301-400	401-500	501-600	601-650
Ref.	T&W/TF	T&W/TF	T&W/TF	T&W/TF	T&W/TF	T&W/TF	T&W/TF	T&W/TF
N+1	T&W/TF	T&W/TF	T&W/TF	T&W/TF	T&W/TF	T&W/TF	T&W/TF	T&W/TF
N+2	T&W/TF	S-BWB or SBW/TF	S-BWB or SBW/TF	T&W/TF	T&W/TF	T&W/TF	L-BWB/TF	L-BWB/TF
N+3				BW/TF				

Technology scenario T4 (towards electrification)

	51-100	101-150	151-210	211-200	301-400	401-500	501-600	601-650
Ref.	T&W/TF	T&W/TF	T&W/TF	T&W/TF	T&W/TF	T&W/TF	T&W/TF	T&W/TF
N+1	T&W/TF	T&W/TF	T&W/TF	T&W/TF	T&W/TF	T&W/TF	T&W/TF	T&W/TF
N+2	T&W HE (T4a), BE (T4b)	S-BWB or SBW TF (T4a), BE (T4b)	S-BWB or SBW/TF	T&W/TF	T&W/TF	T&W/TF	L-BWB/TF	L-BWB/TF
N+3				BW/TF				

Figure 36: Technology scenarios T1 to T4: Selected technologies for each seat category and aircraft generation

- T&W:** Tube & Wing
- S-BWB:** Small blended wing body
- BW:** box-wing
- L-BWB:** large blended wing body
- TF:** Turbofan
- HE:** hybrid-electric propulsion
- BE:** battery-electric propulsion

4.2. Fleet Simulation Results

The introduction of novel aircraft configurations into the world fleet and their impact on global CO₂ emissions of air transport is modelled following a methodology by DLR [76]. It consists of two steps:

1. Evolution of the world fleet of commercial passenger aircraft responding to a certain air traffic demand in the future, three different air traffic growth scenarios are considered (see below).
2. Forecast of the evolution of fuel and CO₂ efficiency based on the fuel efficiency and carbon intensity of each aircraft model determined as described above, and global CO₂ emissions and traffic calculated by aggregating the single aircraft estimates.

The three different air traffic growth scenarios from IATA's 20-year passenger forecast [1] are selected to simulate the world fleet evolution:

- Baseline
- UP (including policy stimulus and market liberalization)
- DOWN (including pick-up in protectionism, no further travel cost reduction, politically driven travel demand reduction)

The forecast has been determined based on the following parameters:

- Living standard (GDP per capita) – shows a non-linear jump in middle-income range, e.g. in China
- Demographics (Travel demand evolution per age group)
- Real costs of travel have gone down 1 to 1.5% p.a. over the past 70 years, savings from technical improvements were passed through to customers
- Carbon price impact is considered

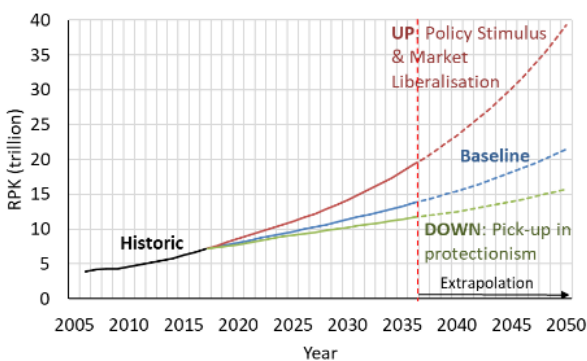


Figure 37: IATA 2017 long-term air traffic forecast

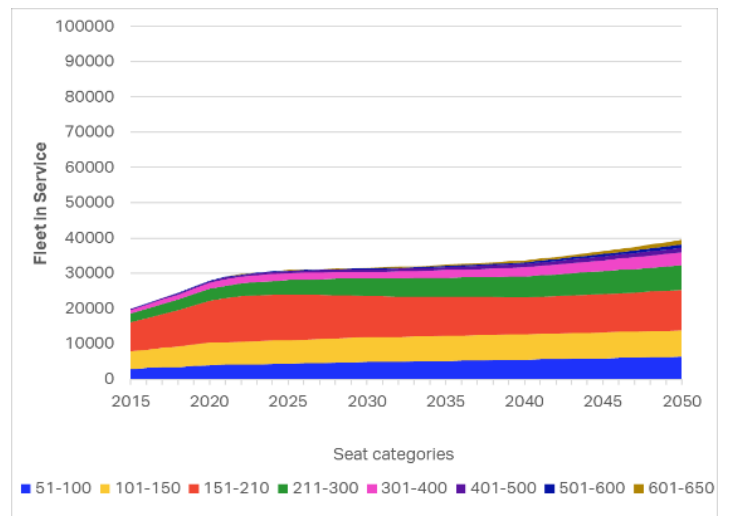


Figure 38: Fleet forecast modelling, based on the IATA DOWN scenario

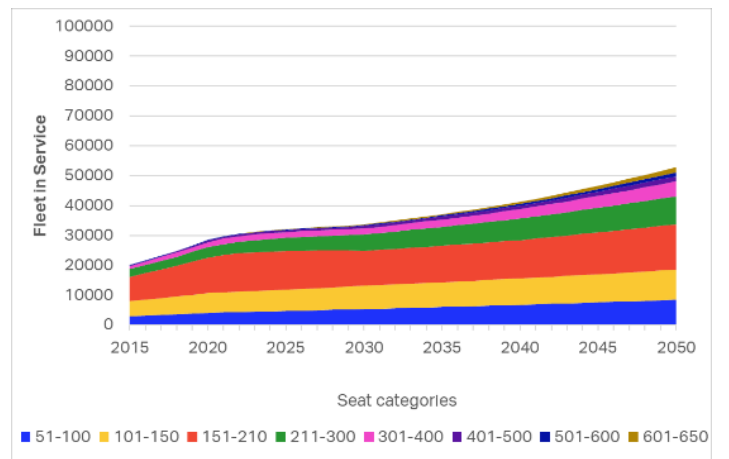


Figure 39: Fleet forecast modelling, based on the IATA BASE scenario

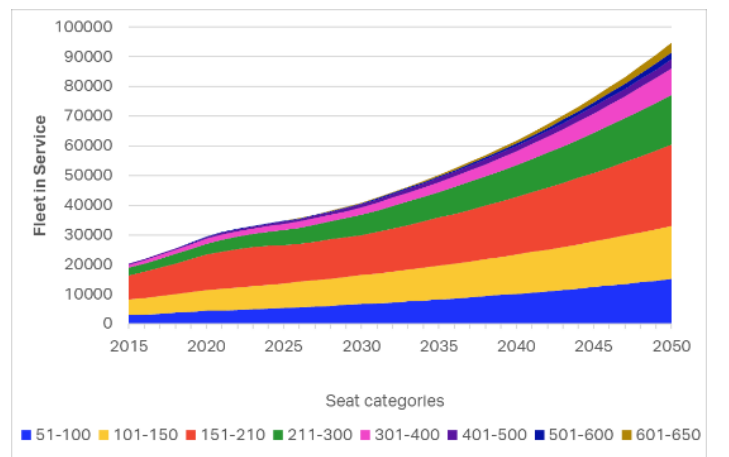


Figure 40: Fleet forecast modelling, based on the IATA UP scenario

4.3. Technology and Aircraft Program Sensitivity: Fuel Calculation Results

The following figures show the annual CO₂ emissions as resulting from the modelling calculations. For each technology scenario three cases for minimum, mean and maximum emissions improvement are shown (see Table 5). In addition to the effect of fuel-efficient aircraft technologies, improvements due to more efficient operations and better airport and airspace infrastructure (Pillars 2 and 3 of the IATA strategy) of 0.2% p.a. are

considered. Furthermore, the fuel efficiency of in-production aircraft is continuously improved over the lifetime of the aircraft program by the implementation of numerous small improvements. This effect is accounted for with another 0.2% p.a. However, this simulation does not consider additional CO₂ savings from the introduction of sustainable fuels.

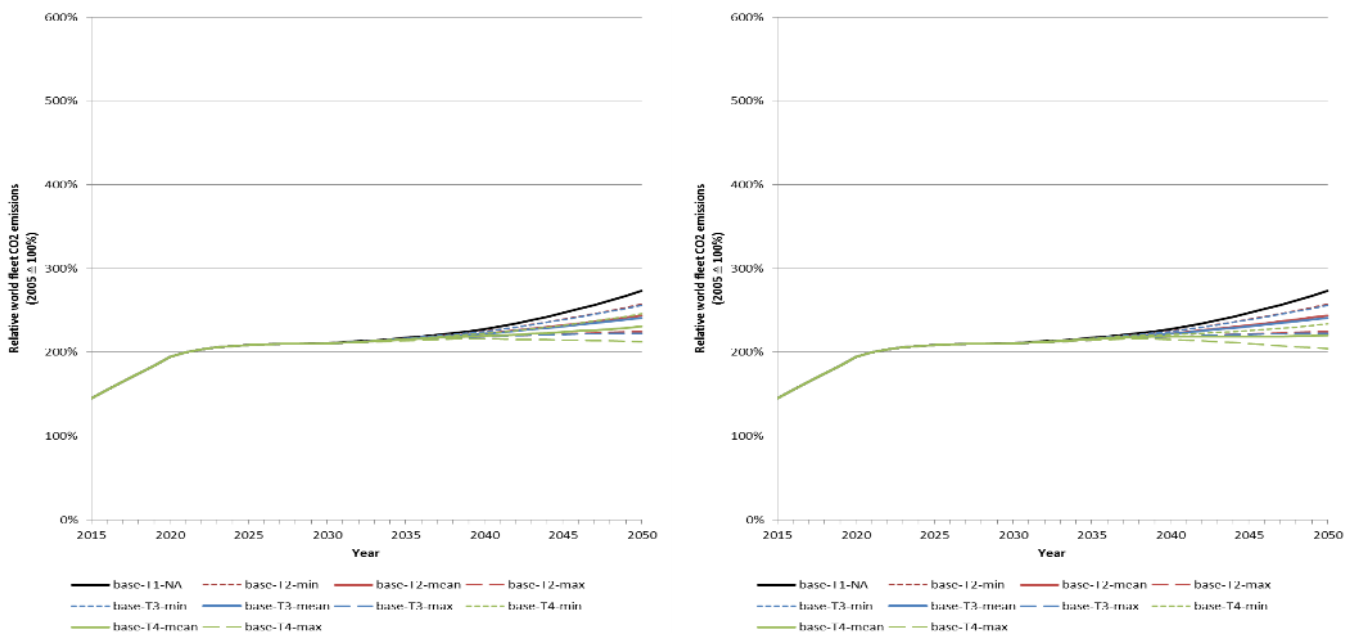


Figure 41: IATA DOWN traffic scenario: Relative world fleet CO₂ emissions for technology scenarios T1, T2, T3, T4a (left), T1, T2, T3, T4b (right)

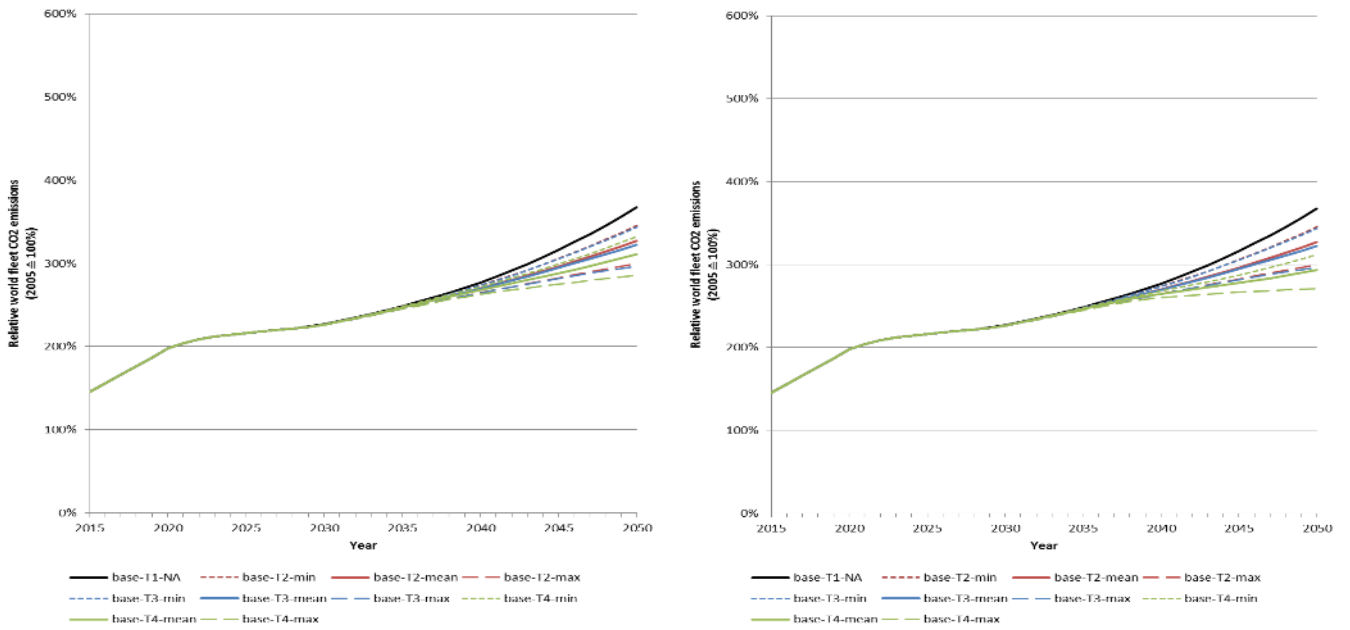


Figure 42: IATA BASE traffic scenario: Relative world fleet CO₂ emissions for technology scenarios T1, T2, T3, T4a (left), T1, T2, T3, T4b (right)

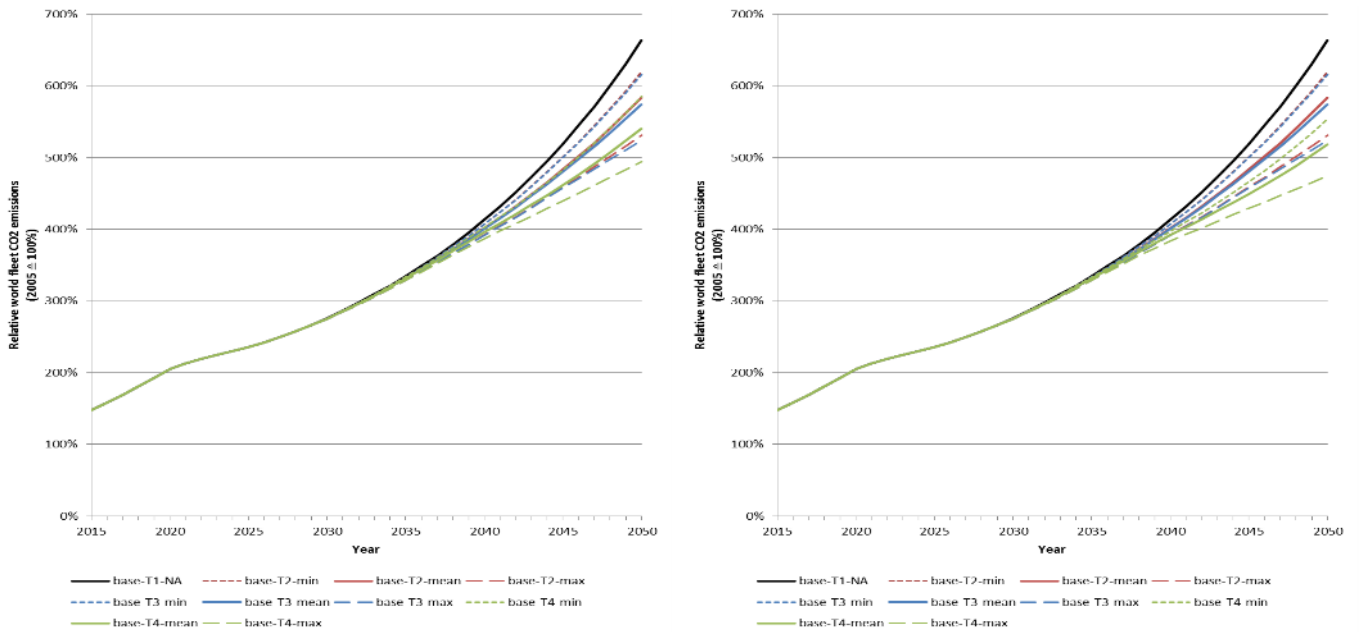


Figure 43: IATA UP traffic scenario: Relative world fleet CO₂ emissions for technology scenarios T1, T2, T3, T4a (left), T1, T2, T3, T4b (right)

4.4. Annual CO₂ Improvements at Global Fleet Level

Year-on-year CO₂ intensity improvements for each of the modelling scenarios described above are calculated based on average world fleet CO₂ intensities, defined as:

$$CO_2 \text{ intensity} = \frac{\text{fleet } CO_2 \text{ emissions [kg]}}{\text{total RPK}}$$

Year-on-year changes of the CO₂ intensity of the global fleet are shown in Figure 43 (IATA DOWN forecast), Figure 44 (IATA BASE forecast) and Figure 45 (IATA UP forecast). Negative values represent an improvement (CO₂ intensity reduction) compared to the previous year.

From these graphs it can be seen that the modelling shows a strong average fuel efficiency improvement in the current years (2015 – 2020), thanks to the introduction of a large number of new aircraft. Obviously, short-term operational aspects, such as reactions to fuel price fluctuations or higher fuel burn for diversions caused by conflict zones of overflight bans, cannot be considered in the model.

In the mid-term (mid-2020s to early 2030s), an annual fuel efficiency improvement significantly lower than today is observed, which can be explained mainly by the lack of new aircraft models in most seat categories.

In the long term (from about 2035), the entry into service of new aircraft types in many seat categories accelerates the fuel and carbon efficiency again, showing the importance of novel technologies, the introduction of electric propulsion clearly having the strongest impact.

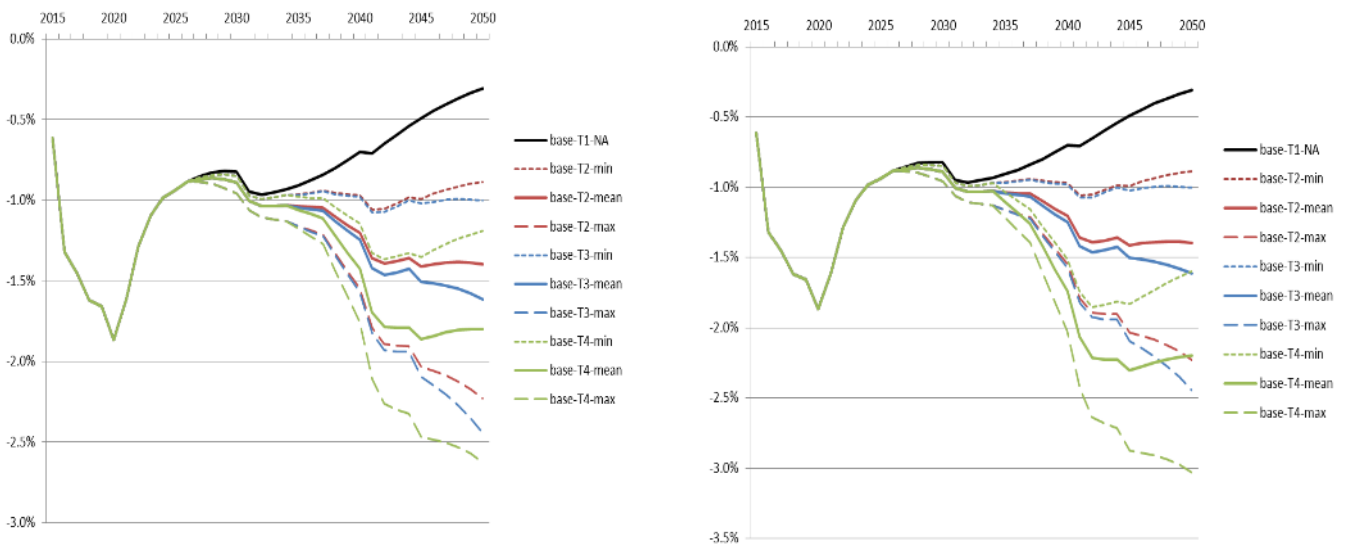


Figure 44: IATA DOWN scenario. Year-to-year improvement in CO₂ intensity of the global fleet, for technology scenarios T1, T2, T3, T4a (left), T1, T2, T3, T4b (right)

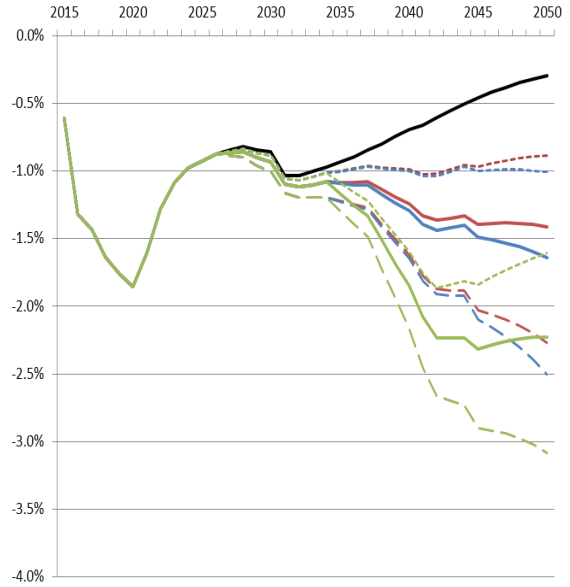
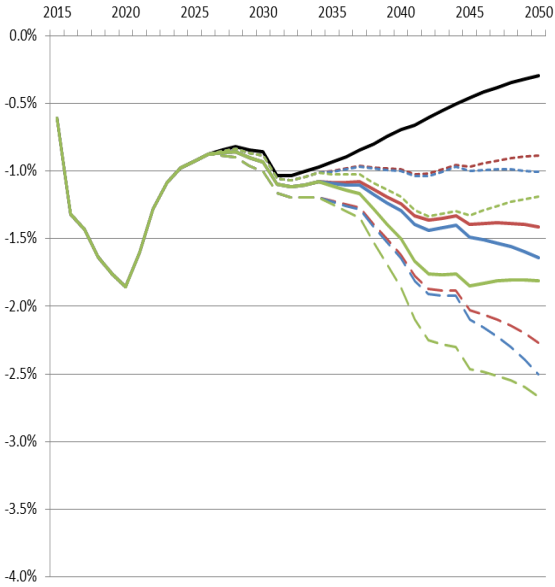


Figure 45: IATA BASE scenario. Year-to-year improvement in CO₂ intensity of the global fleet, for technology scenarios T1, T2, T3, T4a (left), T1, T2, T3, T4b (right)

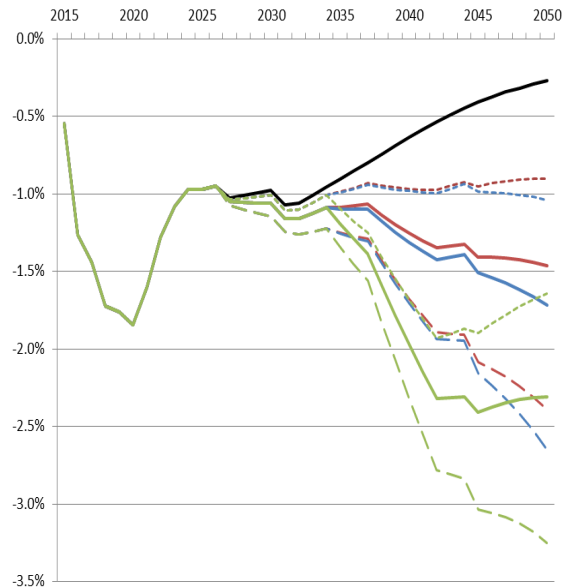
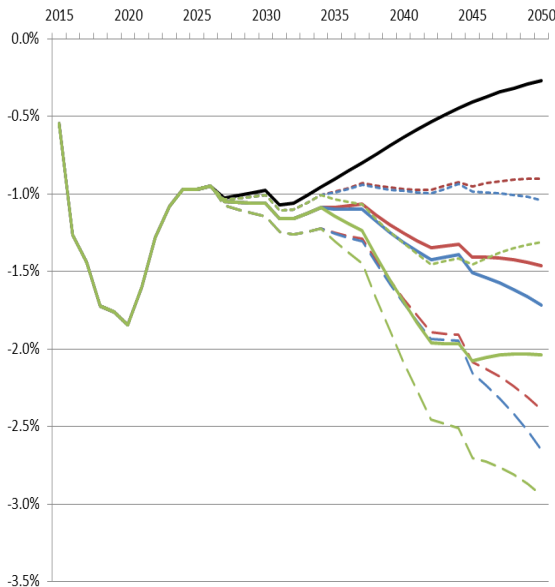


Figure 46: IATA UP scenario. Year-to-year improvement in CO₂ intensity of the global fleet, for technology scenarios T1, T2, T3, T4a (left), T1, T2, T3, T4b (right)

5. Disruptive Technologies

The radically new aircraft configurations described in Chapter 3, while needing certain infrastructural adaptations, do not completely change the structure of the air transport system. Beyond that, other concepts for high-speed transport are being developed, which might seriously change the current nature of air travel. New companies are entering the transport industry market with a variety of disruptive technologies that may enter service within the next decade. The two most concrete disruptive transport concepts are described here:

- On the short-haul side, the “Hyperloop” concept, ground-based, but operating at speeds comparable to flight, would be able to replace busy air connections up to around 1000 km.
- On the long-haul side, supersonic travel is experiencing a revival with several manufacturers engaged in new aircraft projects, starting with the business aviation market.

Once these disruptive concepts are approaching implementation, airlines will face the question whether they should include them in their own business models by cooperation agreements and intermodal network concepts.

Hyperloop

Hyperloop is an emerging new transport mode for both passengers and cargo, low in CO₂ emissions, which consists of capsules driven by magnetic levitation through a tube with reduced air pressure at speeds similar to aircraft flight. It is envisaged to replace short air connections with strong traffic, similarly to today’s high-speed railway lines, but with an additional speed advantage. Compared to air travel, it could start from city centers, saving considerable travel time to and from airports, and would not need additional time for take-off and landing against the wind and for holding patterns. For example, while the flight time from Stockholm to Helsinki (400 km distance) is 55 minutes and the entire travel time from city to city around 3.5 hours, supporters of the Hyperloop say it could do the same trip in 28 minutes through a tunnel under the Baltic Sea. Its potential for covering distances of up to about 1000 km in significantly less time than either flight or high-speed train could make it a useful option for this travel segment including feeder connections to long-haul flights. In case of success, it might cause a considerable reduction of short-haul flights, similar to the introduction of high-speed train connections such as the TGV in France.

Virgin Hyperloop One is the first commercial company working on building Hyperloop transport lines. Its objective

is to start operations by 2021 [77]. Various other companies have been founded in the last years, which are investigating the potential of numerous routes on several continents. Several successful tests have been done, however at speeds only up to 400 km/h so far. A number of technical issues related to safety and reliability still have to be solved.

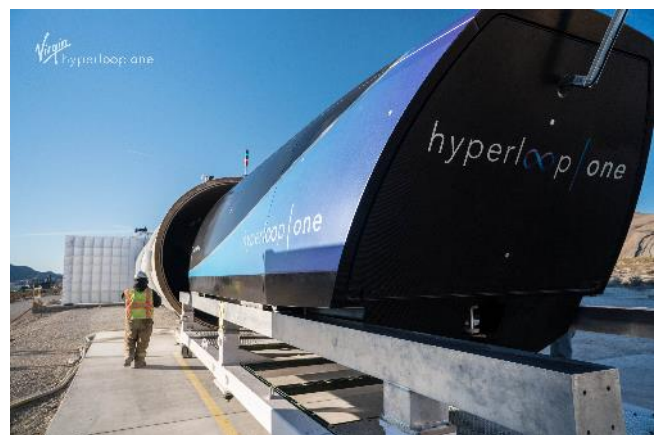


Figure 47: Virgin Hyperloop One: Design of tunnel and capsule

Supersonic Commercial Jet

Supersonic flights are again under consideration 15 years after the end of Concorde operations, targeting now both the business and the commercial aviation market. Boom, a startup based in Colorado is working closely with Virgin Group and Japan Airlines on a supersonic jet that is expected to enter service by 2020. For the route from New York to London, Boom indicates a flight time of 3.5 hours at Mach 2.2, which is half of today’s typical flight time. While ticket prices for the Concorde flights were a constraint to broader demand in the past, allowing only a few to fly with it, Boom claims its flight fares could be similar to today’s business class flights. Fuel burn and the related costs are predicted to be about 30% lower than for Concorde, mainly

thanks to weight-saving advanced carbon fiber technology. This would be a main contribution to significantly lower ticket prices. It is, however, still uncertain if supersonic flight will become widely accepted by commercial aircraft passengers, or rather be limited to a relatively small category of business aviation users, for whom dedicated point-to-point connections with supersonic aircraft would offer a maximum time saving.

The environmental impact of supersonic aircraft is considerably higher than that of subsonic ones. In particular, supersonic flights are still very high in CO₂ emissions. In addition, the problem of reducing the sonic boom noise to a level that is no longer annoying on ground is still not fully solved. Therefore, flying at supersonic speed, especially with larger commercial aircraft, may still be limited to route segments above seas, as is the rule today [77].



Figure 48: Supersonic Commercial Jet designed by Boom

6. Conclusions and Recommendations

6.1. Conclusions

From this report, it can be seen that a broad range of technological innovations is under development to improve aircraft fuel efficiency and reduce their CO₂ emissions. The global focus on climate action has triggered a strongly increased intensity of research and technology (R&T) activities to improve energy efficiency and expand the use of renewable energies. More specifically, R&T in aviation has been inspired by the Industry's high-level goal to reduce the global CO₂ footprint of air transport by 2050 compared to 2005, and similar goals and targets.

A number of conclusions can be drawn from the assessment of these technologies:

- There has been a constant evolution of the current tube-and-wing aircraft configuration powered with hydrocarbon fuel combustion engines. Since the early jet age, aircraft fuel burn per passenger-km has been reduced by over 70%, and there is potential to reduce today's fuel burn by another 30% approximately without going to radically different aircraft configurations and propulsion. The potential of these evolutionary technologies, mostly in the areas of aerodynamics, lightweight materials and structures, new engine architecture and aircraft systems, will however diminish over the years. Evolutionary technologies will thus not be enough to keep a similar CO₂ emissions reduction rate as today and contribute significantly to the 2050 CO₂ emissions reduction goal, more radical configuration changes will be required in addition.
- In the period between the early 2020s and the early 2030s, there are currently no concrete announcements for new aircraft programs in most seat categories so far. The only exception is the "middle-of-the-market" segment between 210 and 300 seats, where discussions about potential new aircraft models have recently become more intense. However, no development program has been officially launched so far. Although new technologies are expected to reach maturity during this period, they could be prevented from implementation due to the lack of new aircraft programs. Furthermore, fleet renewal might also become less attractive if no brand-new fuel-efficient aircraft are available.
- Many of the revolutionary aircraft technology concepts offer other benefits than fuel efficiency. Two examples: (a) Electric propulsion systems require much lower maintenance efforts and costs than combustion engines. (b) Small blended wing bodies allow faster boarding and disembarking than similarly sized single-aisle aircraft. This leads to shorter turnaround times and better daily aircraft utilization. These direct operating cost (DOC) benefits need to be added to fuel cost savings when establishing the business case for new aircraft models from an airline perspective. Lower DOCs compared to existing aircraft models could justify a higher aircraft purchase price to a certain extent, however, it is important to keep in mind that aircraft prices remain accessible to airlines and do not reach a level where they present a prohibitive risk.
- Investing in sustainable aviation fuels (SAF) and offsetting emissions through market-based measures such as CORSIA may appear easier and cheaper than implementing radically new aircraft and propulsion technologies. However, the available quantities of SAF feedstock and production are likely to be limited; the same is expected for greenhouse gas reduction projects underlying the generation of offset credits. Reducing the industry's fuel demand through the development and use of significantly more efficient aircraft helps reducing the demand for SAF and offset credits.

6.2. Recommendations

- Airlines are under public pressure to achieve substantial carbon reductions in future. They should clearly articulate their interest in aircraft with strong fuel efficiency improvements, including radically new ones in the longer term, to give aircraft manufacturers the confidence in potential demand that they need for starting new developments. It needs to be taken into account that the lead time for radically new aircraft is significantly longer than for conventional configurations.
- Airlines should work with governments to stress the importance of publicly funded research and technology to achieve the aviation industry's carbon reduction goals.
- Although numerous studies have been done on revolutionary aircraft configurations and technologies, more specific investigations on the implementation of

these technologies into day-to-day operations are needed to give a more reliable projection on their operational, environmental and economic benefits.

- Airlines have an important role in the development of new aircraft and technologies. They should actively participate in their evaluation under day-to-day operational conditions, in order to ensure that aircraft and engine manufacturers and technology developers meet the users' requirements. As the development of a new aircraft program represents a very high investment, it is crucial to ensure that it fits the needs of a broad variety of customers including their requirements for operational flexibility.
- For a seamless market penetration of radical aircraft technologies, all aviation stakeholders such as airlines, manufacturers, airports, air navigation service providers, governments and research institutions, need to work together to prepare the prerequisites for the implementation of these technologies into the future air transport system and to overcome the challenges they impose on operational, regulatory and

other levels. Such challenges could be, amongst others: accessibility of ground services and new maintenance procedures for radically new aircraft configurations, availability of batteries with sufficient energy density for regional flights, standardization of batteries to allow easy exchange and high-power electricity supply at airports to recharge batteries.

- Electric aircraft producers and other technology innovators will enter the industry as new stakeholders. They will need to build up the same level of cooperation with other stakeholders in the industry as the traditional manufacturers to ensure that radically new aircraft can be integrated into the future air transport system. Partnerships between airlines, innovation companies and research establishments are already taking place and should be extended. Some examples: KLM and TU Delft for the Flying-V, EasyJet and Wright Electric or SAS, Airbus and Rolls Royce for electric aircraft,

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Acknowledgements

This Technology Roadmap was established in cooperation with the German Aerospace DLR. We thank Kai Wicke, Ivan Terekhov, Thomas Schilling, Malte Nikolaß and Robin Ghosh for their engagement and their valuable contribution.

We also thank Kay Plötner and Holger Kuhn (Bauhaus Luftfahrt), Michel Goulain (Clean Sky), Kolja Kindler and Björn Nagel (DLR), Dimitri Mavris (Georgia Tech), Fay Collier (NASA) and Ashish Kumar (Zunum Aero) for valuable discussions.

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