
# TOWARDS ZERO-EMISSION AVIATION

How DLR’s Aviation Research Strategy supports the European Green Deal 2050



# Contents

# Summary

Aeronautics research approaches aircraft and air transport as a complete system. **DLR takes an open-minded approach to the various technologies, evaluating and integrating them into this system**. It sees itself as an architect and integrator in aeronautics research. DLR is working towards achieving the vision of zero-emission aviation together with our international partners from research, (air transport) industry and commerce.

**Vision – zero-emission aviation**

Research at DLR is paving the way for the air transport system of tomorrow and shaping its transformation to climate-neutral flight.

**Mission – DLR as a virtual manufacturer**

DLR is developing highly integrated technologies and methods, processes and solutions for climate-neutral aviation, thereby contributing towards the European Green Deal. DLR staff are involved in research and development in the fields of new aircraft concepts, components and alternative propulsion solutions, with a focus on the use of Sustainable Aviation Fuel (SAF), including new energy carriers (for example, hydrogen) and climate-optimised flight routes. In doing so, DLR is taking on the role of a virtual aircraft manufacturer (Virtual OEM).

## Low-emission aircraft engines

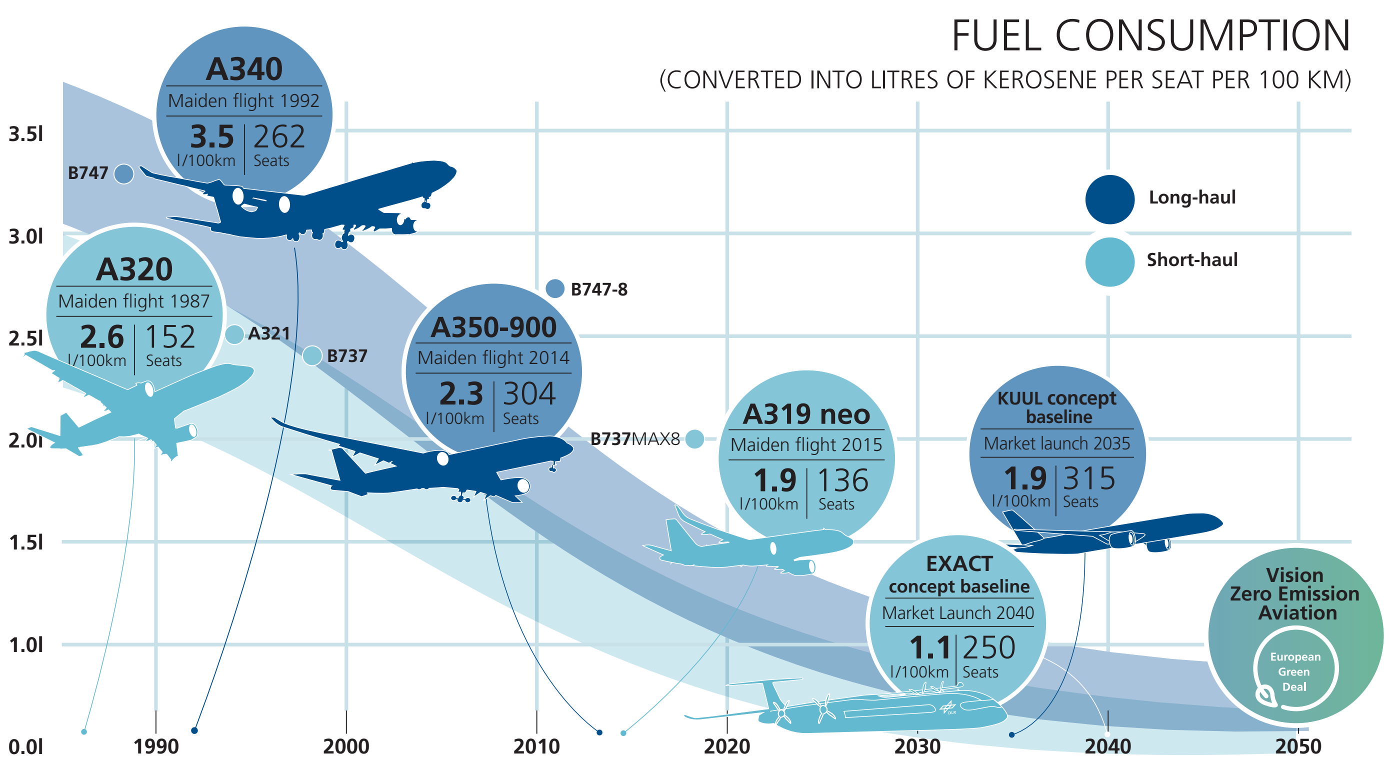
**Turbo engines with Sustainable Aviation Fuels**
Highly efficient turbofan engines along with regeneratively produced kerosene offer the promise of a largely climate-neutral operation on short- to long-haul flights. This technology could be applied to the entire existing fleet with only minimal technical modifications to engines and infrastructure.

**Hydrogen as an energy carrier**
Using hydrogen has the potential to cut aviation-related local carbon dioxide emissions to zero. However, volume, weight, integration and safety all pose particular challenges for hydrogen-powered propulsion systems and necessitate extensive research into hydrogen tank systems, including the system architecture and innovative aircraft concepts, which address the impact of fuel volume. In the medium term, hydrogen will be particularly suitable for aircraft operating on regional and short-haul routes. Research into safe and reliable hydrogen combustion and the handling of this energy carrier is to prepare for commercial applicability in aircraft up to demonstration in the next five years.

**Electric propulsion systems with hydrogen or batteries as energy carriers**
Despite their very high efficiency, batteries and fuel cells will only be suitable for use in small and regional aircraft for the foreseeable future. High-performance electric motors, batteries and hydrogen-powered fuel cells all require research for aviation applications. A medium-term application for commercial aircraft may be decided upon in the next five years.

## Energy-efficient aircraft

**Energy requirements of future aircraft need to be reduced by at least half by 2050.** Lower aircraft energy requirements directly reduce the fuel consumption of their propulsion systems, decreasing residual emissions and offsetting the higher costs of future energy carriers. Accomplishing this requires technologies capable of reducing aerodynamic drag and total weight, together with innovative flight control and sensor systems. To ensure the optimal integration of such technologies, they must be taken into account in new aircraft configurations from the very start of the design phase.




Air transport emissions per passenger per 100 kilometres have fallen continuously over recent decades. New aircraft concepts, such as those being developed as part of DLR's EXACT (Exploration of Electric Aircraft Concepts and Technologies) and KUUL (climate-friendly, ultra-efficient long-haul flights), promise further potential emission cuts. DLR's vision is zero-emission aviation.

## Air transport system

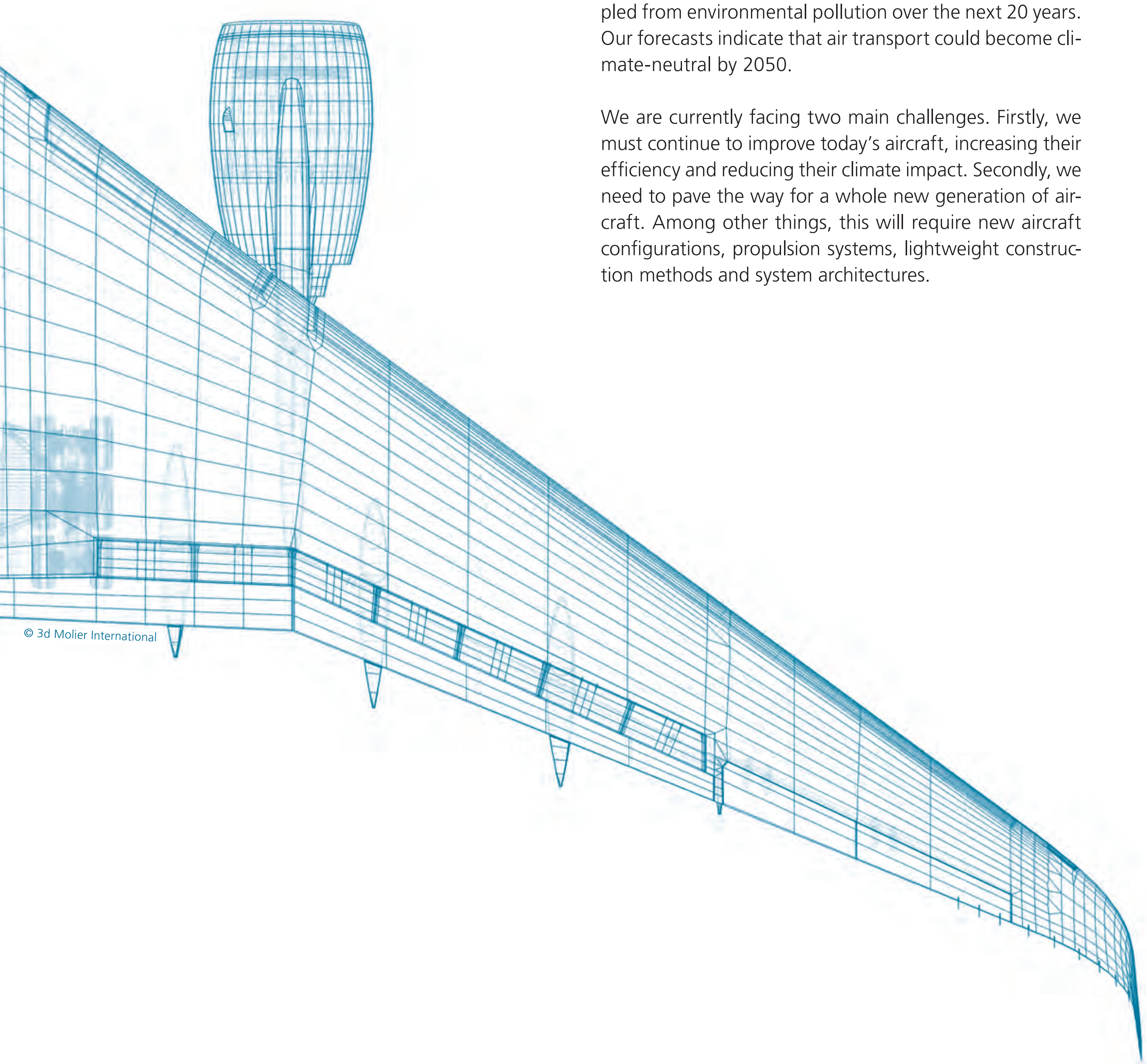
**Overall system evaluation**
The evaluation of the air transport system encompasses all aspects of its operations and their effects. Its findings will be used to assess the impacts of each part of the system and facilitate a redesign. To this end, a comprehensive assessment and simulation platform for the entire air transport system will be set up over the next five years in order to further strengthen DLR's profile as an architect, integrator and consultant in this field.

**Climate impact and flight paths**
Efforts to cut non-carbon-dioxide emissions also have great potential for reducing the climate impact of air transport, particularly through the judicious routing of long- and medium-haul flights. Demonstrating the commercial feasibility and effectiveness of climate-optimised flight routes over the next five years will require policy frameworks and the introduction of technical innovations. Measures will include increasing automation and standardisation in aircraft, air traffic management and flight guidance.

## Digitalisation

**Digitalisation as a catalyst is accelerating progress towards climate-neutral air transport.** Both digital tools and methods, as well as decision-making processes supported by the use of artificial intelligence, help to explore new concepts and technologies for sustainable air transport in larger and more creative design spaces. At the same time, the advanced conformity between virtual and physical products promotes an accelerated transferability of research findings into applications.

# Foreword



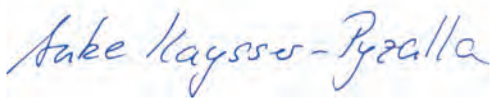

**Aviation is an integral part of our society and global mobility. It contributes to inter-cultural exchange and creates economic growth.** However, aviation is undergoing one of the most radical transformation processes in its entire history. The end result should and will be climate-friendly air transport, as the consequences of climate change require resolute action. In order to achieve this goal, the growth of air transport must be decoupled from environmental pollution over the next 20 years. Our forecasts indicate that air transport could become climate-neutral by 2050.

We are currently facing two main challenges. Firstly, we must continue to improve today's aircraft, increasing their efficiency and reducing their climate impact. Secondly, we need to pave the way for a whole new generation of aircraft. Among other things, this will require new aircraft configurations, propulsion systems, lightweight construction methods and system architectures.

New energy carriers such as Sustainable Aviation Fuel (SAF) and, in the longer term, hydrogen will play an important role in reducing the climate impact of both carbon dioxide emissions and non-carbon-dioxide effects. Flying climate-friendly routes is another promising option, which, however, requires establishing the right technological and operational conditions. The entire aircraft lifecycle must also be considered more closely in the future, from material formation all the way through to development, production, operation, maintenance and decommissioning. All of this will be embedded into an overall assessment of the air transport system and will enable a comprehensive analysis of the impact of all aspects of aviation on the environment in general and on the climate in particular. It will then be possible to determine the necessary innovations and implement them in a more targeted manner.

Achieving climate-neutral flight entails a considerable need for research and development, which will require ongoing funding and support. The transfer of knowledge to industry and the economy is particularly important. The expertise and capabilities of the more than 25 DLR institutes and facilities that are working on aeronautics and their unique research infrastructure give the organisation a broad-based understanding of air transport and all of the options for making aviation fit for the 21st century. As such, we see ourselves as an architect and integrator in aeronautics research.

**Through DLR's new aviation strategy, we are now pursuing its vision of zero-emission aviation in line with the European Green Deal. To this end, we are conducting research and development work across the entire spectrum, in conjunction with our industry partners and other research institutions in Germany and abroad. This ranges from aircraft concepts and components as well as alternative propulsion solutions using new energy carriers to devising climate-optimised flight routes. This is DLR's contribution to addressing the challenges presented by the Green Deal.**



Prof. Dr.-Ing. Anke Kaysser-Pyzalla,
Chair of the DLR Executive Board

Dr.-Ing. Markus Fischer,
Divisional Board Member for Aeronautics

# 1. Introduction

*Air transport emissions need to be decoupled from the exponential increase in air traffic volume if the world is to move towards climate-neutral air transport.*

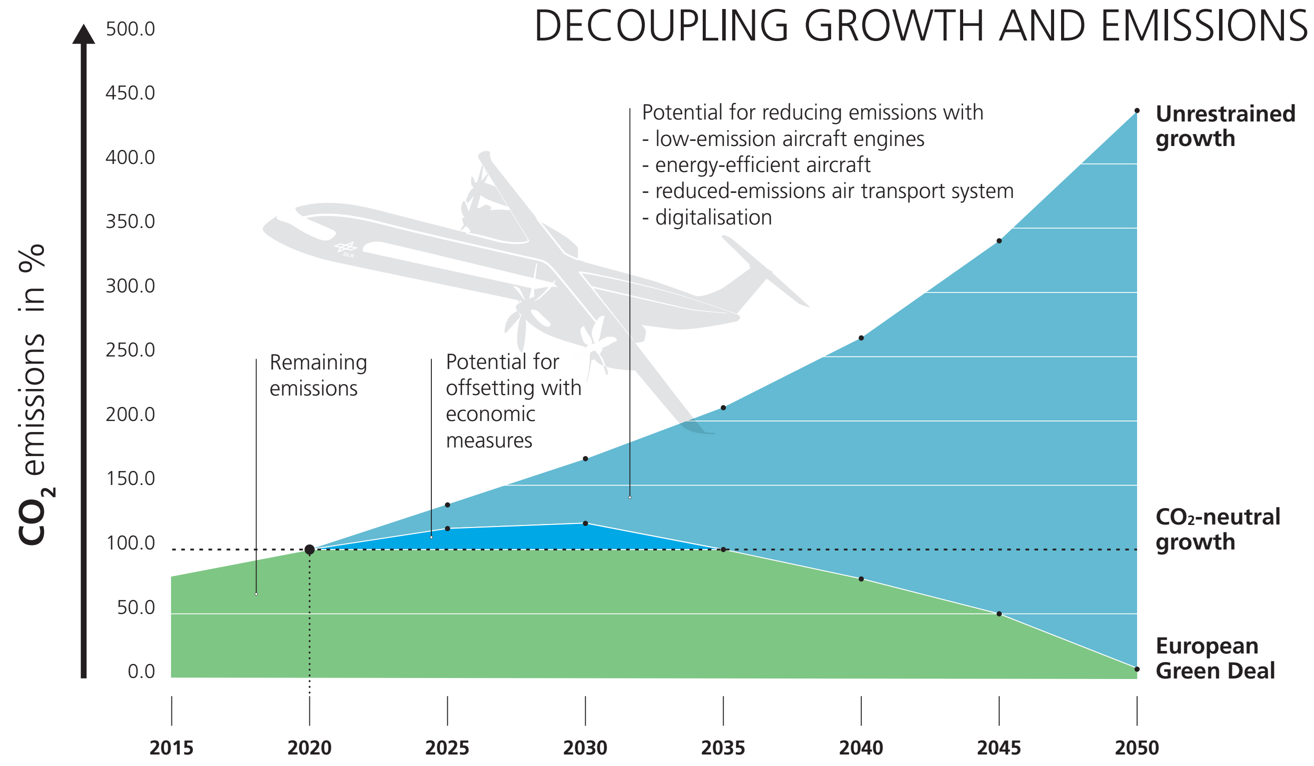



Figure 1: Despite the brief downturn in air traffic during the COVID-19 pandemic, exponential traffic growth is set to return in the medium term. If the world is to move towards climate-neutral air transport, the associated emissions need to be decoupled from the exponential increase in air traffic volume.

The effects of anthropogenic climate change are well known, and the need to permanently reduce carbon dioxide emissions is beyond question. While global air transport accounts for only 2 to 5 percent of anthropogenic climate warming, its exponential growth requires immediate action.

**Air traffic is doubling in volume every 15 years. At present, every generation of aircraft is only seeing an increase in efficiency of approximately 15 percent over a comparable period of time.** Air transport emissions have numerous undesirable effects and need to be reduced urgently – a goal that cannot be achieved by simply refining today's aircraft. Revolutionary new technologies are also needed to counter the environmental impact of aviation. While steps are being taken to significantly increase the eco-efficiency of individual aircraft, a globally sustainable supply chain, in all its complexity, including existing production processes, materials and aspects of the infrastructure, must also be considered. Ground-breaking and immediately available solutions for zero-emission aviation do not currently exist due to the immense technological challenges they entail, particularly with regard to the energy and power density of alternative propulsion systems.

**The considerable technical and financial risks and the safety requirements, which have to be satisfied under all operating conditions, make a technology transition in aviation a lengthy, cost-intensive process, especially due to the extensive certification procedures involved.** In addition, the aviation sector has been hit hard by the COVID-19 pandemic. At the time of writing, it is unclear when the industry will see a sustained recovery. The International Air Transport Association (IATA) does not expect air traffic to return to previous levels until 2024 at the earliest.

One thing is clear: air traffic will grow again over the longer term. This makes an important question all the more urgent: **What is the path to zero-emission aviation in the future?**

In order to make air transport climate-neutral by 2050, the various stakeholders must work closely together in three key areas – aviation research, energy research and legislative matters.

*Approximately two thirds of the climate impact of aviation is due to non-carbon-dioxide effects such as contrails. In this document, carbon dioxide emissions are used as an established metric for comparing alternative propulsion systems.*

### TERMINOLOGY

While it is possible to decouple the growth of air transport from its environmental impact, aviation affects the environment in a number of ways, so a nuanced approach is necessary. The following terms are used in this document:

- **Emissions** are understood to mean both the release of certain, usually harmful, substances and intangible disruptive factors such as noise. The effects of these emissions are referred to as immissions.
- The **vision of zero-emission aviation** represents an ideal that can only be approached asymptotically. While actual zero emissions are unlikely to be achieved, technologies and operational processes will be geared towards achieving this as far as is possible.
- **Environmentally sustainable aviation** takes into account all possible emissions but does not commit to a figure of absolute zero for the emissions in question.
- **Climate-neutral aviation** balances the climate impact of all carbon dioxide and non-carbon dioxide effects so that aviation no longer makes a net contribution to global warming. Noise is not taken into account for these purposes.
- The concept of **carbon-dioxide-neutral aviation** considers carbon dioxide emissions as a simple, established and measurable variable that can be offset by various technical and market-based mechanisms. However, research shows that carbon dioxide emissions are only responsible for approximately one third of the climate impact of air transport.
- **Carbon dioxide equivalen**t is a measure that enables emissions of different greenhouse gases to be compared on the basis of their global warming potential. For that purpose, quantities of other gases are converted into the equivalent amount of carbon dioxide with the same global warming potential.
- The **concept of sustainability** is an umbrella term for the aforementioned target concepts and also takes societal aspects into account.
- In this context, the **system boundaries** define the area in which the air transport system is considered and separate it from its surroundings. Opportunities for action can only be harnessed within the system boundaries; the influences of the surrounding environment are simply considered peripheral conditions.

### Aeronautics research for energy-efficient aviation

**Innovative mobility, propulsion and fuel concepts call for new and efficient aeronautics architectures.** These need to be modular and flexible and cater to a much broader range of mobility than before. The low energy and power density of alternative propulsion systems and the significantly more costly Sustainable Aviation Fuel (SAF) necessitate a substantial reduction in the energy requirements of new aircraft. Achieving this requires unprecedented efforts in aeronautics research in order to at least double the current efficiency of aircraft, which is what will be needed in the future. A thorough assessment of the necessary technologies requires an ability to design and assess the overall system across all disciplines. **There is substantial need for research in the following key areas of focus: low-emission aircraft engines, energy-efficient aircraft, reduced-emissions air transport system and digitalisation** in aviation. The focus is on technology development, the integration of technological components into the aircraft, and an understanding of how all of these aspects affect the aircraft and the air transport system as a whole. Flight tests are absolutely vital for the systematic development of the technologies and the demonstration of their capability to reduce climate impact, while ensuring high safety standards.



*The European Union aims to be climate neutral by 2050. By then, there should be net-zero greenhouse gas emissions. Economic growth should be decoupled from resource consumption and the transition to a resource-efficient economy should be fair and inclusive.*

### Research for sustainable energy carriers

The energy transition in aviation will require close cooperation between the energy and aviation sectors. **Climate-neutral aviation is dependent on carbon-dioxide-neutral energy sources and the sustainable fuels that can be produced from them.** As such, one of the top priorities is ensuring the economic availability of renewable energy sources and sustainable aviation fuels.

### Legislation for the consistent implementation of a sustainable aviation policy

In order to be able to implement sustainable solutions for climate-neutral aviation, the **foundations for the certification of novel propulsion concepts and their integration into airframes** must be established in close cooperation between research, industry and regulatory authorities. As sustainable energy carriers and the implementation of climate-optimised flight routes will in all likelihood also result in rising costs, legislators need to take a globally coordinated approach. Global regulations are also required to establish and implement market-based measures such as emissions trading and climate compensation.

### The European Green Deal

In December 2019, the European Commission presented a new growth strategy for Europe in the form of the European Green Deal, which makes climate protection, sustainability and ecology the focus of its political agenda. The overarching goal is for **the EU to be climate neutral by 2050.** By then, its net greenhouse gas emissions should be zero, economic growth should be decoupled from resource consumption, and there should be a fair and inclusive transition to a resource-efficient economy. This will also require climate-neutral, resource-saving aviation.

The European Green Deal is intended as a roadmap for a sustainable economy in the EU. Its action plan addresses the most important goals and measures in the fields of energy, transport, the environment and climate protection. For this, the EU plans to promote innovations for climate-neutral products and circular economy solutions. This will foster research and development initiatives that reduce the carbon footprint of aviation every step of the way across the board. **The development of sustainable technologies is also intended to strengthen European competitiveness.**

**The European Green Deal addresses a rapid shift to sustainable and smart mobility.** Achieving climate neutrality requires reducing all transport-related emissions by 90 percent before 2050. All modes of transport are tasked with helping to bring this about. Subsidies for fossil fuels will be abolished and the European Commission will review current tax exemptions, including those for aviation fuels. **These measures are intended to eliminate the competitive advantages of conventional fuels and allow alternative fuels to be introduced as a cost-effective option, as they represent the most promising means of reducing emissions over the short term and across the entire fleet.** Alongside such efforts, the EU is planning to promote the production and uptake of sustainable aviation fuels through appropriate legislation and other measures. As part of the EU's emissions trading system, airlines are to be issued with fewer certificates free of charge, as a means of further reducing emissions. In the area of air traffic management, the Single European Sky (SES) will be advanced to optimise the operational efficiency of the air transport system and help reduce air transport emissions through a higher degree of automation. Automated and linked multi-modal mobility and smart traffic management systems enabled by digitalisation will also play an increasingly important role.

New technologies, sustainable solutions and ground-breaking innovations are crucial to achieving these goals. **In addition to the large-scale introduction and proof of concept of new technologies across all sectors, new and innovative value chains must be created. At least 35 percent of the budget from the EU funding programme Horizon Europe is dedicated towards new climate protection solutions.** The necessary level of investment will require the mobilisation of both the public and private sectors.

## Global developments and challenges

Over the course of aviation history, ever-changing requirements have influenced developments in the industry. The technological foundations for aviation as another mode of transport were laid from the era of the earliest pioneers to the invention of jet propulsion. These pioneering decades were followed by a phase of industrialisation in the 1930s. The following decades were shaped by ground-breaking technological developments, standardisation and regulation. Technologies were gradually transferred to larger aircraft and the aeroplane established itself as an attractive mode of transport. The third phase, from the 1990s onwards, saw exponential growth in aviation. This was associated with a massive increase in emissions and sparked initial research into the climate impact of aviation. **As early as the 1990s, the focus was on both carbon dioxide and non-carbon-dioxide emissions. The Paris Agreement (2015) and the European Green Deal (2019) marked the beginning of a fourth phase of transformation.** All around the world, people recognised the need to drastically reduce aviation emissions, and political pressure on industry and research was stepped up internationally. German policymakers are also highly committed to sustainability. The government's Aviation Strategy, the National Hydrogen Strategy and the German Power-to-Liquid Roadmap call for a transformation in aviation that aims to enable carbon-dioxide-neutral air transport.

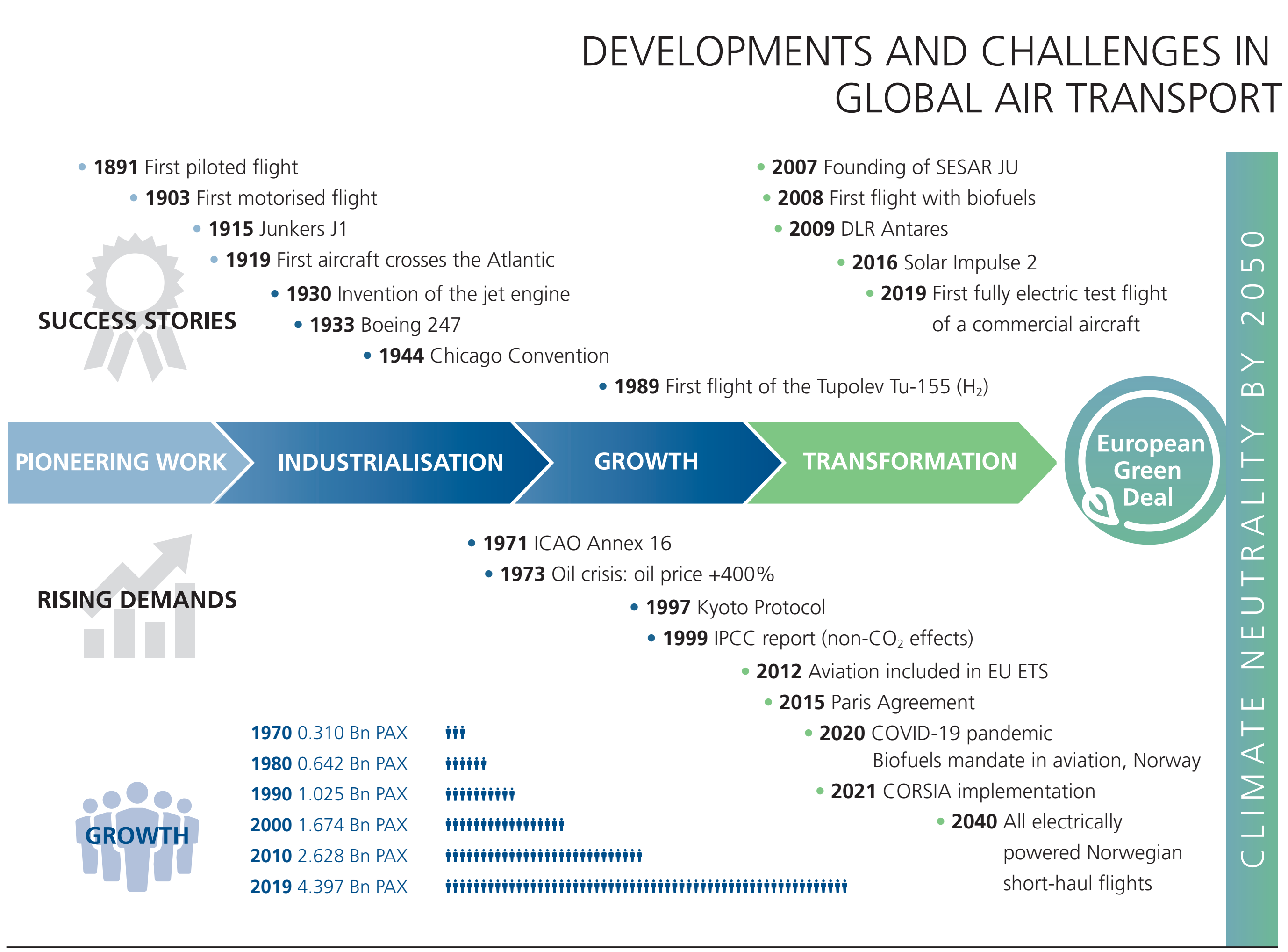
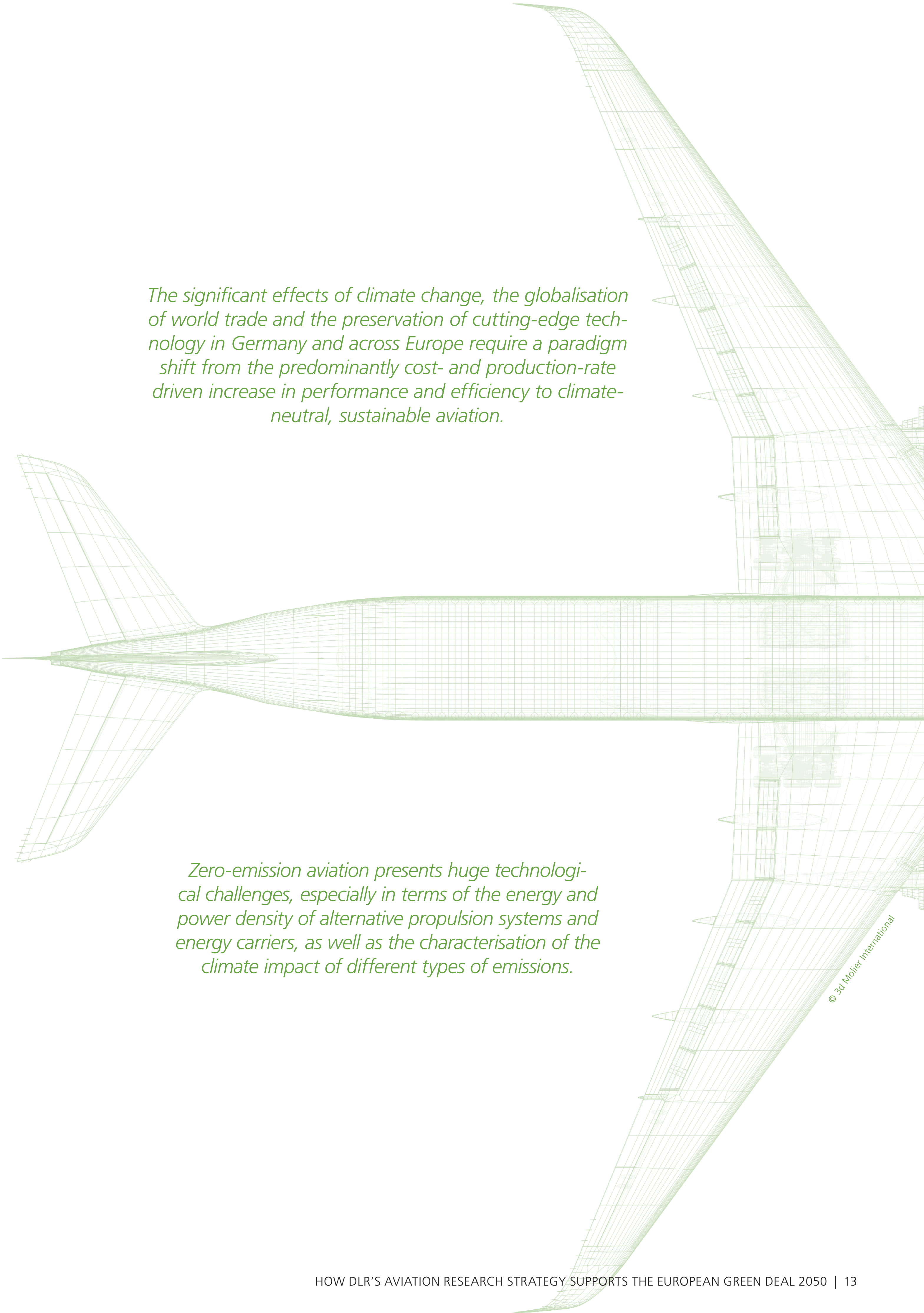



Figure 2: The history of aviation can be divided into four main phases – the pioneering phase, industrialisation, exponential growth and transformation towards zero-emission aviation.




*The significant effects of climate change, the globalisation of world trade and the preservation of cutting-edge technology in Germany and across Europe require a paradigm shift from the predominantly cost- and production-rate driven increase in performance and efficiency to climate-neutral, sustainable aviation.*

*Zero-emission aviation presents huge technological challenges, especially in terms of the energy and power density of alternative propulsion systems and energy carriers, as well as the characterisation of the climate impact of different types of emissions.*

# 2. DLR's approach

In response to current global trends and the challenge of achieving climate-neutral aviation, aeronautics research at DLR has set itself the ambitious goal of creating largely emissions-free air transport. Driven by this vision, it is harnessing its deep expertise to shape progress towards making air transport as sustainable as possible.

### Vision – zero-emission aviation

**With its comprehensive, interdisciplinary range of expertise, DLR is helping to shape the transformation in line with the European Green Deal.** However, the implementation of climate-neutral aviation requires the transfer of research findings to the development of new aircraft and transport products in order to achieve market diffusion across the entire fleet. DLR is playing an active role in shaping this transfer by advising and supporting policymakers and industry.

By focusing on a vision of zero-emission aviation, DLR aeronautics research is pursuing an extremely ambitious goal. Even if entirely emission-free aviation is unlikely to be technically feasible, it makes sense to strive for a largely climate-neutral air transport system. This applies not only to the individual technologies and energy carriers, but also to their entire lifecycles and combined effect on the whole air transport system.

**Reducing emissions and the climate impact of aviation to almost zero requires major developments in the areas of sustainable aviation fuels, new energy carriers and aircraft concepts and components, as well as alternative propulsion solutions and their operational implementation with climate-optimised flight routes.** This goal must be coupled with political, legislative and social drivers to combine environmental implementation with economic feasibility. The energy transition in aviation requires a wide range of investments in development, certification and infrastructure, as well as support through political decision-making at the national and international level.

## VISION AND MISSION OF DLR'S AERONAUTICS RESEARCH

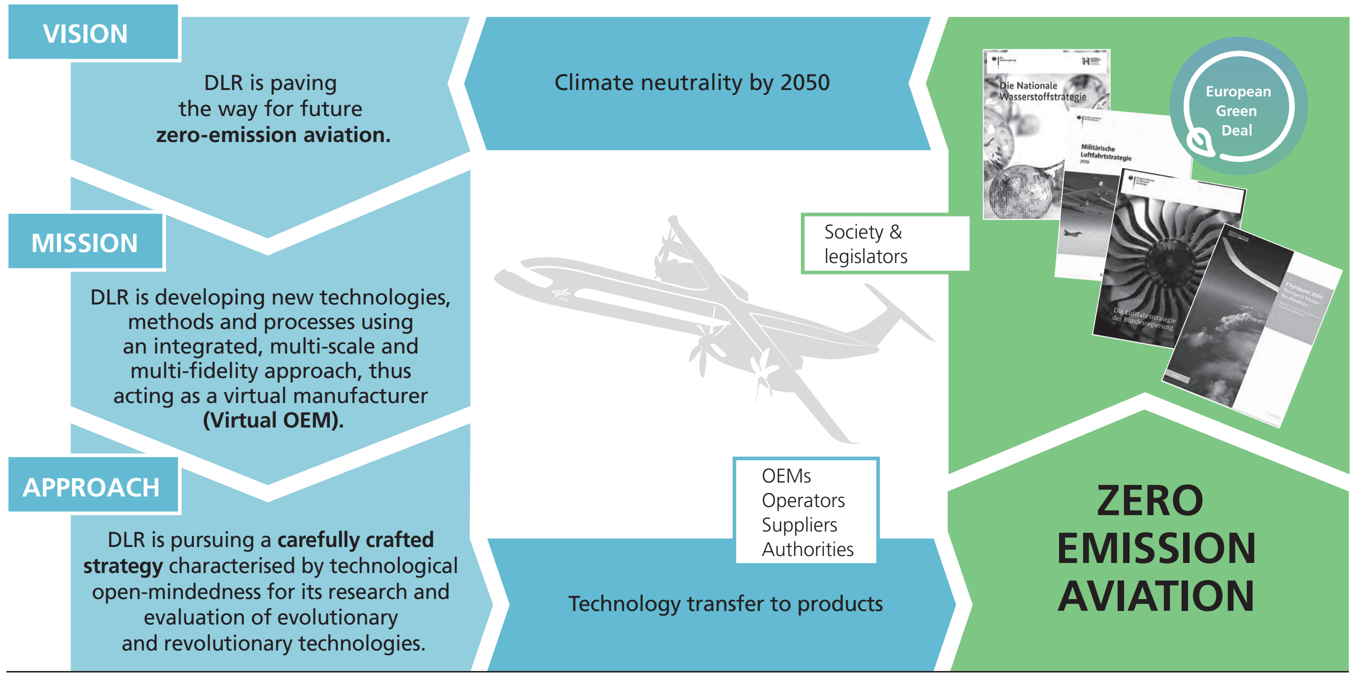



Figure 3: In support of the European Green Deal, DLR is following a vision of zero-emission aviation. In this sense, DLR is acting as a virtual manufacturer (Virtual OEM) and applying its technologies, methods and processes in cooperation with industry and public authorities.

*The path towards climate-neutral aviation is possible. DLR's aeronautics research is paving the way in its capacity as a virtual manufacturer (Virtual OEM).*

### Mission – DLR as a virtual manufacturer

DLR is developing multi-scale and multi-fidelity technologies, methods and processes to provide solutions for an aviation system with the lowest possible emission rate. Its aeronautics researchers take an integrated approach to identifying systemic solutions. **DLR always considers aircraft and air traffic, with all their respective interrelationships, as an overall system. This system expertise enables it to take on the role of a virtual manufacturer (Virtual OEM), thereby involving other participants in aeronautics research, the aviation industry and the wider economy.** In doing so, DLR brings together the expertise from its aeronautics, space, energy and transport research programmes, as well as the cross-sectoral areas of digitalisation and security.

### Approach – technology-open transformation

The path towards carbon-dioxide-neutral aviation is certainly possible, but it requires a gradual and carefully considered transformation as well as revolutionary technologies in all areas, with realistic goals and consideration of all (the) framework conditions and interrelationships. To satisfy these demands, DLR aeronautics research has crafted the following strategy.

**In addition to evolutionary and revolutionary aircraft and propulsion concepts, sustainable aviation fuels and flight control play a central role in this regard.** The successful introduction of such concepts requires transdisciplinary research that takes account of technological, operational and economic factors. **End-to-end digitalisation is a key factor for success. It accelerates the pace of innovation, reduces development risks, allows new technologies to be brought to market more quickly and enables new business models.** DLR is researching the virtual product, looking at digitalisation throughout the aircraft lifecycle, from design to manufacture, certification and operation through to decommissioning. This allows economic and environmental impacts to be predicted and analysed comprehensively and at an early stage.

This strategy document presents the four key areas of focus for climate-neutral aviation, their fields of action and the overarching objectives. It is the result of extensive coordination involving all institutes, the Executive Board and external stakeholders. **At the heart of the strategy are the timescales pertaining to the key areas of focus, along with their challenges, approaches and the unique features of DLR's work.** The derivation and implementation of specific measures is carried out in projects as part of the programme-oriented funding.

In addition to the overarching technological strategy for the European Green Deal, which is described in this document, DLR's aeronautics strategy includes other important aspects of aeronautics research. With regard to military security, for example, research approaches are being developed for future combat aircraft and missiles. Looking beyond fixed-wing aircraft, DLR is conducting research into helicopters and components as part of third-party-funded collaborations with industrial partners, thereby supporting industry and ensuring technology transfer.

*The transfer of research results to the development of new aircraft and air transport products is vital to achieve market diffusion across the entire fleet. DLR plays an active role in shaping this transfer by advising and supporting policymakers and industry.*



*DLR always takes a technology-open view of the entire air transport system, from material formation through to the development, production, operation and decommissioning of an aircraft.*

**Furthermore, through its fundamental research, DLR is strengthening Germany's profile as a prime location for aviation and ensures the preservation of knowledge.** DLR also contributes to training experts for the aviation sector.

### KEY AREAS OF FOCUS

- **Low-emission aircraft engines** – innovative and disruptive technologies, materials and manufacturing methods will enable further improvements in efficiency and the minimisation of emissions for different propulsion concepts, while considering performance and safety requirements.
- **Energy-efficient aircraft** – new and highly efficient aircraft technologies make it possible to significantly reduce energy consumption. The aim is to lower the energy requirements of future aircraft to around half of the current propulsive power.
- **Reduced-emissions air transport system** – minimising the climate impact of air transport by reducing its carbon dioxide and non-carbon-dioxide effects is absolutely essential. This can be sustainably supported by a more effective design of the air transport system.
- **Digitalisation** – as a methodology, the digitalisation of aviation has the potential to develop and evaluate new solution approaches in a more time-efficient and cost-effective manner, in order to accelerate the transformation towards climate neutrality.

## THE DLR APPROACH

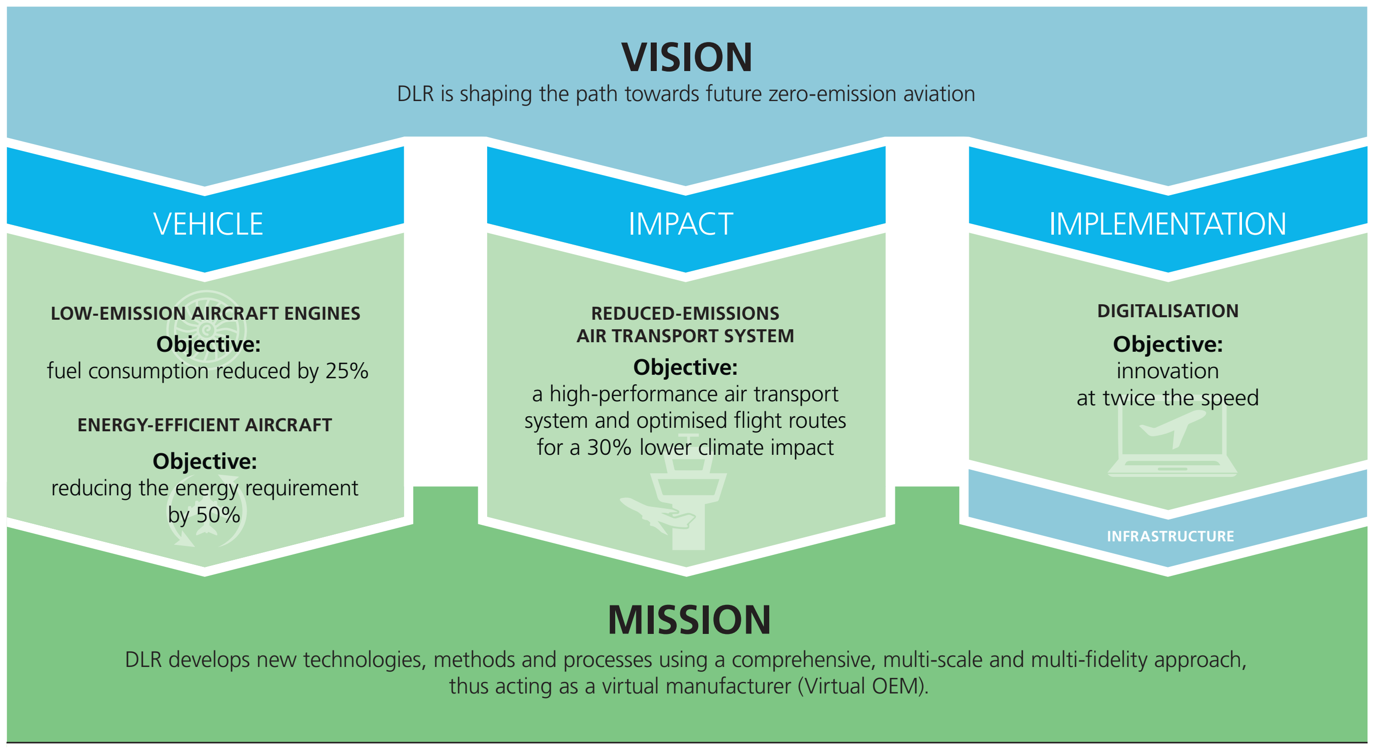



Figure 4: In order to make the vision of zero-emission aviation a reality, DLR conducts research in four key areas of focus – low-emission aircraft engines, energy-efficient aircraft, a reduced-emissions air transport system and digitalisation.

# 3. Key areas of focus



**In order to fully exploit the potential for minimising emissions, evolutionary aeronautical technologies to reduce aerodynamic drag and aircraft weight must be pushed to the limits of what is technically feasible, alongside research into revolutionary propulsion technologies.** This will make it possible to significantly reduce energy consumption, which, in addition to the direct decrease in emissions, will enable the use of alternative propulsion concepts. The use of sustainably produced kerosene will also play a decisive role, as this can be used for all classes of aircraft and can be implemented over a relatively short timescale.

The reduction in emissions that can be achieved by 2050 through the use of various technologies is shown in Figure 5.

## ASSUMPTIONS

- The **reduction in carbon dioxide emissions** serves as an easily measurable indicator. Noise and (the) climate impact of non-carbon-dioxide effects are not considered here. Although these non-carbon-dioxide emissions are actually responsible for most of the climate impact, they are associated with considerable uncertainty and can also be mitigated with climate-optimised flight routes, improved propulsion technologies and the use of sustainable energy carriers.

- In addition, a **technology maturity level of TRL 6** is considered as a target value in order to distinguish technological potential from product and market developments, as these can no longer be influenced by research. As a result, product strategies and the often considerable delays in the market launch and penetration of new technologies are not taken into account.

- The underlying **traffic scenario** is based on the statistics of the International Council on Clean Transportation (ICCT) for 2019, with 7 percent regional aircraft, 51 percent short- and medium-haul aircraft (mainly comprising narrow-body aircraft) and 42 percent long-haul aircraft (mostly wide-body aircraft).

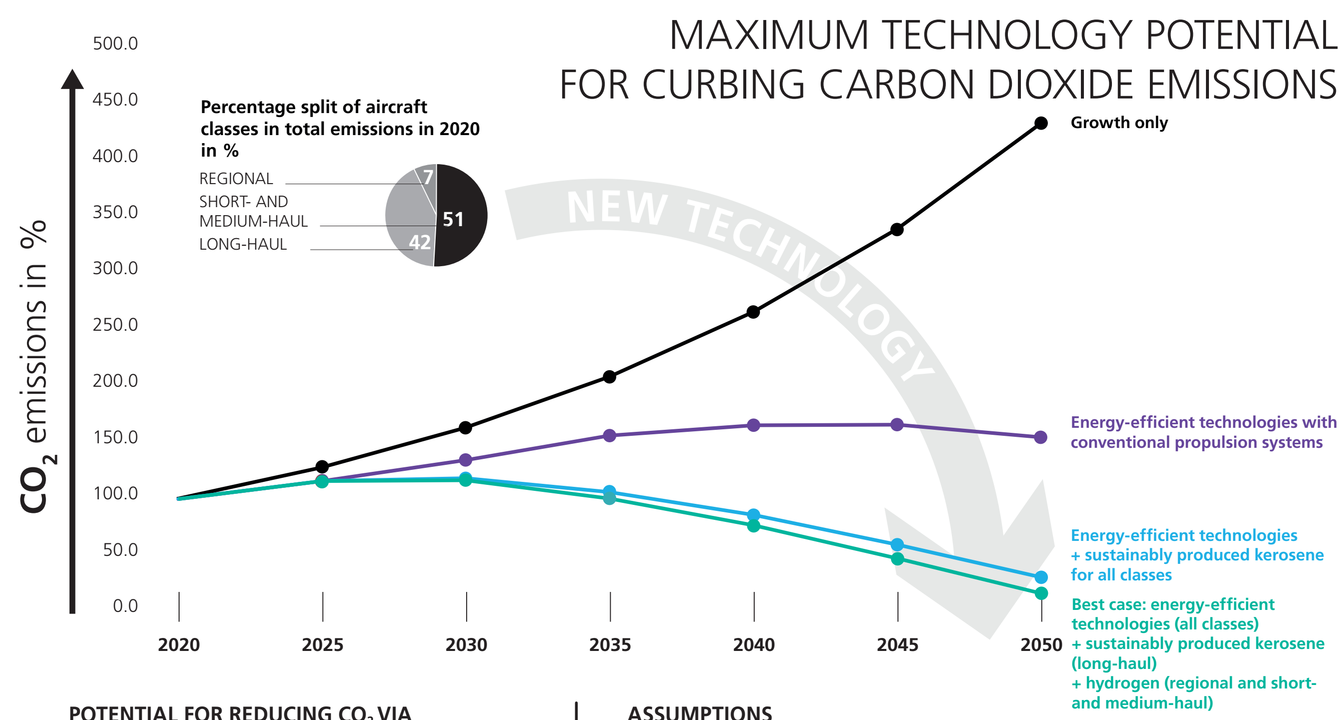
- It is also assumed that **fuel cells** can only be used for regional aircraft due to their low power density and that **hydrogen combustion** is only possible for short- and medium-haul aircraft due to the large increases in volume and weight resulting from integrating a hydrogen tank.

- The **potential of the various Sustainable Aviation Fuels (SAF) to reduce carbon dioxide** is 100 percent for hydrogen-powered fuel cells and hydrogen combustion and 80 percent for the combustion of sustainably produced kerosene. The fact that hydrogen combustion also produces climate-affecting nitrogen oxides in addition to water vapour must be considered.

- The **potential for carbon dioxide reduction using energy-efficient technologies** in the airframes, engines and flight trajectories amounts to a total of 3.4 percent per year. This corresponds to a 64 percent reduction in carbon dioxide by 2050.

- At present, air traffic is experiencing a temporary reduction due to the COVID-19 pandemic. However, a **full recovery** is expected.

- For all technology scenarios, it was assumed that sustainably produced **kerosene and hydrogen will be available in sufficient quantities** by 2050, so these are not a limiting factor.




**POTENTIAL FOR REDUCING $CO_2$ VIA**

- Energy-efficient technologies 3.4% per year
- Hydrogen fuel cells 100%
- Hydrogen combustion 100%
- Sustainably produced kerosene 80%

**ASSUMPTIONS**

- No delay for market introduction
- Sufficient quantities of fuels available
- Non-$CO_2$ effects not taken into consideration
- Not all technologies can be used on all classes of aircraft

Figure 5: Aircraft emissions can be decoupled from the growth of air traffic through a combination of energy-efficient technologies and sustainably produced kerosene and hydrogen.

## Sustainably produced kerosene

**At present, drop-in and near-drop-in fuels – sustainably produced kerosene – represent the most realistic alternative to conventional kerosene for long-haul flights.** Their development and impact on the atmosphere are being researched at DLR, from fundamental experiments to flight tests, and this must be further advanced. **If the technologies being investigated at DLR are harnessed in full, they can be used to decouple carbon dioxide emissions caused by aviation from the exponential growth in air traffic and bring them towards zero.** These include new, alternative propulsion technologies, energy-efficient technologies that reduce energy demand, novel flight paths that minimise the impact on the climate, and sustainable aviation fuels in a future air transport system. **The greatest leverage for reducing carbon dioxide comes from the fact that sustainably produced kerosene can be used for all aircraft classes in combination with energy-efficient technologies.**

## Alternative energy carriers

For regional aircraft, DLR is continuing to study the potential of batteries and fuel cells to achieve the necessary power density. **For short- and medium-haul aircraft, DLR's researchers are also developing concepts for hydrogen combustion with the necessary tank technologies** and determining the technical potential of hydrogen-based propulsion systems. DLR's aeronautics research does not cover the availability of a hydrogen-tailored infrastructure or the safe handling of hydrogen, these areas are being investigated within the scope of energy research at DLR. **An essential milestone on the path towards carbon dioxide neutrality is the timely consideration of all costs pertaining to the proposed technologies against the benefits of their emissions reduction, particularly from a market perspective.** The increased energy demand and cost of sustainably produced kerosene must also be weighed against the elevated costs for using hydrogen in aircraft and examined in specific market scenarios.

*For the climate-neutral air transport system of the future, DLR is identifying the optimum combination of all potential technologies – from improving the efficiency of aircraft to high-efficiency engines in combination with sustainable aviation fuels, hydrogen and electricity, all the way through to improved air traffic management.*

### KEY FINDINGS

- Without corrective measures and with current technologies in aircraft, carbon dioxide emissions from global air traffic are expected to more than quadruple by 2050.
- If every possible technical measure is implemented to reduce aircraft energy requirements, by developing particularly efficient engines and optimising flight routes, the increase in carbon dioxide emissions can be limited to be just 50 percent of 2020 levels.
- If energy-efficient technologies are combined with the introduction of sustainably produced kerosene, a reduction in carbon dioxide emissions to just under 30 percent of 2020 levels can be achieved by 2050.
- **If all currently feasible options for reducing carbon dioxide are integrated, the result for the year 2050, based on today's perspective, will be a marginal threshold of only approximately 17 percent of carbon dioxide emissions compared to 2020.**

## Energy-efficient technologies

**To fully harness the potential of energy-efficient technologies, it is crucial to dramatically reduce aerodynamic drag and aircraft weight.** Laminar flow on both the wing and aircraft fuselage is a prerequisite to reduce frictional drag. Reducing induced drag entails increasing aircraft wingspans significantly without extending the surface area of the wing. DLR will consequently pursue its research, development and proof of concept of these highly sophisticated technologies to make the necessary fluid mechanical, structural and system-related concepts a reality.

## End-to-end digitalisation

End-to-end digitalisation plays a major role in achieving a more efficient way to create a climate-neutral product lifecycle of an aircraft, from design and production to operation, maintenance and finally decommissioning. This is because **it speeds up the pace of innovation and the time it takes to bring new technologies to the market. DLR is conducting research into the 'virtual product' – the end-to-end digitalisation of an aircraft including all its components and technologies throughout its lifecycle.** This allows early prediction and comprehensive analysis of economic and environmental impacts across the aircraft's lifecycle. Digitalisation also makes it easier to identify the potential of new technologies for more environmentally friendly and economically viable air transport and accelerates their implementation.

## Overall system evaluation

In its effort to achieve climate-neutral air transport in the future, DLR is setting the course for a carefully crafted, reflective and technology-open research strategy, rather than following a rigid, long-term forecast. **After a maximum of five years, DLR will evaluate all the available technologies and increasingly focus on the ones that show the most promise for reducing the environmental impact of aviation over the entire lifecycle,** particularly with regard to fuel cells and hydrogen tanks. DLR's research priorities will continuously adapt to the latest findings and will be aligned with the potential of the technology transfer.

*For medium- and long-haul flights, a combination of highly efficient aircraft engines and Sustainable Aviation Fuels will render operations largely climate-neutral in the short term. The aim is to reduce the fuel consumption of propulsion systems by a further 25 percent by 2050.*

## Low-emission aircraft engines

### OBJECTIVE AND SIGNIFICANCE

Research into the use of alternative energy carriers is currently under way, including turbofan engines using sustainably produced kerosene, turbofan engines using hydrogen as energy carrier, hybrid fuel cell propulsion systems with hydrogen and battery-powered propulsion systems. Sustainable energy carriers will be essential for achieving emissions targets. However, the precise potential and applicability of the different technologies across various aircraft categories and flight operations are yet to be determined.

More efficient propulsion technologies are crucial because there is a direct correlation between energy consumption by the propulsion system and generated emissions. Initially, SAF will be scarce and significantly more expensive than fossil fuels, and tank volumes and tank weight will limit the scope of application, particularly in hydrogen combustion systems.

The goal of low-emission propulsion technologies is to develop aircraft propulsion systems – already a highly advanced technology – that achieve a **25 percent reduction in fuel consumption** and allow for the use of sustainable fuels by 2050.

**Challenges, approaches, unique features**

In order to reduce emissions and the climate impact of air transport as quickly and sustainably as possible, fossil fuels should be replaced with sustainably produced kerosene. This can be used by existing aircraft with only minor technical modifications (near-drop-in fuels) or without any modifications at all (drop-in fuels), thus enabling rapid market introduction. **The production of sustainably produced kerosene should be accelerated. International partnerships, investment models and supply chains need to be established and cost-effective production processes developed.**

To reduce emissions and ultimately the required primary energy input, hydrogen should be investigated as an energy carrier for aviation applications and engines should be qualified for hydrogen combustion. **This calls for systematic research and the development of safe, reliable and low-pollution hydrogen combustors, along with the safe handling and management of hydrogen and solutions for an increased water vapour content in the hot gas section of the engines.**

**Hybrid-electric aircraft propulsion systems that use hydrogen in fuel cells along with the use of electrical power in high-performance propulsion systems will be the subject of further research.** Albeit, technological maturity, performance as well as performance density achieved so far are insufficient to operate larger commercial aircraft. Ongoing studies into the ability of batteries address temporary high-power requirements during critical flight phases (particularly take-off, climb and go-around after aborted landings). Other battery-powered applications are being developed for ever larger aircraft and longer flight operations.

**Technical objectives**

At the outset, **all aircraft operated beyond 2030 must be equipped with 100 percent SAF-capable engines,** particularly for medium- and long-haul aircraft, but also to achieve rapid market penetration in the short-haul sector. This applies mainly to sustainably produced kerosene. The low-emission combustion of sustainable aviation fuels will be subject to very stringent requirements (for example, concerning nitrogen oxides, carbon particulates), elevating the **research and development of innovative combustion systems for such altered chemical composition of SAF** to a top priority. Achieving this will drastically reduce nitrogen oxides and carbon particulate emissions in tandem with net-carbon dioxide emissions, resulting in an effective reduction of the negative impact of air transport on the climate and air quality.

To reduce the fuel consumption of turbofan engines, we need to research and qualify **novel materials and construction methods** and benefit from them to develop highly efficient propulsion components. This requires **innovative design approaches and adapted construction rules.** High-precision simulation processes and virtual systems are an ideal resource, offering much faster development times and a considerably reduced risk.

Research into and qualification of **safe and low-emission combustion** of hydrogen entails the development of specific hydrogen combustors. The necessary test stands must be fully hydrogen-capable and the entire process chain, from atmospheric testing on individual combustors to comprehensive testing under realistic temperature and pressure conditions, needs to be reproduced. **The year 2040 could see the first hydrogen-capable aircraft and engines for medium-haul flights.** An almost carbon dioxide neutral operation on medium-haul routes will be a real possibility and contribute to minimising the impact on the climate caused by this important transport segment.

The first step to implementing fuel cell-electric propulsion systems in aircraft in the medium-term is to design such an engine within the one to two megawatt power class by 2030, investigate them closely and test them under high-altitude conditions. In addition to the **hydrogen-related infrastructure, researchers will require a high-altitude engine test stand,** which makes it possible to simulate the complete flight process on the ground. This is the only way to identify shortcomings at an early stage and eliminate risks for later full-scale experiments. A further necessity will be to develop and validate high-performance electrical systems for flight applications and to ensure the electromagnetic compatibility of all electronic systems, which will again require specialised test facilities.

**Regional air transport – a sector under considerable public scrutiny – is scheduled to implement the first fuel cell-electric propulsion systems by 2040, putting it on a path to being completely climate neutral.** This accomplishment will take a significant improvement of the power density of the fuel cells and all electrical components and the development of highly integrated propulsion units, that can be installed in aircraft with reasonable limitations.

*Hydrogen-, fuel-cell- or battery-powered propulsion systems are of particular interest for smaller aircraft up to a category of regional class, as they heavily influence the volume and weight of the aircraft while being limited by a relatively small amount of energy available.*

## LOW-EMISSION AIRCRAFT ENGINES

FIELDS OF ACTION

| | 2020–2030 | 2030–2040 | 2040–2050 |
|---|---|---|---|
| Turbofan-engines | Innovative composite materials, optimised SLM components, active noise reduction and low-emission SAF combustion | Engines with innovative fan and turbine blades and open rotors with 100% hydrogen combustion | UHBR engines and open rotors with low-emission hydrogen combustion available |
| Electrical components | High-power components developed and electromagnetic compatibility validated on the test stand | Increased power and higher power density validated on the test stand | Validation of improved system architecture, further increases in power, and increased power density on the test stand |
| Distributed thrust | Optimisation and virtual integration of propulsion using distributed thrust | Proof of propulsion concepts with distributed thrust through experiments | Overall configurations with distributed thrust ready for use |
| Fuel cells | Aviation-compatible fuel cell stacks with increased power are available and validated in long-term tests | Aviation-optimised fuel cell stacks with a further-developed design and increased power are available and validated in long-term tests | Aviation-optimised fuel cell stacks with a further-developed design and increased power ready for use |
| Hybrid electric fuel cell propulsion systems | Fuel cell electric propulsion systems developed and tested on the altitude test stand | Highly integrated fuel cell electric propulsion systems developed and tested on the altitude test stand | Highly integrated fuel cell electric propulsion systems ready for use |
| Revolutionary propulsion systems | Revolutionary propulsion system components developed and tested on the test stand | Integrated revolutionary propulsion system validated on the test stand | Revolutionary propulsion system concept validated on the altitude test stand |
| Hydrogen technology | Concept for the safe storage and use of hydrogen in aircraft devised and validated | Numerical methods validated, for evaluating the effects of water vapour corrosion and embrittlement | Integrated concept for cryotechnology / superconductivity developed and validated |
| Digitalisation and virtualisation | Virtual engine can be used for multidisciplinary engine design | AI ready for modelling and predictive digital twins | Simulation-based certification of engines and engine components |

Figure 6: Fields of action in the area of low-emission aircraft engines include turbine engines, electrical components and the use of hydrogen. Aspects of integration are also important in all areas.

## Energy-efficient aircraft

### OBJECTIVE AND SIGNIFICANCE

The aim is to reduce the energy requirements of future aircraft so that they only require half of the propulsion power that they do today. This means using new insights and methods to push all established aircraft construction technologies to the limits of what is physically and technically feasible. There is a straight line from lower energy requirements of aircraft to lower fuel consumption by propulsion systems. It reduces residual emissions and offsets the higher costs of future energy carriers. To ensure the best possible integration of all necessary technologies, their consideration within new aircraft configurations need to be factored in at the very beginning of the design phase. One particular challenge in this context is the as of yet untested correlations of individual technologies pertaining to aerodynamics, aeroelasticity and structure and systems for reducing drag, load and weight.

The goal of the energy-efficient aircraft is to **reduce energy consumption by up to 50 percent by 2050.** Based on current research findings, reducing the aerodynamic zero-lift drag coefficient by 40 percent and the total weight by 10 percent while increasing the wing aspect ratio up to 15 will achieve this objective.

**Challenges, approaches, unique features**

On the one hand, wings with a **significantly higher aspect ratio** are required to reduce the induced drag that occurs when lift is generated. Achieving **laminar flow** around the wing is essential to reduce frictional drag, and it is imperative to apply the same objective to the fuselage, with far-reaching implications on support structures and systems. On the other hand, any known **potential for lightweight construction** should be consistently harnessed and optimised. **Load reduction methods** should be combined with novel sensor and control concepts, sensor-based structure monitoring implemented, and new lightweight construction methods developed and tested so that secondary structures and system elements can contribute as much as possible to load transfer. To achieve effective technology integration, established **aircraft configurations** must be improved and fundamentally redeveloped for new types of energy carriers such as hydrogen. **Consistent numerical simulation and multidisciplinary optimisation** are absolutely essential if all disciplines are to interact in a precise and robust way.

To overcome the aforementioned challenges, DLR is following the approaches listed below:

- Creation of a dual, coordinated pathway for a **virtual and physical development and testing environment** for new, reliable and validated whole aircraft systems

- Research, development and testing of **artificial intelligence** (AI) based sensor and control concepts for real-time monitoring and load-dependent adaptation to any flight conditions in order to reduce energy and maintenance requirements

- Development and demonstration of multi-component and **multifunctional structures**

- Assessment of aircraft with a view to **strengthening simulation-based certification,** including all disciplinary calculation methods, in close cooperation with manufacturers and certifying authorities for the commissioning of new energy-efficient technologies with the highest level of safety

- Development of energy-efficient, versatile **cabin and cargo systems**

- Creation of additional **tools for technological advancement and evaluation of aircraft** with regard to Maintenance, Repair and Overhaul (MRO), acoustic signature and Life Cycle Assessment (LCA)

DLR has all of the necessary research and development expertise required to address energy-efficient aviation technologies. It can also demonstrate technological developments with industrial-scale manufacturing facilities, test stands, wind tunnels and research aircraft. DLR has practical experience of carrying out complex, large-scale flight tests and can validate technology and digital models on a wide range of research aircraft. **DLR therefore has the capabilities and the tools to research and develop system architectures up to an industrial technology maturity level.**



*In addition to improving propulsion systems, it is vital to reduce drag and weight as much as possible for all classes of aircraft. The aim is to halve the energy requirement by 2050.*

**Technical objectives**

For **wings with a very high aspect ratio** (≈15), structural, system-related and configurational measures are to be developed (passive load adaptation, active load control, bracing) and technically consolidated by 2030 so that certification and **series production readiness can be achieved by 2040.**

Technologies for **laminar-flow wings** (with high lift, self-cleaning and de-icing) in the range of Ma > 0.75 and for hybrid laminar retention on the fuselage are to be demonstrated in flight tests by 2040, to enable **serial implementation from 2040.**

**Multidisciplinary lightweight system construction** using modern lightweight materials, innovative assembly concepts, Structural Health Monitoring (SHM), system and cabin integration, the incorporation of secondary structures, load reduction and the ability to passively and actively affect the laminar flow will be tested in ground-based demonstrators by 2030 and prepared for **certification using flight tests by 2040.** At the same time, the necessary manufacturing technologies for integrating structures and systems to such a degree need to be further developed.

By 2030, **load adaptation technologies** must be proven, flutter and flight dynamics control demonstrated, and AI-based sensor and system concepts established. These must then be optimised and certified using flight tests by 2040 and become an integral part of designs for energy-efficient aircraft from that point onwards.

**Technology concepts for the integration of hydrogen tanks and systems in aircraft will be developed and tested by 2030** so that nothing stands in the way of obtaining certification for aircraft that use hydrogen as an energy carrier.

The capability for rapid multidisciplinary design of complete aircraft must be expanded quickly so that, **by 2030, suitable aircraft configurations for alternative propulsion concepts** (distributed propulsion, boundary layer ingestion, integration of hydrogen tanks) can be determined and the integration of performance-improving technologies (high-aspect-ratio wings, laminar flow on wings and fuselage) tested virtually.

### ENERGY-EFFICIENT AIRCRAFT
FIELDS OF ACTION

| | 2020–2030 | 2030–2040 | 2040–2050 |
|---|---|---|---|
| **Drag reduction** | Maintenance of laminar flow on the wing; wings with a high aspect ratio, wing tip shape, turbulent flow control researched | Maintenance of laminar flow on the fuselage and tanks; management of turbulence-inducing structures; demonstration of highly elongated wings | Designing aircraft with optimised laminar / turbulent flow is routine |
| **Reducing weight with lightweight construction** | Potential for function-integrating structures determined, including shape variability, condition monitoring, energy storage, system integration, etc. | New material, structure and manufacturing concepts demonstrated in flight as prototypes; LCA and OeL assessment integrated into the design | Function-integrated structures in ultra-light construction certified; production technologies and industrial applications mastered |
| **Stability and load control** | Load adaptation proven; flutter and flight mechanics control emonstrated; AI-based sensor and system concepts | AI sensor-based control of the entire aircraft system (flight condition, stability, load) | The best possible combination of load / energy reduction is an industrial element for new aircraft |
| **Optimising the on-board systems** | Electric flight control systems available, including load-adaptive wings | AI condition monitoring implemented with a high level of reliability and evaluated in flight. AI-optimised load distribution | Superconducting technologies for power distribution / propulsion. Reliable morphing wing flaps, etc. |
| **Propulsor integration** | Assessment of propulsion technologies (UHBR, propeller) assessed; mastering of critical hybrid-electric system components | Demonstration of system architectures for electric, hybrid-electric and non-electric drives; UHBR for SAF and $H_2$ | Optimisation and digital testing of configurations for integrating revolutionary UHBR propulsion systems |
| **$H_2$ tank technology** | Concepts for a substantial increase in the gravimetric index and robust production tested with prototypes | Design and application mastered for weight-optimised integration of large $H_2$ tanks into aircraft | The cost-effective production of gravimetrically high-quality $H_2$ tanks is routine in the industry |
| **Cooling concepts for fuel cells and electric systems** | Cooling concepts created; effects on aircraft configurations determined | Function and feasibility of cooling concepts proven for the megawatt range | Integrating cooling concepts is standard in aircraft development |
| **Configurations** | Optimal configurations digitally tested for different propulsion concepts and missions | Testing of target configurations with scaled demonstrators and in-flight simulation | Verification of the green functionality by measuring pollutants and consumption on different missions |

Figure 7: The main fields of action for energy-efficient aircraft centre around an integrated approach to aerodynamics, aeroelasticity, structure and systems.

*The climate effects of non-carbon-dioxide emissions due to air transport can be reduced significantly with optimised flight routes, particularly on medium- and long-haul routes. The goal is to reduce the climate impact by 30 percent.*

## Reduced-emission air transport system

### OBJECTIVE AND SIGNIFICANCE

Aircraft operations offer numerous options for reducing fuel consumption and the associated emissions near airports and in flight, as well as minimising the overall climate impact (both carbon dioxide and non-carbon-dioxide effects). The optimisation of lateral and vertical flight profiles appears promising as a means of achieving efficiency gains. Flight control can also be designed in such a way that the effect of the emissions, which depends on atmospheric conditions, can be minimised through climate-optimised routes. Flight trajectories that are optimised for low climate impact should significantly reduce the contribution of air transport towards global warming, particularly on medium- and long-haul routes.

The goal, therefore, is to enable an **air transport system that is as efficient and low in emissions as possible,** which includes innovative aircraft configurations, to cut the climate impact of air transport by more than 30 percent, by minimising non-carbon-dioxide effects through climate-optimised routing.

**Challenges, approaches, unique features**

A number of technological challenges must be overcome in order to achieve this ambitious goal. The air transport system and the air traffic management landscape in particular are characterised by an organisational structure that is geared towards national borders. Because of this, operations are fragmented and there is a markedly low level of automation. As part of the Single European Sky (SES) initiative, the SESAR programme (SES ATM Research) is aimed at developing the necessary innovative, robust and safe technologies and operating procedures. Up until now, there has been no such comprehensive European programme designed to cover the operational and technological aspects of minimising the climate impact of air traffic by reducing the carbon dioxide and particularly the non-carbon-dioxide effects. **The overall effect of climate-friendly technologies can only be observed at the level of the air transport system.** Until now, however, **there has not been a suitably detailed evaluation or simulation platform** with the capability of assessing new technologies, operating procedures and fuel technologies in terms of the performance of the air transport system and the possibilities for reducing the climate impact of air transport.

In order to overcome these hurdles, DLR is conducting comprehensive research into new concepts and technologies for the air transport system of tomorrow. Its research includes the **development of operational concepts and new technologies for integrated operating procedures** in the fields of Communications, Navigation and Surveillance (CNS) and Air Traffic Management (ATM), including security, with optimal use of **advanced automation.** DLR researchers are also studying everything from the use of performance-based operations and the identification and use of climate cost functions to minimise the climate impact of air transport through to integrated CNS, including the necessary security measures. The **development of new, smart concepts for airports and zero-emission Urban Air Mobility (UAM)** should also help to reduce emissions such as sulphur and nitrogen oxides or particle dust in the vicinity of airports. **Additional focus is placed on the expansion of a comprehensive and highly detailed evaluation environment for the entire air transport system.** DLR has expertise in the field of climate-neutral air traffic management including UAM, smart airport concepts, and the necessary impact assessment at all development stages, from basic research to the creation of application-oriented prototypes. Its researchers are looking in great detail at the concepts required for comprehensive traffic management, the effects on the climate, and the individual technologies required for communications, navigation, flight control and weather forecasting.



*The growth of air traffic can be decoupled from emissions through the combined use of low-emission aircraft engines with sustainable aviation fuels, energy-efficient aircraft, and a reduced-emissions air transport system.*

**Technical objectives**

The plan is to **develop a comprehensive, detailed simulation platform for the entire air transport system,** which will also enable a climate assessment of technologies and operating procedures within four years in order to identify and conduct a comprehensive evaluation of technological solution paths. In addition, **a formal dialogue needs to be established with policymakers** in order to illustrate the interaction between policy measures, technological development pathways and their climate impact.

**Defining a comprehensive, validated and robust climate impact function** is indispensable and can be used in performance-based air transport operations. Such studies need to take account of the atmospheric uncertainties of non-carbon-dioxide effects. In the next five years, DLR intends to demonstrate the commercial feasibility and effectiveness of **reducing non-carbon-dioxide effects through climate-optimised flight trajectories.**

Ultimately, cooperation between research, industry and policymakers needs to be intensified over the next five years in order to develop **global, integrated standards and measures,** that can better mitigate the impact of future pandemics.

## REDUCED-EMISSIONS AIR TRANSPORT SYSTEM
FIELDS OF ACTION

| | 2020–2030 | 2030–2040 | 2040–2050 |
|---|---|---|---|
| **Climate-impact-optimised flight paths** | Radiative forcing for classic propulsion systems understood and climate cost function integrated into trajectory planning | Climate impact of new $H_2$ propulsion technologies understood | Climate- and eco-friendly flight paths implemented in full |
| **Automation of Air Traffic Management (ATM)** | Higher productivity and capacity through automation verified | Gradual operational implementation of disruptive processes | Full automation of ATM possible |
| **Zero-emission Urban Air Mobility (UAM)** | UAM traffic management developed (optimised for noise and emissions) | Full airspace integration demonstrated and social acceptance achieved | Complete integration of UAM with all modes of transport |
| **Zero-emission airport** | Noise-optimised flight paths (24/7) for taking off and landing; zero-emissions taxiing demonstrated; air quality recorded; impact of Ultra-Fine Particles (UFPs) verified | Automated airport possible (airside, performance-based airport management); air pollutant-reducing strategies devised and implemented | Climate-neutral airport operation achieved |
| **Multi-modal transport connections** | Climate impact understood for reference journeys on different modes of transport | Cross-modal traffic management developed | Seamless 4D passenger routes established |
| **Impact assessment** | Modelling for aircraft / mission, airport / ATM and air transport level available, leading to recommendations for policy, business and society | Interactions with other modes of transport / intermodality understood and evaluated | Air transport achieves climate targets |

Figure 8: The fields of action relating to the air transport system seek to evaluate the system as a whole, particularly the enabling of climate-optimised flight routes.

## Digitalisation

### OBJECTIVE AND SIGNIFICANCE

As a cross-sectoral technology, digitalisation plays a decisive role in enabling ambitious developments in aviation. Without it, the achievement of the 2050 climate targets cannot be guaranteed. On the one hand, only consistent digitalisation will clear the way to make the stated goals of reducing emissions and energy requirements a possibility by coordinating the different disciplines, technologies and various elements of the air transport system. On the other hand, conventional development cycles in aviation are lengthy and associated with enormous technical and financial risks. The extensive virtualisation of development and continuous digitalisation of manufacturing and operations will significantly reduce development times and risks, optimise operational processes, and minimise the impact of air transport on the climate.

The aim is to develop tools that **accelerate the speed of innovation by a factor of two** and accelerate the market launch of new technologies.

**Challenges, approaches, unique features**
If we are to achieve the ambitious goal of climate-neutral aviation, it is essential that aviation-specific technological challenges in the field of digitalisation are overcome. **Current standards to calculate physical phenomena are neither precise nor quick enough to achieve the most extensive virtualisation of design, development and certification.** This means that a multitude of phenomena and their interactions cannot be predicted in the context of multidisciplinary analysis and optimisation, and the necessary synergies cannot be leveraged. In addition, data and digital models cannot be used consistently due to different data formats, unconnected data storage and uncertain data security. **This means that there are no realistic models of future aircraft and products that can serve as a basis for the targeted development and evaluation of new technologies.** Similarly, it is not possible to predict the future state of physical objects and to optimise operating and maintenance processes on this basis. **Furthermore, digital components cannot be integrated into physical systems because the safety of the digital systems cannot be verified.** All this also means that different partners are not able to work together efficiently in a common development network.

DLR is currently pursuing a number of approaches to overcome these hurdles:

- Development and validation of **high-precision numerical methods** for all relevant areas of application in the air transport system
- Development and validation of **Multidisciplinary Analysis and Optimisation** (MDAO) platforms and the necessary optimisation algorithms, with targeted focus on High-Performance Computing (HPC) architectures
- Development of **rapid analysis tools and algorithms for trouble-shooting** (Reduced-Order Models, ROMs) for fast coupled MDAO studies in aircraft design
- Development and validation of an **independent platform for standardised data and model exchange** with uniform data formats and secure solutions for handling the data
- **Development and use of virtual products** that enable the highly detailed calculation of all interdisciplinary interactions of future products
- **Development of digital twins,** in which the continuously recorded actual state is mapped in order to calculate expected changes and identify an optimal course of action
- Creation of **certification concepts for autonomous systems** and systems with artificial intelligence
- **Creation of digital development processes** and optimisation of interactions between all partners (Model-Based Systems Engineering, MBSE)



*Digital methods and artificial intelligence will significantly advance the design, manufacture and operation of all aircraft. The aim is to develop tools that* ***accelerate the speed of innovation by a factor of two*** *and improve the time to market of new technologies.*

DLR operates the large-scale facilities required for application-oriented validation and has both fundamental and application expertise. Thanks to many years of research in the field of numerical simulation, it also has the necessary know-how to devise and validate application-oriented models. This makes it possible to develop and apply MDAO platform technologies and make them efficiently usable on high-performance computers. In addition, DLR has the technical expertise concerning data formats that span the whole of aviation, as well as long-term financing and a reputation as a trusted neutral partner able to take responsibility for a standardised exchange platform. **Only DLR has the methods and expertise in aeronautics to design highly accurate and application-oriented models for future products.** In terms of infrastructure, DLR operates large-scale, application-oriented systems that allow researchers to test the safety of autonomous and AI-based systems, with high-precision computing methods that test and validate condition monitoring and forecasting during operation. The key factor here is that only DLR, with its 55 research institutes, has all the competences required to be able to investigate and apply digital development processes with multiple independent partners as part of its programmatic research.

**Technical objectives**
The main objectives of DLR aeronautics research in this area are the **consistent development, creation and implementation of suitable digital methods, tools and research processes for virtual modelling, along with testing, validation, evaluation and optimisation of all elements of the aviation system** with the aim of halving the development time for new generations of aircraft over the next five years and minimising risks.

These activities are supported by the **expansion of collaboration spaces,** such as DLR's Virtual Product House. The objective is to analyse, design and optimise aircraft configurations and their components, considering all relevant technologies and discipline-related aspects, in order to incorporate future-facing technologies in the next aircraft generation in the next five years and join forces with small and medium-sized German companies as technology developers and suppliers.

DIGITALISATION
FIELDS OF ACTION

| | 2020–2030 | 2030–2040 | 2040–2050 |
|---|---|---|---|
| **THE DIGITAL AIRCRAFT** High-precision physics simulation; virtualisation of all product properties | All flight characteristics predictable within the flight envelope | 'Digital first flight' and complete flight testing demonstrated and validated with flight tests | The 'digital aircraft' is a standard part of the certification process |
| **THE DIGITAL TWIN** Modelling of functional relationships; virtualisation of system interactions | Modelling of entire aircraft; link-up of real and simulated data; lifecycle forecasting for components | Modelling of aircraft, their production and operation; aircraft lifecycle forecasting; use of high-precision processes | Air transport system modelled to include environmental and economic factors; real-time fleet forecasting |
| **DIGITAL THREAD** Availability / provision of the necessary data; insights for decision-making | DLR model / data management, all disciplines, data analysis | Automatised interfaces and secure data management with external partners | Usable historical and real-time data from the whole aviation system |
| **DIGITAL ENGINEERING** End-to-end use of digital methods and tools in design and production | Establishment of Model-Based Systems Engineering (MBSE) and HiFi Multi-Disciplinary Optimisation (MDO) | Virtual testing takes place in parallel to physical testing (Synthesis of Experiment and Numerics, SEN) | Optimised simultaneous design of aircraft, operations and production; digital certification of aircraft |
| **SYSTEMS ENGINEERING** Integrated digital management of the entire product development process | Digital research processes for virtual products established at DLR (using MBSE and MDO) | Secure research processes involving external parties are standard at DLR (Virtual Extended Enterprise) | Enterprise Architecture Optimisation |
| **CYBER-PHYSICAL SYSTEMS** Hardware | Autonomy demonstrator for complex missions, roadmap for verification, operational concepts evaluated | First certification examples of complex AI-methods; first autonomous flying systems tested | Certification standards for autonomy; dissemination of autonomy and AI technologies in the industry |

Figure 9: Fields of action in digitalisation cover the entire spectrum of digital reproduction of the air transport system, alongside digital design and integration methods.

# 4. Aeronautics research at DLR

Safe, environmentally compatible and efficient air transport, that is accessible to all is essential for social wellbeing and economic development in Germany and across Europe. The European Union is pursuing the goal of a zero-emission aviation system by 2050. To that end, aeronautics researchers at DLR are working on three pillars for a sustainable aviation system – **strengthening the competitiveness of the German and European aeronautics industry, increasing environmental compatibility and acceptance and ensuring mobility.**

In addition to substantial evolutionary measures to increase efficiency, revolutionary approaches, such as electric flight or using hydrogen as a fuel and deploying artificial intelligence in aviation automation are vital to achieving these ambitious goals.

**DLR's aeronautics research follows an integrated system approach. This means exploring the entire spectrum of the air transport system in depth, from the fundamentals to applications – a multi-scale, multidisciplinary approach.** This encompasses the necessary infrastructure, novel production technologies, the energy-efficient aircraft itself along with the development of its components, an efficient and reduced-emissions air transport system, as well as quantification of the effects on the climate, society and the economy. Only this comprehensive agenda allows DLR to carefully evaluate the revolutionary approaches needed and provide sound advice to decision-makers. **DLR's strategic and programmatic management enables efficient and integrated treatment of prominent scientific topics beyond the boundaries of its institutes.**

**The end-to-end digitalisation, virtualisation and automation of aviation throughout the entire product lifecycle is key to this overall system capability.** It also drives innovation and accelerates the market launch of new technologies thanks to faster development and simulation-based certification. As a virtual manufacturer, DLR can support small and medium-sized companies by taking advantage of the integration into the virtual product, particularly when entering the market. **Applied experiments in the field and laboratory are crucial for validating virtual aviation. DLR's aeronautics research division already has the necessary infrastructure in place, such as wind tunnels, large-scale research facilities, research aircraft and integrated simulation facilities, including High Performance Computers.** Physical and virtual development and testing environments must be closely coordinated in order to create new, dependable and validated systems. In particular, interdisciplinary cooperation at DLR between its **areas of aeronautics, space, energy and transport** is unique in Europe and essential in shaping zero-emission aviation for the future. For example, DLR is one of the few research institutions in the world equipped to conceptualise aircraft capable of using new energy carriers such as hydrogen, record their emissions and model the resulting climate impact within the context of a multimodal transport system. These skills are used to develop and implement regional, national, European and international political strategies and measures, with the support of the **DLR project management agencies.** The specific combination of expertise and interdisciplinarity in research, the integrated approach taken to industry-related large-scale facilities, and DLR's threefold role as research institution / space agency / project management agency make it well placed to act as policy advisor and co-designer of sustainable aviation in the future.

## Professional strengths of aeronautics research at DLR

Aeronautics research at DLR has evolved along with the aviation sector. Up until the 1980s, the focus was on the technological basis for establishing air traffic as a means of transport. The environmental impact of these technologies, including noise, was being identified and analysed as early as the 1990s. The 2000s saw an increased focus on sustainability. **Through its longstanding support for aviation, DLR's aeronautics research has developed specific scientific and technical strengths that are now prerequisites for achieving the goals of sustainable aviation.**

### Numerical simulation

DLR laid the foundations for the complete digital development and description of aircraft and helicopters in its VicToria project (Virtual Aircraft Technology Integration Platform). This project has made a significant contribution to improved physical modelling and numerical and experimental methods, verification and validation using dedicated flight and wind tunnel tests and highly accurate multidisciplinary simulation and optimisation of aircraft on high-performance computers. **Now that the product characteristics of helicopters and aircraft can be described in purely digital form, it will be possible to create a 'digital twin' for an**

*DLR's aeronautics research focuses on three pillars for a sustainable aviation system – strengthening the competitiveness of the German and European aviation industry; increasing environmental compatibility and acceptance; and ensuring mobility.*


**aircraft or helicopter.** This twin can be used to evaluate the trade-offs and harness the potential of new technologies in a virtual design environment, and to assess the effects of the technologies, such as their impact on the environment.

**Technology development**

In the Optimal Load Adaptive Aircraft (oLAF) project, DLR is investigating the potential for increasing efficiency when using technologies for active load reduction in future aircraft designs. **The extensive use of load reduction technologies has a number of benefits – lighter aircraft structures, reduced fuel consumption, reduced operating costs and lower emissions.** With this in mind, oLAF project partners are designing a load-optimised long-haul aircraft, predominantly using coupled high-precision numerical methods for aerodynamics, structure, aeroelasticity, loads, flight control and systems. By integrating the load reduction concepts that have been developed as part of the project the researchers are able to evaluate the effects of aggressive load control on flight performance, operations, maintenance and energy consumption.

**Aircraft engines**

**A conceptual preliminary design methodology for aircraft propulsion systems is being developed** as part of the DLR PERFECT project (Preliminary design and evaluation of future engine concepts). **This methodology allows new types of propulsion systems to be developed in a preliminary design stage, correlating their components and optimising overall performance.** In a further step, the developed methodology is to be applied to innovative propulsion systems for regional, medium- and long-haul aircraft. With the expertise of the newly founded Institute of Electrified Aero Engines in Cottbus, the scope is to be expanded to include electrical components and validated through experiments on new, purpose-built component test stands.



*Through its longstanding efforts, aeronautics research at DLR has developed specific scientific and technical strengths that are deployed and expanded upon in support of sustainable aviation.*

**Aircraft design and technology assessment**

In the DLR project EXACT (Exploration of Electric Aircraft Concepts and Technologies), researchers are working on the development of new technology components for an energy-efficient commercial aircraft. **The overarching goal is to have the technologies for such an aircraft, with at least 70 seats and a range of 2000 kilometres, ready for use by 2040.** Different hybrid-electric propulsion concepts and possible aircraft configurations will be examined in the initial step. In addition, interactions with airport infrastructure must be considered, as well as how new types of propulsion systems affect the atmosphere and thus the climate.

*DLR aeronautics research has excellent national, European and global networks and cultivates a range of relationships and collaboration to help shape the air transport system of the future.*

**Large-scale in-flight testing**
A modular demonstrator makes it possible to test various propulsion concepts. **DLR operates a Dornier Do 228 that provides German industry and research institutions with a unique testing opportunity for hybrid-electric architectures.**

In the Do228hep project, DLR and engine manufacturer MTU are using this research aircraft to investigate the development, implementation and flight demonstration of an electric or hybrid-electric power train with fuel cells. DLR founded the Institute of Electrified Aero Engines in Cottbus specifically to build on this expertise. Its research concentrates on low-emission, usually highly electrified propulsion systems for civil transport aircraft.

**Sustainable Aviation Fuels**
In the ECLIF II project (Emissions and CLimate Impact of Alternative Fuels) in 2018, DLR demonstrated that the use of sustainably produced kerosene can reduce carbon dioxide emissions by 40 percent and soot emissions by up to 70 percent. In 2021, in ECLIFIII DLR collaborates with Airbus, Rolls-Royce, and Neste **to conduct the world's first investigation of emissions from a commercial passenger aircraft (an Airbus A350XWB-900) operated with 100 percent SAF.**

**Climate-optimised flight routes**
Customised flight routes can help to limit the global rise in temperatures caused by human activities. If this goal is to be achieved, air traffic management must be automated to a far greater extent than it is today. The DLR project DIAL bundles research work with the aim of expanding flight control automation. **Flight planners could offer customised, climate-optimised routes for every aircraft in the sky, avoiding areas of the atmosphere with long-term contrail formation, for example.** As part of the DIAL project, DLR researchers are developing processes, that optimise various climate-related parameters, while also facilitating greater capacity for air traffic management. At the same time, the plan is to make air traffic management more productive through increased automation. This will make traffic routing in the sky even more flexible and robust when demand rises again.

**Climate impact**
The COVID-19 pandemic has presented a unique opportunity to study the effects of air pollution. Reduced traffic and emissions from industry made it possible to assess the impact of such emissions on atmospheric chemistry and physics. At short notice, a German research team used this situation for the BLUESKY flight campaign, in which changes in Earth's atmosphere were investigated worldwide using two research aircraft. **The atmosphere was surveyed in a state that could be achieved in the future through sustainable economic activity and environmentally friendly aviation.**


**Policy advisor**
**DLR draws upon its extensive expertise to advise the German Federal Government on its technology strategy for environmentally friendly aviation and assists national committees with decision-making relating to technology selection and funding.** On behalf of the German Federal Ministry for Economic Affairs and Climate Action and alongside other federal ministries, DLR is implementing the National Aeronautics Research Programme. It also provides other national supervisory authorities like the Federal Aviation Office (LBA) with support on the development of standards. DLR also shares its expertise at the European level in collaboration with the European Union Aviation Safety Agency (EASA) and worldwide by contributing to the work of the International Civil Aviation Organization (ICAO).

## Collaboration and partners

The transformation of aviation towards global climate-neutral air transport is not merely a national task; **global challenges require global solutions.** Close international cooperation and the exchange of knowledge between research institutions, universities, industry, policymakers and regulatory authorities with regard to technology development, standardisation and certification are vital to the development of aircraft, that meet the ecological requirements of an international market. This cooperation enables not only the promotion of knowledge transfer between all stakeholders, but also the optimal use of resources and infrastructure, along with targeted technology transfer from research into commercial products.

DLR's aeronautics research has excellent national, European and global networks and cultivates numerous relationships and collaborations to help shape the air transport system of the future. It is playing a leading role in many areas of aeronautics research, both nationally and internationally.

As a member of the SESAR 2020 research programme, DLR has been working with all relevant European interest groups, such as air traffic control services, airports, airlines, aircraft manufacturers and air traffic control equipment makers since 2016 to devise application-oriented measures for safe, low-emission, cost-efficient and coherent air traffic in Europe.

Intensive, diverse collaboration between DLR and the aviation industry is reflected in numerous research contracts. **Its interdisciplinary research covers such a range that DLR is able to optimally support the German aviation industry in consolidating and extending its competitive advantage at a global level.** In the wake of the pandemic, DLR is helping the German and European aviation industry to meet the new challenges and address new research tasks. It not only supports large aircraft manufacturers, but also promotes the growth potential of small and medium-sized enterprises and start-ups. DLR also works closely with other research organisations. In projects such as BLUESKY, for example, DLR has joined forces with the Max Planck Society, universities and other research centres in the Helmholtz Association of German Research Centres to gain fundamental insights into the climate impact of aviation.

**Cooperation within Europe is particularly important to DLR, as the Member States have unique capabilities and operate complementary test facilities that can contribute to an even more comprehensive understanding of aviation as part of international research projects.**

Since 1994, for example, DLR has been a founding member of the Association of European Research Establishments in Aeronautics (EREA). The research institutions that belong to this body are committed to internal cooperation and coordination, and jointly represent their interests to European institutions and partners. **Not only is DLR a co-founder of EREA, but also a leading member, that contributes its technologies and research approaches to joint European research projects under the umbrella of EREA and helps to shape its policy papers on European research and innovation strategy.** EREA Future Sky, a joint research initiative, provides DLR with an opportunity to help shape calls for proposals under the European framework programmes for research and innovation. In this way, it can indirectly influence the EU's aviation research agenda.

**Through its involvement in the Advisory Council for Aviation Research and Innovation in Europe (ACARE), DLR has another means of exercising direct influence on strategic concepts for the future of aviation.** ACARE's task is to create and further develop the strategic research and innovation agenda for aviation and support its implementation. In doing so, it helps to coordinate national and European priorities, in order to develop solutions that are as effective and integrated as possible. ACARE is an important advisory body for public authorities such as Member States and the European Commission. Clean Sky


can be considered a public–private partnership within the EU framework programme, with new technologies such as laminar flow around wings being tested on commercial aircraft.

DLR also plays a prominent role further afield in the International Forum for Aviation Research (IFAR). IFAR is the only global network to bring together governmental aviation research institutions from all continents. It seeks to address the global challenges facing air transport with solutions devised through cooperative aviation research, to promote cooperation and the exchange of information and to advance the next generation of aviation researchers. This environment also enables international harmonisation with regard to regulations and laws, as well as operations. IFAR advises the ICAO on such matters. In addition, large test facilities such as demonstrators can be cross validated within the IFAR network, in tandem with key EREA partners such as ONERA and NLR, and international partners such as NASA, JAXA and NRC. **DLR is the initiator and coordinator of various IFAR activities. In 2020, for example, the Zero Emission Aviation Statement was published worldwide on the initiative of DLR. In this statement, research institutions from 13 IFAR member organisations declared environmentally friendly aviation to be a common goal.**

# Conclusion

**Over the coming decades, aviation is set to reinvent itself as a climate-neutral economic driver and source of intercultural exchange. The European Green Deal makes this an explicit target for Europe. Growth in air traffic must be decoupled from its emissions in the future.**

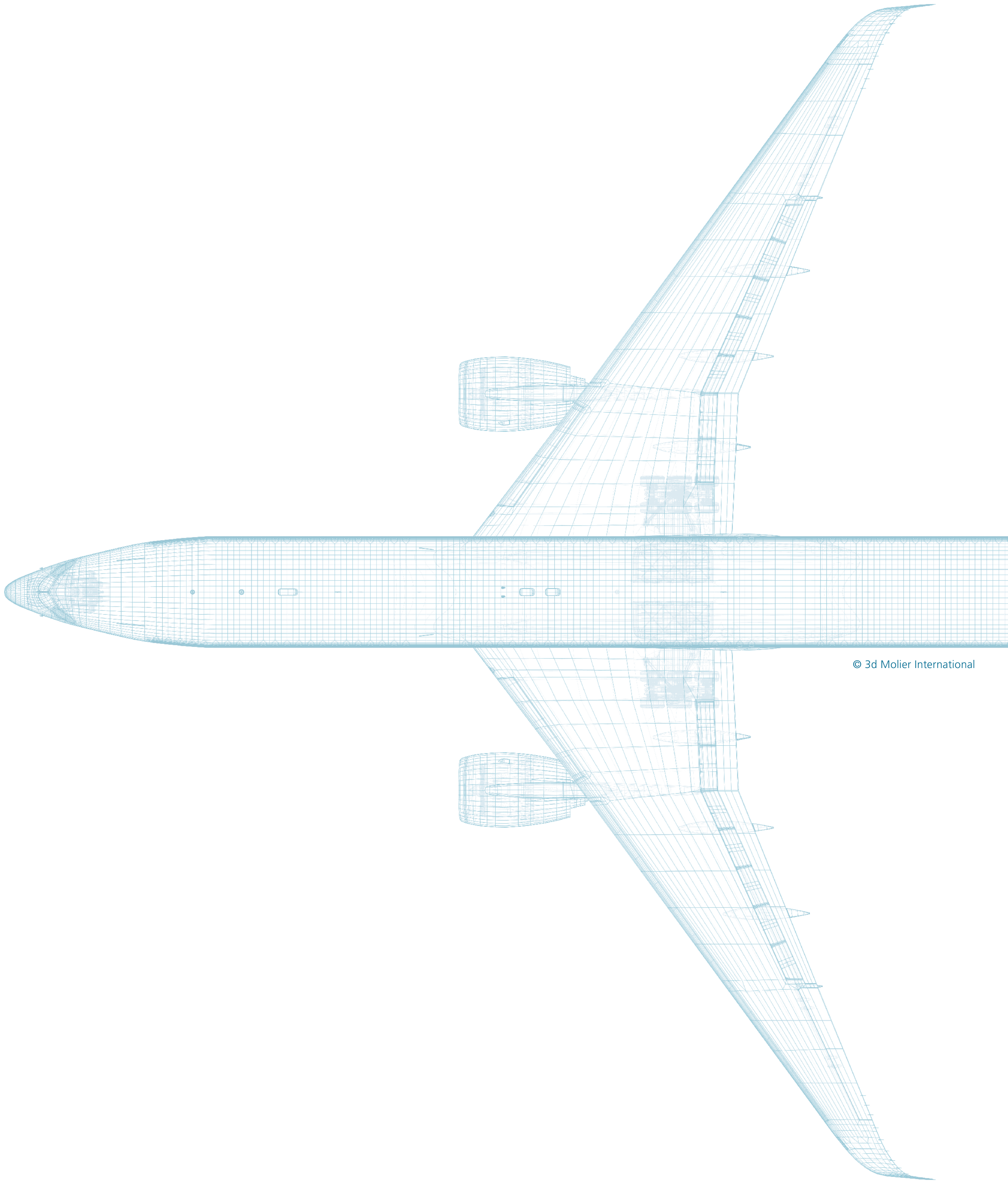
DLR is committed to a vision of zero-emission aviation. Its researchers take an integrated approach to developing comprehensive solutions. By virtue of its expertise in the aviation system as a whole, DLR plays the role of a virtual manufacturer (Virtual OEM), integrating other players in aviation research, the air transport industry and the wider economy.

The technological capabilities show that **it is possible to make climate-neutral aviation a reality by the middle of the century. This transformation must be multifaceted and open to new technologies.** Evolutionary steps are just as important as the systematic use of ground-breaking new technologies. There are four key fields of action: low-emission aircraft engines, energy-efficient aircraft, reduced-emissions air transport system and digitalisation. **The target of climate-neutral aviation by 2050 can only be achieved by connecting these different areas.**

The strategy presented here focuses on the introduction of sustainable aviation fuels, particularly **sustainably produced kerosene, for all classes of aircraft.** This can reduce climate-relevant emissions by **80 percent** in the short term. **Energy-efficient technologies** for propulsion, aircraft and air transport system must also be developed, as these can more than **halve the remaining emissions on all routes** by 2050. Alternative types of propulsion systems must be promoted in an effort to further reduce emissions, in particular **hydrogen combustion for short- to medium-haul routes and fuel-cell electric propulsion systems on regional routes. Digitalisation** is a crucial tool for future development across the board. By 2050, digitalisation should make it possible to find **new solutions more cost-effectively and twice as quickly as today,** thus speeding up the transformation to climate neutrality.

DLR is in an excellent position to shape the transformation towards zero-emission aviation in scientific and technological terms. Only DLR, with its 55 institutes, has all the necessary expertise to drive digital development processes as part of its research programme, alongside many external partners. **The combination of expertise and interdisciplinarity, integrated programmatic approach, industry-related large-scale facilities and identity as a composition of a research organisation, a space agency and a project management agency give DLR the role of architect, integrator, policy advisor and co-designer of a sustainable prosperous aviation of the future.**

*Research at DLR is paving the way for a climate-neutral future in aviation.
This is our contribution to the European Green Deal.*



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**About DLR**

DLR is the Federal Republic of Germany's research centre for aeronautics and space. We conduct research and development activities in the fields of aeronautics, space, energy, transport, security and digitalisation. The German Space Agency at DLR plans and implements the national space programme on behalf of the Federal Government. Two DLR project management agencies oversee funding programmes and support knowledge transfer.

Climate, mobility and technology are changing globally. DLR uses the expertise of its 55 research institutes and facilities to develop solutions to these challenges. Our 10,000 employees share a mission – to explore Earth and space and develop technologies for a sustainable future. In doing so, DLR contributes to strengthening Germany's position as a prime location for research and industry.

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