ZERO EMISSION AVIATION

GERMAN AVIATION RESEARCH WHITE PAPER

BDLI

DLR

PREAMBLE

This White Paper was prepared before the outbreak of the Corona pandemic.

Although the impact of the virus on aviation cannot yet be reliably predicted, the worldwide slump in air traffic and the current travel restrictions prove that the aviation industry is one of the most affected sectors of the pandemic and is expected to be one of the last to recover from the effects.

The pandemic has the potential to change the face of aviation, but the vision of zero-emission air transport remains unaffected.

Now is the time to set the course for a successful energy turnaround in aviation. To this end, this document lists the current state of research, the research and technology needs and recommendations for action.

STATEMENTS

The DLR has been researching technologies for sustainable aviation for many years. Our results are technologies at a pre-competitive maturity level, while the transfer into market-ready products takes place in industry. This White Paper summarises today's state of knowledge for a "Green Deal" of tomorrow's aviation. It not only contains our research view, but also the view of feasibility through cooperation with companies in the BDLI. I am very pleased that together we have succeeded in making such a comprehensive document available to policymakers. In Germany, aviation research is strongly supported by politics: at the regional level through state initiatives, at the national level through the Aeronautics Research Programmes and the DLR's funding, and at the international level through participation in EU funding programmes. In this respect, this White Paper is also a result of this support. The DLR is ready to implement as much of it as possible with our industrial partners for a "Zero Emission Aviation – ZEMA".

Prof. Rolf Henke
DLR Executive Board

We want the aircraft of the future to be built in Germany and Europe. As an innovative industrial nation, we want to be the pioneer of climate-neutral flying. Germany has a strong research network with excellent facilities that will work with industry to create the technological foundations for climate-neutral flying. For this reason, the BDLI and the DLR have jointly produced a White Paper that outlines the technologies essential for our future of climate-neutral flying. Now it is a matter of implementing them in close cooperation between research, politics and industry. After all, the energy turnaround in the skies can only succeed with the efforts of society as a whole.

Reiner Winkler
BDLI Vice President Aviation

SUMMARY

The path to climate-neutral aviation requires radical technologies in all areas. In addition to revolutionary aircraft and propulsion concepts, synthetic fuels and flight guidance play a central role. The successful introduction of such concepts requires transdisciplinary research into technological, operational and economic factors. So far, there is no overview of the current state of research in the various research disciplines. For this reason, the German Aerospace Center (DLR) and the German Aerospace Industries Association (BDLI) have brought together the current research and the current technological fields of action, thereby pointing the way to emission-free aviation and supporting the technology strategies of research, industry and politics.

Global aviation is responsible for about 2.5% of man-made CO_2 emissions and further contributes to global warming through its non-CO_2 effects. In addition, the increase in air traffic volume further exacerbates the situation. The central challenge is therefore to minimise the consequences for people and the environment. The interaction of all factors has not yet been sufficiently researched and must be better understood as a basis for decision-making by industry and politics.

The evolutionary further development of gas turbine concepts in combination with synthetic fuels already allows for significantly reduced emissions in air traffic in the short term. Drop-in fuels require no engine modifications and can already reduce CO_2 emissions by 40% today. In addition, new fuel designs can prevent 50-70% of soot and particle emissions. The effects of drop-in fuels can be maximised by allowing higher blending rates of more than 50%. Obstacles to large-scale introduction are currently production capacity and price. Near-drop-in fuels can reduce CO_2 emissions by up to 80%, soot and particulate emissions by up to 90% and NO_x emissions by almost 100% when co-optimising fuel and burner.

Further improvements are possible by using non-drop-in fuels such as hydrogen, which can reduce local emissions of CO_2, soot and aerosol precursors to zero. However, the climate impact benefits of hydrogen are highly dependent on the production path. Therefore, the only way to reduce CO_2 emissions is to use hydrogen produced from renewable sources. In addition to technical developments, sustainable production paths must be developed and promoted.

Revolutionary heat engine concepts have the potential to be virtually emission-free. They can be operated with drop-in fuels in conventional aircraft as well as with hydrogen in new types of aircraft. Nevertheless, the climate impact of such propulsion concepts is still not fully understood today. Further research and technology development are needed to obtain a clear picture.

Electric propulsion systems are currently the only known alternative that does not produce emissions from aircraft.

Aircraft with battery electric propulsion are completely emission-free in operation. However, due to the low energy density of current battery technologies they only allow a relatively short range of about 300 km. This makes these aircraft particularly suitable for urban air mobility and for travel within conurbations or as feeder aircraft. By combining different energy storage systems in hybrid propulsion systems, the range can be significantly increased. Turbo-hybrid electric drive systems with alternative fuels thus allow emission-free battery-powered operation at the airport and, at the same time, at least CO_2-neutral operation in cruising flight. From today's perspective, the fuel cell in combination with green hydrogen has the potential to provide sufficient power and range for commercial aviation in the long term. This would enable largely emission-free air traffic. Current results show that a pure hydrogen fuel cell aircraft should be feasible.

Since the technological maturity of alternative propulsion solutions for aviation is still very low, there is a great need for research in numerous areas: the power and energy density of all components in the system must be increased; solutions for efficient hydrogen storage must be found; in the field of fuel cells, heat management must be optimised and a revolutionary cooling technology must be developed; the potential of emission-reducing structures is still not exhausted. Furthermore, the effects of new propulsion systems on the entire aircraft must be investigated and the current airport infrastructure must be taken into account. To answer these questions, numerical analyses as well as systematic experimental and real flight tests with suitable demonstrators are necessary.

The development of certifiable technologies for climate-neutral (long-range) aircraft is possible by 2040. The market penetration up to complete fleet renewal requires enormous industrial efforts.

While the introduction of new technologies for the world's aircraft fleet is a lengthy process, new operational measures such as the implementation of climate-friendly routing could be applied to a significant part of the fleet in a very short time. Studies by the DLR show that even small changes in flight guidance with only a 1% increase in operating costs can reduce the impact on the climate by up to 10%.

Yet to achieve the goal of climate-neutral air traffic the economic aircraft life cycle must not be ignored: aspects such as automated production processes, digitalisation in aviation, the linking of concept, design and production as well as maintenance data play an essential role in the development and introduction of new products. A climate-neutral aircraft must be put into the operational context. Possibly increased costs could be compensated by a unique travel experience. The necessary technologies must also be developed.

The goal of emission-free aviation can only be achieved through close cooperation between the network of industry, politics and science as well as funding at regional level, through the aviation research programme and other measures at national and EU level.

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INTRODUCTION

1

With regard to the global growth of air traffic, the most important task for research and industry is to significantly reduce the ecological footprint of air transport. Aviation is still responsible for only 2.5% of global anthropogenic CO_2 emissions. If the effects of non-CO_2 emissions such as water vapour and nitrogen oxide are added, the impact of air traffic on global warming increases to around 5%. The vision for the future of aviation is the Zero Emission Aircraft – an aircraft that emits no pollutants in both flight and ground operations. This ambitious goal requires substantial research and development in the areas of sustainable fuels, energy sources, new aircraft concepts and components, and alternative propulsion concepts.

Sustainable fuels represent a great potential because, as well as reducing CO_2 emissions, they reduce pollutants such as soot. In addition to synthetic fuels, the use of hydrogen produced from renewable sources is very promising. The currently low production capacity, the high production price and further technological improvements still represent an obstacle to replacing conventional kerosene with 100% sustainable fuels. However, the high demands on the future air transport system not only require the further development of existing technologies, but also call for completely new approaches to minimise the negative environmental impact. Electric flight, with batteries or fuel cells, offers a fundamental opportunity to fulfil the increasing mobility requirements with minimal climate impact. However, the low level of maturity of the technologies requires a wide range of investments in development, production, approval and infrastructure.

Sufficient production capacities for Sustainable Aviation Fuel (SAF) are not currently available in Germany or in Europe. In order to increase SAF production capacity to an effective and economical level, a clear political framework is just as essential as effective promotional instruments, especially for the producers of alternative fuels.

The distinction is currently made between three categories:

1. drop-in fuels that are compatible with the current infrastructure

2. near-drop-in fuels requiring minor modifications in the aircraft

3. non-drop-in fuels requiring significant modification of the aircraft

This shows that the future focus must be on modular and multifunctional structures, as different applications with different fuel solutions are possible with regard to new mobility concepts.

The successful development and introduction of new technologies will change tomorrow's aviation. Unmanned prototype aircraft allow a glimpse into the urban air mobility of the future. The first applications of unmanned aircraft will be to supply poorly connected areas and deliver urgently needed goods such as medicines, as well as to support emergency services in disaster relief. Unmanned autonomous flying is also seen as a solution for fast, low-emission passenger transport in urban areas or between cities. While battery-electric regional aircraft will soon be used for travel within conurbations or to the nearest major airport, aircraft with propulsion concepts based on fuel cells will in future replace today's short- and medium-haul aircraft. On long-haul routes, new gas turbine concepts in combination with sustainable fuels will represent an important technology in the coming years. In the long term, hydrogen will play an increasingly important role, as it has a high energy density and can be produced from renewable energies. However, the use of turbo-hybrid electric propulsion concepts and a fuel cell drive system are also conceivable in the long run. Depending on the combination of energy source and propulsion concept, all concepts promise a longer range compared to battery-powered aircraft.

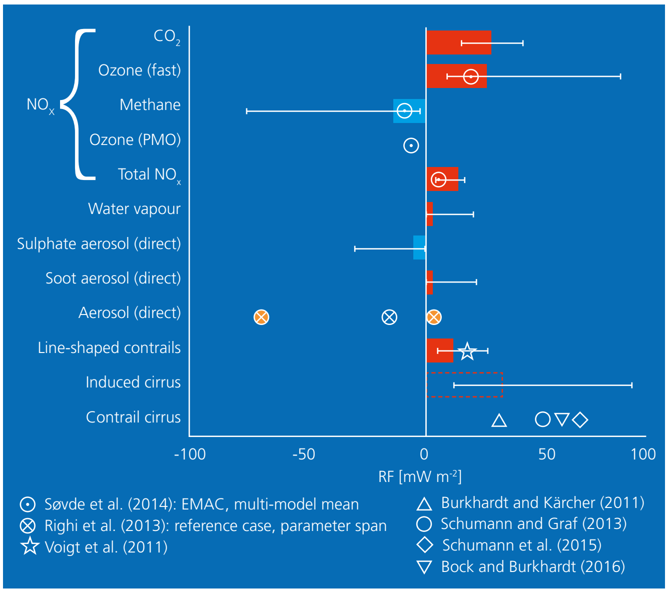
New mobility, propulsion and fuel concepts require new and efficient aeronautical structures and the associated digital methods. Tomorrow's aviation structure must be modular and flexible enough to serve a much broader spectrum of mobility than it does today.

In order to be able to comprehensively evaluate the technologies described above, a cross-disciplinary ability to design and evaluate the overall system is necessary, which the German aviation landscape should definitely rebuild, maintain and consistently develop further. Essential research is needed in component development, the integration of components into the aircraft, and to understand the effects of all aspects on aircraft level and the overall aviation system. Flight tests are necessary for the further development of technologies and safety requirements. To this end, the aviation landscape and politics should facilitate investments for a targeted demonstrator programme that paves the way for the emission-free air transport of tomorrow.

FUTURE DEMANDS ON AVIATION

2

Measurements show that the climate is changing, and that global air traffic contributes to the climate impact through its pollutant emissions. However, the influences of the different types of emissions are not yet fully understood in order to adequately address the challenge of "environmental protection in air traffic".



Radiative forcing due to CO_2 emissions and the non-CO_2 effects of aviation. The symbols are based on a selection of recent work.

2.1.
INFLUENCE OF AIR TRAFFIC ON CLIMATE

Air traffic was responsible for around 2.5% of global anthropogenic CO2 emissions in 2018. According to the International Civil Aviation Organization (ICAO), this figure could double in the coming decades up to 2050. The impact of emissions on global warming is described by radiative forcing, i.e., the change in the overall energy balance of the planet, which ultimately influences the change in temperature. Positive radiative forcing results in warming, negative in cooling. Human-induced CO_2, including that from air traffic, causes positive radiative forcing and thus leads to a warming of the earth.

In addition to CO_2, a number of other emissions from air traffic also contribute to a change in the radiation balance and thus contribute to climate change. The main contributors are water vapour, nitrogen oxide emissions, direct and indirect aerosol effects and contrails. These non-CO_2 effects were already discussed in the 1980s and 1990s and summarised in a special report of the International Panel on Climate Change (IPCC, Aviation and the Global Atmosphere) in 1999. It was estimated that the total radiative forcing of air traffic for the scenarios examined there was between two and four times higher than that of CO_2 emissions alone. Although the existence and effects of such emissions have been recognised, their quantification has thus far only been possible with great uncertainty due to the many complex non-linear processes involved. So far it is clear that the largest contribution by far comes from cruising flight.

“There is a great need for research into the climate impact of different types of emissions – especially the effect of water vapour“.

CARBON DIOXIDE (CO_2)

CO_2 is the largest component of aircraft emissions. The gas mixes almost homogeneously in the atmosphere with the same direct warming effect that occurs when it is emitted from other fossil fuel combustion sources. The fuel consumption produces CO_2 in a ratio of 3.15 kg of CO_2 per 1 kg of fuel consumption, regardless of the flight phase. Due to its extended lifetime in the atmosphere, CO_2 is particularly effective as a greenhouse gas. After emitting a certain amount of the gas, about half of it is removed from the atmosphere over 30 years, another 25% disappears within a few hundred years and the remaining 25% is still in the atmosphere after a thousand years and is removed very slowly.

WATER VAPOUR (H_2O)

The main reaction product from the combustion of hydrocarbons such as kerosene is water vapour (H_2O) – analogous to combustion processes in other sectors such as road traffic and shipping. However, a large proportion of H_2O is emitted by air traffic at cruising altitude, i.e., between eight- and thirteen-kilometers altitude. There, the natural background concentration of water vapour is several orders of magnitude lower than at ground level and the atmospheric lifetime of H_2O is significantly longer. At the same time, however, its lifetime of a few days to a few weeks is too low to allow a homogeneous distribution (horizontally and vertically) of the additional H_2O. Therefore, air traffic makes a noticeable contribution to the local total concentration of H_2O. Similar to CO_2, H_2O acts in the long-wave part of the radiation, i.e., the thermal radiation of the earth. The size of the radiative forcing depends on the temperature difference between the ground and the altitude at which the substance is located. At cruising altitude, the atmosphere is particularly cold and therefore the radiative forcing is particularly high.

The additional water vapour caused by air traffic leads to a warming of the atmosphere. Due to the strong local dependency of H_2O in terms of radiative forcing, there is potential for optimisation through flight guidance. There is also a need for research on its influence on clouds.

NITROGEN OXIDES (NO_X)

As an undesirable by-product of combustion, nitrogen oxides (NO_X) are also produced during combustion due to the oxidation of nitrogen from the air. The NO_X emissions affect the temperature of the earth in reaction with a large number of other hydrocarbons in the atmosphere. The primarily generated ozone (O_3) has an atmospheric lifetime of two to eight weeks and is therefore not homogeneously distributed in the atmosphere. It causes a warming of the atmosphere, especially in the long-wave part of the radiation. This effect should not be confused with the effect of the so-called ozone hole via the UV part of the radiation, which is associated with cancer. A side effect of the above-mentioned O_3 production is the decomposition of methane (CH_4) in the atmosphere and consequently a reduction of the natural O_3 production as well as a reduced formation of stratospheric water vapour. The time scales of these processes are in the range of 10 years and they lead to a slight cooling of the earth. However, if one considers all the processes mentioned here, which are originally based on the NO_X emissions of air traffic, they all together lead to a warming of the earth.

CONTRAILS

Under suitable thermodynamic conditions, the water vapour emissions of air traffic lead to the formation of linear condensation trails, which grow into linear clouds and form so-called contrails, which can hardly be distinguished from natural cirrus clouds. The lifetime of

such clouds ranges from a few minutes to several hours. Depending on their properties and the radiation conditions, these anthropogenic clouds have a warming or cooling effect in individual cases. Averaged over the globe and throughout the day, contrails and cirrus clouds are currently warming the earth. The associated radiative forcing is greater than that from CO_2 alone. Due to the strong dependence of the effect on local conditions, this emission also offers the potential to be reduced by optimising flight routes.

There is still need for research, especially with regard to the predictive capability of contrails from hydrogen-powered aircraft.

DIRECT AND INDIRECT AEROSOL EFFECTS

Air traffic emits both aerosols, such as soot, and aerosol precursors, such as nitrogen and sulphur compounds, from which aerosols are formed. These have a lifetime of days to weeks. Depending on the type, they have a cooling effect (e.g. aerosols containing sulphate) or a warming effect (e.g. soot). Their overall contributions to climate change are small. However, aerosols introduced into the atmosphere in this way can develop into cloud condensation nuclei in the atmosphere. They then influence "natural" clouds. If there are more condensation nuclei, there are more cloud droplets and crystals, but they are smaller. Thus, clouds become more durable and reflect more solar radiation. In addition, condensation nuclei can be transported far and only allow the formation of new clouds once the appropriate background conditions are available.

With regard to the effect of the condensation nuclei from air traffic, there are only initial estimates. Presumably, the sunken condensation nuclei modify low (warm) water clouds in such a way that a cooling effect is produced. Because of the inexact knowledge of the processes the aerosols undergo, the estimates of the associated radiative forcing are known at best to a factor of ten. No reliable statements can yet be made for higher lying ice clouds. For this reason, the indirect aerosol effects of air traffic are currently not generally taken into account in the overall assessment of its climate impact. Better measurements and models of these effects are therefore needed.

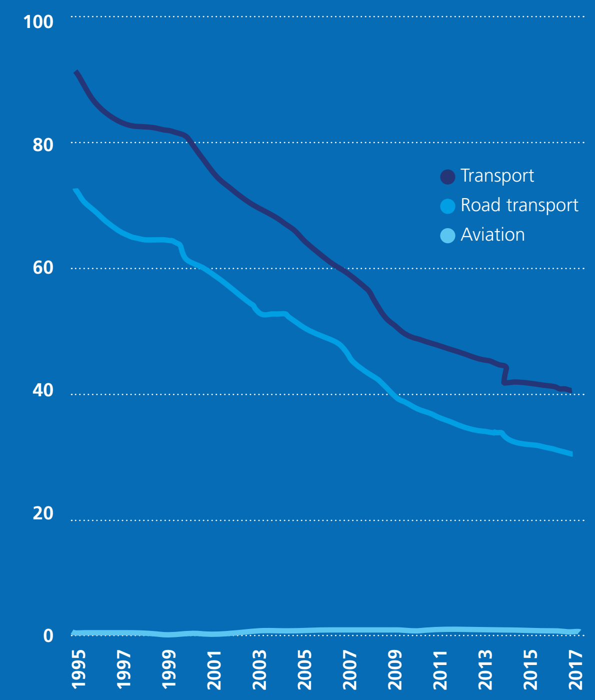
2.2.
AIR AND GROUND POLLUTION CONTROL AND ENVIRONMENTAL ASPECTS

In addition to its effects on the climate, air traffic also has an impact on the local air quality at airports and their surroundings. In this context, the ultra-fine particles with a diameter smaller than 100 nm, which also play a role in road traffic, are the focus of attention. This is due to the expected toxicological properties of the released particles. Although there is no final evaluation in this respect, the particles emitted by aircraft engines and Auxiliary Power Units (APUs) are able to penetrate deep into the human lung given their size of less than 30 nm. The ultra-fine particles have not yet been recorded in regular environmental monitoring and there are no binding measurement standards as yet.

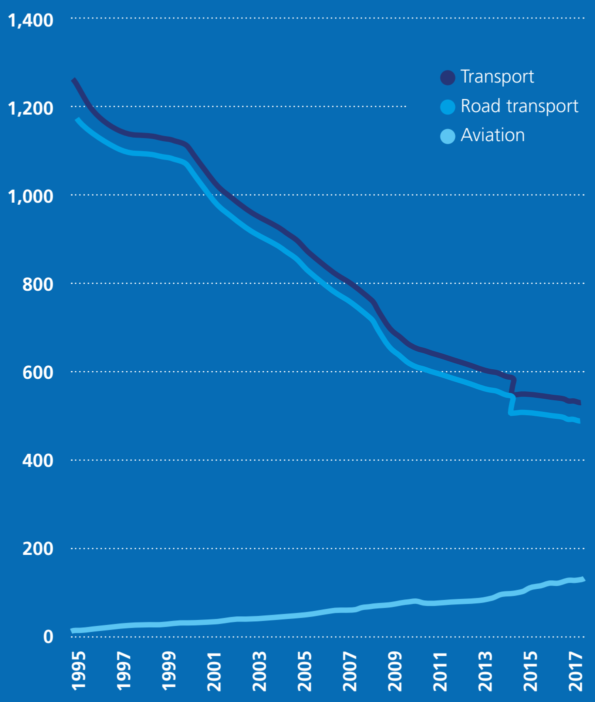
Due to the emission certification of engines, recently also with regard to ultra-fine particle emissions, it can be assumed that the available data for future environmental and dispersion modelling at airports will improve, but these particles are viewed differently in environmental and certification measurements. While environmental analysis always covers the entirety of all airborne particles, certification test bench measurements focus on the fraction of non-evapourable par-

DEVELOPMENT OF EMISSIONS 1990-2017 FOR TYPICAL AIR POLLUTANTS

Emission trends for Germany since 1995, PM10 in kt



Emission trends for Germany since 1995, NO_x in kt



ticles. This fraction of the particles can be demonstrably reduced to a considerable extent directly by modern engine technologies and alternative fuels. However, secondary particles that only form in the aging exhaust gas, for example, from the emitted sulphur and nitrogen compounds, are also observed in high concentrations. Low-sulphur or sulphur-free fuels are promising options to reduce the amount of these particles, thereby improving the local air quality at airports. In comparison with other sources of particulate matter, aviation accounts for only a smaller share of these emissions, at around 1%.

Currently, the limits for nitrogen oxides in the vicinity of the airport are not yet exceeded. However, if limit and guideline values for ultra-fine particles are included in the pollutant assessment in the future or if the limit values are further restricted, there is a risk that they will be exceeded. Proactive measures should therefore be taken with regard to both measurement standards and further emission reduction.

2.3.
NOISE

The noise emission of today's commercial aircraft is largely caused during take-off by the turbofan and turboprop propulsion systems, and also during landing by airflow noise on the aircraft such as flaps and landing gear. In addition, noise sources are caused by the aerodynamic interaction of components. A rather minor proportion of aircraft noise comes from the core engine, which provides the power for the actual propulsion by means of a gas turbine. In addition to its pure noise level, the perception of this aircraft noise is significantly influenced by other properties such as the frequency spectrum and its temporal course. For example, an isolated sound is much more disturbing than a uniform noise. The same applies to strongly changing noise levels. Overall, aircraft noise reduces the acceptance of air traffic in the vicinity of airports by the residents living near them, which leads to the introduction of operational restrictions such as night flight bans. Possible noise reduction measures include lower fan-tip speeds, shielding or distributed propulsion.

“If all potentials are exploited, climate-neutral aviation will be within reach.“

CURRENT NEED FOR ACTION

At the Paris Climate Change Conference in December 2015, 195 countries agreed for the first time on a legally binding global climate protection agreement. The states agreed to limit the increase of global average temperature to less than 2° C by substantially reducing emissions in order to significantly reduce the consequences of climate change. As described, emissions caused by aviation have a harmful effect in several respects and must therefore be reduced as a matter of urgency. A mere consideration of CO_2 emissions is not enough. Examples such as the round-the-world flight of the solar airplane SolarImpulse or the first electric aircraft products in niches such as training planes show that completely emission-free aircraft are possible in principle. For larger aircraft, an emission-free or even emission-neutral solution is extremely difficult to realise as long as hydrocarbons are used for energy generation, since they always produce CO_2 and H_2O. However, if all potentials are exploited, climate-neutral aviation will be within reach, in which emissions are largely reduced and their effect on the atmosphere is greatly diminished by climate-optimised flight guidance.

In conjunction with the increasing growth of air traffic, the central challenge will be to decouple growth from its consequences for people and the environment. This goal is pursued by a research policy of the least environmental impact – "least impact aviation". Aviation research is investigating promising technological and operational options for this approach, which are presented and explained below. In addition to combustion-based concepts such as alternative fuels and hydrogen in combination with new gas turbine concepts, the focus is on (hybrid) electric propulsion systems, research into and the use of noise-reducing materials and structures in the aviation sector, and the requirements for a future infrastructure. In addition, innovative concepts of flight guidance are considered. All aspects have an impact on aircraft level and bring about different requirements for the configuration of an aircraft.

COMBUSTION-BASED CONCEPTS

3

Current aircraft engines for commercial aviation are almost exclusively based on the combustion of kerosene in gas turbines. This principle has proven its worth due to its high specific power output, its high efficiency and its compact and lightweight design. However, fuels are always burned and thus the above-mentioned emissions are emitted. Possible ways to reduce these emissions are a further increase in the efficiency of gas turbines, the introduction of new gas turbine cycle processes with reduced pollutant emissions and climate impact, and the use of sustainable fuels such as synthetic kerosene or hydrogen.

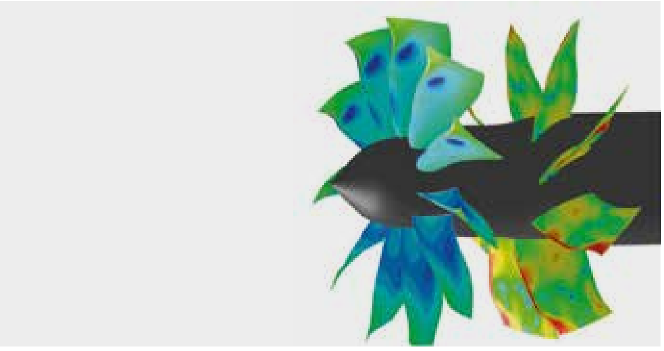
3.1.

EFFICIENCY OPTIMISATION OF CONVENTIONAL GAS TURBINE PROPULSION

With the introduction in commercial aviation of the first jet engines based on gas turbines in the 1960s, air transport has developed into a means of mass transportation with more than 4 billion passengers in 2017. Since then, the specific consumption of the gas turbine has almost been halved.

This has primarily been achieved through higher bypass ratios (from ~1 to 12 today), which improve propulsion efficiency, higher overall pressure ratios (from ~15 to 50 today) and turbine inlet temperatures, which increase thermal efficiency. Further improvements were achieved by increasing the efficiency of all components, optimising the installation or using lightweight materials.

The most important new development in the field of aircraft engines in recent decades is the geared turbofan engine, which Pratt & Whitney developed in collaboration with MTU. In contrast to the conventional turbofan, where the fan and low-pressure turbine rotate on a single shaft at the same speed, the geared turbofan engine has a gearbox



The virtual engine enables a highly accurate design capability connecting the two components. This allows the large fan to rotate more slowly and the low-pressure turbine to rotate faster. This enables high bypass ratios (>12) for high propulsion efficiency and improves the efficiency of the fan and low-pressure turbine, so that fuel consumption and hence carbon dioxide and noise emissions are significantly reduced. In addition, propulsion becomes easier, since fewer stages are required in the low-pressure turbine and low-pressure compressor. Current studies show that further improvements are possible on the basis of the geared turbofan engine. For example, the propulsion efficiency is to be further improved by higher bypass ratios (up to 20) and the thermal efficiency by higher temperatures and pressure ratios (up to 70). The results of the currently completed EU technology programmes of the 7th Framework Programme show that further developments of the geared turbofan engine can reduce fuel consumption by 25%-36%, depending on the application, compared to an engine built in 2000.

The geared turbofan engine will therefore be the standard engine in commercial aviation for decades to come. The necessary technologies, such as integrated compression and expansion systems or high-temperature lightweight materials, are currently being developed for the next generation of the geared turbofan engine. Concepts such as blisks and lightweight construction fans (CFRP fan) and production processes such as 3D printing offer further potential for optimisation.

This shows that the potential for creating emission-reducing structures is far from exhausted. The integration of various functions into the structure creates considerable lightweight construction potential and opportunities to reduce weight and production costs, since integral, multifunctional structures allow process steps and the number of components to be optimised. This is supported by the digital representation of the structure (digital twin).

3.2.

EFFICIENCY OPTIMISATION THROUGH NEW THERMAL TURBOMACHINERY

The further increase in the total pressure ratio and turbine inlet temperature is progressively reaching its limits. Higher temperatures are limited by the permissible material temperatures, which cannot be compensated even by larger cooling air volumes, and higher pressure-ratios lead to very small blade heights in the final compressor stages and thus to poor efficiencies.

Various national and European research programmes are therefore investigating options for overcoming these limitations. The following ideas appear promising:

- The cooling of the compressed air between the low-pressure and high-pressure compressor by an intercooler, together with higher overall pressure ratios, improves the thermal efficiency.
- The gas turbine with intercooler and exhaust gas heat exchanger goes one step further. Here, the energy that is dissipated to the environment with the turbine exhaust gas is used to heat the compressed air between the compressor outlet and the combustion chamber inlet by means of an exhaust gas heat exchanger. This reduces the necessary fuel supply in the combustion chamber and increases the thermal efficiency.
- The energy in the exhaust gas is also used by so-called bottoming processes, which feed the exhaust gas energy of the primary gas turbine to an additional heat engine such as a steam power process, which generates additional power. Stationary gas turbines achieve extremely high efficiencies with this principle, but cannot be used in aviation because of the large installation space required. One possible modification would be the "Water Enhanced Turbo

> *"DLR proved that alternative fuels reduce CO_2 emissions up to 40% and non-CO_2 emissions up to 70%".*

fan (WET)" process being developed by MTU. It also uses the turbine of the gas turbine process for the steam power process by injecting steam into the gas turbine combustion chamber. The required water is separated directly from the turbine exhaust gas. Wet combustion also reduces NO_x emissions and the formation of condensation trails is likely to be greatly reduced by the condensation of water in the exhaust gas. The greatest challenge for this propulsion concept is the design of condensers and steam generators that can be integrated into the aircraft.

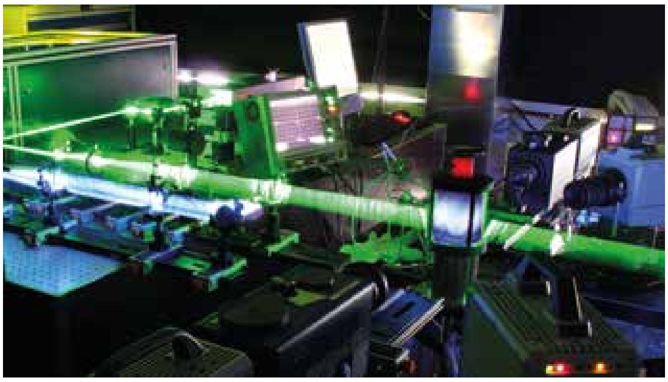
- There are various ways to further increase the pressure, such as the use of a piston engine, "pulse detonation" (explosive combustion with pressure increase) or the principle of the "wave rotor" (pressure increase through pressure waves). In this way, combustion could be transferred to a free-piston engine, which increases the pressure via a free-piston compressor. Since combustion is not continuous here, the increased pressures and temperatures are acceptable for the material. The greatest challenge is the increased NO_x emissions due to the high temperatures and the coupling of the continuous turbine process with the discontinuous piston process.
- A promising candidate in the field of combustion chambers is the FLOX burner for gas turbines. Although it was originally developed for industrial purposes, it is currently being adapted for aerospace applications by the DLR together with industrial partners. In this process, fuel, air and exhaust gas are strongly mixed before they are used in combustion to avoid local temperature peaks in the flame and NO_x formation. Further advantages beyond the lower emissions are high stability and great fuel flexibility.

3.3.

COMBUSTION OF HYDROGEN IN THE GAS TURBINE

The use of hydrogen in gas turbines is not new and it is possible without fundamental changes to the overall system. Especially in the field of stationary gas turbines, manufacturers are preparing for the use of hydrogen as an energy source and plan to be able to offer their product portfolio for 100% hydrogen by 2030.

The greatest need for development in gas turbines is in the area of the combustion chamber. Here, the challenge is to use hydrogen safely and stably with the lowest possible NO_x emissions and under the very wide operating conditions in the aircraft gas turbine. Due to an extended stability range when using hydrogen, combustion can be operated under leaner conditions. This reduces the flame temperature and is therefore advantageous with regard to thermal NO_x production, so that with suitable burner technologies, very low NO_x-combustion is also possible in hydrogen operation. Due to its high reactivity, but also due to the complex pressure dependence of its ignition behaviour, hydrogen is not easily usable in conventional combustion systems. Therefore, there is still a considerable need for development in the area of novel combustion chamber technologies that enable low-emission, flashback-resistant combustion of hydrogen. However, with sufficient development efforts NO_x emissions can be reduced to such an extent that they no longer have a demonstrable effect on the climate. Furthermore, the use of hydrogen changes the composition of the exhaust gas. The higher proportion of water leads to different heat transfer at components, thus making it necessary to adapt the cooling concepts.



Hydrogen feed-in combustion at the DLR in Stuttgart

Aircraft with high range requirements such as medium- and long-range aircraft require a correspondingly large volume to accommodate the liquid hydrogen. As a result, performance losses are to be expected due to the greater aerodynamic resistance and the higher structural mass. The effects on the components of a large amount of water vapour in connection with combustion processes are still unclear today. In this context, it makes sense to develop different fuel alternatives depending on the mobility concept.

Depending on the fuel price scenario and range, fuel costs represent ~20-50% of the direct operating costs. The conventional technology improvements in terms of engine efficiency, aerodynamic quality and structural lightweight design will gain in importance due to the limited and expensive production possibilities of synthetic fuels. Therefore, the design of an efficient aircraft with regard to propulsion, aerodynamics, lightweight construction and flight control remains of great importance. In this respect, traditional aviation must transform itself in order to adequately meet the challenges of tomorrow's aviation.

3.4.
USE OF SUSTAINABLE FUELS

The energy source is of extraordinary importance in aviation, since the energy requirement is extremely high, but at the same time both the available volume and the mass of fuel to be carried are limited. In addition, safety is a top priority. All three points are currently fulfilled by conventional kerosene as a highly specialised, safe and cost-effective product. In addition, the energy source is of great importance for the emissions produced. A distinction must be made between local emissions from the aircraft and emissions over the entire life cycle. This concerns both the effect of CO_2 on the climate and the non-CO_2 effects described above. There is a lack of uniform sustainability criteria for a well-founded assessment of the benefits of sustainable fuels. These should, for example, define the system boundaries and specify how the various emissions are to be measured.

HYDROCARBON-BASED FUELS

In order to be able to continue using existing aircraft and infrastructure, the drop-in concept was introduced in the certification for sustainable aviation fuels. These are approved mixtures of synthetic and conventional fuels. They can already be used in all aircraft and infrastructures without restriction or modification exactly like conventional fuels. Currently, up to 50% admixture with conventional kerosene is permitted. Over its entire life cycle, pure synthetic kerosene can reduce CO_2 emissions by 80% compared to fossil kerosene, if the ecological footprint of the manufacturing plant itself is adequate.

Projects conducted by the German Aerospace Center (DLR) such as ECLIF (Emission and CLimate Impact of alternative Fuel) or airegEM demonstrate the fundamental potential of alternative drop-in fuels to reduce emissions. For example, a 50% admixture can reduce CO_2 emissions by 40%. In addition, 50-70% of soot and particle emissions could be avoided by designing the synthetic fuel accordingly. The use of largely aliphatic hydrocarbons is expected to result in an additional reduction. Together with an optimisation of the burner, a complete avoidance of NO_x emissions can also be expected.

Alternative drop-in fuels are already used on commercial flights today. However, the quantities are still at less than 1% of global aviation fuel consumption. In Europe, alternative fuel is already being used exclusively in Oslo. In-depth scientific monitoring of the usability and the corresponding reduction of emissions was, for instance, demonstrated in the BMVI project DEMO-SPK (research and demonstration project on renewable kerosene).

The current obstacles to large-scale introduction are production capacity and price. This is not yet available in sufficient quantities, as there is no demand or market certainty. According to aireg – Aviation Initiative for Renewable Energy in Germany eV, the expectation is that, based on forecasts from the USA and Asia, an increase in production will drive the price of alternative fuels down to a factor of 2 as compared to fossil kerosene (depending on the development of crude oil prices – their price being significantly higher today).

Quotas for alternative fuels are currently being discussed; in Norway, for example, a quota of 0.5% already applies. Here in Germany, aireg is calling for the introduction of a state-mandated quota for the use of sustainable aviation fuels. This would provide the necessary investment certainty for producers and pave the way for airlines to achieve the ambitious climate targets by 2050. An expansion path for large-scale production, including continuous technological improvement and the associated cost reduction, does not yet exist. It depends largely on political measures for market certainty and the financing of production units and technology development.

In addition, production requires resources such as land, water, renewable energy, carbon sources and capital. In particular, the calculated demand for renewably generated electrical energy far exceeds the current expansion path for Germany's energy turnaround. The carbon source used also influences the amount of renewable energy needed. The widely used Fischer-Tropsch process primarily uses industrial carbon monoxide CO from steel or cement production, for example. In pursuit of the Paris climate targets, however, these processes produce less and less CO. Other processes use used fats or other biomass instead and thus require more land that is no longer available for agriculture. The direct use of CO_2 from air in the "Direct Air Capture" (DAC) process requires a lot of additional electrical energy. It is clear that, for reasons of flexibility, there must and will be a mix of different production processes with a broad spectrum of raw materials. Projects such as EU H2020 JETSCREEN and the US High Performance Fuels Program are trying to reduce these costs and the risk of failure during the approval process.

The effects of drop-in fuels can ultimately be directly maximised by higher blending rates of more than 50%. So-called aromatics-free near-drop-in fuels are ideal for minimising the climate impact. These differ from drop-in fuels in that they may require minor modifications to aircraft, infrastructure or operations (for example, use only in suitable aircraft). However, they offer greater potential for optimisation and thus for reducing emissions. There is currently no certification for such fuels. Near-drop-in fuels are a research goal in the DLR cross-sectional project Future Fuels. By co-optimising fuel and burner, CO_2 emissions can be reduced by up to 80%, soot and particle emissions by up to 90% and NO_x emissions by almost 100%. Boeing has already demonstrated in March 2017 that 100% aromatics-free fuels from biomass can be used in a Boeing 777F. Sustainable synthetic kerosene can be produced in a potentially climate-neutral way with defined properties such as density and energy density. Due to its similarity to fossil fuels, this energy source has therefore no direct impact on the overall aircraft configuration. Today, however, the availability of this energy source in large quantities is still a challenge.

In the ECLIF project, the DLR and NASA investigated the effects of alternative fuels on the environment

USE OF HYDROGEN AS A SUSTAINABLE FUEL

The use of hydrogen in gas turbines combines several advantages. For example, local emissions of CO_2, soot and aerosol precursors can be reduced to zero. In addition, hydrogen can already be produced CO_2-neutrally by electrolysis with regenerative electricity. Processes such as alkali electrolysis are available as a mature technology on an industrial scale. In addition, processes such as the solid oxide electrolysis cell (SOEC) still offer considerable potential for the future.

In order to evaluate CO_2 emissions over the entire life cycle, the CRYOPLANE2 project carried out a complete life cycle analysis for different fuels in an aircraft the size of an Airbus A319. As a result, the use of hydrogen showed a reduction of CO_2 emissions of more than 90% when produced from renewable energies.

Measurements of exhaust gases on the ground and the control station for measurements on the apron of Ramstein Airport

To achieve CO_2 reduction, it only makes sense to use hydrogen produced from renewable sources such as electrolysis or biomass, so-called green hydrogen. According to an IEA report (2019), the majority of the hydrogen produced annually worldwide (about 75%) of about 70 million tonnes is currently still produced as so-called grey hydrogen from natural gas. Although these processes use fossil energy sources, they already offer the possibility of capturing and storing CO_2 at the place of hydrogen production. This would already make CO_2-neutral use of hydrogen feasible today.

In the meantime, several hydrogen production processes have been developed to series production readiness:

- Steam reformers (natural gas)
- Partial oxidation (oil gasification)
- Autothermal reformers (methanol reforming)
- Kværner procedure
- Electrolysis of water
- Biomass (gasification, fermentation)
- Hydrogen from green algae

If hydrogen is to be used on a large scale for energy generation or storage in the sense of a hydrogen energy economy, production from fossil raw materials is no longer sensible. The first four processes in the above list make fundamental use of fossil raw materials.

There are various options for storing hydrogen on board the aircraft: storage as compressed gas requires pressure tanks and currently has gravimetric storage densities of <5%, which are only suitable for small amounts of energy and therefore only for small aircraft. In commercial aviation, the best possible tank volume and weight (gravimetric storage density >5%) can currently only be achieved with hydrogen in liquefied form. Therefore, the tank (-252°C) has to be insulated. However, this requires a new aircraft architecture. The large volume required to store the hydrogen has to be considered in the configuration. This increases the surface area of the entire aircraft that is flushed around the tank, resulting in increased aerodynamic drag and reduced aerodynamic efficiency. The operating empty mass is also strongly influenced by hydrogen tanks, so that the flight performance also depends on them. In order to maximise flight performance, radical lightweight system design is necessary and possibilities to design tanks as a supporting structure are to be investigated. Due to the high operating empty mass, the efficiency is particularly important. The effects of the use of hydrogen on aircraft design are considered in Chapter 6, the requirements for an infrastructure are listed in Chapter 5.3.

“The goal is to replace today's kerosene with 100% sustainable fuels such as green hydrogen.“

CURRENT NEED FOR ACTION

In order to achieve the goal of replacing kerosene with 100% sustainable fuels, the following research is required:

- Further development of gas turbines.
- Technology development for new thermal turbomachines.
- Reliable methods for fuel evaluation and aircraft component design are required. Further research projects are needed for the precise comprehensive identification of the relationships between fuel composition and aircraft.
- The development of fuel sensitive methods for the design of fuel optimised aircraft components, such as combustion chambers, is necessary.
- Fuel effects are very complex and affect various disciplines and industries. The development of a digital platform for interdisciplinary cooperation is necessary for the comprehensive evaluation and optimisation of fuel aircraft systems
- The potential introduction of a new class of fuels has a variety of impacts worldwide. For the implementation of near-drop-in fuels, a strategy of action agreed upon with the stakeholders must be designed and implemented.
- The climate impact benefits of hydrogen are strongly dependent on the production path. Global demand for hydrogen is currently primarily produced from fossil fuels. Therefore, clean production pathways must be further developed and promoted.
- The properties of contrails resulting from the use of hydrogen in gas turbines must be reliably determined, including the size of the ice particles produced (influences the lifetime of the contrails) and the optical properties (influences the radiation effect). The effect can be reduced by suitable flight guidance.
- Hydrogen combustion requires modifications at aircraft and engine level, as the tanks have to be well insulated. Tank volume and weight make lightweight system design necessary. Such aspects must be considered in context to develop an optimal design.
- Differentiation of new demand-oriented mobility concepts and the associated climate-friendly aviation structures, propulsion concepts and fuel solutions.

ELECTRICAL FLIGHT

4

In the medium term, new aircraft configurations that can be operated commercially successfully with significantly lower emission and noise levels are required for tomorrow's environmentally friendly air traffic. Electric or hybrid-electric propulsion systems have the potential to fulfil these requirements.

The call for mobility, and sustainability in particular, places demands on the aviation research, the aviation industry and the air transport system that cannot be completely fulfilled with conventional approaches. Other mobility sectors realise sustainable transport primarily through electrification. Electric propulsion systems also represent a promising approach in aviation to fulfil the increasing mobility requirements with minimal impact on the climate. However, its challenges require major technological developments in a wide range of areas.

The call for mobility, and sustainability in particular, places demands on the aviation research, the aviation industry and the air transport system that cannot be completely fulfilled with conventional approaches. Other mobility sectors realise sustainable transport primarily through electrification. Electric propulsion systems also represent a promising approach in aviation to fulfil the increasing mobility requirements with minimal impact on the climate. However, its challenges require major technological developments in a wide range of areas

Electric propulsion is intuitively combined with a number of advantages. All these advantages are conceptually present, but due to the low level of maturity of the technology they must be researched and investigated in detail in order to be able to make reliable statements. The aerospace industry faces much greater challenges in the electrification of propulsion than ground-based transport, since the demands on the power-to-weight ratio of the propulsion system and the energy density of the energy source in particular are many times greater. The evaluation of the advantages and disadvantages also depends on the choice of drive architecture. The main options are:

- Battery-electric propulsion systems that only use batteries for power supply
- Turbo-hybrid electric propulsion systems, which additionally use a gas turbine generator for the basic supply
- Fuel cell (hybrid) electric propulsion systems, which use a hydrogen fuel cell, possibly with additional batteries, to generate electricity

Due to the advantages and challenges described below, the switch to electric propulsion in aviation will make a significant contribution to environmentally friendly air transport. However, the transformation will be a slow and costly process that requires a wide range of investments in development, certification and infrastructure. The success of such a transition could therefore depend to a large extent on political decisions.

Electrification of the propulsion system requires a large number of electrical components that must also be integrated into the powertrain, which means that the structure must be fundamentally changed. One exception is the battery-electric concept, although here, too, it is possible to move away from traditional concepts towards functionally integrated structures and the associated lightweight construction potential. However, due to the energy and performance requirements in civil aviation, the possible applications are very limited for the foreseeable future.

In addition to efficiency losses in energy conversion and transmission, which can be countered with concepts for sustainable energy management, electric drive systems also have to take into account the additional weights, including the additional mass of cables, power electronics and buffer batteries, all of which have the potential to be integrated into the structure as such. The efficient use of installed power is therefore of paramount importance in electric aircraft. In addition, thermal management is a challenge. The provision of electrical energy and energy management generate heat in the range of maximum 120°C. This heat must be able to be dissipated from the aircraft in any climatic environment and in all flight situations. Consequently, the performance and energy requirements in all hybrid-electric drive systems are initially higher than in conventional architectures. As a result, the concrete requirements for the gas turbine and drive

ADVANTAGES AND DISADVANTAGES OF ELECTRICALLY POWERED AIRCRAFT IN PASSENGER AND FREIGHT TRANSPORT (THE TABLE DOES NOT INCLUDE SMALLER UNMANNED AIRCRAFT)

	Advantages	**Disadvantages**	**Best application**
Battery-electric propulsion	High power density of the batteries allows vertical take-off. Local emission-free propulsion.	Low energy density of the batteries leads to low range.	Short distances <300 km short term.
Turbo-hybrid electric propulsion	High energy density of kerosene leads to greater ranges and passenger capacities. Low emissions when combined with alternative fuels or hydrogen.	The turbine is currently still generating climate-impacting emissions. Higher weight, energy conversion losses and more complex system compared to conventional gas turbines.	Medium distances short term.
Fuel cell (hybrid) electric propulsion	High energy density of hydrogen leads to greater ranges and passenger capacities. Minimal emissions in flight.	Weight of the buffer batteries unused during the cruise flight. Lower power-to-weight ratio compared to the gas turbine. Complex cooling.	Short distance short term. Medium to long distance long term.
Battery – gas turbine as a range extender	Emission-free flight on short distances as well as take-off/landing at the airport possible. High drive efficiency for battery-electric missions.	Additional weight. Higher fuel consumption for long ranges.	Short term regional aircraft. Medium term regional aircraft/short-haul aircraft up to 2,000 km.

integration and their connection to the overall structural concept of the aircraft are crucial here – as is a lightweight system design that integrates electrical cables and batteries in a load-bearing manner and supports efficient thermal management.

The potential that can be realised in the operating behaviour of the gas turbine is the subject of current research. In addition to a more efficient operation in certain flight phases, an extension of the stable operating range and a more agile operating behaviour are being investigated. A major challenge lies in the interaction between the propulsion system and the airframe. The design and evaluation capabilities of highly integrated propulsion concepts are based on a collaborative and multidisciplinary approach between aircraft and propulsion design.

4.1.
BATTERY-ELECTRIC PROPULSION SYSTEMS

In a battery-electric concept, the gas turbine and kerosene are completely replaced by an electric motor with battery and corresponding power electronics. It is therefore an exclusively electrical power transmission and an exclusively electrical energy source.

The main advantages of this configuration are the good power density of the battery, the almost completely height-independent operation and a high efficiency, which is about twice as high as that of a conventional turbo engine. This means that batteries can deliver a lot of energy in a short time and generate relatively low losses. Purely battery-powered aircraft are therefore particularly suitable for short and vertical take-offs, use at high-altitude airports or high airspeeds at high altitudes, for example, for VTOLs in the field of urban air mobility. The key drawback is the low energy density of the battery. This means that a large mass is needed to store a lot of energy. The maximum storage capacity in relation to battery weight is currently 230 Wh/kg, which is about a factor of 25 less than that of kerosene with 11,900 Wh/kg. Even for regional aircraft an energy density of about 1,000 Wh/kg would be necessary. Battery-powered aircraft are therefore not suitable for energy-intensive applications such as long-distance mass transport in the foreseeable future. They are, however, suitable for travel within conurbations or feeder aircraft to regional airports.

Purely battery-electric propulsion concepts have a very high proportion of empty mass due to their very low energy density, meaning that both the size of the aircraft and the range of a fully electric flight in the foreseeable future are very limited. In particular, the energy reserves for alternative flight, holding patterns and eventualities, can be decisive for the dimensions of the overall aircraft. For short ranges, the share of energy reserves can even be larger than the actual mission itself. Nevertheless, if the battery capacity is significantly improved, aircraft can be designed in such a way that a significant proportion of short missions (up to ~800 km) can be operated fully electrically with batteries as the energy source.

Regardless of the architecture of the power supply, electric motors are still very efficient and powerful even in smaller units. The electrical power transmission thus facilitates the implementation of unconventional drive integration into the aircraft with the aim of identifying efficiency advantages on the aircraft side and thus generating an improvement in the overall transport system. They are, for example, ideally suited for novel aircraft designs that involve concepts such as multifunctional, integrated structures, distributed propulsion, boundary layer suction and the elimination or reduction of conventional components (high-lift systems, landing gear work).

A drive system architecture consisting of a battery, controller and electric motor has an overall drive efficiency that is hard to beat due to the high efficiencies, while at the same time the system complexity is low. A further limitation of the purely battery electric configuration results from the limited number of charging cycles for the batteries. In order to limit the disadvantages of the large operating empty mass on the aircraft side, reserves that are normally not flown out but always have to be carried can be carried in the form of liquid energy sources. The combustion engine required for this purpose, however, makes for a higher degree of complexity and weight than in a purely battery-powered aircraft. This is already a special form of hybrid-electric aircraft.

After initial investments in the development and implementation of the new technologies, it can be assumed that, in the future, taking into account new structural concepts, the manufacture, maintenance and repair of electrical aircraft components will be more cost-effective than with current propulsion concepts as the electrical components contain fewer moving parts. The lower complexity of the propulsion system in electric flight offers additional potential for reducing maintenance costs. It can be assumed that the maintenance of electrical concepts potentially benefits the entire value chain: from storage costs to the reduction of components to extended maintenance intervals. However, to estimate the maintenance costs, new models must be developed that take into account the novel aircraft system architectures and components.

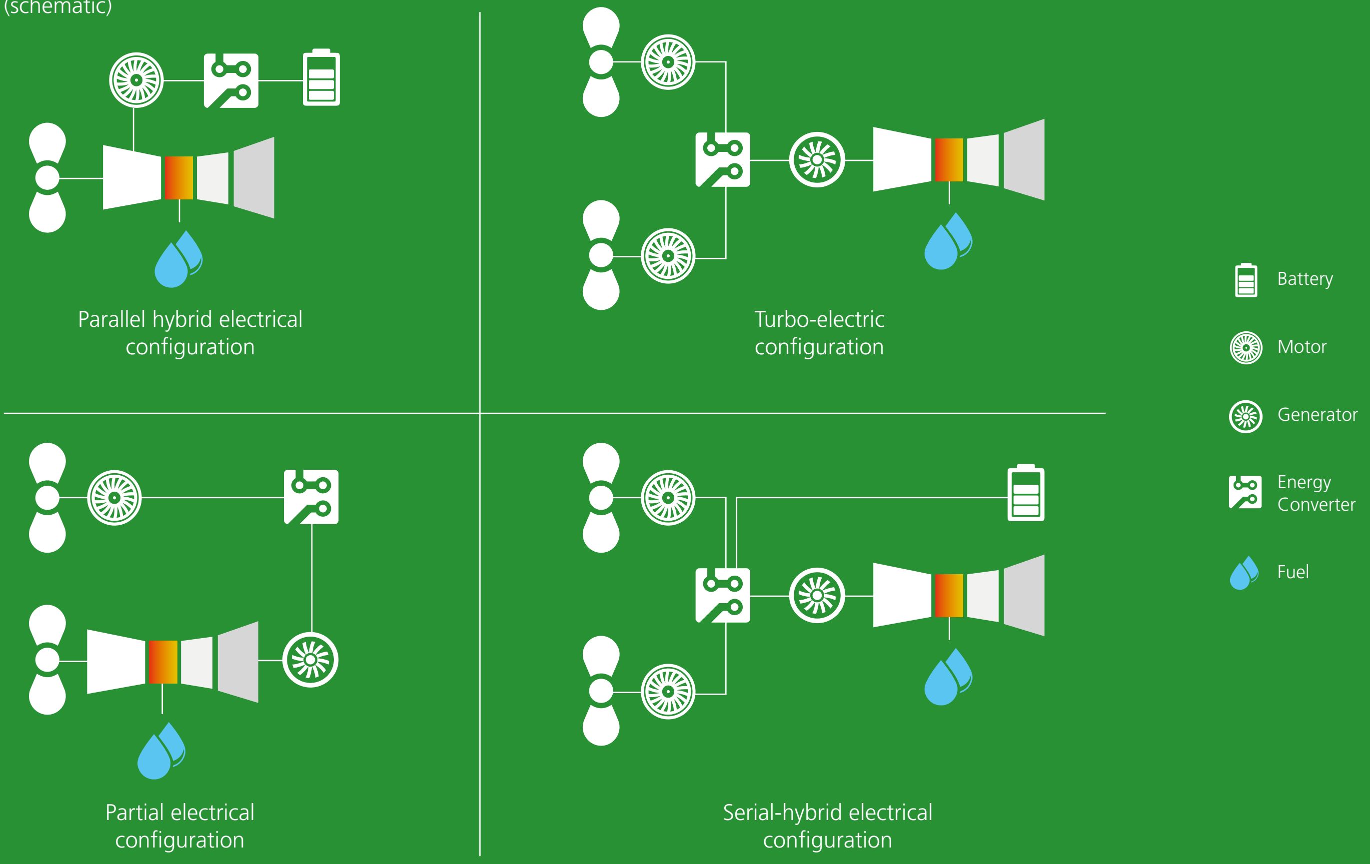
4.2.
TURBO-HYBRID ELECTRIC PROPULSION SYSTEMS

The low energy density of batteries can be compensated for by adding an internal combustion engine to the system, leading to turbo-hybrid electric architectures of various designs. The configurations are shown schematically in the figure. Overall, turbo-hybrid electric propulsion systems open up new degrees of freedom for aircraft and propulsion design. However, the combination of several components results in lower efficiencies than in a pure turbomachine, a significantly higher weight and a higher complexity.

- In a turbo-electric configuration, power is derived solely from the fuel carried, which provides electrical power for propulsion of electric motors via a gas turbine and generator
- If a turbo-electric configuration is supplied with electrical energy in addition to kerosene by means of a battery, it is a hybrid-electric concept
- Propulsion generators such as fans or propellers can be driven by the electric motor alone (serial-hybrid concept) or by the electric motor and gas turbine together (parallel-hybrid concept)

If the entire powertrain is not electrified, the turbo-electric and hybrid-electric architectures are also referred to as partial-electric. Here, only part of the required thrust is provided by an electric propulsion system and the other part by a conventional engine. These partial-electric propulsion systems are found, for example, in concepts with conventional engines, from which additional power is withdrawn and fed to one or more electrically driven propulsors. Each architecture can be operated in different ways. It is usually assumed that the turbine is permanently running at the optimal operating point and that load fluctuations are absorbed by the battery. This allows further optimisation of the gas turbine. Alternatively, it is also conceivable to fly mainly battery electric and to use the combustion engine only when circumstances require it. This may become neces-

ELECTRICAL DRIVE ARCHITECTURES
(schematic)



> *“Electrification of the propulsion system requires the integration of a large number of electrical components, which means that the structure has to change fundamentally.“*

New engine technology and propulsion concepts: electric engine of a passenger aircraft

sary, for example, when approaching an alternate airport. In this case, the gas turbine acts as a reserve and range extender, thus increasing the flexibility of a possible aircraft product.

As shown above, CO_2-neutral concepts for internal combustion engines already exist, but they currently continue to emit other harmful emissions such as soot or NO_X.

Nevertheless, new combustion chambers and cycle processes in combination with alternative fuels have the potential to significantly reduce CO_2, NO_X and contrails. By combining turbo-hybrid electric drive systems with alternative fuels, it is possible to achieve emission-free battery electric operation at the airport and at the same time at least CO_2-neutral operation in cruise flight. Further harmful emissions can also be significantly reduced, as described above, through systematic co-optimisation of fuels and combustion chamber.

However, intercontinental flights such as those with an Airbus A350 or Boeing 777 will not make sense with this technology in the foreseeable future. This is because the battery-powered take-off system would have a disproportionately greater effect on the performance of the aircraft on long-haul flights due to the longer distances involved. Apart from component development, there is a significant need for research in the system understanding of the various hybrid-electric variants. In this context, both regulating issues in the interaction of the power distribution between battery and gas turbine as well as the mutual dynamics, operating strategies and possible emergency maneuvers are relevant. To answer these questions, numerical analyses as well as systematic experimental, realistically coupled investigations on suitable test rigs are necessary. On the component side, the following aspects require extensive research and development work: power and energy densities of gas turbine-generator systems and batteries in particular, as well as the development and investigation of power management systems, thermal management and power

Electric flying enables new aircraft configurations, for example, distributed propellers at the leading edge

distribution at high power levels. High capacitive storage densities are also possible by suitable designs of the load-bearing structure of an aircraft.

In fundamental terms, all energy sources and propulsion concepts can also be useful in mixtures with different proportions in order to combine the respective advantages. For example, reserves for otherwise fully electric aircraft can be provided by combustion engines. In addition, load peaks during take-off or climb could be buffered by batteries. This allows engines designed for efficient cruising flight to be made smaller and lighter. In addition to these off-design hybrids, it may also make sense to separate the energy sources and power generators for propulsion and on-board supply.

However, when considering the entire aircraft, there are also disadvantages, for example, with regard to larger system masses. Therefore, in aircraft design it is of great importance to consider the effects of individual technologies in a cross-disciplinary context. The biggest limitation for the operation of turbo-hybrid electric aircraft is the extremely low energy density of today's batteries. Today's batteries are about 50 times heavier than kerosene. But because the efficiency of the electrical system is almost twice as high as that of systems using chemical energy sources, the disadvantage is reduced by about half. Hybrid-electric configurations will therefore be heavier than conventional turbo aircraft. A further increase in weight is to be expected due to the additional mass of the cables, power electronics and buffer batteries. This additional weight must be compensated by extremely lightweight construction and advantages in aircraft efficiency in order to achieve a more efficient aircraft overall. This is where the potential for lightweight construction comes into play again, with modular, multifunctional and integrated structures. By mapping the structure in the digital twin, it is possible to virtually simulate, among other things, the influences that design, choice of material and function have on the complete environment of the holistic structural concept. In order to make a final assessment, the entire aircraft must therefore be considered. Another aspect that also affects the overall weight of the aircraft is cooling. An electrical power distribution system usually connects some central components with the drive units, for example, on the wing. Conventional propulsion systems, on the other hand, concentrate the power conversions on the drive units on the wing. The waste heat of the electrical systems is generated at low temperature levels, but the total output of the waste heat is similar to that of pure combustion engines. This poses a challenge for the cooling system, which becomes larger and heavier, thus affecting the overall performance of the aircraft. It must be integrated into the overall aircraft with low aerodynamic resistance. A lightweight system design that allows thermal loads to be dissipated through the support structure can support the cooling system and improve the overall performance of the aircraft.

4.3.
FUEL CELL HYBRID-ELECTRIC PROPULSION SYSTEMS

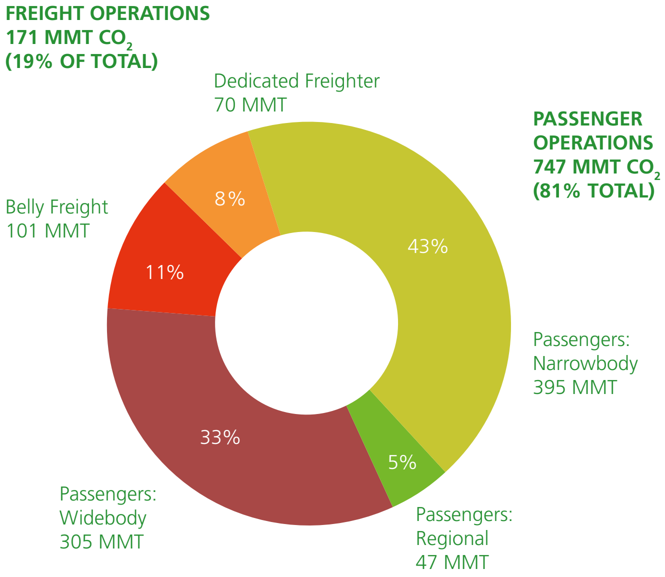
A fuel cell is an electrochemical cell for direct conversion of the chemical energy of hydrogen and oxygen into electricity. Up to now, the power-to-weight ratio of the fuel cell from the automotive industry of about 1-2 kW/kg at system level has not been sufficient for aviation applications as the electric motor and tank also contribute to the total weight. In contrast, a pure gas turbine system has a power density of about 5-15 kW/kg. As opposed to the battery, the fuel cell is an energy converter and the energy itself is stored in a tank that determines the range. Emissions such as CO_2, soot or NO_X do not occur with fuel cells, since the fuel cell is not based on a combustion process but on a catalytic reaction. Fuel cells therefore cause no emissions with the exception of water and are also characterised by a high efficiency of about 50%.

Fuel cell propulsion for a four-seater aircraft

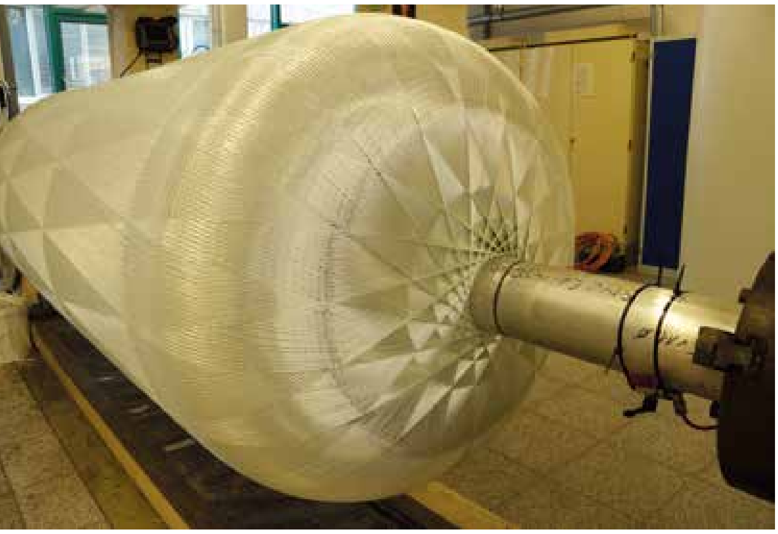
Although there is still a great need for research, significant progress has been made in recent years in terms of power-to-weight ratio and service life, making the fuel cell interesting for aviation. There are fundamentally different types of fuel cells, such as the Solid Oxide Fuel Cell (SOFC) or the Proton Exchange Membrane Fuel Cell (PEMFC). As a rule, hydrogen is used as fuel. Researchers around the world are working to optimise all technologies. Due to its degree of maturity, high power-to-weight ratio and short reaction time, the PEMFC is the only technology currently available for use in aviation.

The advantages of zero-emission operation and high efficiency face major challenges that prevent rapid adoption in aviation and require further technology development:

- The power-to-weight ratio of the fuel cell must be further improved. Up to now, the aviation industry has resorted to fuel cell stacks that have been optimised for automotive applications and thus do not exploit their potential in terms of power-to-weight ratio.
- Despite the high degree of efficiency, considerable amounts of heat are generated in the fuel cell, which must be cooled. A problem is the relatively low temperature in the PEMFC fuel cell of about 80°C, which leads to a very small temperature difference compared to the environment (up to 40°C at startup). This makes extremely large cooling surfaces necessary. In contrast, gas turbines release the waste heat to the atmosphere directly in the exhaust gas jet at high temperatures.
- The storage of hydrogen also poses the same challenge for fuel cells as for the operation of a gas turbine with hydrogen. The integration of the voluminous tank into the aircraft will require a new form of lightweight construction and new aircraft concepts.



CO_2-emissions by aircraft class and transport in 2018



Ultralight CFRP high-pressure tank for hydrogen

With regard to the climate impact (among other things, influence on clouds) of the water vapour (or liquid water) emitted at low temperatures, only very rudimentary results are available at present, i.e., there is a considerable need for research in order to obtain reliable results and verify the assumed reduced formation of contrails.

From today's point of view, the fuel cell, in combination with sustainably produced hydrogen, has the potential to provide sufficient power and range for commercial aviation in the long term, thus enabling emission-free air traffic. However, fuel cell development for aviation applications is still in the research and development stage. The dimensioning of the cooling system is determined by the take-off case (high power, low temperature difference) and is therefore much easier and faster to implement for aircraft with low power. Currently, approx. 43% of CO_2 emissions are emitted on flights with distances below 2,000 km. All these segments could be performed emission-free with fuel cell technology.

A further possible increase in efficiency would be conceivable with high-temperature fuel cells such as solid oxide fuel cells, as these have a higher efficiency and can also be cooled more efficiently due to their higher operating temperature. However, the gravimetric power density of this type of fuel cell is still far too low for aviation applications. In addition to issues such as seals, thermal cracks and poor dynamics, the lack of vibration resistance also poses a challenge for commercial aviation operations. Here, it makes sense to investigate to what extent the structure of the aircraft can optimise the energy balance of the system by integrating special functions (heat-converting concepts, cooling systems, etc.).

Aviation research is currently focusing on the Proton Exchange Membrane Fuel Cell (PEMFC), which promises to be successfully used in aviation in the short term. Experience gained over the last 20 years and investments in the automotive sector amounting to more than 15 billion euros are ensuring that durability, performance and inte-

> *"Current results show that a pure hydrogen fuel cell aircraft is feasible."*

gration have been greatly improved. It has been shown that power densities in the core subsystem of up to 6 kW/kg are possible – still with an efficiency of 50%. Power densities of 2.5 kW/kg can be realised in the overall system including air supply and cooling.

Due to the differences of components and properties in the system (e.g. reaction time), hybridisation is today necessary as a first step. However, current results show that a pure hydrogen fuel cell aircraft is feasible. Due to the supercapacitor behaviour, short-term strong currents are buffered and the system is protected against short circuits. Experiments at low temperatures have shown that a cold start of the systems is possible from -30°C, with preconditioning even from -50°C. With very good control and regulation of the relative humidity and optimal air conditioning before the stack, high temperatures of up to 95°C are possible with today's technology and thus a higher temperature difference, which reduces the necessary cooling capacity. The thermodynamically optimised system design is the key to usability.

Hydrogen has a higher energy density than kerosene or synthetic fuels. For the same energy content, hydrogen as a fuel therefore has a lower mass. The change in aircraft mass during a flight is much smaller, so the difference between take-off mass and landing mass is much smaller. Thus, when designing appropriate aircraft configurations, an appropriate high-lift system must be provided. Fuel cells have a relatively low power density, so airspeed and reasonable ranges may be limited initially.

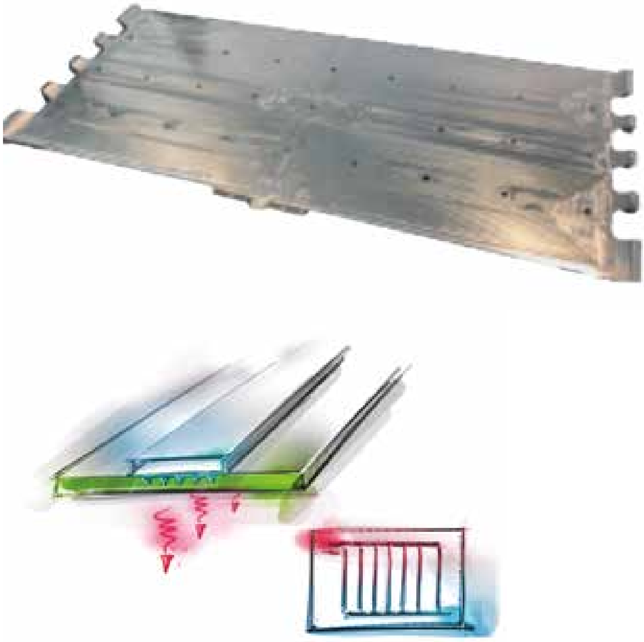
Depending on the type of fuel cell, efficiencies of 45-70% can be achieved. The lower the efficiency, the more heat must be dissipated from the aircraft. With solid oxide fuel cells, the potential efficiency and the working temperature of around 800°C are very high, so although the cooling effort is unproblematic, the mass is still quite high due to the materials required. Further research is needed here.

The Hy4 is the world's first four-seat passenger aircraft powered by a hydrogen fuel cell battery system. Its first flight was completed in 2016.

Synergies could arise from the use of superconducting motors, generators and power transmissions for high-power (>10MW) electrical concepts. The hydrogen used to cool these superconducting components can be used directly as primary fuel, which means that the hydrogen stored in liquid form is used twice.

4.4.
STRUCTURE AND SYSTEM INTEGRATION IN THE STRUCTURE

In the previous subchapters, various drive variants are described. What they all have in common is that the energy required to propel the aircraft must be stored, converted and as much of it as possible must then be released into the surrounding airflow in which the aircraft is moving.



Multifunctional structure: supporting cooling plate for battery stacks

In this consideration, the structure of the aircraft must not be forgotten or underestimated in its importance. On the one hand, it is the structure, or rather the cabin, which the paying passenger experiences and "pays for". On the other hand, the structure takes on the leading role in connecting all systems, starting with the cabin, lift, the drive train, avionics and others. The structure can therefore never be considered in isolation from the overall aircraft design. It must be developed in parallel with the new propulsion systems so that they can successfully contribute their specific advantages and fulfil requirements. The demands on the structure will thus change as disruptively as the propulsion system.

Today's existing requirements such as the provision of usable space, load capacity / load bearing capacity, insulation against cold air, hot exhaust fumes, etc., lightweight construction are largely retained. They are additionally enriched by the requirement to take on system functions.

The increasing electrification of airplanes brings with it a multitude of electrical components which, due to their power density, operate with large currents and thus also large power losses, which must be dissipated thermally. Particularly during flight conditions in which a lot of power is converted at short notice, for example, take-off or restart, peak loads arise for which the entire system must be thermally designed. The structure must accommodate this variability in passive and active cooling requirements and provide this conduction and cooling function as efficiently as possible, i.e., without additional, heavy monofunctional components. The cooling plate shown in the figure is an example of this: it is inserted between battery stacks in the multicopter "CityAirbus", carries cooling water and carries the battery stacks.

In abstract form, we differentiate today between the following functionalities, which can be performed by the structure in addition to their supporting function:

> *“The structure must be developed in tandem with the novel propulsion systems in order to successfully incorporate their advantages.“*

ADVANTAGES AND DISADVANTAGES OF ELECTRICALLY POWERED AIRCRAFT IN PASSENGER AND FREIGHT TRANSPORT (The table does not include smaller unmanned aircraft)

Function	**Status**	**Potential/Demand**
Noise absorption	State-of-the-art: use of sound absorbing materials; great demand for systems/structures to reduce engine noise.	🟨🟨🟨⬜⬜
Thermal management / Insulation	Very broad range of topics: from insulation to energy recovery as a system; great demand for new solutions for new propulsion systems – symbiosis of propulsion system structure.	🟩🟩🟩🟩🟩
Energy transfer / conduction	So far used as earth return/grounding	🟨🟨🟨⬜⬜
Energy storage	Very ambitious according to the current state-of-the-art; great risk in the implementation	🟨🟨🟨⬜⬜
Antenna	First structure-integrated antennas in development, feasibility is good	🟩🟩🟩🟩🟩
Absorption of energy-rich radiation (e.g. radar)	"Low-observability" properties are required and partially available ("stealth") in the military sector, but are not state-of-the-art and demanded in Germany	🟩🟩🟩🟩🟩 (military)
Specific / Conditioned storage (e.g. “battery housing“)	Advanced to series production in the automotive sector, hardly developed in the aircraft sector; great demand and potential	🟩🟩🟩🟩🟩
Leading media	Example: Conduction of hot air for de-icing: Today, the function is available as independent systems, but not integrated, as separation of functions is not available	🟨🟨🟨⬜⬜
Morphological properties (e.g. piezo effect)	First function demonstrators in the R&T environment available, e.g., area actuator	See 6.1
Energy generating (e.g. solar cell)	Available in demo stage for years, but energy yield is much too low, so potential is small	🟨⬜⬜⬜⬜
Safety	Example: structure that is fire-retardant in addition to its load-bearing capacity: implementation via coatings, etc., conceivable	🟨🟨🟨⬜⬜

The list shows how relevant the role of structures can be when giving additional tasks to the supporting shell. If one understands the imminent depth of change of the overall aircraft system when the engine is substituted, it becomes clear that the structure will have to take on additional tasks in the future.

From today's point of view, the development towards an emission-free aircraft (similar to the automotive industry) will initially lead to a hybridisation of the current drive system. The more alternative energy carriers (such as hydrogen or batteries) are used, the more pronounced the functional expansion of the structure with regard to energy storage will be.

Due to the aforementioned differences in energy density between current (mostly kerosene) and future solutions, it can be assumed that more volume will need to be allocated in the flying structure for the function of storing energy. If synthetically produced fuels are excluded from the analysis, batteries and hydrogen remain as potentially promising energy carriers. Structurally, both place additional demands on the surrounding structure, be it the greater weight of the battery on the one hand or the demanding temperature and pressure conditions for cryogenic hydrogen on the other. Gaseous hydrogen is from today's point of view not a viable alternative to liquefied hydrogen due to its 5.6 times larger specific volume, which would lead to an even larger volume requirement in the structure of the aircraft.

In both cases (battery and cryogenic hydrogen) it is obvious that the structure will undergo a considerable change to meet these specific energy storage constraints. See the following figure.

4.5.

FURTHER REQUIREMENTS FOR ELECTRICAL FLIGHT

The certification of novel aerospace components is one of the main challenges for the introduction of electric propulsion in aviation. The already slow and expensive approval process for electric propulsion systems is further aggravated by the fact that there are currently no established verification procedures for electric aircraft engines.

In addition, the high power requirements of aircraft engines in the range of several megawatts place special demands on the electrical system. These manifest themselves in high voltages and currents that can have safety-relevant consequences, such as voltage flashovers and power losses. There are no proven concepts available for the safety of individual components such as lithium-ion batteries to date. On the other hand, there are possible inherent redundancies of electrical systems, such as in the design of electric motors with several windings or in the packaging of batteries. These technological challenges are the subject of many research and demonstration projects. However, a considerable lead time must be expected before solutions are established on the market.

"The certification of novel aerospace components is one of the main challenges for the introduction of electric propulsion in aviation".

CURRENT NEED FOR ACTION

- The power and energy density of all components in the system must be increased to increase the range and efficiency of electric aircraft.
- Certification guidelines for electrical components and propulsion systems must be developed.
- The question of efficient hydrogen storage must be solved.
- There is a need for research in the system understanding of the different hybrid-electric variants. Therefore, not only numerical analyses are necessary, but also experimental and real investigations on test benches.
- In the field of fuel cells, heat management must also be optimised, an efficient cooling technology must be developed, and the potential of multifunctional structures must be highlighted and utilised.
- The structure has to be developed according to the specific requirements of the selected powertrain, especially to answer the questions of the efficient/multifunctional integration of system functions.
- With new fuels / energy storage media, numerous questions arise regarding operational safety, which can often be answered by structural precautions. There is a great need for research here.
- The performance management system must be investigated and further developed.
- The influence of electric drive systems and powertrain integration on the overall system must be further investigated, including the areas of distributed propulsion, boundary layer suction and lightweight system design with integrated distribution of electric power and thermal loads.
- The extremely close coupling of engine and aircraft, and thus the need to consider engine interior aerodynamics and aircraft exterior aerodynamics in parallel, must be considered in order to make valid statements for the overall system.
- The low-resistance integration of high efficiency heat exchangers at low temperature differences requires a joint optimisation of cooling airflow, airframe and system components.
- Noise research: particularly in concepts such as boundary layer ingestion or distributed propulsion, both exterior and cabin noise must be optimised in terms of sound pressure and frequency spectrum.
- Starting with the control systems and extending to the software embedding of the control algorithms, the challenge lies in the monitoring and processing of the system status.
- Power distribution and operational safety are the key to the introduction of electric drive technology. For redundancy reasons, operational safety can only be achieved with modular power distribution.
- Studies on aircraft with battery-electric, turbo hybrid electric and fuel cell hybrid electric propulsion systems are necessary to determine the optimal overall concept.

IMPROVED FLIGHT ROUTES, GROUND PROCESSES AND INFRASTRUCTURE

5

> To create the smallest possible ecological footprint, aviation does not only have to work on the engines. Aspects such as flight control, ground processes and infrastructures must also be adapted to the new challenges.

5.1.
FLIGHT GUIDANCE WITH MINIMAL CLIMATE EFFECT

Today, the focus on air traffic control is driven by cost minimisation, i.e., only those environmental aspects associated with Direct Operating Costs (DOC) are taken into account, such as CO_2 due to its correlation with fuel consumption. Other environmental impacts are considered due to the associated charges, such as noise or NO_x emissions in the vicinity of airports that have issued regulations.

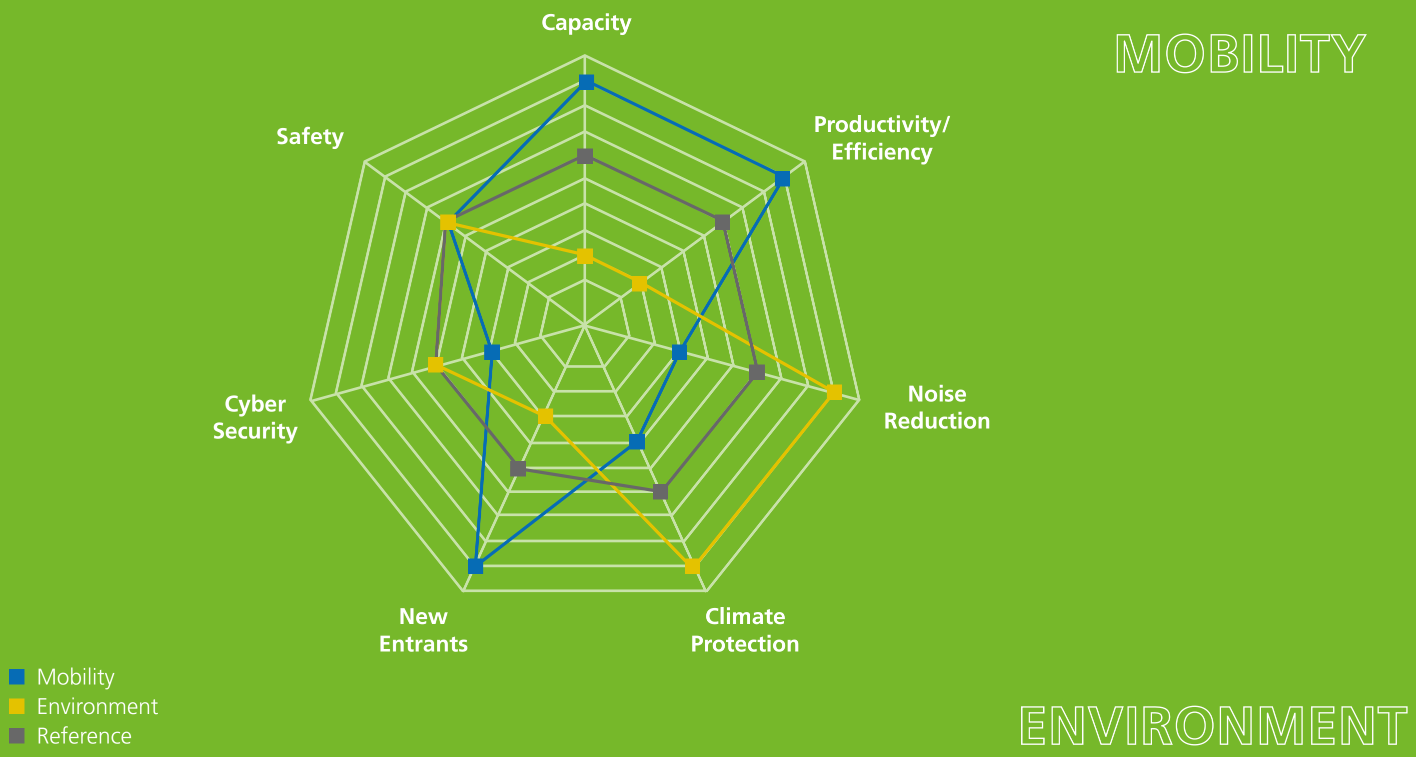
Changes in atmospheric ozone and methane concentrations, as well as the formation of contrails and cirrus clouds, also contribute to global warming. However, they are currently not considered in flight guidance due to a lack of incentives. As described above, the climate impact due to non-CO_2 effects is strongly dependent on flight altitude, geographical location and time of emission, i.e., both the daily and seasonal cycle and the current weather situation. Therefore, the climate impact of aviation can be reduced by avoiding climate-sensitive regions where emissions have the greatest impact.

DLR studies show that even small changes in routing with an impact on operating costs of only 1% lead to a reduction in climate impact of up to 10%. This was achieved primarily by avoiding areas where warming contrails occur, but also by reducing the climate effects caused by NO_x emissions. The small increase in costs due to optimised routing could be offset by market-based measures by imposing additional costs on unwanted non-CO_2 effects. Research shows that the largest daily reduction is achieved with 56% of the climate impact for certain weather conditions, compared to the path of minimum economic costs under the same conditions. These reductions would then be associated with cost increases of up to 11%.

However, the implementation of climate-friendly routing still poses a number of technical challenges at the level of air traffic control, as this is currently based heavily on fixed routes. A preliminary reduction strategy until then could be relatively static Climate Restricted Airspaces (CRA). These airspaces would be defined by 3D climate change functions that predict the environmental impact of aircraft emissions at specific locations. Similar to military restricted zones, the Climate Restricted Airspaces could be closed or opened to traffic depending on weather conditions.

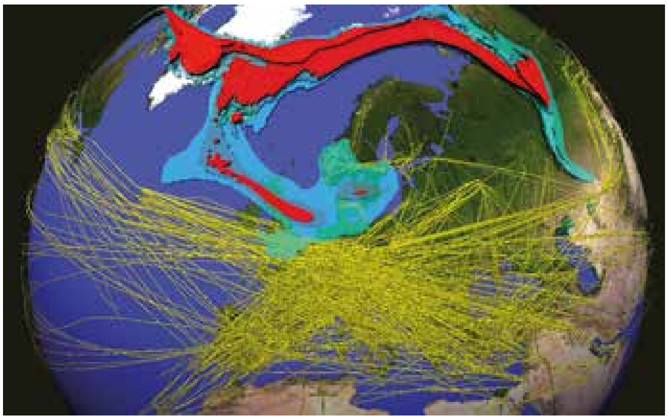
Ozone formation by NO_x can generally be reduced by flying at lower altitudes. This would require improved designs for the changed flight altitude. On the other hand, a flight at higher altitudes is faster and more fuel-efficient due to the lower air density. Lower altitudes are likely to lead to longer flight times, higher fuel consumption and thus to corresponding CO_2 emissions and operating costs, whereby the additional global warming caused by CO_2 is compensated by the weaker warming due to the NO_x effects.

THE CHALLENGE OF AVIATION MANAGEMENT AND IMPACTS



A simple method for reducing emissions during descent is also the Continuous Descent Approach (CDA) or Continuous Descent Operations (CDO). In this approach, the engine is operated at its lowest power setting during descent, thus reducing fuel consumption and noise pollution. In return, the descent takes longer, which has an impact on airport capacity, and the aircraft reacts more slowly. The procedure is therefore only possible under favourable weather and traffic conditions. A reduction in airspeed can reduce fuel requirements and the associated energy costs. At the same time, however, the airline's annual transport work is reduced due to the longer flight time per route. The costs related to this can then decrease or increase accordingly, depending on the airline and the existing cost structure.

While the introduction of a new technology for the world's aircraft fleet is generally a lengthy process, new operational measures could, on the other hand, be applied to a significant part of the fleet in a very short time. In order to overcome the problems resulting from the continuing growth in air traffic, the European Commission decided to defragment the European airspace to create a “Single European Sky”. The goals are to reduce delays and improve safety and flight efficiency, thereby reducing the environmental impact and costs of aviation. The Single European Sky ATM research (SESAR) focuses on modernising European airspace by defining, developing and deploying new or improved technologies and procedures (SESAR Solutions). The introduction of the Single European Sky has the side effect that climate-optimised flight trajectories can be realised more easily.



Quantification of climate impact as well as weather influences and flight route optimisation

5.2.
GROUND PROCESSES WITH MINIMAL CLIMATE IMPACT

Processes on the ground can also make a significant contribution to reducing the environmental impact of air traffic. Although engines need a warm-up before they are fully operational, idle times of the engine on the ground should be minimised. A wide-body aircraft like an A380 can burn a tonne of kerosene in 15 minutes on the tarmac. Electric towing vehicles can significantly reduce these emissions on the ground, as the operation of Lufthansa's TaxiBot at Frankfurt Airport shows.

New processes on the ground are also required to support new types of aircraft propulsion systems such as hydrogen turbines or electric drives. The challenge will be to ensure the safety and cost-effectiveness of these processes. For example, hydrogen tanks or batteries must be able to be recharged in a sufficiently short time to keep the aircraft's turnaround time as short as possible. Currently, the time spent at the gate is about half an hour. Such a short charging time is a major challenge for the battery, so battery-powered aircraft may need to have their batteries replaced or have to plan for longer idle times. In addition, charging times would be the critical path in handling processes and thus have a direct impact on other apron and terminal processes. Punctuality and the perceived service level for passengers are directly affected.

5.3.
INFRASTRUCTURE FOR NEW KINDS OF AIRCRAFT PROPULSION SYSTEMS

The current aviation infrastructure is designed for the rapid refuelling of aircraft with kerosene. Refuelling with hydrogen, but also charging with electrical energy requires additional infrastructure such as hydrogen and power lines. If batteries have to be replaced at the airport because of the shorter turnaround time, additional logistical processes and large battery storage and charging facilities are required. Such infrastructures require extensive investments and each technology for which infrastructure is provided occupies space that is then often no longer available for other uses. Here, the technical and economic feasibility, including questions of resilience as well as safety and acceptance by the population, must be examined.

The widespread use of electricity in aviation would require a considerable expansion of renewable energies. The power grid would have to be expanded to distribute this energy and the airport itself would have to provide infrastructure to distribute the energy to the aircraft. Frankfurt Airport, for example, sells about 15 million litres of kerosene per day. This corresponds to more than 130 GWh of electrical energy per day. The airport's annual electricity consumption is currently around 600 GWh. This would require an immense expansion of the power grid in the vicinity of the airport by a factor of 80. For the expansion of renewable energies in Germany, such a conversion would also represent an enormous challenge. Initial concepts such as those developed by the Innovative Airfield Strategies Consortium for Low-Emission Regional Air Traffic (KIFER) therefore propose a decentralised infrastructure. Since airports typically occupy large areas, the energy required for regional airports could initially be generated locally in a renewable way.

In order for airplanes to be usable worldwide, the interfaces to the power grid must be sufficiently standardised. In the simplest case, this concerns the charging plug. If batteries are replaced, however, the battery bays and battery packs must also be standardised in order to allow the widest possible use and to avoid a multitude of charging technologies and storage locations with corresponding land usage. In addition, a solution must be found to write off the wear and tear of the batteries over different aircraft. This is also necessary in the interest of safety in order to exclude the possibility of faulty batteries being used in aircraft. The sometimes very specific requirements for charging and discharging power, temperatures to be maintained and protection against explosion and fire hazards also place demands on the infrastructure to be provided.

The production of lithium-ion batteries is an energy-intensive process, so concepts for further use (second-life/reuse) can extend the service life and thus significantly reduce the ecological footprint. It is in this context that the degradation of battery capacity must be seen, since once they fall below a defined limit (e.g. 80% of the initial capacity) they are no longer suitable for use in aircraft, for example, due to loss of range. Conceivable approaches for the further use of batteries taken out of service in aviation are primarily seen in the area of stationary applications. Battery modules with similar performance and service life are removed and installed in new "reusable" battery packs, which then serve as energy storage devices in supply networks, in buildings or in telecommunications. At the same time, this can result in economic advantages because the materials used remain in the cycle for a long time. Since there is a lack of standardisation of batteries and the various chemicals, the user of the second-life battery should tailor its application to this. Moreover, even the same model of batteries may have been used for different purposes or treated in different ways, so they may have different "properties" after their lifetime. Similarly, there is a lack of mechanisms that provide incentives for re-use and enable the second-life of Li-ion batteries.

Besides the ecological footprint, the economic aspect of lithium-ion batteries is a key factor for the electrification of aircraft. Most of the economic value of a lithium-ion battery is due to the materials used (such as cobalt, lithium, copper, graphite, nickel, aluminum and manganese). At this point, there is a high potential for recycling the discarded lithium-ion batteries. The main motivation for recycling can therefore be seen in the (re)production of raw materials or in the reduction of the depletion of raw materials. Despite the further development of recycling processes, large quantities of lithium-ion batteries may have to be disposed of due to the rapid growth of electromobility in general.

In order to comprehensively assess the effects of the use of lithium-ion batteries, interdisciplinary ecological life cycle assessments are required that take up the above-mentioned aspects and examine them in detail. The LCA tracks all energy and material inputs and outputs for the manufacture of a specific product from raw material extraction to final disposal. It can help quantify the benefits of battery recycling and identify where process improvements or material substitutions could have the greatest impact. In addition to the further development of lithium-ion batteries, alternative battery concepts (e.g. metal-air batteries) with their advantages and disadvantages for aviation must also be considered and ecologically evaluated.

For the introduction of hydrogen as a fuel, the availability of hydrogen and the corresponding filling station infrastructure is of crucial importance. A major advantage for aviation applications is that only a small number of filling stations are required, and it will probably be sufficient to have such filling stations at central airports. This means that the expansion of the infrastructure is not expected to be as slow in the aviation sector as in the mobility sector. However, aviation can benefit from the development of a hydrogen infrastructure in ground transportation. Standardisation of car filling stations already promises substantial improvements in terms of costs, approval procedures, maintenance and reliability. The technologies developed in the mobility sector can largely be transferred to aviation applications. However, hydrogen for aviation applications will be in liquid form, while in the mobility sector hydrogen is usually supplied to the user in gaseous form at high pressures.

> *“For the operation of novel aircraft concepts, infrastructural measures must be identified and taken into account at an early stage“.*

For the complete supply of an airport like Frankfurt, about 4 million kg of hydrogen per day would be necessary. The choice of the H_2 supply option depends primarily on the location and local conditions:

- A delivery by truck can contain up to 4,000 kg of liquid hydrogen. This is particularly useful for initial demonstrations with low fuel consumption or for smaller landing sites in urban areas.
- A pipeline connection to an H_2 source is necessary to continuously supply large quantities of hydrogen and to supply airports with higher traffic volumes. In 2017 there were almost 400 km of hydrogen pipelines in Germany, worldwide almost 5,000 km.
- The production of hydrogen via electrolysis directly at the site of the filling station is another option. This option is especially possible for large airports and is also more affordable in view of their high traffic volume.

Other technologies for transporting hydrogen, such as the temporary storage of hydrogen in a liquid carrier medium such as oil, are currently under development. The investment costs for an H_2 filling station supplied with liquefied hydrogen are currently around 2 million euros and will fall to around 1.5 million euros by 2050.

This shows that the infrastructural measures necessary for the operation of alternative aircraft concepts must be identified at an early stage. In addition to mapping the effects on the airport infrastructure alone, synergies with other non-aviation sectors must also be taken into account, such as decentralised energy generation via airport areas, electrochemical energy storage at the airport or the production of energy sources on site.

CURRENT NEED FOR ACTION

- Identification and solution of technical challenges for the implementation of climate-friendly routings on the level of air traffic control.
- Ozone formation by NO_X can generally be reduced by flying at lower altitudes. Development of improved designs for the changed flight altitude necessary to reduce ozone formation by NO_X from flying at lower altitudes.
- The ground traffic at the airport should be electrified to reduce emissions significantly.
- For the operation of novel aircraft concepts, infrastructural measures must be identified and considered at an early stage. While the introduction of hydrogen as a fuel requires the availability of hydrogen and the corresponding filling station infrastructure, electrical concepts require worldwide standardisation of the interfaces to the power grid.

EFFECT ON AIRCRAFT LEVEL

6

The application of electric propulsion enables a number of advantageous technologies for the aircraft, such as increased lift and reduced control surfaces through distributed propulsors. In the propulsion system itself, advantages are likely to arise in the optimisation of the operating point, in the usability of complex cyclic processes through integration in the fuselage and in a high propulsion efficiency despite the size limitation of the engine due to a large number of propulsors. However, this is offset by disadvantages such as high additional weight, additional losses due to energy conversion, a complex system and high costs. Only an intelligent combination of the advantages of aircraft and propulsion while minimising the disadvantages can deliver a successful new aircraft and propulsion concept. In addition to the possible configurational advantages of electric propulsion systems, the different propulsion types also require changes to the configuration of the aircraft, which will enable the smooth integration of the new technology into the overall system. This also results in new balances in the life cycle of an aircraft. In order to be able to comprehensively evaluate these aspects, an interdisciplinary ability to design and evaluate the overall system is necessary, which the German aviation landscape should definitely build and maintain.

6.1.
CONFIGURATIVE POSSIBILITIES AND CHALLENGES

The potential to fly climate-neutrally depends primarily on the energy sources mentioned above. These determine to a large extent the overall structure of the aircraft, the propulsion technology, but also the configuration and flight performance itself. All propulsion architectures influence the main quality characteristics of aircraft:

- Propulsion efficiency (specific energy demand)
- Aerodynamic efficiency (glide ratio)
- Lightweight system construction (operational empty mass)
- Safety (probability of system failure)

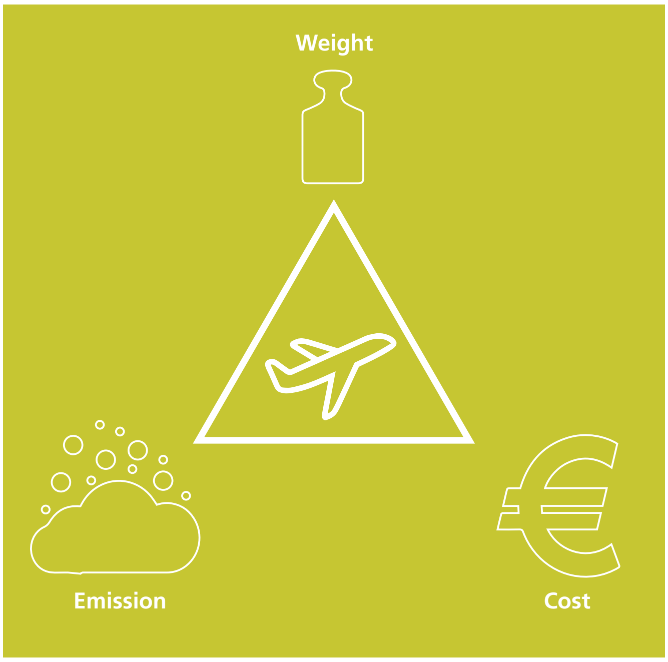
Each energy source and the corresponding propulsion technologies also influence operating costs, impose infrastructural constraints or

“New materials, construction methods and the integration of electrical and thermal systems into the supporting structure offer a potential for saving up to 40% of total aircraft mass compared to today's aircraft structures“.

have advantages and disadvantages with regard to production, maintenance and decommissioning/recycling and have different effects on noise emissions.

INTEGRATION OF NEW TECHNOLOGIES IN AIRCRAFT DESIGN

The efficiency improvements of the current aircraft generations compared to older types have been achieved largely through developments in engine technology towards higher bypass ratios and through improvements in wing aerodynamics. The further increase in engine efficiency and the integration of very large engines continue to offer great potential for designing climate-friendly aircraft and ensuring economical operation. The integration of ever larger engines, however, is subject to geometric, structural and aerodynamic limits, especially on the fuselage and wings. Continuous improvements in structural quality also contribute to an ecological and economical operation. In some cases, the disadvantages of the novel propulsion architectures at aircraft level must also be compensated for in these areas. In particular, electric or hybrid-electric flying represents a paradigm shift for lightweight construction: while lightweight construction has so far been necessary for the safe transfer of mechanical loads, in the future it will also have to take over the distribution of electrical power and, to a large extent, thermal management tasks in order to compensate for additional masses and maximise flight performance and mission safety. Lightweight construction becomes lightweight system construction. New materials, construction methods and the integration of electrical and thermal systems into the load-bearing structure offer potential savings of up to 40% in total mass compared to current aircraft structures.



Challenges, components and systems

Digital transformation offers the possibility to simulate the possible final result with all its interactions when creating the aircraft design. The aerodynamic quality of an aircraft configuration also has a considerable influence on the energy required for the transport mission.

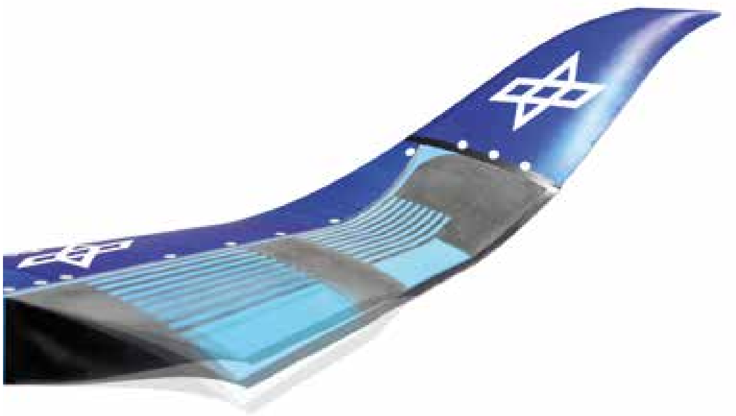
The design of the wing and fuselage as well as the aerodynamic integration of the engine and tail units, and in particular the minimisation of drag, are thus among the key technologies on the way to emission-free flying. Here, too, the disadvantages of the novel propulsion architectures can be compensated. A whole range of technologies is conceivable, including natural and hybrid laminar structures, riblets, morphing and distributed propulsion. In addition, the technology of boundary layer ingestion would be a useful option, especially for large areas such as hydrogen tanks. Here, efficiency advantages of up to 20% could be achieved.

Retrofit plays a major role in optimising the current global aircraft fleet with regard to its climate impact in order to ensure early emission reductions. However, radical technologies are not useful as retrofit solutions, as the entire aircraft must be completely redesigned with regard to the optimisation target and eco-efficiency. This may also mean giving greater weight to marginal cases in the operating spectrum in order to enable flexible climate-friendly routing. It is therefore necessary to carry out a cross-disciplinary integration of all individual technologies in aircraft design in order to develop the individual advantages into a double-digit percentage overall advantage for the aircraft. At this point, it should be pointed out once again that improvements in aerodynamic quality and systematic lightweight construction are, in addition to the engine, essential "enablers" for fuel-efficient and economical operation of climate-neutral aircraft.

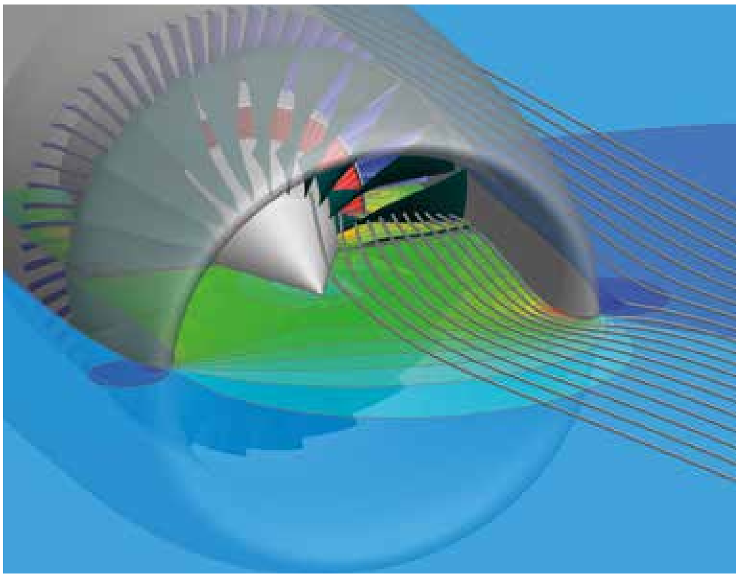
The current aircraft fleet will not be replaced by a new generation for another twenty to thirty years. On the one hand, current aircraft, which already have a very high degree of maturity, must therefore be improved with retrofit solutions, for example, the DLR project Low Noise ATRA is investigating conversions to reduce noise, while on the other hand additional investments must be made in new radical technologies. Since these developments have to run in parallel, the result is a much more complex R&T than before.

The challenges of integrating new technologies into aircraft design have already been outlined in Chapter 3 Electrical Flight with regard to research into the various drive solutions. For the sake of completeness, they are summarised here in condensed form.

An advantage of concepts with electric motors is the possibility to distribute the propulsion on the aircraft at configuration level. The availability of electrical propulsion energy thus enables the integration of the novel aerodynamic technology into new aircraft. In addition, synergetic effects such as favourable mass distribution, modu-



Morphing wing and laminar structure



Engine integration

larity or super-redundancy can be used to further improve the efficiency of aircraft.

Battery-electric propulsion concepts limit the size of aircraft and the range of a fully electric flight in the foreseeable future. The low energy density of the battery leads to a high proportion of empty mass. Especially the energy reserves for evasive flight, holding patterns and contingencies can have a dimensional impact on the entire aircraft. A propulsion system architecture consisting of battery, controller and electric motor has an overall propulsion efficiency that is difficult to surpass due to the high efficiencies and at the same time low system complexity. In order to limit the disadvantages of the large operating empty mass on the aircraft side, reserves in the form of liquid energy sources can be carried along. However, the combustion engine required for this purpose particularly influences a higher degree of complexity than in a purely battery-powered aircraft. This is already a special form of hybrid-electric aircraft.

Compared to kerosene or synthetic fuels, hydrogen has a higher energy density. For the same energy content, it therefore has a lower mass as a fuel. The change in aircraft mass during a flight is much smaller, so the difference between take-off mass and landing mass is much smaller.

When designing appropriate aircraft configurations, a corresponding high-lift system must be considered. A disadvantage, however, is energy storage, which currently requires a large volume to accommodate the hydrogen. This must be considered regarding the configuration. This increases the surface area of the entire aircraft that is flushed around, which increases the aerodynamic drag and reduces aerodynamic efficiency. The operating empty mass is also strongly influenced by hydrogen tanks, so that flight performance also depends on them. The efficiency of the propulsion system particularly influence the configuration. Fuel cells have a relatively low power density, which may limit airspeed and useful range.

For gas turbines with hydrogen combustion, the same configuration effects apply as for fuel cells with regard to the energy source and the storage of energy. Aircraft with high range requirements (medium- and long-haul aircraft) require a correspondingly large volume to accommodate the liquid hydrogen. This means that performance losses must be expected due to the greater aerodynamic drag and the higher structural mass.

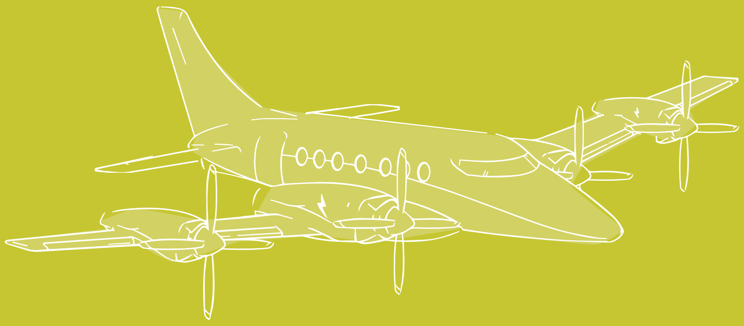
6.2.
TECHNOLOGY IMPACT ASSESSMENT IN THE ENTIRE AIRCRAFT LIFE CYCLE

For a holistic economic and ecological life cycle assessment, appropriate digital methods and models are needed to make the effects of the use of technology measurable. In doing so, the infrastructural requirements for operation of the different system architectures must be modelled and examined with regard to the degree of maturity, the environmental impact as well as costs over the life cycle.

DEVELOPMENT OF METHODS AND MODELS

Existing models can be used for this purpose (for example, to determine the climate impact). However, the existing models have to be extended considerably for the new aircraft concepts. This includes, for instance, fundamental atmospheric physics issues that need to be clarified, such as the formation criterion for contrails and properties of contrails of an aircraft powered by synthetic kerosene or hydrogen. In addition, fundamentally new methods must be developed for estimating the technological impact, e.g., on maintenance costs. In addition

Electric regional aircraft with distributed propulsion



Battery-electric 19-seater transports synthetic fuel and a gas turbine as a reserve to the consideration of the effects in individual areas, the interconnection, transfer and interaction of the results of the different models over the life cycle are critical for the overall view in order to obtain a statement about the sustainability of the applied technologies. Since the results of the technical, economic and ecological analyses are not always coordinated, the transfer into a holistic assessment is necessary.

THE ECONOMIC LIFE CYCLE: THE DEVELOPMENT OF COST AND REVENUE MODELS

With regard to the economic life cycle, a number of possible advantages and disadvantages seem to emerge. A key characteristic of electrical flight is the elimination or, in the case of hybrid-electric flight, the reduction of the use of fuels. Since fuel costs represent a significant proportion of operating costs, a major economic impact on airlines can be expected from the choice of energy source. The development of the energy market is a decisive factor in evaluating the economic and ecological advantages of electrical flight. In terms of operating costs, the price development for fossil kerosene, synthetic kerosene, hydrogen and electricity and their taxation is the main driver for the introduction of the respective technology. Here, energy scenarios for all modes of transport must also be developed. Sensitivity analyses can then help to build up a better understanding of the system and estimate the future development of fuel and electricity prices, efficiencies, storage costs and thus the economic viability of the aircraft.

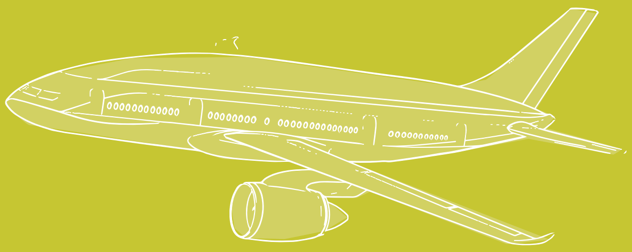
In addition to cost models, novel revenue models for cost-benefit analyses must also be investigated and created. On the one hand, it is necessary to analyse the influence of passenger acceptance with regard to price development under the influence of technology and the operating environment such as energy costs and regulatory measures. Furthermore, it is necessary to be able to depict the effects of aircraft requirements that deviate from the current reference system. This includes, for example, investigating the effect of slower airspeed on passenger demand. Similarly, the resulting implications for network, fleet and rotation planning must be identified and evaluated. This information must then be transferred to maintenance planning, but also to ecological analysis to determine the climate impact of the aircraft fleet.

The studies on economic implications in the production of battery-electric, turbo-hybrid electric, fuel cell propulsion or hydrogen powered aircraft must take into account both the aircraft production itself and the provision of energy sources or energy storage. Since these are components that will not be used until the future, appropriate methods and models must be derived for the cost estimates.

After the aircraft or its components have reached the end of their service life, they must be disposed of or recycled. This has an economic impact, as costs are incurred due to the necessary disposal of certain materials or components. However, it is also possible to recycle selected materials and components and reuse them in the same or other life cycles, increasing the residual value of the aircraft at the end of its useful life. Accordingly, it is necessary to analyse which components of the considered aircraft concepts can be disposed of or recycled and which end-of-life scenarios are associated with them. These are then used to calculate the end-of-life costs.

THE ECOLOGICAL LIFE CYCLE: ENVIRONMENTAL IMPACT ANALYSIS

In terms of ecological considerations, a systematic and consistent analysis of environmental impacts on the basis of selected performance indicators throughout the entire life cycle should be aimed for. In addition to the effects of purely aircraft operation, the life cycle



Gas turbines that burn synthetic fuels enable fast cruising flights. Fuel cells are used for taxiing on the ground. Both systems used in parallel generate maximum energy for take-off.

Example of an overall evaluation of the aircraft design

Development and validation of improved multi-material production technology

> *“For a holistic economic and ecological life cycle assessment, appropriate digital methods and models are needed to make the effects of technology use measurable“.*

phases of production and disposal must also be included in the analyses and the balance sheet. This is intended to identify the sustainability potential that arises from the use of electric or hybrid-electric aircraft compared to conventional aircraft or the use of sustainable fuels such as hydrogen or drop-in fuels. Therefore, it is essential to consider the entire life cycle of an aircraft, so that the aircraft configurations applied in the future are the best possible solutions in terms of a life cycle assessment and have the potential for a minimum ecological footprint.

In general, the question of energy production is relevant when evaluating the ecological balance. To achieve true emission neutrality, the synthetic kerosene, electricity or hydrogen must be produced from renewable energies. In this case, the background scenarios to be used for the evaluation of the climate impact of pure flight operations have to be adapted according to the energy mix. This means that in addition to the direct emissions caused by the operation of new types of aircraft, indirect emissions and environmental impacts caused by the production of the energy sources must also be considered. This also includes the replacement of various components during the aircraft's service life, such as batteries, fuel cells or hydrogen storage systems. In a study on the eco-efficiency of an Airbus A320, it was found that its operation makes the largest contribution to the overall environmental impact of the aircraft at 99.9%, with kerosene combustion causing the largest share of emissions. During the A320's construction phase, the wing and engine components contribute 63% of the environmental impact, while CFRP material accounts for 10% of the total material share but contributes 45% of the manufacturing burden.

In addition to the evaluation of the climate impact of direct flight operations, it is necessary to establish suitable evaluation architectures for the technologies to be researched. The basis for the climate evaluation is spatial emission distributions, which can be calculated using emission register models. For this purpose, the theoretical basis for emission behaviour must be developed and the applied climate models must be adapted to the technologies under consideration. Based on this, individual trajectories can then be planned for each flight. This has implications for air traffic management and requires new air traffic control concepts, especially on long distances.

For the ecological analyses in the area of production, not only the cell but also the drive system and the energy storage system must be balanced. Energy and material flows serve as a basis for this, which can be used equally for the economic analysis. In the case of operation with batteries, the required number of batteries over the life cycle must be determined and integrated into the lifecycle assessment. The above-mentioned aspects are equally relevant for the decommissioning of the aircraft itself, as well as the associated system components (e.g. disposal of batteries).

TRANSFORMATION OF THE AVIATION INDUSTRY

7

Technological change in aviation is a lengthy and costly process that requires high investment in research and development, as well as in certification, and requires constant political support. There are many challenges on the way to climate-neutral aviation that can only be solved through cooperation between research and industry. However, the use of sustainable fuels in conjunction with new aviation structures, modern engine technology, alternative propulsion solutions and energy sources such as hydrogen open up numerous opportunities for the environmentally friendly air transport of tomorrow.

7.1.
HELICOPTERS

In global air traffic, helicopters account for a much smaller share of CO_2 emissions than the dominant commercial aircraft sector. Nevertheless, future helicopters and so-called VTOL (Vertical Take-Off and Landing) aircraft can achieve a significant reduction in gas emissions and thus contribute to improving the climate, especially in their use in inner-city areas (e.g. air rescue, policing, passenger transport). In addition, emission-free flying already represents a major requirement for the potential growth of the new market segment of Urban Air Mobility (UAM), which will hardly be accepted if the environmental impact is not acceptable.

To this end, the German helicopter industry has established a research and technology roadmap that describes the path to emission-free flying. This plan pursues on the one hand the development of necessary technology components, primarily in the field of propulsion, rotors and novel structural designs, and on the other hand their integration and testing in real environments (flight demonstrators). Both hybrid and fully electric propulsion concepts are considered, which are suitable for different platforms in the field of conventional helicopters as well as VTOLs for UAM.

7.2.
SMALL AIRCRAFT AND URBAN AIR MOBILITY

All-electric and increasingly autonomous flying offers a way to transport people quickly and with low emissions in urban areas or between neighbouring cities.

Such air-taxis could also be used, for example, as a supplement to rescue services to transport emergency doctors quickly to the scene of an accident. However, due to the high payload requirements, patient transport itself will remain the preserve of conventional helicopters in the foreseeable future. The trend here is towards larger, more powerful helicopters with improved patient care already in the air.

A further trend is accompanied by the development of unmanned aerial systems (UAS), which are on the threshold of becoming very important in the civil sector. Technological advances are currently enabling the emergence of a new industry in the field of unmanned systems, but also new types of flying transport media for urban population centres and their connection. There are currently signs of a significantly higher speed of innovation in the aviation industry.

The first applications of unmanned air vehicles are the supply of poorly connected areas and the delivery of urgently needed goods such as medicines, as well as supporting emergency services in disaster relief.

> *"The use of sustainable fuels in conjunction with new aviation structures, modern engine technology, alternative propulsion solutions and energy sources such as hydrogen open up numerous possibilities for the climate-neutral air traffic of tomorrow".*

The exchange of urgently needed production parts between industrial sites is also conceivable. The use of unmanned logistics solutions reduces the number of conventional delivery vehicles such as trucks, especially in conurbations. Since small unmanned aerial systems are mainly electrically powered, their use has an impact on better air quality, especially in cities. The first prototype aircraft allow a glimpse of the urban air mobility of the future. However, current UAS concepts show great differences. In the next step the concepts must be evaluated regarding their suitability and feasibility. While in the past, worldwide trials of UAS were limited to a manageable number of tests, the rapid growth of the entire industry will require a significant increase in the number of system trials to enable a holistic technology development.

7.3.
REGIONAL AIRCRAFT

The switch to purely electric propulsion in aviation can contribute to environmentally friendly air traffic in certain areas, since battery-electric propulsion is currently the only propulsion technology that can allow aircraft to fly completely without emissions. In a fully electric propulsion concept, the gas turbine and kerosene are replaced by an electric motor with battery and corresponding power electronics. In commercially successful operation, battery-electric powered aircraft with a range of up to 300 km will be feasible in the near future. They are particularly suitable for travel within conurbations or as feeder aircraft, as the low energy density greatly limits the range.

7.4.
SHORT-HAUL

In the future, short-haul aircraft will be replaced by new aircraft with hybrid propulsion concepts that promise reduced pollutant emissions. In addition, they score points for their greater range than purely battery-powered propulsion solutions. Hybrid propulsion concepts with turbines generate the same emissions as a turbine drive, but the aircraft and the gas turbines can be better optimised for electrical power supply, so that a small reduction in emissions can be expected – provided that the additional weight does not have a negative effect. With pure battery operation, emission-free operation is possible in the airport area or on very short flight routes. Propulsion architectures with fuel cells hold great potential, since they generate only water vapour as exhaust gas. This means that soot, NO_x, SO_x and CO_2 are completely avoided. The effects of the remaining water vapour can also be minimised by choosing a climate-friendly route. In addition, the formation of condensation trails due to low exhaust gas temperatures could be avoided. Investigations on this are still pending.

Irrespective of the combination of energy source and propulsion concept, turbo-hybrid electric and fuel cell concepts promise a longer range than battery-powered aircraft. From today's point of view, the fuel cell in combination with green hydrogen has the long-term potential to provide sufficient power and range for commercial aviation. At the airport, emission-free air traffic with aircraft for about 120 passengers and ranges of about 2,000 km could be realised in the short term.

7.5.
MEDIUM- AND LONG-HAUL

Sustainable aviation fuels will be an important technology for environmentally friendly air traffic in the coming years as a drop-in concept. Fuels blended with alternative fuels can already be used today as drop-in fuels in all aircraft and infrastructures without restriction or modification, exactly like conventional fuels. Measured against the existing global fleet, there is a considerable potential to minimise climate-damaging effects, because both CO_2 effects and non-CO_2 effects can be reduced. Alternative fuels are already being used as drop-in fuels on commercial flights. However, the quantities are currently still less than 1% of global consumption. In the long term, hydrogen will play an increasingly important role in reducing environmental impacts. Hydrogen is particularly promising because it has a high energy density and can be produced completely regeneratively from renewable energies. In the future, the use of turbo-hybrid electric and fuel cell propulsion concepts on medium- and long-haul routes is also conceivable. Due to the low level of maturity, however, considerable investment and research is still required in the areas of energy storage and propulsion, vehicle and overall design, as well as transport system and operation.

THE PATH TO THE CLIMATE-NEUTRAL AVIATION OF THE FUTURE

			Short-term 2035	**Long-term >2050**
Urban air mobility	Passengers	~ 4	Battery-electric propulsion Turbo-hybrid electric propulsion Fuel cell propulsion system Alternative fuels > synthetic fuels	Battery-electric propulsion
	Range	0-100 km		
Commuter	Passengers	6-19		Turbo-hybrid electric propulsion Fuel cell propulsion system Alternative fuels > hydrogen New thermal turbomachinery
	Range	50-600 km		
Regional	Passengers	20-120		
	Range	500-2,000 km		
Short haul	Passengers	100–200	Turbo-hybrid electric propulsion New thermal turbomachineryn Alternative fuels > synthetic fuels	
	Range	1,000-4,000 km		
Medium haul	Passengers	180-300		
	Range	2,000-8,500 km		
Long haul	Passengers	> 200	Alternative fuels > synthetic fuels	
	Range	5,000-18,000 km		

RESEARCH AND TECHNOLOGY NEEDS

8

As described in the previous chapters, the technologies that need further development can be grouped as follows: environmental impact, new thermal engines, electrical flight, hydrogen, alternative fuels, new aircraft concepts and structures, optimised components and flight control. The different technologies are best suited for corresponding target products. As described below, these topics can best be addressed regionally, nationally or internationally due to their different characteristics and requirements.

8.1.
REGIONAL MEASURES

The report of the Coordinator for German Aerospace 2017 underlines the rapid development of the market for civil unmanned aviation in recent years.

As part of the European innovation partnership "Smart Cities and Communities", the German government has selected five Urban Air initiatives as model cities or model regions: Aachen, Hamburg, Ingolstadt, Münster and Northern Hesse. These initiatives consider the topic of mobility concepts regarding air-taxis as well as other forms of UAS applications. They focus in particular on the respective regional specifics regarding the suitability and demand for UAS applications. As a new form of mobility, passenger transport by air-taxis plays a major role for cities and regions. But for air-taxis to be able to fly in our cities one day, a number of challenges have to be overcome. This is because, in addition to the development of new flight systems – the actual vehicle – new infrastructures as well as transport and service models must be created.

The trend is that research on the flying system itself is mainly carried out by start-ups. However, large players and aviation OEMs are needed for implementation and commercial operation. This growth is accompanied by the development of new concepts, technologies and challenges. Therefore, the industry sees an increasing need for new test procedures. While in the past, international testing of UAS has been limited to a manageable number of tests, the rapid growth of the entire industry will require a drastic increase in the number of system tests. This is the only way to achieve holistic technology development. This results in a need for new testing procedures and possibilities that do not exist in the required form thus far.

DLR provides comprehensive simulation environments for the design and pre-development of UAS, and since 2018 is also building up the National Test Centre for Unmanned Aerial Systems in Cochstedt. With the National Test Centre, a unique test environment will be created in Germany, which will allow both research and industry to validate UAS technologies comprehensively and safely in a specially created environment. In order to meet the expected demand for real test environments in the future, several such test fields will be necessary throughout Germany. In order to be able to meaningfully coordinate the abundance of all future test field activities, these will be bundled in a network in which the DLR with its National Test Centre for Unmanned Aerial Systems plays a central, integrative role.

While Bavaria is stepping up its investment programme and intends to invest 2 billion euros in science and research by 2023, including unmanned aerial vehicles, the Federal Government is investing in the former coal-mining regions of North Rhine-Westphalia, Brandenburg, Saxony and Saxony-Anhalt. NRW benefits from 2.6 billion euros, Brandenburg from 1.9 billion euros, Saxony from 1.8 billion euros and Saxony-Anhalt from around 1 billion euros. The Federal Government is investing in technology research in these regions to develop

DEMONSTRATOR PLAN FOR THE DEVELOPMENT OF TECHNOLOGIES FOR ENVIRONMENTALLY FRIENDLY AIR TRAFFIC

DLR INITIATIVES

H2HEP: Modular test carrier for hybrid-electric architectures

Propulsion integration

Conversion of a modular test carrier for hybrid-electric architectures

Continuous test flights with different architectures

Integration of fuel cells in the feeder class

Electrical maiden flight of the test carrier

Test carrier for H2 and E components in the 500 kW class

Fuel cell system ready for approval

Evaluation of different hybrid-electric architectures of the 500 kW class (e.g. fuel cells, H2-GenSet, co-optimised burner)

H2Atmo: Practical laboratory for hydrogen combustion under real flight conditions

Hydrogen combustion in general aviation

Further measurement campaigns

Parallel hybrid experiment in the regional class

Hydrogen combustion in the regional class

First quantified emission measurement or hydrogen combustion

First flight with parallel hybrid architecture in the 1.5 MW class

Proof of the climate effect of water vapour at real flight altitude

Comprehensive data on the climate impact of water vapour emissions from an optimised parallel hybrid drive

SAFinFlight: Alternative near-drop-in fuels in conventional gas turbines

Functional verification

SAF and routes

Co-optimised gas turbine and SAF

First verification of function and proof of climate impact

Comprehensive comparative data for adjusting approval processes and sustainability criteria

Climate-optimised conventional gas turbine as a comparison system for hydrogen and hybrid-electric architectures

INDUSTRY

H2EnergyBird: Ground tests for hybrid wide-body aircraft

Ground tests for hybrid wide-body aircraft

Hybrid propulsion in the large aircraft class

Optimisation of the components

Validated large aircraft ground test stand in realistic scale

H2Urban: Wasserstoff-Hybridarchitekturen im Bereich Urban Air Mobility

Hybrid architectures with vertical takeoff

Integration of a hybrid electric propulsion concept in a VTOL configuration for Urban Air Mobility

Year 2020 2025 2030

🟨 E-Flight 🟧 Hydrogen ⬜ Fuel cells 🟥 SAFs and routes and establish new forms of industry, all of which are to contribute to the environment and a better climate. In these regions, a structural change towards new branches of industry such as unmanned flying would be conceivable.

8.2.
THE AVIATION RESEARCH PROGRAMME (LUFTFAHRTFORSCHUNGSPROGRAMM - LUFO)

Research within the aviation research programme of the Federal Ministry of Economics and Energy (BMWi) to strengthen the German aviation industry will, among other things, drive forward the further development of future technologies such as new thermal engines, hybrid-electric aircraft and hydrogen technologies in the coming years. The holistic view of the digitalisation of aviation in connection with climate-friendly flying is becoming increasingly important.

In the debate about climate-friendly flying and digital transformation, not only the aircraft itself must be considered, but also the preceding production processes and materials. The challenges for future aircraft include high adaptability to customer needs, efficient rate ramp-up and a complex global, sustainable supply chain, regardless of whether it is the propulsion system, the cabin or the structure. Due to the energy density of hydrogen, fuel cells could be further developed into the energy suppliers for long-range aircraft. To achieve this, however, the functionality, risks and safety should first be tested in smaller aircraft classes. Some aspects such as the efficiency of the propulsion system have a particular influence on the configuration and therefore need to be further investigated. Fuel cells have a relatively low power density, which may limit airspeed and reasonable ranges. Especially because of the low operating temperature of low-temperature fuel cells, cooling is not only a technological challenge, but may result in a significant loss of performance at the aircraft level. Further developments in the field of lightweight construction can partially compensate for these performance losses.

RECOMMENDATION: FLIGHT DEMONSTRATOR FOR HYDROGEN FUEL CELLS IN THE FEEDER CLASS

All these properties could be optimally investigated by a flight demonstrator – a flight demonstrator with fuel cells in the feeder class of around 500 kW. This would be the first flight of a fuel cell propulsion system in the 500 kW class. Such a demonstrator would enable research into the integration of these components into the aircraft, including cooling, power distribution, new structural concepts and certification, which could deliver a fuel cell system for 500 kW engines ready for certification. While research continues to use the demonstrator as a test bed, the industry could concentrate on the development of a larger product.

Fuel cell systems are also being investigated with regard to their possible scaling. However, this requires further research efforts in power density and cooling. This requires the development and testing as well as integration solutions for cooling concepts for fuel cell systems in the MW range.

Other interesting projects within LuFo could include the monitoring of local air quality to better understand the effects of combustion and its impact on human health. Thus, measurement methods could be investigated to establish a basis for future measurement standards.

Fuel impacts are complex and affect different disciplines and industries. The development of a digital platform for interdisciplinary cooperation is necessary for the comprehensive evaluation and optimisation of the fuel-aircraft system. This will enable linking process simulation and cost analysis for a comprehensive evaluation platform of alternative fuels, from production to use. In addition, a techno-economic

> *“In the debate about climate-friendly flying and digital transformation, not only the aircraft itself must be considered, but also the preceding production processes and materials“.*

and techno-ecological evaluation of new manufacturing processes as well as a cost-benefit evaluation of fuel performance versus manufacturing costs are required. At the overall system level, the influence on fuel infrastructure, aircraft performance and maintenance cycles must be researched in order to quantify the fuel effects on the entire value chain in the aviation industry. Currently, production capacity is an obstacle to large-scale introduction. Projects investigating PtL (Power to Liquid) production on a semi-industrial scale are important in order to analyse the production of promising fuels and to evaluate upscaling to large industrial levels.

The development and investigation of battery systems for aerospace applications will also lead to maximising power density, analysing cooling solutions and increasing safety through more redundancy and improved monitoring.

LuFo will also support projects on hydrogen combustion. In order to optimise hydrogen combustion, a hydrogen combustion chamber system will be developed and brought to a flight demonstration. In addition, a combustion chamber system will be developed that allows the reliable combustion of hydrogen. Further aspects such as fuel storage, increasing the gravimetric storage density, control and flight integration will be investigated in order to achieve emission optimisation in the future.

8.3.
FURTHER MEASURES ON THE NATIONAL LEVEL

The critical disadvantage of battery-electric aircraft is the low energy density of the battery. This means that a large mass is needed to store a lot of energy. The maximum storage capacity in relation to battery weight is currently 230 Wh/kg, which is about a factor of 25 less than that of kerosene with 11,900 Wh/kg. Even for regional aircraft, an energy density of about 1,000 Wh/kg would be necessary. Battery-powered aircraft will therefore not be suitable for energy-intensive applications such as mass transport over long distances in the foreseeable future. They are, however, suitable for travel within conurbations or feeder aircraft to regional airports. Nevertheless, in the future aircraft can be designed in such a way that a significant proportion of short deployments (up to ~800 km) will be fully electric with batteries as the energy source.

Besides the development of components, there is a significant need for research in the understanding of the different hybrid electric systems. To answer these questions, numerical analyses as well as systematic experimental, realistic coupled investigations on suitable test carriers are necessary.

RECOMMENDATION: FLIGHT DEMONSTRATOR FOR SHORT-HAUL ELECTRICAL PROPULSION ARCHITECTURES

The construction of a modular test carrier with which the corresponding components can be tested in a real environment would be ideal. This would require the conversion of an aircraft in order to develop a flying test carrier for electric components in the 500 kW class. Initially, a battery-electric configuration would be conceivable, then moving on to fuel cell propulsion systems via turbo-hybrid electric propulsion. This would optimise the batteries, electronics, motor, control, superconductivity and fuel cells in order to simultaneously improve the components and their integration.

> *“In the course of retrofitting the engine of a regional aircraft for hydrogen combustion, flight tests could be carried out to quantify the atmospheric effects and determine the efficiency of the technology“.*

RECOMMENDATION: FLIGHT DEMONSTRATOR FOR HYBRID PROPULSION ARCHITECTURES IN URBAN AIR MOBILITY

The growing need for mobility can be supplemented by unmanned flying. Such vehicles are normally VTOLs (vertical take-off and landing aircraft) and battery-electric powered. Although this propulsion concept enables emission-free flying, it is limited in terms of flight duration and range due to the current state of technology in battery power. An alternative would be a hybrid-electric configuration consisting of fuel cells and batteries. These would be integrated on an adaptive VTOL platform, thereby addressing the specific integration aspects related to this platform. The performance should be studied in flight to evaluate the improvement in flight time and range in a realistic environment and to identify the potential risks.

RECOMMENDATION: FLIGHT DEMONSTRATOR FOR HYBRID PROPULSION AND APPROVAL FOR A SECONDARY ENERGY SYSTEM IN THE LARGE AIRCRAFT CLASS

The considerable potential of hydrogen and fuel cells has already been demonstrated. However, the possible use of fuel cells is not limited to propulsion but is also suitable for the secondary energy system. However, further research is needed for this purpose. To this end, it would be important to set up a validated large aircraft ground test bed on a realistic scale, which could be used to further develop various fuel cell applications. This would allow to specifically investigate under real conditions topics like the propulsion system on the ground, the functions of a system-integrated lightweight structure, the cabin power supply and performance and weight-optimised decentralised hydraulic power packs as an alternative to the central hydraulic circuits that are no longer available. Such a demonstrator would also provide the opportunity to optimise the corresponding components. The results would prepare the ground for the future development of a real-scale hybrid propulsion system for the secondary energy system in the large aircraft class, including the necessary adapted lightweight structure. Today, the design and approval of such aviation concepts raises a multitude of questions that can often only be answered if the coupled system of operation, vehicle and propulsion technologies is considered together. Such a realistically scaled prototype would also serve to clarify certification issues.

RECOMMENDATION: FLIGHT DEMONSTRATOR FOR HYDROGEN COMBUSTION FOR MEDIUM- TO LONG-HAUL FLIGHTS

Retrofitting an engine of a regional aircraft for hydrogen combustion would enable flight tests that quantify the atmospheric effects and test the efficiency of the technology. For example, water vapour emissions in the atmosphere could be studied to better understand its complex processes. Initially, compatibility with gas turbines could be investigated, including new combustion chambers. At the same time the relationship between flight control and the effect of water vapour emissions could be further investigated in order to reduce the climate impact of this technology as far as possible. The result of such a flight demonstrator would then be hydrogen combustion tested under altitude conditions, including quantified climate impact. Meaningful follow-up activities would be the industrial development of a hydrogen engine for the A320 class and the performance of further measurements in the research area in order to optimise route guidance.

RECOMMENDATION: SUSTAINABLE FUELS AND ROUTING FOR ALL AIRCRAFT CLASSES

The effects of drop-in fuels can ultimately be directly maximised by higher blending rates (>50%). So-called aromatics-free near-drop-in fuels are ideal for minimising climate impact. There is currently no approval for such fuels. Since the blending limit of 50% (or 10% for SIP) represents a safety buffer, reliable methods for fuel evaluation and aircraft component design are required, for example, testing all gaskets. Further research projects are needed for the precise comprehensive identification of the relationships between fuel composition and aircraft.

By co-optimizing fuel and burner, near-drop-in fuels can reduce CO_2 emissions by up to 80%, soot and particulate emissions by up to 90% and NO_x emissions by almost 100%. This requires research into the development of fuel-sensitive methods for the design of fuel-optimised components. Long-term measurements of real passenger flights with near-drop-in fuels would provide the necessary measurements in real environments to optimise the fuels in connection with combustion. This would allow both CO_2 and non-CO_2 emissions to be minimised, especially if the flights are guided by climate-optimised routing. This would provide comprehensive data for adjusting approval processes and sustainability criteria. Initially, the industry should switch to alternative fuels, while research continues to investigate optimised route guidance.

The design of the wing and fuselage, the aerodynamic integration of engine and tail units, drag minimisation and systematic lightweight construction are among the key technologies on the way to emission-free flying. It is therefore necessary to integrate all the individual technologies in aircraft design across disciplines in order to develop the individual advantages into a double-digit percentage overall advantage for the aircraft. At this point, it should be pointed out once again that improvements in aerodynamic quality and a fundamental new concept of lightweight system design are, in addition to the engine, essential "enablers" for fuel-efficient and economical operation of climate-neutral aircraft.

Here, the technical and economic feasibility, including questions of resilience as well as safety and acceptance by the public, must be investigated. For the use of new energy sources such as hydrogen or even electricity, new infrastructure must be created to distribute the energy to the airplanes. All these aspects have to be considered in all demonstrators in order to achieve the lowest possible climate impact as well as to evaluate their feasibility and economic efficiency.

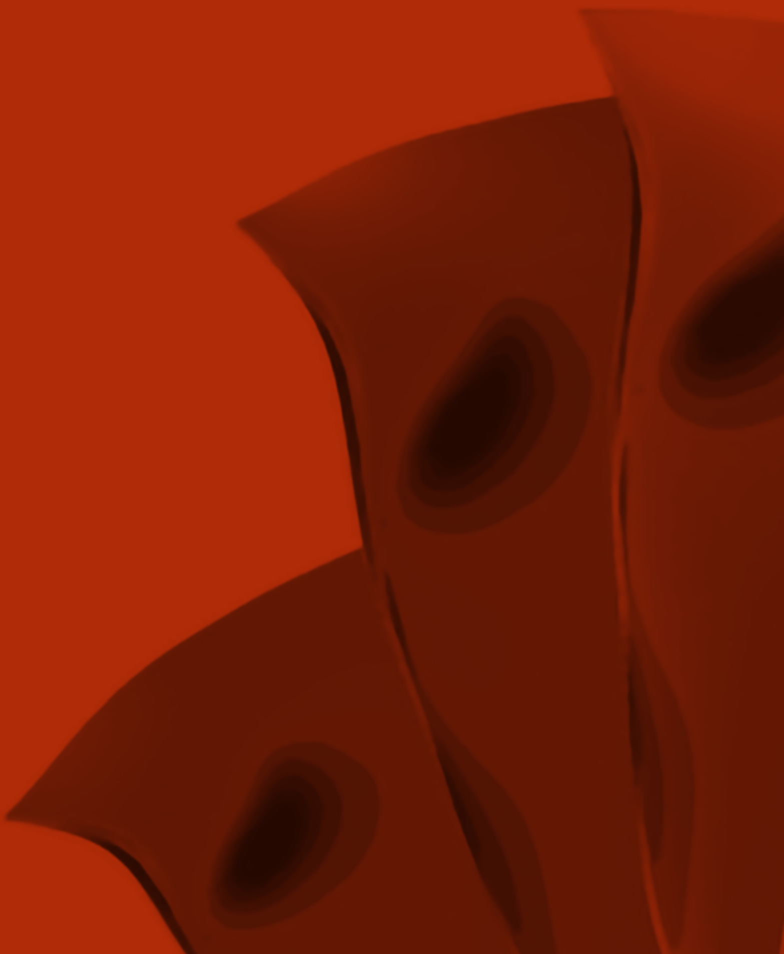
8.4.
EU LEVEL

On the basis of the European Commission's "Green Deal", significant funding for climate-relevant research and thus also for environmentally friendly air traffic is expected within the next European Research Framework Programme "Horizon Europe" (2021-2027). In line with the Clean Sky approach to date, private stakeholders are proposing a total volume of 12 billion euros for a possible "Clean Aviation" partnership, with 4 billion euros in funding for electrical and hybrid-electrical flight, highly efficient gas turbines and alternative fuels. In addition, the Commission's regular work programmes include other topics on climate-neutral air transport and a European demonstrator with a volume of around 5 billion euros is also conceivable.

Furthermore, synergies are planned with expected partnerships on the topics of ATM (successor to SESAR 2020), fuel cells (successor to FCH2), batteries (new partnership), circular economy (successor to BBI) and digitalisation (successor to ECSEL). These partnerships are also to be flanked by regular Commission work programmes. However, the exact scope of European funding, technical content and funding instruments are not expected until the end of 2020.

CONCLUSION

9



With the vision of emission-free air traffic, aviation has set itself a lofty goal. In order to reduce its ecological footprint to zero, significant developments are needed in the listed areas of sustainable fuels, new energy sources, new aircraft concepts and components, and alternative propulsion solutions. Due to the high degree of maturity of current aircraft, completely new radical technologies must be considered. In addition, all aspects have an impact on the aircraft level. This means that for a smooth integration of new technologies into the overall system, changes to the configuration of the aircraft are necessary, which are reflected in the entire life cycle of an aircraft. In order to be able to comprehensively evaluate all these aspects, an interdisciplinary ability to design and evaluate the overall system is required. The German aviation landscape is already well positioned in this respect, but in view of the challenges ahead it is important to maintain and further develop these capabilities.

Tomorrow's aviation is environmentally friendly, quiet and safe. The introduction of the new technologies will change the air traffic of the future significantly: the use of sustainable fuels represents great potential. Approved drop-in fuels, a mixture of synthetic and conventional fuels, can already be used in all aircraft today just like fossil fuels. However, the costs and availability of sustainable aviation fuels currently do not meet the needs of aviation and require massive investments. In the future, hydrogen will become increasingly important due to its high energy density and its considerable emission reduction potential, combined with new gas turbine concepts. Unmanned and autonomous flight is seen as a solution for fast and low-emission passenger transport in urban areas, battery-electric regional aircraft will be used for short trips within conurbations, and aircraft with propulsion concepts based on fuel cells will replace today's short- and medium-haul aircraft. Sustainable fuels in combination with new gas turbine concepts have great potential for emission reductions. The use of turbo-hybrid electric propulsion concepts and even fuel cells is also conceivable for long-haul flights.

The transformation of the aviation industry requires diverse investments in development, certification and infrastructure, as well as support for national and international political decisions. Efficient research into new key technologies and concepts requires rethinking in all areas, which means that the educational system must also adapt to future market developments. The aviation engineer of today is no longer the aviation engineer of tomorrow. Due to new market requirements, the digital transformation and the associated changes in the working world and special fields of activity in aviation, the needs of the industry are also changing in relation to academic education and large-scale industrial research. Therefore, in the context of the transformation of the aviation industry, they are required to develop concepts to be able to react adequately to these changes.

The successful introduction of key technologies for climate-friendly air traffic necessarily involves flight tests and thus a scheduled demonstrator programme. Until the global aircraft fleet is replaced by the next generation in around 20-30 years, investments in new technologies and parallel financial resources for improving current aircraft in terms of their climate impact are unavoidable. Consequently, aviation will be confronted with special efforts in the next thirty years with regard to its environmental friendliness, which research, politics and industry can only solve in a joint, coordinated effort.

Publisher
German Aerospace Center (DLR)
Linder Höhe, 51147 Cologne

Design
CD Werbeagentur GmbH, cdonline.de

Print
Meinders + Elstermann GmbH & Co. KG

Publication
11/2020

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