Technische
Universität
Braunschweig

Accelerating the path towards carbon-free aviation

Publisher: CoE „Sustainable and Energy Efficient Aviation“ (SE^{2}A) and
Aeronautics Research Centre Niedersachsen (NFL)

Editors: Jens Friedrichs, Rolf Radespiel, Henri Werij, Roelof Vos

Authors: Valentin Batteiger[a], Roeland DeBreuker[b], Irene Dedoussi[b], Jan Delfs[c], Friedrich Dinkelacker[d], Ali Elham[e], Santiago J. Garcia[b], Jens Friedrichs[f], Stefan Goertz[c], Volker Grewe[b], Wim Haije[b], Christoph Herrmann[f], Frederic Lachaud[g], Axel Mertens[d], Joseph Morlier[g], Ulrike Krewer[h], Rolf Radespiel[f], Arvind Gangoli Rao[b], Peter Schmollgruber[g], Uwe Schröder[i], Jörg Seume[d], Mirjam Snellen[b], Andreas Strohmayer[j], Leo Veldhuis[b], Irene Fernandez Villegas[b], Roelof Vos[b], Henri Werij[b], Feijia Yin[b]

a Bauhaus Luftfahrt e. V., Germany
b TU Delft, Netherlands
c DLR (German Aerospace Centre), Germany
d Leibniz University Hannover, Germany
e University of Southampton, United Kingdom
f TU Braunschweig, Germany
g ISAE-SUPAERO, France
h Karlsruhe Institute of Technology, Germany
i Universität Greifswald, Germany
j Universität Stuttgart, Germany

https://doi.org/10.24355/dbbs.084-202207041441-0

Accelerating the path towards carbon-free aviation

1. Motivation

Meeting the global mobility demands in combination with the goals on environmental protection translates into drastic requirements for reducing the overall climate footprint of the air transport system as well as for substantial reductions in noise emission, without compromising reliability, safety, and economic viability. Following these requirements means to define ways to make aviation truly sustainable by drastically reducing and finally minimizing all its operational emissions. In this respect the role of the on-board fuel or energy carrier is obvious. By burning fossil fuel CO_2, other gaseous and aerosol emissions are released into the atmosphere, affecting air quality and contributing to enhanced global warming. Already on the energy carrier level several options to tackle this issue are currently on the table but a lot of uncertainty remains with suggestions about the most promising routes.

In addition to that it does not make sense just to purely focus on the fuel or energy carrier of an aircraft if an optimal environmentally friendly system is aspired. The high energy demand of transport aircraft, the physics of flight, its wide spread of operating conditions and the very complex integration and interaction of all technologies on-board of an aircraft do require to adapt and redesign all aspects of the vehicle. For good reason there is no other vehicle where shape and performance are as strongly coupled as in an airplane.

In our days, the combination of kerosene as a high-density liquid energy source with direct burning in gas turbines with high thermal efficiency combined with propulsors that provide high propulsive efficiency can be - apart from its environmental effects – considered an excellent solution for large passenger aircraft that has been optimized over decades. Changing certain properties or parameters of this system, e.g. emissions, must not lead to a problem shift which means adversely affecting other crucial parameters such as operability, safety or – above an economically tolerable margin – cost.

New technologies to make aviation more environmentally sustainable are proposed throughout academia, research, industry, and governments. Besides new energy carriers which have come to the fore as batteries, synthetic kerosene and hydrogen, many of these technologies target a certain parameter in performance: they reduce drag, weight, or the thrust-specific fuel consumption. All these promising ideas involve different potentials in energy saving, fuel burn reduction and avoidance of emission but they also require different efforts in research and development as well as investment into production to achieve the required technology readiness level for aviation. Finally, some of these ideas are not compatible or are even conflicting with others on overall aircraft level or on aviation system level.

This paper, created by a group of aviation and energy experts from renowned universities and research centres in Europe, who oversee the fields of energy carriers, energy storage and conversion, propulsion, aerodynamics, flight mechanics, controls, structures, materials, multidisciplinary design, and life-cycle engineering, aims to give an overview and assessment of promising future technologies. The paper therefore identifies the potential as well as research demands of these technologies on the path to a sustainable and more environmentally friendly aviation.

2. Methodology

Defining the needs for long-term research and technology development in the fields of future aviation energy carriers, propulsion systems, vehicle technologies and aircraft design to master the transformation to sustainable aviation of the future is difficult. It needs comprehensive insight into the current status of those energy and aircraft technologies that offer viable potential for the next decades of aircraft operation from a technological and performance perspective, as well as regarding the economic framework of availability and costs. Here, yet unexploited synergies with new systems for energy storage and power conversion have to be taken into account.

Individual technologies were then evaluated according to:

- Technology description and potential
- Complexity, associated risks and research demands

The technology descriptions provide a first-order characterisation of the main technology scope and its current readiness for application as well as a judgment of the present research intensity in Europe.

Technology complexity is an important dimension within the individual areas and across the disciplines and use phases because it determines the cost and risk of implementation. The expected outcome of new technology and its effect on the aircraft value is a measure of attractiveness for both the manufacturer and the air carrier. Moreover, the technology effect on societal, overarching needs and goals may be evaluated. Here, the group evaluated the potential for resource savings in propulsive power and hence fuel, waste of raw materials, CO_2 and other emission reductions, the resulting economic technology value, and re-cycling potentials. The authors of this study wish to emphasize that such numbers are subjected to significant uncertainties that reflect today's rather limited knowledge. Uncertainties on future technology impact are especially high in cases where simultaneous technological progress in several areas is required to advance technology readiness. In some cases, a vision of the potential value of a certain technology does exist, but quantification is not yet possible. The metrics associated with these evaluation dimensions were qualitatively rated by using only three levels, namely "low", "medium", "high", as such prediction into the future bears significant uncertainties.

3. Energy carriers

3.1. Introduction

This chapter gives an overview of the most relevant options regarding energy carriers for future air transport by discussing the current status of the technology required, the main challenges, possible showstoppers, and guidelines for further research and development.

The starting point for the quest toward climate-neutral aviation is to look for net carbon-free energy carriers while taking the whole cycle into account. However, it is certainly necessary to address non-CO_2 effects (NO_x, soot, water vapour, SO_x, O_3, contrails, cirrus-clouds, etc.) as well, since the non-CO_2 emissions also contribute to global warming equally or even more than CO_2. In this discussion, the timescale plays an important role. We have to distinguish between long-term and short-term effects. CO_2 accumulates in the atmosphere having a long residence time, whereas the average residence time of water is much shorter. Contrails and cirrus cloud formation play an important role in the radiation balance of the Earth and on average lead to forcing of global warming. Avoiding contrail formation and, therefore, the aviation-induced cloudiness might require flying at lower altitudes, which then affects future aircraft design. Furthermore, burning fuels with low soot emissions alters the characteristics of contrails, and therefore, the contrail's climate impact. The cruise flight level is also important for the lifetime of emitted NO_x. The higher the altitude, the higher is the lifetime of NO_x and its adverse effect on the climate. We thus need to have an integrated view when considering the impacts of emissions.

To allow for a careful and balanced assessment of aviation energy carriers and its conversion processes a classification into climate-neutral operation and CO_2-neutral operation and its related technology is recommended. Climate-neutral operation is the strictest criterion and appears to be fully achievable only based on battery-stored, green electric energy. CO_2-neutral operation still bears a climate impact driven by gaseous and aerosol emissions (see also chapter "Climate Impact"), requiring additional mitigation measures.

Energy carriers considered

For this study, the following sustainable energy carriers are considered, while comparing these with fossil jet fuel.

- Batteries (Li-ion, other)
- Liquefied hydrogen
- Biofuels
- Synthetic kerosene
- Liquefied synthetic methane or bio-methane
- Ammonia

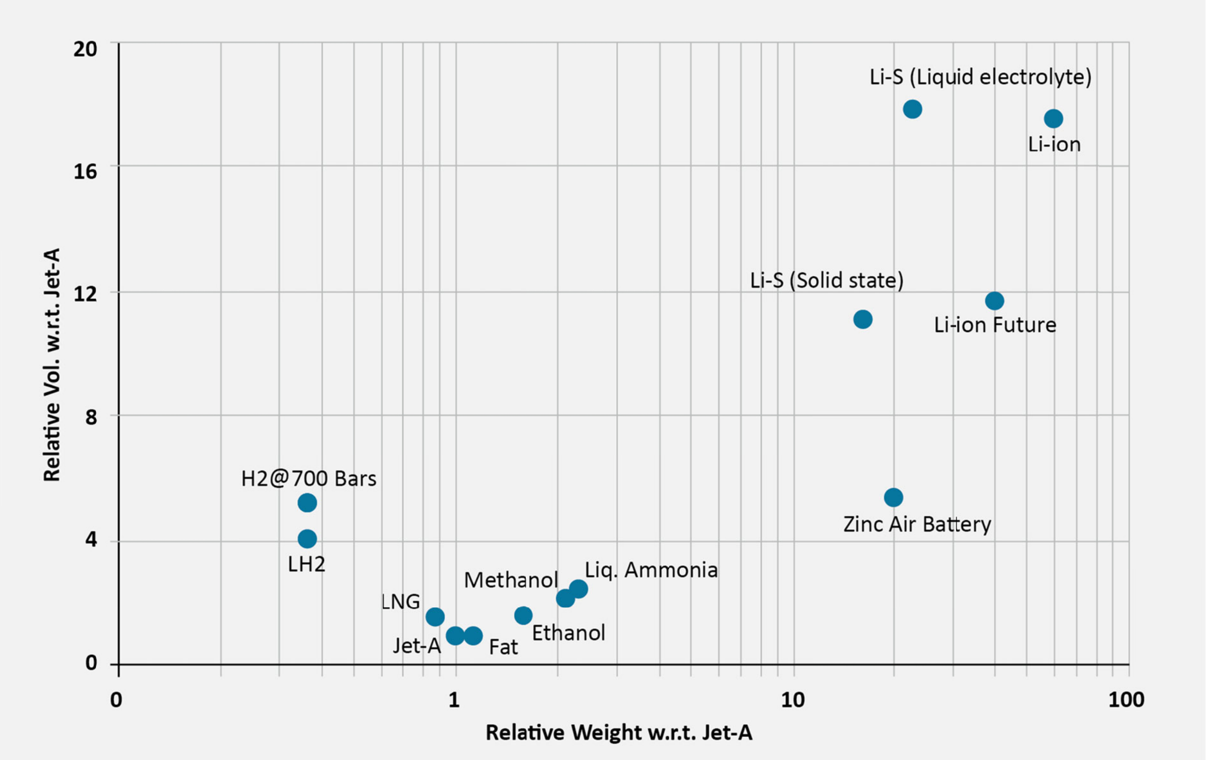

Fig. 3.1 *Weight and volume comparison of various energy carriers w.r.t. kerosene for identical energy content*

When comparing different energy carriers, several factors have to be considered, many of which are interrelated. In particular, we mention:

- Energy density (both gravimetric and volumetric energy density)
- Emissions and climate impact (including both CO_2 and non-CO_2 effects)
- Overall energy efficiency in terms of shaft power divided by primary power source needed to produce the on-board fuel/energy carrier. As mentioned before this will include the conversion efficiency considered in this chapter and the energy-to-propulsion efficiency mentioned in the next chapter.
- Availability of sustainable energy, feedstock, raw materials or scarce materials
- Production, transport and storage, including infrastructure, TRL and time required to reach TRL6
- Cost of fuel (depending on above mentioned parameters)
- Safety
- Compatibility with infrastructures, airports and current aircraft

3.2. Batteries

Technology description and potential

When using green electricity as a starting point, batteries in combination with electric propulsion are the optimal choice from an energy efficiency point of view, since energy losses while charging and discharging are small and the efficiency of electric engines is superior when compared to any kind of combustion engine. Also, no direct emission occur during the flight, while the CO_2 emission per passenger kilometre related to the production of the batteries is approximately an order of magnitude less compared to conventional aircraft using kerosene, assuming 1000 battery charge cycles. However, the big issue is the relatively small specific energy a.k.a. gravimetric energy density (MJ/kg).

For the cruise phase of flight, the following equation holds: $Range = \frac{E_{available}}{m_{aircraft} \cdot g} \cdot \frac{Lift}{Drag} \cdot \eta_{overall}$

Where lift and drag are representing the aircraft efficiency and $\eta_{overall}$ is the total efficiency from battery power to propulsive power (cf. chapter II), $E_{available}$ is the available stored energy from the battery and $m_{aircraft}$ is the mass of the aircraft including payload and batteries. Compared to kerosene this shows not only the demand for high battery energy density but also the aspect of a constant $m_{aircraft}$ along a battery-driven mission compared to a continuous mass reduction when fuel is burnt. For metal-air battery, weight even increases during a mission.

For transportation and especially for aviation, it is obvious that the gravimetric energy density of the battery packs should be as large as possible. Therefore, a lot of research is being carried out worldwide (at universities, research institutes and industrial labs) with the goal to increase battery energy densities, by improving both the positive and negative electrode material and the used electrolyte. Unfortunately, a lot of the information on the latest battery improvements is proprietary or incomplete with regard to the system or application level. Currently, the best performers in terms of practical energy density achieved at reasonable current rates at larger cells are Li-ion batteries using a liquid electrolyte. By modifying the cathode and anode composition (e.g., by replacing part of the Co atoms in the cathode by Ni and Mn), it is possible to increase the energy density, but this typically leads to a decrease of the battery life in terms of useful charge/discharge cycles. This is related to the mechanical stress in the electrodes when absorbing and releasing Li-ions, which demands more research in degradation mitigating measures. Another promising development is the research in solid-state batteries, where the liquid electrolyte is replaced by a solid electrolyte (polymers, ceramics, or a combination thereof).

Regarding the available specific energy of a battery pack, it is important to realize that this is always lower than that reported for a battery cell. Factors we have to take into account include:

- **Lifetime:** Specific energy drops with the number of charging/discharging cycles
- **Minimum State of Charge:** At least 10% (or even 20%) of the total charge should remain in the cell at all times
- **Maximum State of Charge**: Cells can be charged to around 90% of their full capacity, else the battery life is adversely affected
- **Temperature**: the optimal operating temperature for Li-ion cells is around 15-35 °C. The specific energy and lifetime of battery cells decreases rapidly if the temperature deviates from the above-specified range.
- **Rate of discharge**: The effective energy density reduces if the batteries are discharged faster.
- **Packing**: Battery cells must be put in a pack for mounting, control electronics, thermal control (lowering the specific energy, a.k.a. gravimetric energy density, by approximately 30%)

As a result, the gravimetric energy density of a battery pack (including the cooling system) is typically around half of that of the cells. Nowadays the best Li-ion battery cells have a specific energy of close to 400 Wh/kg. If one assumes a useful pack density that amounts to 50% of this value, while the battery pack takes 25% of the total aircraft mass including payload, an L/D ratio of 20 and $\eta_{overall}$ = 80%, a range of ~290 km is obtained, without taking into account energy needed for the taxi, climb, avionics, heating, reaching an alternate airport after a missed approach, contingency (headwind, routing changes) and 30 to 45 minutes final reserve for holding patterns.

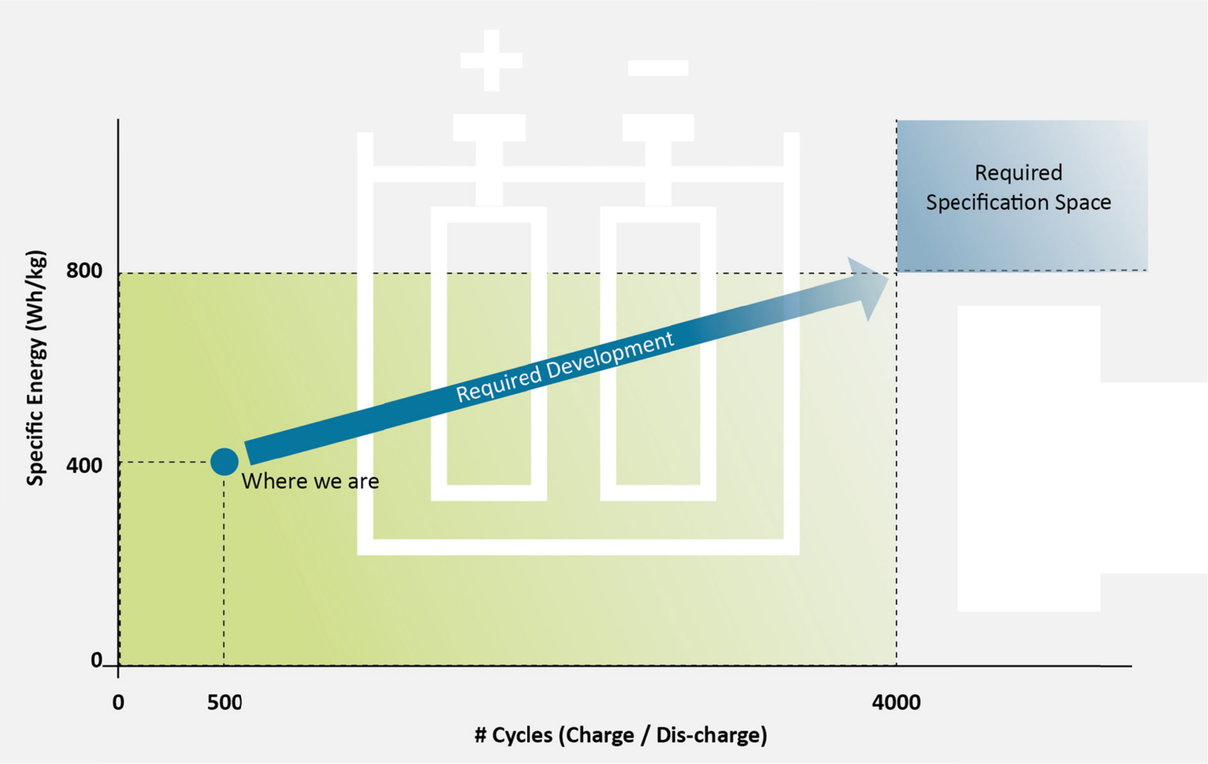

Fig. 3.2. *Required development of battery energy density and the available number of charging cycles.*

Research demands, complexity and associated risks

It is clear that a lot of progress will have to be made for battery-powered aviation to take off, even for being viable at a regional level. It is difficult to predict the development in the next two decades. To set the bar for battery developers from an aviation point of view, the gravimetric energy density at cell level should be around 800 Wh/kg (also at operational temperatures), capable of delivering high power (without significantly lowering the available energy), while at the same time being capable of going through at least 4000 discharge/charge cycles before losing 10% of the specific energy. In other words, not only the energy density should be increased (which has the tendency the lower the number of charging cycles), but also the available numbers of cycles by a significant factor. This implies that the necessary battery development (in terms of specific energy times available charging cycles) does not just require a factor of two improvements but a leap of one order of magnitude (see Fig. 3.2).

Figure 3.3 shows the specific (gravimetric) energy density and volumetric energy density of various battery types that are being used today and are in development. It can be seen that the energy density is reduced at the system level due to thermal management and power management issues. Therefore, the packing of cells should be further improved to keep energy density at pack level as high as possible. Availability/scarcity, environmental effects, e.g., related to the mining of elements like Cobalt, geopolitical aspects and energy required to manufacture batteries have to be considered as well.

Even when the above battery specifications are reached, additional improvements will be needed in other areas of the aircraft to achieve a range of 1000 km, while still having enough energy for necessary reserves. Despite the big advantages of batteries in terms of energy efficiency and the absence of any emission, for the vast majority of passenger-kilometres flown, another form of sustainable energy carrier must be considered.

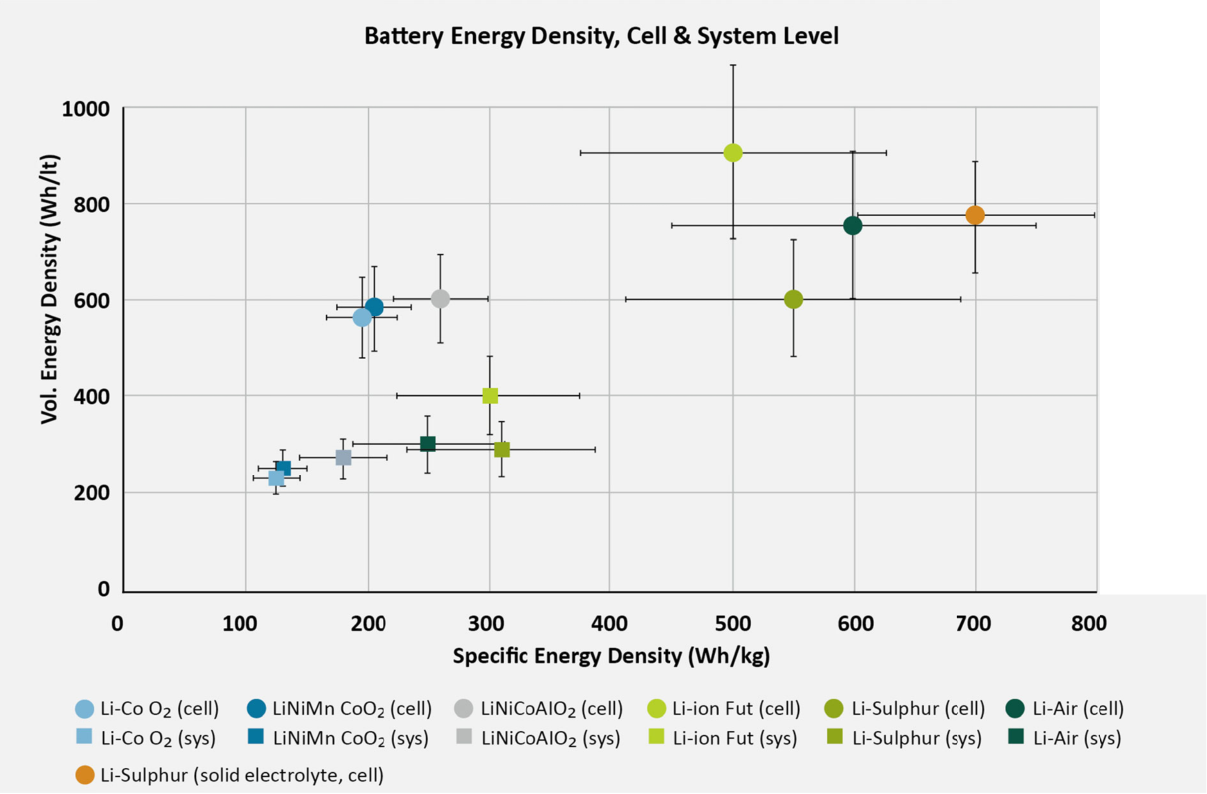

Fig. 3.3: *Representative energy density (volumetric and gravimetric) of some battery types, both at the cell level and system level*

3.3. Liquefied hydrogen

Technology description and potential

Hydrogen is considered to play a crucial role for future energy carriers in aviation. Either directly as an on-board energy carrier (for use in fuel cells or combustion systems) or as an ingredient in the production of sustainable aviation fuel (based on biogenic feedstock or CO_2 captured from the air).

The advantage of H_2 as an energy carrier is its high specific energy (33 kWh/kg), which is almost three times higher than that of kerosene. However, taking into account the weight of the storage tanks, the weight advantage of hydrogen is significantly reduced but is still a factor of 2 higher compared to the case of kerosene[1]. The disadvantage of H_2 is its relatively low volumetric energy density, which even in the liquefied form is a factor of four lower than that of kerosene for the same energy content. The volumetric energy density of gaseous H_2 pressurized at 700 bar is roughly 5 times lower than that of kerosene. The danger related to extremely high pressures and lower volumetric energy density make pressurizing a less preferred option compared to liquefying. Moreover, the weight of the storage vessels for higher pressures is more than that required for cryogenic storage. Liquid H_2 should be stored at cryogenic temperatures (<20 K), at normal pressures. However, the insulation required to prevent the cryogenic liquid from boiling significantly increases the volume of the storage vessel. Therefore, it is obvious that the increased volume requirement of storing LH_2 will have a detrimental effect on the overall aircraft L/D ratio and therefore will play a significant role in designing future H_2-compatible aircraft. There are different routes to producing hydrogen. For greener aviation, the following options are particularly relevant:

- **Green H_2:** Made by electrolysis of water using green electricity from renewable resources (wind, PV)
- **Blue H_2:** Hydrogen made from steam reforming of natural gas with carbon capture and storage of the resulting CO_2. Even though this is not a preferred solution, the process can be adapted quickly and economically to start the energy transition in aviation
- **Pink H_2:** Made by electrolysis of water using electricity from nuclear power plants.
- **Turquoise H_2:** Thermal cracking of methane into hydrogen and carbon in such a way that the resulting carbon can be stored underground or can be used for making other products (like graphite, tyres, etc.).

When considering the green production route, the first step involves the production of hydrogen using renewable electricity from photovoltaic sources (PV), wind or other renewables. The efficiency of electrolysis is in the order of 70%[2]. When liquefying hydrogen, a significant amount of energy, in the order of 11 kWh/kg is needed. It is expected that this number will drop down to 7 kWh/kg by 2030[3]. This implies that the liquefaction efficiency factor is between 75% and 80%. Another factor for storage, transportation and boil-off losses that must be considered, which depends on whether hydrogen is liquefied at the airport or the production site. The latter efficiency amounts to between 96-99%. The overall electrical power to LH_2 efficiency is therefore estimated to be around 50%.

In a trade-off between using H_2 for a fuel cell based an electric propulsion or using H_2 as a fuel for combustion, the involved conversion efficiencies, power densities and emissions must be considered. The aspect of energy conversion efficiency will be treated in the next Chapter on Power Systems. However, the emission aspect is discussed in the current chapter.

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[1] Energies 2018, 11, 105; doi:10.3390/en11010105

[2] 20200507_Hydrogen Powered Aviation report_FINAL web quality withoutISBN.PDF

[3] FINAL-Integration-of-Hydrogen-Aircraft-ACI 2021.pdf

Hydrogen in fuel cell: In view of the non-CO_2 effects, it should be stressed that when using fuel cells, the only emission product is water, which in this case is disposed of in a low-contrail-producing way due to the absence of soot or other condensation nuclei. The lifetime of the produced contrails is short and the optical depth is thin, therefore the overall climate impact is expected to be low.[4]

Hydrogen in combustion engines: When using H_2 with combustion engines, such as gas turbines, no CO_2 is emitted, but both water vapour and NO_x will be emitted. However, it should be noted that due to the lower flammability of H_2 and high diffusivity, there is a significant potential to reduce NO_x emissions as compared to kerosene. Moreover, the climate impact of contrails from H_2 combustion is expected to be lower than in the case of kerosene due to the absence of soot emissions. However, H_2 slip can add to the greenhouse effect as an indirect contributor (interaction with hydroxyl radicals, methane, and ozone).

Research demands, complexity and associated risks

To meet the huge demand for green hydrogen, a worldwide investment is needed in production and transport, which include large-scale PV facilities and wind turbines (e.g., floating wind-at-sea farms, floating solar farms, PV desert farms, etc., with on-site H_2 production). More research is required to improve the electrolysis efficiency (now around 70%), transport, and storage, which involves the development of LH_2 compatible materials, like those being needed on-board aircraft.

3.4. Biofuels

Technology description and potential

The use of biofuels in civil aviation is still at a very low level (<.1% per annum), despite a growing number of conversion pathways, which are approved as a blend stock (see Table 3.1). Biofuel blends largely resemble the physical and chemical properties of conventional jet fuels (referred to as 'drop-in' fuels), yet their molecular composition is different. Alternative fuels show a slightly higher specific energy, low sulphur and aromatic content. Consequently, the emissions and associated climate impact can be reduced by cleaner-burning fuels.

Process	Blend ratio	Feedstock	Conversion process
HEFA-SPK	up to 50%	Lipids (plant oils, fats)	Hydroprocessing, including isomerization
AtJ-SPK	up to 50%	Sugars, starch, cellulose	Fermentation, dehydration, oligomerisation
FT-SPK	up to 50%	Various organic feedstock	Gasification/reforming, Fischer-Tropsch
HFS-SIP	up to 10%	See ATJ-SPK	Fermentation of sugars into farnesane (C15)
FT-SPK/A	up to 50%	See FT-SPK	FT and alkylation of light aromatics
CHJ	up to 50%	Lipids	Catalytic hydrothermolysis
HC-HEFA	up to 10%	Hydrocarbons, lipids	Similar to HEFA specific to one algae species
Co-processing (5%vol)		FT syncrude, lipids	Co-processing in crude oil refineries

Table 3.1: *Summary of seven approved alternative fuel pathways (ASTM D7566, 2020). Furthermore, limited amounts of up to 5%vol FT syncrude or lipids may be co-processed in conventional refineries (ASTM D1655, 2020).*

So far, aviation biofuels are mainly produced from hydro-processed plant oils and fats (HEFA). The conversion technology is proven and commercial plants are in operation, the main bottleneck is the

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[4] Girrens, K., Theory of Contrail Formation for Fuel Cells, Aerospace, 8, 2021

availability of sufficient and sustainable feedstock. Staples et al. estimate the potential future availability of waste oils, fats and greases at 23 Mt/yr[5]. A comparison with the current biodiesel production of 35 Mt/yr shows that a significant expansion of the lipid-based diesel and jet fuel pool will induce additional demand for plant oils. Due to environmental concerns, EU legislation caps the use of food and feed-based biofuels at max. 7% share, biofuels with high indirect land use should be phased out by 2030. Consequently, the bulk volume of the future jet fuel demand needs to come from additional feedstock. Alcohol-to-Jet (AtJ) pathways synthesize kerosene via fermentation of sugars, starch or cellulosic sugars. The Fischer-Tropsch pathway converts intermediate synthesis gas (H_2 and CO) that can be derived from various organic feedstock via gasification or reforming. Further pathways, such as pyrolysis or hydrothermal liquefaction (HtL) thermo-chemically convert various organic materials into intermediate oils, which get subsequently upgraded to fuels. However, pyrolysis and HtL fuels are still under development and approval for civil aviation is pending.

Research demands, complexity and associated risks

None of the mentioned biofuel pathways is competitive with the recent average jet fuel prices. In turn, regulation or supporting schemes are required to induce biofuel demand. It is of particular importance to justify such support by credible sustainability benefits in terms of climate impact, but also many of the sustainable development goals. Key performance indicators include land demand, water footprint, eco-toxicity, biodiversity as well as sustainability indicators that measure the socio-economic impact of biofuel production in mainly rural environments.

When compared to the Power-to-Liquid (PtL) fuels, mentioned below, the amount of land surface required for bio-kerosene is typically at least one order of magnitude higher, while the water demand is several orders of magnitude larger[6]. Therefore, it is unlikely that biofuels will play a dominant role in replacing the current massive amounts of kerosene as a more sustainable energy carrier I the long term. On the other hand, biofuels still seem to be more cost-effective than PtL fuels. Therefore, when using organic waste streams (e.g. a by-product of food production), producing biofuel remains an attractive option, be it that the total biofuel amount will remain a small fraction compared to the worldwide demand for fuels, such as kerosene. The total yearly production of all biofuels amounts to 120 million metric tons, a majority of which is used in road transport. Compared to that, the total need for jet fuel alone is approximately 350 million metric tons per year.

Although biofuels (and also for PtL) can be balanced as CO_2-neutral, the non-CO_2 emission impact has to be regarded as well. According to chapter 8 below, this impact can be in the order twice that of the direct CO_2 impact. Therefore, if kerosene is just replaced by bio-kerosene the overall impact is reduced from 3 to 2 times the pure CO_2 impact but not to zero impact. Most aviation biofuels do not contain aromatic hydrocarbons and will therefore reduce soot emission compared to conventional jet fuel, while NOx emissions are barely affected by current biofuels. In consequence, non-CO_2 climate impact is reduced but not eliminated.

Eventually new "advanced synthetic fuels" might be found, where the particle, NOx and contrail impact is reduced drastically[7], than the situation of the overall environmental impact would be

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[5] M.D. Staples, R.Malina, S.R.H. Barrett: The limits of bioenergy for mitigating global life-cycle greenhause gas emissions from fossil fuels, Nature Energy 2, 16202, 2017. ISSN 2058-7546

[6] V. Batteiger, P. Schmidt, K. Ebner, A. Habersetzer, L. Moser, W. Weindorf, T. Rakschaet al:. Power-to-Liquids – A scalable and sustainable fuel supply perspective for aviation, Background Paper, German Environment Agency, 20202022, www.umweltbundesamt.de/publikationen/power-to-liquids

[7] A. Goldmann, W. Sauter, M. Oettinger, T. Kluge, U. Schröder, J.R. Seume, J. Friedrichs, F. Dinkelacker: A Study on Electrofuels in Aviation, Energies 2018, 11, 392, pp 1-23; DOI:10.3390/en11020392

improved significantly. Recent research proposes some alcohols as potential candidates[8] for an ultra-clean lean prevaporized premixed combustion concept, being however so far in an early research status.

Regarding the direct use of alcohols as the on-board carrier, methanol, ethanol, n-propanol, and n-butanol are liquids at normal pressure and temperature. Their gravimetric and volumetric energy density is half to two-third of that of kerosene. The mentioned alcohols are all fossil feedstock based except ethanol. They are toxic and cannot be dumped. These fuels can be blended to a certain extent. Alcohols do tend to change the combustion processes and further properties of the fuel. Therefore more research is needed in this area to investigate the suitability of alcohol blending with kerosene and its impact on aircraft performance, engine performance, combustion dynamics, emissions and climate impact.

3.5. Power-to-Liquid (PtL) and solar fuels

Technology description and potential

Compared to biofuels, synthetic fuel production from water and CO_2 via Power-to-Liquid and solar fuel pathways can achieve much higher area-specific yield. In case of solar fuels suitable areas are complementary to areas for agricultural production, while wind turbines cover only a small fraction of the land such that agriculture is still possible[Fehler! Textmarke nicht definiert.]. Also, the water demand is substantially less, a very important factor given global fresh water scarcity. When starting from solar energy, we can follow two main routes: 1) using solar heat; 2) using photo voltaic-generated electricity. The latter route is the same for any other renewable electricity source (wind, water).

Solar fuels: Solar fuels production involves photo-electrochemical or thermochemical technologies to directly split water and/or CO_2 (preferentially obtained using direct air capture), a syngas is created, which by using a Fischer-Tropsch process is converted into liquid hydrocarbons, including kerosene[9]. For thermochemical redox cycles this has been demonstrated experimentally in the European Union's Horizon 2020 SUN-to-LIQUID project[10]. Desert-like areas in several places of the world in such

Electricity-based fuels (e-fuels, e-kerosene): Using renewable electricity, H_2 can be produced using electrolysis for which the efficiency is in the order of 70%[11]. Using CO_2 obtained from direct air capture, syngas is created, which by using a Fischer-Tropsch process is converted into liquid and wax like hydrocarbons, that can be further processed through hydrocracking to kerosene. The overall power-to-liquid efficiency optimized for jet fuel currently is in the range of 25%-30%. Careful choice of catalysts can improve and fine-tune the composition of the obtained kerosene[12]. The big advantage, however, is that e-fuels can be stored and transported world-wide very easily with the storage and transportation infrastructure already existing.

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[8] S. Nadiri, P. Zimmermann, L. Sane, R. Fernandes, F. Dinkelacker, B. Shu, Kinetic modeling study on the combustion characterization of synthetic C3 and C4 alcohols for lean premixed prevaporized combustion, Energies, 2021, 14, 5473. DOI:10.3390/en14175473.

[9] D. Marxer, *Demonstration of the entire production chain to renewable kerosene via solar-thermochemical splitting of H_2O and CO_2*, Energy & Fuels, 2015; P. Furler, Solar Kerosene from H_2O and CO_2, AIP Conference Proceedings 1850, 100006 (2017)

[10] E. Koepfet al, *Liquid Fuels from Concentrated Sunlight: Development and Integration of a 50 kW Solar Thermochemical Reactor and High Concentration Solar Field for the SUN-to-LIQUID Project*, SolarPACES2018, Stefan Zoller, Doctoral Thesis, ETH Zurich 2020

[11] 20200507_Hydrogen Powered Aviation report_FINAL web quality withoutISBN.PDF

[12] Daniel H. Konig, Nadine Baucks, Ralph-Uwe Dietrich, Antje Worner“ Simulation and evaluation of a process concept for the generation of synthetic fuel from CO2 and H2“, Energy 91 (2015) pp. 833-841.

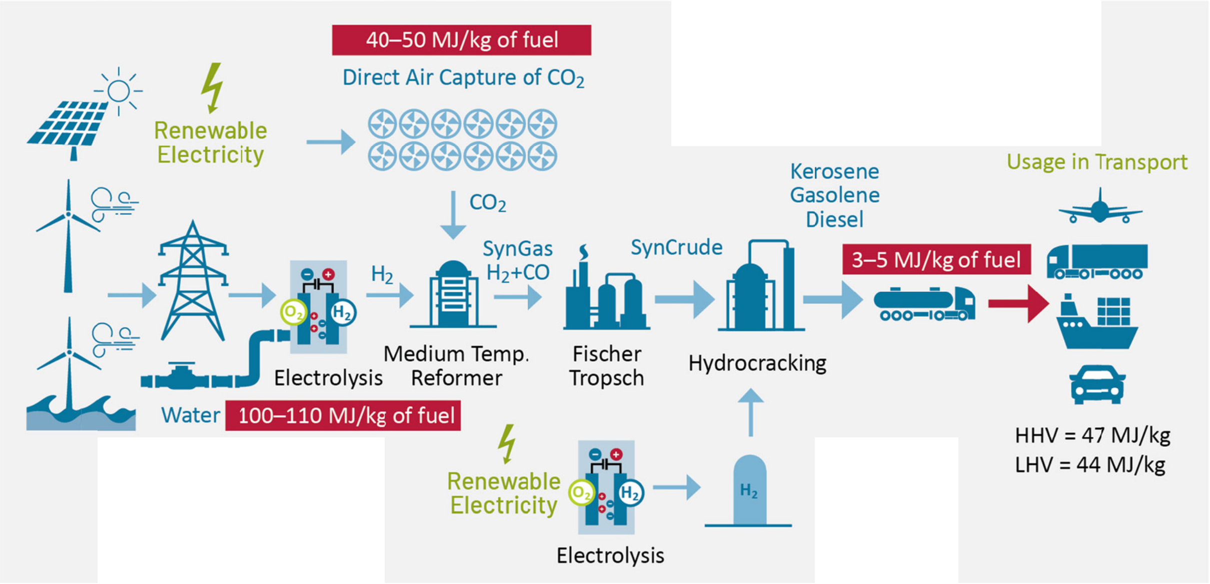

Fig. 3.4: *Schematic of processes and energy required in producing e-fuel. The amounts of energy required in the various steps are expressed (in red) in energy per kg fuel produced*

Research demands, complexity and associated risks

Currently, the efficiency of producing synthetic kerosene is very low, in the order of 25%-30% when taking direct air capture of CO_2 into account. This energy conversion efficiency should be increased towards 40% or higher since the amount of renewable energy available in the world is finite and scarce, and energy conversion efficiency is directly related to production cost and the life cycle CO_2 footprint of the fuel. Therefore, the efficiency of this process must be increased substantially in the coming years. Additionally, the impact of the non-CO_2 emissions has to be considered, as is described in Chapter 4.2 before. In general, synthetic fuels have the potential to decrease the non-CO2 climate impact compared to conventional jet fuel, mainly as a consequence of lower soot emissions. However, non-CO_2 emissions are not eliminated by synthetic kerosene.

3.6. Liquefied Green Methane

Technology description and potential

Even though methane has a carbon atom in it, the hydrogen to carbon ratio of methane is twice that of kerosene (fossil as well as synthetic), thus liquefied methane is hydrogen-rich. Some of the advantages of L-CH_4, when compared to LH_2, are as follows

- Volumetric energy density of liquefied methane is twice that of LH_2
- L-CH_4 liquefaction is less complex and less energy intensive compared to LH_2
- L-CH_4 is stored at -161°C rather than -253°C for LH_2
- Combustion properties of methane are better than hydrogen
- L-CH_4 is much safer and easier to be transported
- L-CH_4 can be mixed with LNG (liquefied natural gas)
- L-CH_4 can be made following the bio route using biomass waste

Disadvantages of L-CH4 as compared to hydrogen are:

- Direct air capture of CO_2 is required for large-scale production of L-CH_4
- Methane slip during operations can lead to global warming as CH_4 has a higher greenhouse potential than CO_2 (approximately 34 times compared to CO_2 over a 100-year period).

Producing L-CH_4 using renewable electricity and direct air capture shares similarities with the process of synthetic kerosene. Even though the efficiency of making e-LCH_4 (30-35%) is slightly higher than e-kerosene, the latter is better in terms of compatibility with current aircraft. The advantages and disadvantages of CH_4 as compared to e-kerosene are highlighted below.

Advantages of e-CH_4/bio-CH_4 over e-Kerosene/bio-kerosene

- Hydrogen to carbon ratio for e-LCH_4 is better than that of e-kerosene thereby reducing the amount of CO_2 required from direct air capture for synthesizing (around 25% less for the same energy content of the fuel)
- Higher selectivity and slightly higher energy conversion efficiency
- Combustion characteristics of Methane are better than those of kerosene, leading to significantly lower NO_x and soot emissions than kerosene
- eL-CH_4 can be mixed with liquefied natural gas
- Bio-CH_4 is an easier pathway than bio-kerosene

Disadvantage of e-CH_4 compared to e-Kerosene

- Thermodynamic equilibrium conversion of methane is roughly 8 times better than for syn-kerosene leading to intrinsic separation steps (which are expensive), also here separation enhanced methanation can help to obtain 100% conversion
- e-LCH_4 has to be liquefied. This consumes energy and reduces to overall electricity to fuel efficiency
- LNG/L-CH_4 is not compatible with existing aircraft and requires modification of airports (facilities and logistics for tanking L-CH_4 are not existing)
- L-CH_4 storage requires pressurized tanks and good insulation to keep the fuel cool, resulting in increased aircraft Operating Empty Weight (OEW)
- CH_4 is about 33 times more potent greenhouse gas than CO_2 and therefore, methane slip is harmful for global warming.

Research demands, complexity and associated risks

Since e-CH_4 is made in a similar way as e-kerosene, however, using e-CH_4 in an aircraft does not merit substantial advantages. Therefore, further developing this route does not seem to be relevant for aviation except for the thermodynamic conversion numbers.

3.7. Green Ammonia

Green ammonia (NH_3) is produced from nitrogen and green hydrogen via the Haber-Bosch process. Ammonia is liquid at 1 bar and 240 K, or at 8 bar and 293 K. The gravimetric and volumetric energy density is less than half of kerosene. Unlike cryogenic fuels, the liquefaction costs of NH_3 are less than a per cent of the fuel energy content.[13] Another key advantage is reduced effort for extraction of N_2 from air, compared to direct air capture of CO_2. A potential showstopper for NH_3 is the fact that it cannot be dumped due to its corrosive and toxic nature. It does not add to CO_2-associated global warming but it may have a non-CO_2 impact. In addition, ammonia has an adverse effect on the local air quality and bio-diversity. Combustion of NH_3 tends to lead to high amounts of NO_X formation and therefore cannot be used in the engine directly, in addition to potential NH_3 slip emissions. One

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[13] Front. Mech. Eng., 29 May 2020 | https://doi.org/10.3389/fmech.2020.00021

approach would be to dissociate NH_3 N_2 and H_2 at high temperatures (typically >800 K) using a catalyst, which comes at the cost of reduced efficiency and additional weight and complexity. The released H_2 can subsequently be used in a gas turbine or a fuel cell. However, fuel cells require a very high purity of hydrogen and might require additional purification steps. Usage of suitable NH_3 - H_2 mixtures in gas turbine combustors, however could eventually allow a very flexible combustion application, as the combustion properties of both fuels are opposite to each other and might allow a match to that of current fuels[14].

3.8. Climate impact

For a holistic assessment of the climate impact of aircraft emissions during operation (not considering production-related emissions) for the above-listed energy carriers, the following definitions appear to be important:

Climate-neutral operation: Ideally, all emissions that lead to aviation's climate impact should be prevented, including effects from CO_2, NO_x, water vapour, contrail-cirrus generation, direct aerosol effects, or indirect aerosol-cloud effects. Unfortunately, only batteries as energy carriers can achieve this target (although strictly speaking CO_2 emitted while producing the batteries as well as the electric energy stored in these batteries must be taken into account). Even propulsion based on green H_2 (be it using fuel cells or combustion) does not fully match the zero-emission requirement due to water emission. In case of combustion, also NO_x and related effects on contrail and cirrus generation should be accounted for. The atmospheric mechanisms involved are complex and currently under research. For instance, contrail and cirrus generation are strongly dependent on flight levels as well as concentrations of condensation nuclei.

CO_2-neutrality: When using carbon-containing synthetic fuels, CO_2 emissions during operation should be equal to the air-captured amount of CO_2 during the synthesis process or biomass growth. This applies e.g. to synthetic kerosene based on a direct-air-capture operated with renewable energy. Despite being CO_2-emission-neutral, such technologies do have a climate impact due to the non-CO_2 emissions such as NO_x, water vapour, soot and other minor compounds produced during combustion.

The climate impact is dependent on the change in the species concentration, radiative forcing, and global mean near-surface temperature change, and are affected differently based on their lifetimes, the local atmospheric chemistry, and the Earth system's thermal inertia.

Climate indictors: The climate effects of aviation emissions differ in sign, magnitude and lifetimes. To have a consistent measure for evaluating or mitigating aviation's climate impact, we need climate metrics. The choice of climate metrics is often a compromise between relevance and uncertainties as indicated in Fig. 3.5 below. The relevance regarding the impact of emissions increases as we proceed downward in the cause and effect chain, while the uncertainties increase as well. In other words, the emission quantity is easier to determine, but the assessment of the climate impact contains larger uncertainties due to the extremely high complexity of the system.

The following indicators are being used:

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[14] A. Goldmann, F. Dinkelacker, Experimental Investigation and Modeling of Boundary Layer Flashback for Non-Swirling Premixed Hydrogen/Ammonia/Air Flames, Comb. Flame 226, 362-379, 2021. DOI: 10.1016/j.combustflame.2020.12.021

- Quantity of emissions (E) causes changes in atmospheric concentrations (C). This can serve as the first indicator, but not for comparing different species, and not necessarily for comparisons between significantly different operations (i.e., emissions location).
- Radiative forcing (RF) indicates the radiation change caused by a concentration change. While using RF, assumptions are already made, e.g., the emission scenario or the reference time. Also, past emissions are often used to calculate the concentration change;
- Global Warming Potential (GWP) sums up future impacts of radiation changes from today's concentration change to a chosen time horizon (e.g., 20, 50, 100 years).
- Global Temperature Potential (GTP) translates the radiation changes caused by concentration change to temperature change at a selected time horizon;
- Average Temperature Response (ATR) is the mean future temperature development over a period up to the chosen time horizon.

Compared to the quantity of emissions, both RF and GWP allow a comparison on the same scale, though they do not yet consider the climate effects, i.e., temperature change. Therefore, GWP can be seen as a bridge between RF and climate change. To evaluate the effects of climate change, GTP and ATR are the most suitable. The main difference between these two is that using ATR reduces the dependency on the time horizon as compared to that of GTP. The Figure 3.6 shows the effective radiative forcing from various aircraft emissions from 1940 to 2018, which amounts to around 100 mW/m^2 (± 45 mW/m^2)

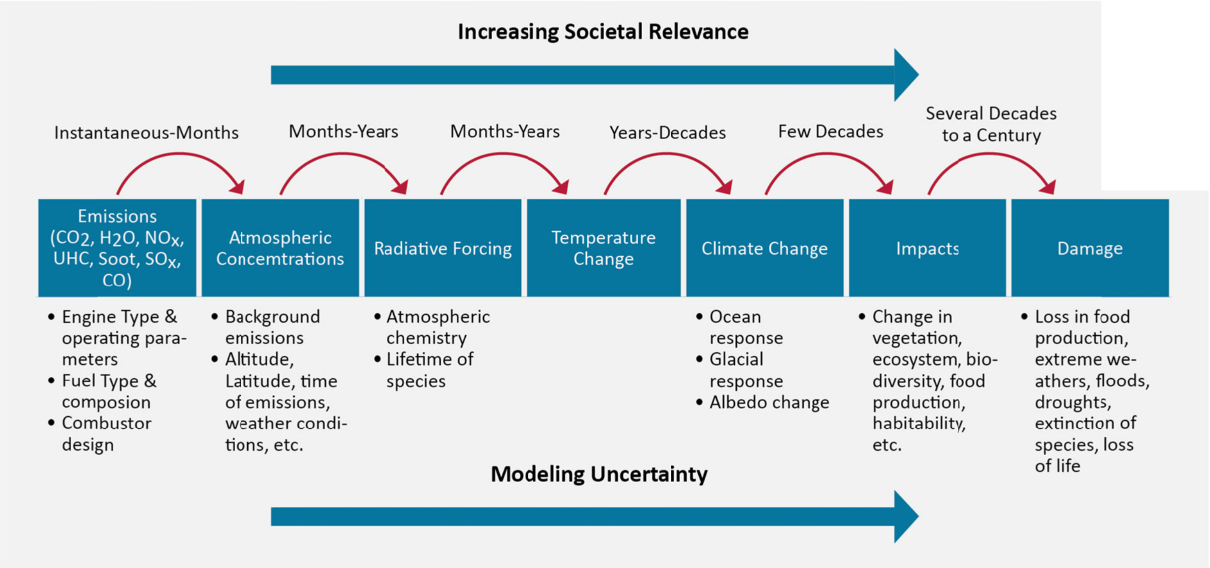

Fig.3.5. *The cause-effect chain from emissions to climate change and damages* (inspired by Fuglestevedt, et al.[15]).

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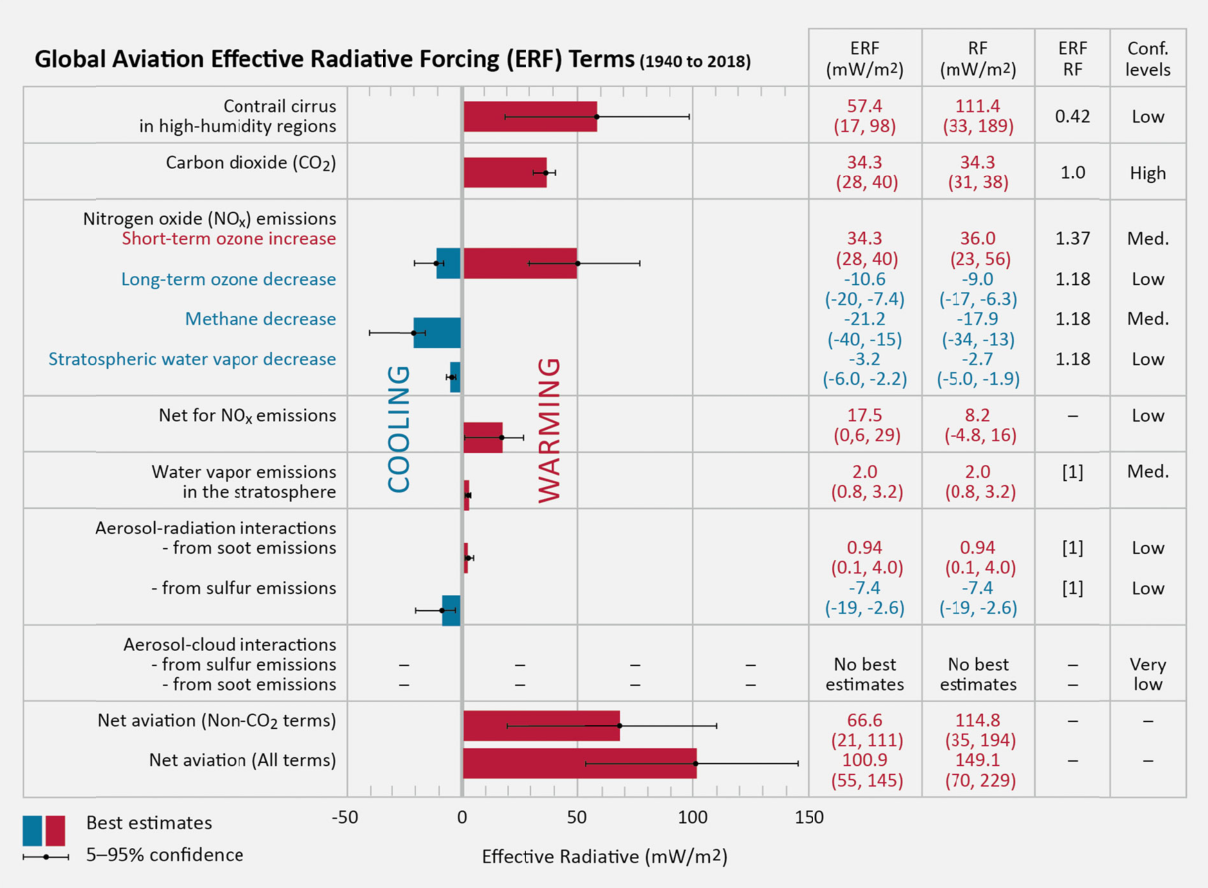
[15] Fuglestvedt, J.S., et al., Metrics of climate change: Assessing radiative forcing and emission indices. Climatic Change, 2003. 58(3): p. 267-331.



	ERF (mW/m2)	RF (mW/m2)	ERF/RF	Conf. levels
Contrail cirrus in high-humidity regions	57.4 (17, 98)	111.4 (33, 189)	0.42	Low
Carbon dioxide (CO$_2$)	34.3 (28, 40)	34.3 (31, 38)	1.0	High
Nitrogen oxide (NO$_x$) emissions Short-term ozone increase	34.3 (28, 40)	36.0 (23, 56)	1.37	Med.
Long-term ozone decrease	-10.6 (-20, -7.4)	-9.0 (-17, -6.3)	1.18	Low
Methane decrease	-21.2 (-40, -15)	-17.9 (-34, -13)	1.18	Med.
Stratospheric water vapor decrease	-3.2 (-6.0, -2.2)	-2.7 (-5.0, -1.9)	1.18	Low
Net for NO$_x$ emissions	17.5 (0,6, 29)	8.2 (-4.8, 16)	–	Low
Water vapor emissions in the stratosphere	2.0 (0.8, 3.2)	2.0 (0.8, 3.2)	[1]	Med.
Aerosol-radiation interactions - from soot emissions	0.94 (0.1, 4.0)	0.94 (0.1, 4.0)	[1]	Low
- from sulfur emissions	-7.4 (-19, -2.6)	-7.4 (-19, -2.6)	[1]	Low
Aerosol-cloud interactions - from sulfur emissions - from soot emissions	No best estimates	No best estimates	– –	Very low
Net aviation (Non-CO$_2$ terms)	66.6 (21, 111)	114.8 (35, 194)	–	–
Net aviation (All terms)	100.9 (55, 145)	149.1 (70, 229)	–	–

Fig. 3.6. *Best estimates for climate forcing terms from global aviation from 1940 to 2018. The bars and whiskers show ERF best estimates and the 5–95% confidence intervals, respectively. Red bars indicate warming terms and blue bars indicate cooling terms. Numerical ERF and RF values are given in the columns with 5–95% confidence intervals along with ERF/RF ratios and confidence levels*[16]

3.9. Costs and overview

Calculating the production costs and procurement prices for the aforementioned energy carriers is difficult since it includes all economic aspects and uncertainties starting from the different current TRL of each carrier along with the economy of scale coupled to different productions processes and up to political (taxes) and consumer market demands in the entire future field of energy production and distribution, not just related to aviation. Nevertheless, a rough estimate for selected energy carriers (LH$_2$ and synthetic kerosene) can be made just based on process-related energy demands and efficiencies:

Assuming the availability of electric power from fully renewable resources at a given cost level and following the efficiency assumptions explained in Chapter 3.1, LH$_2$ is expected to be producible in large-scale processes at a level of roughly a factor of 2.5 to 3 compared to the electric power costs. At a renewable electric energy cost of 3 US$ct/kWh, this leads to approx. 7-10 US$ct/kWh or around 2.3-3.5 US$/kg. For synthetic kerosene following the Fischer-Tropsch or methanol-based synthesis process, another cost factor of approximately 2 to 3 has to be considered which would lead to a price per kWh of approximately 15 to 25 US$ct/kWh. However, PtX fuel might become more competitive if

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[16] D. S. Lee, D. W. Fahey, A. Skowron, M. R. Allen, U. Burkhardt, Q. Chen, S. J. Doherty, S. Freeman, P. M. Forster, J. Fuglestvedt and others, “The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018,” Atmospheric Environment, vol. 244, p. 117834, 2020.

CO_2 emission taxes are levied and enforced. A CO_2 emissions tax of e.g. 30 US$ct/passenger/100km would increase the kerosene fuel cost by approximately 20-25%.

The table below gives a qualitative overview of different energy carriers. As can be seen, there is currently no energy carrier that meets all the criteria. This means that different energy carriers will have to be used for different aircraft types and missions. Moreover, hybrid solutions (using more than one energy carrier) should be explored to find synergies between two energy carriers.

Parameter	Kerosene	Biofuel	Batteries	eKerosene	LNG*	LH_2**	e-L-CH_4
Specific energy	+	+	- -	+	+	+ +	+
Vol. energy density	+ +	+ +	- -	+ +	+/-	-	+/-
Emissions	- -	+/-	+ +	+/-	-	+	+/-
Cost	+ +	-	+	- -	+ +	-	-
Availability	+ +	-	-	-	+	+/-	- -
Infrastructure	+ +	-	+/-	+/-	+	-	+
Safety	+	+	-	+	+/-	- -	+/-
Compatibility	+ +	+ +	-	+ +	+/-	-	-
Air Quality***	- -	-	+ +	-	+	+	+
Climate Impact***	- -	+/-	+ +	+/-	+/-	+	+/-
LOSU climate impact	med.	med.	high	med.	low	very low	low
TRL	9	8	5	7	4	3	4

Table 3.2: *Qualitative comparison of different energy carriers for aviation. (* refers to fossil based LNG; ** refers to green LH2; *** refers to impacts during operation only; TRL=Technology Readiness Level).*
LOSU = Level of Scientific Understanding

4. Power Systems

4.1. Introduction

The combination of kerosene as a high-density liquid energy carrier with gas turbines of high thermal efficiency is the standard power systems basis for all large transport aircraft since more than five decades. Its high energy density (approx. 43.0MJ/kg and 34.5MJ/l), good combustion and handling properties, as well as the usage of ambient oxygen as reactant and emission of reaction products over-board, and thus allowing for flying with decreasing weight (Breguet's range equation) are the main advantages. This makes kerosene in combination with gas-turbine energy conversion the current reference for aviation power systems.

Without going into the details of gas turbine thermodynamics and propulsor technologies, the current generation of jet engines reaches an overall thermodynamic efficiency (Joule-Brayton-Cycle) of approx. 55% coupled with transmission efficiencies between 80% and 85% which leads to full conversion efficiencies (stored energy to exhaust jet energy) of approx. 47%. Note that for overall efficiency also the propulsive efficiency needs to be assessed.

$$\eta_{thermal} = \frac{thermal\ energy\ of\ fluid\ behind\ core}{fuel\ energy\ content}$$

$$\eta_{transmission} = \frac{energy\ of\ jet\ exit\ at\ core\ and\ bypass}{thermal\ energy\ of\ fluid\ behind\ core}$$

$$\eta_{propulsive} = \frac{propulsive\ power}{thermal\ power\ of\ fluid\ behind\ core} \approx \frac{2 \cdot flight\_speed}{flight\ speed\ + exhaust\ jet\ speed}$$

$$\eta_{overall} = \eta_{thermal} \cdot \eta_{transmission} \cdot \eta_{propulsive}$$

Since the propulsive efficiency for a given propulsor setup is strongly coupled to the aircraft flight speed, a more reasonable way to compare different systems of on-board power conversion appears to account for the jet power created by the propulsor and leaving propulsive efficiency out of the balance. A more universal definition which is also applicable to alternative drive concepts is then:

$$\eta_{jet\ power} = \frac{kinetic\ of\ jet\ exit\ at\ core\ and\ bypass/or\ behind\ propeller}{stored\ energy\ in\ energy\ carrier\ (fuel, H2, battery)}$$

Novel energy conversion processes or power trains on board future aircraft make most sense if they are coupled with new energy carriers as well. As a direct alternative to fossil liquid fuels, only PTX (Power-to-x) processes, i.e. Power-to-Gas (PTG, e.g. hydrogen) or Power-to-Liquid (PTL) processes are expected to reach the targets for CO_2 emissions, see chapter 3. on energy carriers.

Power systems considered

Within the above defined framework a large design space for energy conversion from the energy carrier on-board to propulsive power is possible. Despite the wide range of possible derivatives or subsystem solutions, general top-level energy conversion architectures can be classified by considering the conversion from stored on-board energy to jet power and by accounting the conversion from jet to propulsive power as described above:

Conversion from energy storage to jet power ($\eta_{jet\ power}$)

- Full battery electric (FBE)
- Liquid hydrogen with direct burning (H_2B)
- Liquid hydrogen with fuel cell conversion (H_2FC)
- Future gas turbine (FTG)
- Hybrid architectures

Conversion from jet power to propulsive power ($\eta_{propulsive}$)

Improvement of propulsion efficiency is hence the second but very important field of the on-board power system energy conversion chain. Hence, choice of propulsor (i.e. ducted fans, propellers) can be considered as another design parameter, beside to the energy conversion from storage system to shaft power. This spans a matrix which allows combining propulsors with the above discussed internal power conversion, e.g. a duct fan can be combined with a FBE system as well as a H2B system. This makes the propulsive efficiency improvement a more independent task which is confirmed by e.g. the observed increase of propulsive efficiency by increasing bypass ratio of fan engines over the last decades. However, there is a very strong coupling between propulsive efficiency and the extent of propulsion integration. The most important dimensions of novel propulsion integration to be considered for future transport aircraft are:

- Boundary layer ingestion (BLI)
- Distributed propulsion (DP)

BLI and DP will be discussed in chapter V do to their strong coupling to the physics of flight.

4.2. Full battery electric (FBE)

Technology description and potential

Full or pure battery electric systems describe an architecture relying only upon energy storage in batteries on-board an aircraft. The stored energy is converted via high-power electronics to drive electric motors which in-turn drive the propulsion unit (fan or propeller). For the latter, state-of-the-art propeller and fan efficiencies can be assumed (see Table 4.1) which shifts the focus to the most important performance indicators of batteries, power electronics and electric motors. Here, achieving high power density for the electric motor as well as high energy density for the battery systems have been revealed as the most challenging requirements. Electric motors do offer conversion efficiencies up to 98-99% and are thus superior compared to gas turbine based conversion. However, the scaling of electric motors to achieve installed unit power in the range of gas turbines and the required high gravimetric power density are severe challenges. In the electric power train, the power electronic converter is the most efficient and most lightweight part. The availability of SiC MOSFETs for voltages above 1200 V enables large improvements, since these devices come with lower conduction losses and lower switching losses when compared to silicon-based IGBTs. Efficiencies in the range above 99% are realistic.

Research demands, complexity and associated risks

A major demand in order to allow for FBE-based flying calls for improvement of the battery energy content, their power density and cyclic stability as already described before. Yet, the subsequent efficient and low-weight energy transmission and conversion may pose an equally demanding challenge. For the electric motors, the critical constraint limiting the maximal unit power is the balance between heat losses and heat dissipation by the cooling system once scaling up electric motor size. Reducing the current density as it is done for large stationary applications is not an option since it decreases the gravimetric power density even further. A solution to combine high conversion efficiency with high gravimetric power density is (relatively high-temperature) superconductivity. Since the introduction of superconductivity is a very complex task from a systems point of view it is expected that electric motor solutions for aviation will group into two classes, a) unit sizes which do allow for high voltage levels but still operate with conventional cooling concepts. Such concepts are expected to cover a power range of up to approx. 1MW per unit and b) systems based on high-temperature-superconductivity allowing higher unit power. While the first class is expected to reach TRL 5 in the next decade, the second class needs much more fundamental research and technology development to even come to a sound assessment and the key performance indicators for aircraft operation. Due to the high safety requirements, the propulsion drive system design also needs to take reliability into account. Here, an effect that has to be considered is cosmic radiation. It causes a certain failure rate of the power electronic semiconductors that rises with altitude and exposure time. Therefore, highest expectations on reliability come together with increased failure rates compared to conventional ground-based applications of power electronics. Redundancy on component level (DOR - degree-of-redundancy) and for subsystems is a means to counteract. However, any step-up in the DOR level results in reduction of gravimetric and volumetric energy density. Feasible solutions based on a high voltage distribution grid, enabled by the available rating of the semiconductor devices with high breakdown voltage as well as special topologies for high voltages and high currents need to be investigated. This raises the question regarding the best architecture of the electric network and distribution system. De-centralized solution concepts reduce the demand to route high electric current via central components, but this limits the flexibility for power distribution and crossover supply scenarios.

4.3. Liquid hydrogen with direct burning (H2B)

Technology description and potential

While SAF or SAF-blends are defined and certified including a drop-in capability for current aircraft and current gas turbine technologies, LH_2 to be burnt in a combustion process does not include drop-in capability. This defines the requirement for modified or newly designed gas turbines.

Research demands, complexity and associated risks

While drop-in capable biofuels are already at TRL9 and drop-in SAF at TRL7[17] non-drop in solutions (LH_2 and as well as LNG/L-CH_4) are still at much lower TRL and require more detailed research not just to adapt the gas turbines to special conditions (e.g. flash-back for fuel with a very high flame speed) but also on related subsystems. The combustion of hydrogen results in similar or even higher turbine-inlet temperatures (TIT) compared to conventional fuels and thus requires the integration of advanced cooling concepts[18]. The desired higher TIT implies a higher fuel-to-air ratio, which results in a greater amount of steam in the combustor exit flow. Also heat transfer become more relevant and experience gathered by steam-turbine designers may become more relevant to aircraft propulsion. As described in the previous chapter, for such new “non drop-in SAF” detailed research is required to understand the short and long term climate effect of their individual emission within a climate model which takes the individual operation or mission into account. Finally, as aviation’s environmental

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[17] https://www.airbus.com/newsroom/stories/A350-fuelled-by-100-percent-SAF-just-took-off.html, accessed on 10.07.2021

[18] Chyu, M. K.; Siw, S. C.; Karaivanov, V. G.; Slaughter, W. S.; Alvin, M. A. (2009): “Aerothermal Challenges in Syngas, Hydrogen-Fired, and Oxyfuel Turbines – Part I: Gas-Side Heat Transfer”, ASME. J. Thermal Sci. Eng. Appl., doi:10.1115/1.3159480

footprint comprises of climate, air quality and noise impacts, a complete environmental assessment of these alternatives would be beneficial required considering all changes in gas turbine technologies for design and off-design operation.

4.4. Liquid hydrogen with fuel cell conversion (H2FC)

Technology description and potential

In general, the efficiency of fuel cell based energy conversion is coupled to the free enthalpy offered by the chemical reaction of the individual process. Thus it can be higher compared to the conversion efficiencies of thermal power engine described by the Joule or Brayton process, see also Figure 4.1. Although a significant range of such conversion processes using different fuels are possible, the most promising candidates are the PEM-FC (Proton exchange membrane fuel cell) and maybe the SOFC (solid oxide fuel cell).

On PEM-FC stack level, a specific power of 2.0 kW/kg was disclosed in 2014 in commercial systems[19], while in 2020 stacks on the market already offered 4.7kW/kg[20]. Due to significant drawbacks in system weight, PEM-FCs will be operated at the highest achievable efficiency which is higher than in current road vehicles. Efficiencies of 60% and more are achievable based on two strategies, a) recycling the product heat for air conditioning purposes or the Meredith thermal thrust generation[21,22] and b) operating the FCs at a lower current density[23]. Besides the fuel cell itself, the additional components of a FC-system have significant influence on system weight and thus aircraft performance. For a liquid cooled FC-system the total mass of the compressor systems plus tank system is expected to be in the range of the fuel cell stack itself. In addition another half to two-third of the stack mass is expected for the thermal management system[24]. Thus, on the FC system level the above described levels for power density have to be divided by at least a factor of 2.5.

Currently PEM-FCs operate at a relatively low temperature level of about 70°C, which is beneficial for system start-up time and response time as well as thermal stress on materials resulting in less induced premature failures. On the other hand, the moderate temperature defines a high demand for the cooling system for an aviation PEM-FC system. Due to the low temperature level customized coolant fluids are required and potential large heat exchanging surfaces will be accompanied by parasitic drag increase.

SOFCs in general do have comparable conversion efficiencies as PEM-FC with maybe small advantages for the SOFC. SOFCs operate at much higher temperature levels (700-1000°C) and offer the possibility of using fuels other than purified hydrogen, which allow better integration into hybrid propulsion concepts[25]. The biggest advantage stems from the higher quality or temperature level of the waste heat which allow a more efficient heat management or cooling system, and a more

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[19] https://www.toyota-europe.com/download/cms/euen/Toyota%20Mirai%20FCV_Posters_LR_tcm-11-564265.pdf, accessed on 10.07.2021.

[20] https://www.ballard.com/docs/default-source/spec-sheets/fcgen-hps.pdf?sfvrsn=704ddd80_4, accessed on 10.07.2021

[21] Hepperle, M., 2012. Electric flight-potential and limitations.

[22] Kožulović D. Heat Release of Fuel Cell Powered Aircraft. Proceedings of Global Power and Propulsion Society 2020.

[23] Kadyk, T., Winnefeld, C., Hanke-Rauschenbach, R. and Krewer, U., 2018. Analysis and design of fuel cell systems for aviation. Energies, 11(2), p.375.

[24] Till Lennart Kösters. Active Cooling Design Optimization for a Novel Hybrid Fuel Cell/Hydrogen Thruster Aircraft Engine Design.

[25] Roth, B.; Griffin, R. (2010): “Fuel Cell Hybrid Propulsion Challenges and Opportunities for Commercial Aviation”, 46th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, 25 - 28 July 2010, Nashville, TN. Paper AIAA 2010-6537, doi:10.2514/6.2010-6537

effective generation of thrust out of the waste heat flux. SOFCs based on conventional ceramics do have an unfavourable power density compared to PEM-FCs, which makes them larger. Further, in contrast to the fast start-up time of PEM-FCs, SOFCs can only deliver power significantly above 500°C and material-issues do not allow for frequent shut-down/start-up, i.e. the temperature should be maintained at operating temperature always. The high temperature gradients present in a SOFC, together with the different thermo-mechanical properties of the materials used create high mechanical stresses within the fuel cell during transient operation. The use of ceramic-metal (cermet) composites for the electrodes in metal-supported solid oxide fuel cells (MS-SOFCs) reduces such stresses.

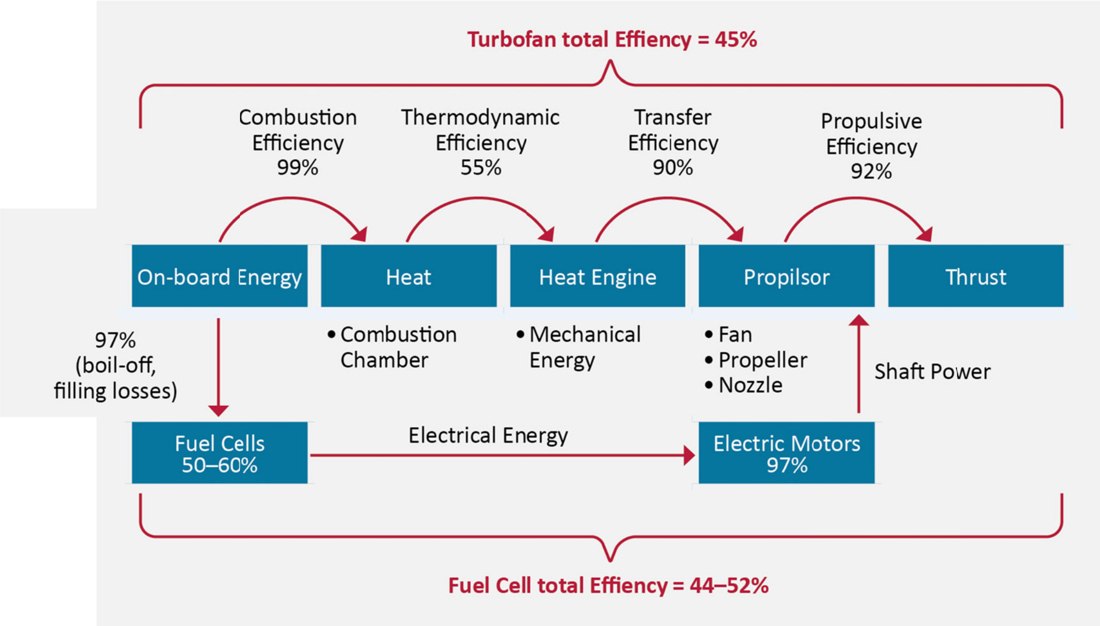

Fig. 4.1. *Comparison of efficiency chain for turbofan engines and fuel cell driven propulsion systems*

Research demands, complexity and associated risks

With respect to fuel cell chemistry, there are numerous efforts worldwide which indicate that an increase in power densities of membrane-electrode assemblies of PEM-FC by a factor of 2-3 is feasible by using new catalysts, improved electrode and gas diffusion layer design, and by thinner membranes[26][27]. It was suggested, e.g. that the current density could be doubled by re-arranging the carbon fibre angles inside the gas diffusion layer of the PEM-FC[28]. However, such improvements are still on very low TRL, partly not yet exceeding the level of numerical simulations. Significant further improvement may obtained by tackling passive fuel cell components: bipolar plates may account for up to 80% of the weight of a fuel cell stack, and there is comparably little research on weight reduction. In order to compensate for the deficiencies resulting from the moderate operating temperature, temperature elevation as well as phase-change plus heat-pumps as part of the cooling system appear promising. To increase the operating temperature of a PEM-FC, new membrane materials are needed that are stable and operable at higher temperatures. Phase change cooling is a

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[26] Kadyk, T., Winnefeld, C., Hanke-Rauschenbach, R. and Krewer, U., 2018. Analysis and design of fuel cell systems for aviation. Energies, 11(2), p.375.

[27] Eslamibidgoli, M.J.; Huang, J.; Kadyk, T.; Malek, A.; Eikerling, M. How theory and simulation can drive fuel cell electrocatalysis. *Nano Energy* **2016**, *29*, 334–361.

[28] Zhu, L., Wang, S., Sui, P.C. and Gao, X., 2021. Multiscale modeling of an angled gas diffusion layer for polymer electrolyte membrane fuel cells: Performance enhancing for aviation applications. International Journal of Hydrogen Energy, 46(39), pp.20702-20714.

well industrialized technique, e.g., in heat pipes. It requires only a fraction of the coolant mass stream compared to liquid cooling but has yet just been deployed in very few PEM-FC products[29]. When phase change cooling is working together with a heat pump, the temperature level of the waste heat can be significantly increased. However, since the current TRL for such combined cooling systems is rather low (TRL 2-3), further fundamental, materials, and system focussed research is required.

With advanced metallic bi-polar plates and new membrane-electrode assembly designs, a power density of 8-10kW/kg at stack level can be expected[30]. Coupled with new cooling systems, it seems that a 4-5kW/kg specific power can be reached on the system level in future.

Besides the stack and its subsystems, weight and volume reduction of cryogenic tanks is a major enabler. It has to be considered that the aviation operation scheme is distinctively different from road operation. While a typical road vehicle tank design is based on “full-to-full” operation, aircraft on-board tanks require “empty-to-empty” making the average storage time much shorter. Regarding the expected life-time, PEM-FCs already achieve 20,000 hours. Nevertheless reliability on system level has to be improved to save additional system weight drawbacks due to redundancy levels that might be required for certification. To reduce the degree-of-redundancy (DOR), a more detailed understanding of the failure processes in a PEM-FC system combined with system state identification and failure prediction is required which demands further investigations.

SOFCs could become an option for aviation, if power density can be increased significantly and suitable stack designs and the required manufacturing methods successfully address the transient thermal stress problem mentioned above[31]. At power densities of 3.13 W/cm^2 at 0.7 V cell voltage and operating temperatures of 800°C, an enhancement by a factor of 10 compared to the literature was recently reported[32] at the single-cell level, i.e. at a TRL of approx. 2 to 3. The authors name scalability of the stack design beyond tens of kW and durability beyond the demonstrated 1,000h combined with the start-up behaviour among the most pressing challenges which remain to be addressed.

4.5. Future gas turbine (FTG)

Technology description and potential

Emissions of CO_2 and NO_x for fossil and drop-in SAF may also be reduced by moving one step further towards steam-turbines: In the water-enhanced turbofan (WET) engine concept, water is injected into the combustor and converted to superheated steam. As a result, more energy is extracted from the working fluid in the turbine downstream. The associated increase in fuel burn efficiency is estimated around 10-15%[33] taking into account the increased system mass introduced by the WET-cycle. From a systems perspective the WET engine concepts is currently at TRL 2-3. Additional efficiency improvements in gas turbines might be achieved through direct use of coupled unsteady

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[29] https://www.ballard.com/fuel-cell-solutions/fuel-cell-power-products/fuel-cell-stacks, last visit 11.07.2021.

[30] Kadyk, T., Winnefeld, C., Hanke-Rauschenbach, R. and Krewer, U., 2018. Analysis and design of fuel cell systems for aviation. Energies, 11(2), p.375.

[31] Gao, JT., Li, JH., Wang, YP. *et al.* Self-Sealing Metal-Supported SOFC Fabricated by Plasma Spraying and Its Performance under Unbalanced Gas Pressure. *J Therm Spray Tech* **29,** 2001–2011 (2020). https://doi.org/10.1007/s11666-020-01096-5

[32] Udomsilp, David et al. (2020): Metal-Supported Solid Oxide Fuel Cells with Exceptionally High Power Density for Range Extender Systems. Cell Reports Physical Science, Volume 1, Issue 6, 24 June 2020, 100072 https://doi.org/10.1016/j.xcrp.2020.100072

[33] Pouzolz, R.; Schmitz, O.; Klingels, H. (2021): Evaluation of the Climate Impact Reduction Potential of the Water-Enhanced Turbofan (WET) Concept, Aerospace 2021, 8, 59, doi:10.3390/aerospace8030059

combustion and flow dynamics. However, the latter currently are at low TRL, such that they are not relevant for the present scope.[34] Another advantage of the WET-cycle is the significant reduction of NO_x-emission up to 90% if new combustion chamber designs are realized.[35]

Research demands, complexity and associated risks

A WET engine concept operating in cruise requires extracting the water from the turbine exhaust and condensing it for re-injection into the combustor. This is not only needed to reduce the amount of water required for the mission, but also to reduce the water emission with regards to contrail and cirrus formation. Both, the required condenser as well as the steam provide new challenges in heat transfer, system mass, engine packaging, and integration into the aircraft. A lightweight and at the same time highly low-cycle fatigue tolerant system is required for the heat exchanger. The low-pressure turbine, condenser and exhaust system have to cope with two-phase flow, with the amount and location of liquid water generation depending on the ambient condition and engine operation point. At the same time condensed water has to be extracted efficiently from the gas path to keep the heat transfer conditions unchanged. The heat exchangers on the cold condenser side will have to offer large surfaces to maintain the thermal power transfer at low temperature differences, and aircraft integration with low pressure losses might require additional coolant fluids. At the same time, the core engine will have to be further downsized due to the higher specific power of the WET-cycle which generates new research demands to keep the gas-path related losses at their current levels or below. However, the reduction in core engine mass will be offset by the new subsystems which are estimated to be in the range of 40% of a current gas turbine system mass.[36]

4.6. Hybrid architectures

Technology description and potential

Although a very wide range of different architectures seems possible, a general classification into serial hybrid concepts and parallel hybrid concepts is common practice. Hybridisation as defined here, assumes a hybrid energy or powertrain on-board the aircraft. Thus it explicitly does not cover effects occurring from propulsion integration as for example distributed propulsion (DP) or boundary layer ingestion (BLI) – see next chapter for these. Key feature of a serial hybrid powertrain is the routing of all power via the electric part, while conversion from the energy carrier can be realized by batteries, gas turbines or fuel cells. In contrast to that a parallel hybrid concept allows the routing of mechanical power and electric power in parallel up to the propulsor. Both concepts have their individual pros and cons. A significant disadvantage of a serial hybrid is the weight increase of the system, since all components and sub-systems have to be full-power capable. Here, the parallel hybrid architectures offer a real benefit. In parallel to the power routing, hybridisation – especially combining electric propulsion with gas turbines do offer more design freedom for propulsion integration since electrical power may be routed via cable much easier compared to mechanical power via shafts and the local propulsion unit just requires an electric motor.

Research demands, complexity and associated risks

Although benefits of hybridisation can be expected and shown for design point operation, there is more challenge for off-design and failure cases. The more the subsystems of a parallel hybrid system

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[34] https://www.sfb1029.tu-berlin.de/menue/sfb_1029/parameter/en/

[35] Pouzolz, R.; Schmitz, O.; Klingels, H. (2021): Evaluation of the Climate Impact Reduction Potential of the Water-Enhanced Turbofan (WET) Concept, Aerospace 2021, 8, 59, doi:10.3390/aerospace8030059

[36] Schmitz, O.; Klingels, H.; Kufner, P. (2021): Aero Engine Concepts Beyond 2030: Part 1—The Steam Injecting and Recovering Aero Engine. ASME Journal of Engineering for Gas Turbines and Power, Vol. 143, https://doi.org/10.3390/aerospace8030059

are optimized for power and load sharing, the more sensitive is their off-design behaviour, especially for higher degrees of hybridization. For example, off-design handling like surge margin management and nozzle adaption of turbo machinery subsystems can become even more difficult. This clearly stems from different physical off-design characteristics of different subsystems, e.g. the rather different part-load power and torque characteristic of electric motors compared to gas turbines. Serial hybrid systems, from a fundamental perspective, do not suffer from these effects since all components are capable of handling the full power, but his in turn leads to their major drawback which is a significant weight increase at constant power level.

On the other hand, due to the very flexible propulsion integration using hybrid systems, the performance shown for such system often benefits primarily from other physical effects, e.g. BLI my be enabled by hybridisation[37]. Also hybridisation using combustion technologies and battery-stored green electricity can lead to rather non-typical operation points, where e.g. electric energy is used and fuel is saved for mission reserves.

Taking the different power requirements during the typical mission segments into account, feasible architectures may be found by combining the individual strengths of high specific (peak) power and high efficiency of e.g. turbomachinery, fuel cell and electric motors. Enabling such a benefit from hybrid aircraft powertrain architectures on a real block energy or operational cost level surely requires a holistic tool chain for preliminary aircraft design and assessment, including design spaces for radical aircraft configurations and being coupled to multidisciplinary optimization (cf. chapter 6).

Table 4.1 provides an overview and comparison of the aforementioned energy conversion routes on-board of an aircraft, beginning with the energy carrier during its refuelling or charging process and ending up with the propulsive power. For the sake of a fair comparison all efficiencies are expected values for entry-into-services past 2035.

Technology	Energy storage /carrier eff.	Conversion eff. "Step 1"	Conversion eff. "Step 2"	Conversion eff. "Step 3"	$\eta_{jet\ power}$
FBE	97% (normal temp. level and 1C discharge rate)	99% (cable and power electronics)	98% (electric motor)	92% (fan / prop eff.) (no turbine)	86%
SAF+convGT	99% (no storage but combustor loss)	55% (thermal efficiency)		83% (fan / prop. eff. and turbine eff.)	45%
SAF+FGT	100% (no storage losses)	65% (thermal efficiency)		83% (fan / prop. eff. and turbine eff.)	54%
H2B	97% (boil-off rate, no losses during tanking)	55% (thermal efficiency, H2 burning in GT)		83% (fan / prop. eff. and turbine eff.)	44%
H2FC	97% (boil-off rate, no losses during tanking)	60% (fuel cell eff., part power cruise)	99% * 98% (cable, power electronics, motor)	92% (fan / prop eff.) (no turbine)	52%

Table 4.1: *Comparison of energy conversion systems "from tank to jet power"*

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[37] Bowman, C.L.; Felder, J.L. and Marien, T.V.: Turbo- and Hybrid-Electrified Aircraft Propulsion Concepts for Commercial Transport. AIAA Propulsion and Energy Forum 2018, DOI: 10.2514/6.2018-4984

Taking additionally the production process for hydrogen and SAF into account in order to characterize the efficiency of the entire energy conversion route from green electricity to jet power as also shown in Figure 3.4.

$$\eta_{electricity\ to\ carrier} = \frac{stored\ energy\ in\ energy\ carrier\ (fuel, H2, battery)}{energy\ required\ for\ production\ processs\ of\ specific\ energy\ carrier^{38}}$$

For hydrogen production plus liquefaction, $\eta_{electricity\ to\ carrier}$ is expected in a range of 50-60% while for SAF it will be approximately 25-30% (see chapter 5.1). This does lead to overall efficiencies from green energy to jet power of approx. 15% for SAF+FGT while H2B will be in the range of 22-26% and H2FC between 26% and 31%. Due to the opportunity of a direct storage (charging) of green electricity in batteries, the overall efficiency for FBE stays at 86% as shown in Table 4.1.

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[38] All energy demands during production i.a.w. Figure 3.4. plus energy for additional liquefaction of H_2 to LH_2. Not considered are energy demands for production of storage units, e.g. LH2 tanks or batteries.

5. Flight Physics, Materials and Structures

5.1. Introduction

During the design, manufacturing and operation of commercial aircraft engineers are faced with numerous interactions between the aircraft's flight physical behaviour, its structure, and its systems including those that provide energy storage and conversion. It appears as a naive approach to promote the replacement of current aircraft propulsion systems by novel concepts that could meet sustainable aviation requirements without considering the main technological consequences that this transformation will have for viable commercial aircraft.

The assessment of long-term technology and subsequent research needs in the fields of flight physics, structures, and materials builds on a range of working hypotheses that result from careful analysis of the impact that a paradigm change towards sustainable aviation will have in the future:

- The availability and cost of the aforementioned future energy carriers (e.g. LH_2 and synthetic hydro-carbon fuels) will lead to a strong demand for new aircraft technologies that reduce the energy demand and direct operating cost of future transport aircraft and aircraft emissions.
- The limited energy density of batteries imposes strong constraints on the range of full electric short-range aircraft, while the low volume-specific energy density of LH_2 causes a significant growth of the needed aircraft volume for longer ranges. Hence, the payload-range performances of full-electric and long-range H_2-based aircraft depend much more on aircraft drag and aircraft structural weight as with conventional fuels.
- New aircraft concepts for sustainable aviation make specific enabling technologies of the airframe inevitable. Examples are technological capabilities of tailoring novel materials, cryogenic tank technologies for H_2-based propulsion, structure-conformal battery integration for electric aircraft, and sustainable manufacture technologies.
- Compliant function integration in future aircraft requires comprehensive and automated design approaches that find optimum topologies and details of geometry, structures, and systems.
- Sustainable manufacturing and end-of of-life approaches need to be developed to avoid problem shifting from the operations stage to those other stages in the life of the aircraft.

Further reflection on these hypotheses and the variety of the interactions in an aircraft indicates that assessment of on-going research and development of aircraft technologies should be performed on overall aircraft level, at fleet level, and at aviation level.

Technologies considered

A range of individual technologies are evaluated in this chapter:

- Synergies between airframe and propulsion
- Radical Drag Reduction
- Radical Aircraft Control
- Structural Integrity
- New Materials
- Physics Based Artificial Intelligence for Structures, Materials, and Flight Physics
- Sustainable Manufacturing and End of Life of Aircraft

For each of these, technology descriptions provide a characterisation of the scope and its current readiness for application as well as a judgement of the present research intensity in Europe. Furthermore, an estimate is provided how many years it would take to achieve TRL6, which represents a turning point at which the primary responsibility for a technology is put into the hands of industry.

The expected benefit of a technology is expressed in the saving potentials in terms of propulsive power and hence fuel, usage of raw materials, CO_2 emission reductions, the resulting economic technology value, and re-cycling potentials. Nevertheless, such quantifications are subject to significant uncertainties that reflect today's rather limited knowledge. Uncertainties on future technology impact are especially high in cases, where technological progress in several areas is required for advancing technology readiness. In some cases, a vision does exist on the great value that the technology could possibly have, but quantification is not yet possible. Since technology complexity is an important dimension which determines cost and risk of implementation, the technology complexity through the assumed life cycle is assessed as well.

5.2. Synergies between airframe and propulsion

Wing size, lift-to-drag ratio and its structural weight play a key role in aircraft efficiency and thus fuel consumption. While improving the cruise drag coefficient is traditionally in the focus of wing design this approach fails to address the relation between the lift coefficient and the integrated propulsion system during all phases of flight and the consequence of efficient lift production and structural integration. Moreover, the need of energy efficient propulsion in sustainable aviation calls for novel propulsion systems layout, i.e. distributed open-rotor and BLI based designs. This opens new synergies of propulsion integration that can be exploited to improve aircraft performance for a required mission and the operations performance on airline fleet level.

Technology description and potential

Future energy-efficient regional and medium range aircraft will have to rely on open rotor propulsion, either in a conventional turboprop layout or in a distributed fashion, because of the high propulsive efficiency. These propulsion concepts can benefit from aero-propulsive interaction effects, particularly in case of distributed propulsion. At low-speed conditions, the required high-lift systems are deployed in a flow field that is augmented by the open rotors, and hence, higher lift coefficients are attainable. This can be exploited to reduce the required wing size for a given mission, for simplifying the high-lift system, or for improving high-lift performance. At cruise conditions, the integration of distributed propulsion (DP) must be optimized to reduce induced drag and adverse interference drag, as well as for achieving best propulsive efficiency of the integrated propulsor. First analyses at cruise conditions based on overall aircraft design methods as described in the last chapter indicates a potential increase in aircraft performance (L/D) in the range of 5 to 7% which is accompanied by a higher energy demand (3-4%) of the aircraft due to increase of its operation empty weight. Particularly, the interaction of distributed propulsion and laminar flow technologies are not yet understood. Technology readiness in these fields of propulsion-wing interaction is TRL 2-3.

Pure DP without any synergetic effects may only be of interest for cruise-optimized (long range) missions. However, potential synergies of DP with other technologies may increase the DP-related benefit. As such the power limitations of electric propulsion motors in DP compared to large single drive units can be seen. Limiting the unit power of motors does efficiently reduce the waste heat and therefore thermal management problem.

For medium to long range aircraft designs that exploit the effect of Boundary Layer Ingestion (BLI) are considered as an important option. Analysis based on first principles reveals that propulsive efficiency is significantly improved if propulsion fills up the momentum loss due to viscous drag in the wake, instead of working on an undisturbed portion of the air stream. The aircraft fuselage has a wake with the momentum deficit being clustered at the aircraft rear end. This indicates that ingesting the boundary layer losses of the fuselage into the aero engine for augmenting its propulsive efficiency is most promising, with estimates of the gains between 5-10%, depending on the technical concept. Presently existing assessments of Boundary Layer Ingestion potentials mostly stem from concept studies, and TRL-levels in Europe are yet moderately low, around 3.

On airline fleet level, there will be the need to employ aircraft that minimize the climate effect of aviation operations by flying lower and slower, but short door-to-door travel times will be also important for commercial viability. Hence, the low-speed take-off and landing conditions of future commercial aircraft for operations on smaller airfields will become an important design knowledge. Quantifying the technology potential in terms of aircraft efficiency is difficult, as the potential strongly depends on the top-level aircraft requirements. However, gains in fuel burn of 10-20% appear possible for future short-range aircraft.

Research demands, complexity and associated risks

Fundamental research in DP is needed on the problem of boundary-layer development on movables in presence of strong pressure gradients and high levels of propeller-induced vorticity. The phenomenological understanding on efficient high-lift production, either with or without additional flow control techniques, will be crucial in the design of future short- and possibly medium-range aircraft, by allowing the design of smaller wings that reduce drag during the cruise phase of the flight. With regards to BLI not only the aerodynamic and structural (rotor-dynamic) off-design behaviour of the propulsors have to be fully understood but also conflicting interaction with active flow control since both, advanced rotors and inlets needed for BLI technologies make use of the same boundary layer.

Distributed propeller propulsion has the potential of low noise footprint, due to the relatively low propeller loading, while achieving that goal calls for integrated aerodynamic and acoustic design capabilities that are not yet available. Comprehensive design approaches for integration at cruise conditions that take all relevant drag components and the propulsive efficiency of the rotors into account do not yet exist. There will be the need for a range of validated methods with varying fidelity. We estimate it may take about 10 years to achieve TRL 6.

Besides aerodynamic performance the close coupling between propeller and wing will also introduce aero-acoustic and vibration issues. Preliminary investigations for a pylon-mounted propeller have confirmed the strong unsteady loading on the wing due to the periodic impingement of the propeller tip vortices. For the high-lift case, these unsteady effects will be further amplified because of a stronger upstream effect of the wing on the propeller loading. So far only very limited data are available that quantifies the effects. For optimal integrated performance, the aeroacoustics and vibrations must be considered at full scale conditions that are hardly attainable in practice. Hence careful scaling studies are required allowing wind tunnel and CFD results to be extrapolated to full scale. Lift and its distribution both in spanwise and chordwise direction plays a key role in wing bending, twisting and their coupled static and dynamic effects in a clean configuration as well as in highly integrated propulsion systems concepts like tip mounted propellers.

5.3. Radical drag reduction

The drag of a well-designed commercial aircraft depends on aircraft size, its weight and on the breakdown of its drag coefficient into friction, induced, wave, and component interference portions. While a number of known approaches exist to reduce induced drag, wave drag, and interference drag by geometry optimisation, the potential of reducing turbulent skin friction has turned out to be less than 10% of its hydraulically smooth reference. Since turbulent skin friction comprises the largest drag portion with more than 50% of total aircraft drag, the silver bullet for radical drag reduction is comprehensive laminarisation of the aircraft components.

Technology description and potential

The extent of laminar boundary layer is generally determined by three factors: Reynolds number, pressure distribution over the surface, and active control of surface flow condition (AFC). The aerodynamic and structural technologies for wings with natural laminar flow without AFC have been developed up to TRL6 for commercial aircraft of small and medium size. This has the potential of an overall drag reduction of around 15%-20%, assuming successful application on upper and lower surfaces. However, laminarisation of the lower wing surface is not yet state of the art, since high-lift requirements call for yet non-existing sealing technologies of the leading edge device, or for morphing of the leading edge with current TRL around 2-3. Comprehensive drag reduction for wings of large aircraft and for the fuselage makes application of AFC by suction necessary.

Preliminary design studies indicate that the overall aircraft drag reduction is about 45%-55% depending on aircraft mission, if the snowball effects on OAD level, e.g. new wing design and re-sizing of aircraft, are taken into account. The drag reduction translates directly into reductions of fuel, aircraft exhaust emissions into the atmosphere, and the consumption of primary energy by aviation. However, the technology risks put a significant uncertainty margin on the viable reductions; we presently estimate the uncertainty with 20% of the overall benefit. The re-sizing of aircraft due to drag reduction will result in an aircraft empty-weight reduction of 4-8%. However, that will be most likely offset by the additional weight of the AFC system as well as the energy required to power the system. Nevertheless, the huge technology potential on aircraft energy consumption make it a strong enabler of electric flight with batteries and fuel cells, and for transitioning to CO_2 neutral flight in general.

Research demands, complexity and associated risks

Technology key of comprehensive drag reduction by laminarisation are compliant suction shells with acceptable cost and weight. Such suction shells carry structural loads and hence allow a fully stressed design. Surface sheets with tailored micro holes, additive manufacturing and innovative bonding are critical technology ingredients that need still to be developed and industrialised. Significant research on HLFC for controlling crossflow instability at the nose region of swept wings has led to TRL3 in Europe. On the other hand, there is practically no research on LFC for fuselages, in spite of the fact that very low suction rates theoretically suffice to keep a large portion of fuselage surface laminar. We estimate that the laminar fuselage will require around 15 years of long-term research to achieve TRL6.

Laminarisation of aircraft bears significant complexity because of the strong and multiple interactions between flow physics, compliant structures, and suction systems design. The requirements of acceptable cost and resilience during operation will be only met through significant investment into industrialisation of manufacturing concepts and by introducing new concepts of distributed systems for wing, fuselage and the other aircraft components. New levels of quality assurance during production of laminar aircraft components need to be introduced and significant efforts must be spent on function monitoring during operation. Maintaining the high requirements on surface smoothness and the function of AFC during aircraft life time will lead to significant additional cost of MRO. These effects reduce the economic value of technology for the manufacturers and for the airlines. The lack of fundamental knowledge on compliant structures for AFC, the lack of industrial experience in resilient system design and the lack of knowledge on cost-efficient production lead to significant technology risk. This risk can only be reduced by strategic long-term research action.

5.4. Radical aircraft control

The control of an aircraft entails mainly four disciplines: flight dynamics, structures, aerodynamics and control. There are two types of control considered here: flight dynamic and structural control. Flight dynamic control is about controlling the static and dynamic attitude of the aircraft while structural control is about controlling the vibration modes of and loads on the aircraft structure. Flight dynamic and structural control cannot be dealt with individually in case of flexible or non-conventional aircraft because typically, the natural frequencies of flight dynamic and structural modes grow closer and hence start to interact with each other. Active and passive aircraft control can alleviate loads and hence reduce structural aircraft mass. Furthermore, it can enable non-conventional aircraft configurations. Both effects combined lead to less fuel consumption and associated emissions.

Technology description and potential

The ultimate goal of radical aircraft control is to create a wing that is sized by little more than 1g loads for a significant part of the wing. Obviously not the entire wing can be sized by 1g loads only, otherwise the aircraft would not be able to manoeuvre. Manoeuvre-load alleviation should be done by off-loading the outer wing and loading the inner wing. This means that the cruise load case will become the sizing case for most of the aircraft wing instead of the typical +2.5g and -1g manoeuvre loads and gust loads. This can be achieved by a combination of passive and active loads alleviation. Passive loads alleviation can be obtained by a proper mass/stiffness distribution of the airframe, such as for instance an aero-elastically tailored wing. The passive loads alleviation technologies will not actively destabilise the aircraft or its structure, but it is limited in loads alleviation potential. Therefore, an active loads alleviation system needs to be designed concurrently with the passive loads alleviation structure because of their contradictory nature. A non-conventional control surface layout on the wings will facilitate this. A significant portion of up to 70% of wing structural mass can be saved using aero-elastic tailoring and active control, but technology readiness to achieve that theoretical optimum is only TRL 2.

The expected outcome of the radically control aircraft is a significantly lighter airframe with an empty-mass saving potential of 20-30% which is well over what is achievable at the moment with current technologies. This translates into similar fuel saving potentials. Furthermore, aerodynamic performance can be improved with radical load control, allowing for larger wing aspect ratios with a lower induced drag. Also, other aircraft designs are becoming feasible, such as more radical aircraft configurations, e.g. weight-efficient Prandtl planes.

Research demands, complexity and associated risks

A much more flexible airframe is expected due to the radically lower structural mass. This results in aircraft structures that are more prone to aero-elastic instabilities within the flight envelope. These instabilities, next to the loads, will be actively controlled by a capable control system. Because of the complex interactions on overall aircraft level, the technology requires the availability of comprehensive multidisciplinary analysis in combination with Artificial Intelligence, see Chapter IV.7. The complexity of the radical control effort is situated into the multidisciplinary modelling and certification of composites and control systems.

The modelling effort requires a multidisciplinary approach combining control, structures, aerodynamics, flight dynamics and aircraft performance, able to deal with non-conventional aircraft configurations. The risk is that the method including all relevant disciplines at the right fidelity level might prove to be computationally too expensive. Furthermore, the extensive use of a variety of non-conventional composites in a single wing will need new approaches towards material characterisation and certification, as well as a demonstrable increase in control system reliability, and its adaptation in failure cases. Moreover, rules of aircraft certification will have to be adapted for coping with these radical control concepts. We assume that it will take between 15 years obtain TRL 6 for such control exploitations.

5.5. Structural integrity

The design and manufacturing of an aircraft can be viewed as a hierarchical sizing process which includes criteria of stress, buckling, vibration, fatigue, damage tolerance etc. Thus, enabling a monitoring of the structural integrity requires modelling, prediction tools, and methods. The future greener aircraft will definitely use smart aero-structures and innovative propulsive systems, such as distributed electric or hydrogen. A new paradigm must be established for their eco-design, and manufacturing using eco-processes, while assessing the integrity of each aero-structures with embedded monitoring systems. These novel aircraft technologies are derived from civil/wind engineering processes.

Technology description and potential

While repairability, reusability, recyclability are essential from an environmental perspective, they can also reduce operational costs. Successful application of these circular design approaches in the aircraft manufacturing and operation life-cycle will lead to a paradigm change in aircraft maintenance. Structural rules historically played a significant role in aircraft design, primarily by estimating the stresses, internal forces and loads through carefully designed strain measurements (Skopinksi tests) during ground and flight tests, and finally flutter speed through ground/flight vibration tests. The era of predictive digital twin technology will help to use smart sensors to monitor the loads but also the health of the aircraft and thus ensure structural integrity. A good example of application could be the hydrogen tank sizing for sustainable aircraft. Finally, the digital twin will open the path to virtual flight tests for predicting fatigue damage and static strength during the entire service life. The technology potential of lighter, smarter and more versatile structures that can detect damage and probably trigger needs for urgent repair is huge. We target a transformation of the methods for aircraft structural integrity, by which maintenance cost could be lowered by 30% and structural weight by 10%. Hence, the economic value of this transformation is very high. This will also reshape the classical structural design processes.

Research demands, complexity and associated risks

Enhanced safety levels predictive capabilities through Machine Learning coupled with more advanced fatigue crack growth models is a research topic for composites and metallic structures. Maintenance will become quasi automatic through the use of robots/drones and associated network of smart sensors with embedded solar energy. Fast and reliable predicting models for multi-physics load including bird/lightning strikes or optimal assembly (adhesive/join/bolt) technologies are also current work in progress. Artificial Intelligence (AI) is also assisting the digital twin updating process for robust health/condition monitoring purposes. However, the central challenges in applying these new methods to aerospace are: how to ensure robustness and interpretability in the structural health monitoring process? How to fuse data from different sensors? How to update digital twins with data? The associated technology risk can only be reduced by strategic long-term research action including a reasoned high-performance computing strategy to create digital clones and by establishing a new market for cheap and robust smart sensor network as it exists in automotive. The digital twin will require 15 years of long-term research to achieve TRL6 with AI-based monitoring being more reliable than human quality control. The smart sensors network and associated robots will require 5 years of long-term research to achieve TRL6.

5.6. New materials

Aerospace materials are the necessary enablers for long-term technological developments in commercial aircraft. Examples are novel passive and active surfaces that adapt topology to flight conditions and environmental conditions in order to optimize drag or reduce ice accretion as well as lighter but more durable materials. Innovations in aerospace materials will have direct and indirect impacts on the environment by reducing the toxicity of materials used and the waste derived from manufacturing and inefficient end-of-life management strategies. New materials will therefore facilitate the transition to circular aircraft, but are to be seen also as key enablers for the implementation of novel fuel and propulsion strategies.

Technology description and potential

Future aircraft materials should ideally be designed considering functionality as well as structural, durability and environmental impact. This requires a significant research and development effort in different material domains that can be grouped in three areas: surfaces; bulk materials; and energy.

Surfaces: This domain poses a range of challenges divided in two aspects: toxicity and functionality. Corrosion protection will remain a critical topic of both aspects. The urgent need to replace CrVI based protective systems (to be banned by 2026) is governing the current discussions. There have been alternatives proposed, such as Li-technology, Mg and Al-rich primers, already at TRL6-7. However, these alternatives are still perceived as temporary mid-term solutions as they face a big challenge to reach the high performance achieved by CrVI technologies. Their cost and resource scarcity poses other long-term questions.

Efforts on new surfaces/coatings will lead to improvements on environmental impact by reduction of drag and weight, providing e.g. 10% of turbulent skin friction drag reduction, 20% ice accretion reduction as well as anticorrosive solutions without critical materials and toxic chemicals within 20 years. Furthermore, new surface treatments or coatings may ultimately play a critical role as enablers of the energy transition through the implementation of strategies to reduce hydrogen embrittlement and hydrogen permeability.

Bulk materials: Polymer-based aircraft pose significant challenges when dealing with circular aircraft concepts that include manufacturing and end-of-life management. Covalent adaptive networks, with vitrimers and covalent self-healing materials as the main representatives, offer an insufficiently explored broad platform of materials to facilitate the transformation towards the concept of circular aircraft. Such materials aim at being stable during operation but become dynamic when demanded so that they can improve manufacturing processes due to formability and stress relaxation principles as well as defect reduction during manufacturing, e.g. 3D print, and post manufacturing healing. Future materials could also increase service life through self-healing during operation and facilitate disassembly and recycling. These polymer technologies have been under development for 20 years mostly driven by academia but also in academia-industry partnerships. The field is academically mature and ready to transit to more application-oriented research which may involve different solutions for different applications.

Efforts in new sustainable dynamic polymers and polymer composites have the potential to become key enablers for the implementation of the circular aircraft concept. First expected high-TRL developments in non-structural parts are considered realistic within 15 years.

Energy: As discussed in previous chapters there is no clear single alternative to currently used kerosene-based fuels. Nevertheless, the use of H2 as energy source seems the most likely to be implemented to aircraft in the mid-term. Hydrogen has a high gravimetric energy density, but a very low volumetric energy density. There are two main ways to bring the volumetric energy density of hydrogen to an elevated level for application in aviation: in hyperbaric pressure vessels (300 up to 700bar) or liquefied through cryogenic conditions. The hybrid version of cryo-compressed storage is also subject of investigation, a relatively inexpensive solution to manufacture storage systems yet reducing hydrogen boil-off. These options pose challenges and inevitably lead to a significant mass increase and structural complexity compared to existing solutions. While the automotive sector is mostly, yet not only, leaning towards the use of pressurized vessels, including cryo-compression, in aviation there is a stronger drive towards the use of liquid hydrogen with an implementation target by 2035. Unfortunately, the automotive developments on fibre reinforced polymer pressurized vessels are not directly applicable to aircraft (e.g. certification is different or inexistent) and face the challenge on how to decrease the associated structural weight of the vessel. On the other hand, the aerospace sector can rely on the built experience around liquid hydrogen used in space missions.

Both strategies bring associated handling risks (e.g. where and when to do the refill of tanks, contamination with O_2 and leaks leading to explosions), intrinsic leakages during use requiring difficult to implement vents and detection systems, risk of explosion due to perforations and fatigue due to filling cycles. Moreover, the use of hydrogen (cryogenic or not) has also associated problems to the so called H_2 embrittlement leading to delamination, leaks and mechanical failure. Besides all this, materials and structures used will suffer fatigue and thermal fatigue due to loading-unloading cycles, having a higher penalty in cryogenic conditions. It should be noted that even such fatigue and H_2 embrittlement challenges are less relevant in space missions due to the inexistent or lower number of cycles and expected lifetime.

In all cases, to reduce weight and increase resistance to fatigue and leaks as well as safety and recyclability, the H_2 strategy requires the development of new light structures and light materials not affected by the presence of H_2 to avoid embrittlement, cracking or degassing, and for coping with the compression-decompression cycles that cause e.g. delamination.

Efforts on novel materials for H_2 storage will have to decrease the risks related to H_2 use in aircraft and on-ground storage and will make it possible to implement H_2 technology in aircraft. Materials developments are therefore regarded as the key enablers.

Besides hydrogen strategy, also biofuels and ammonia technologies need to be considered when dealing with materials. Despite less demanding pressure and temperature conditions (3-4 bar, room temperature) their implementation will pose significant challenges in terms of material selection and structures to ensure long term resistance to corrosion and chemical degradation (e.g. both biofuels and ammonia pose different challenges than kerosene) and implementation of reliable safety systems that prevent environmental disasters (e.g. high toxicity of ammonia).

Research demands, complexity and associated risks

Surfaces. The next generation of sustainable anticorrosive technologies currently at TRL1-2 yet with promising lab-scale results, e.g. microcarriers, biobased solutions or autogenous self-healing coatings, require fundamental and applied research to explore their full potential and reach TRL6. For aircraft, the ultimate long-term replacement technology may rely on a combination of technologies based on deep understanding of their individual and combined performance but also on a revision of the standards and evaluation methods. Besides this, the replacement of solvent-borne paints by waterborne (or water reduced) and introduction of sustainable raw materials requires a better fundamental understanding on how such systems work in order to design more durable and reliable solutions in the next 10-15 years. Surfaces can also contribute to a decrease of the negative environmental impact during operation. Passive solutions for drag reduction (e.g. riblets or sealing technologies to facilitate laminarisation of the lower wing surface) and low icing (e.g. nanoporous surfaces, topology control, carbon networks) are the current mid-term target. Active surfaces that adapt their topology to flight conditions and environmental conditions in order to optimize both drag reduction and ice-control will be developed in the long term (20-30 years).

Bulk materials: Challenges faced by future polymer (dynamic) materials such as creep, manufacturing and end-of-life need to be addressed. With the current level of maturity, investment at this stage may lead to first TRL6 solutions within 10-15 years. Moreover, attention should be put on how to better use sustainable raw materials (e.g. biobased, derived from CO_2 or waste) to make better engineering polymers, which are expected to reach high TRLs within 10-15 years. Finally, the use of biological solutions for specific functions (e.g. CO_2 capture, microbial phagocytation of composite residues) or living materials can be considered at very early stage and high TRLs may only be reached in very long terms.

Energy: The transition to H_2 propulsion poses many material and structural challenges and is expected to take 20 years of development to TRL6 with a very strong financial investment worldwide (e.g. industry hopes to implement cryogenic H_2 propulsion by 2035). H2 technology will certainly benefit from novel materials (e.g. polymeric/hybrid liners, polymer matrices, novel alloys, novel surface treatments) that have improved tolerance to the presence of H_2 and cyclic conditions required for the implementation of this technology. Obtaining higher resistance to fatigue and thermal fatigue cycles, higher toughness at cryogenic conditions, lower/none H_2 diffusion, higher resistance to H_2 embrittlement, lower coefficients of thermal expansion will allow cryogenic storage, transfer and release of hydrogen at lower demanding conditions, consider end-of-life and recyclability. A further aim is to provide higher intrinsic safety offered by materials able to store/release H2 in/from the material lattice, e.g. hydrides, or from so-called rechargeable powerpastes (e.g. magnesium-based paste). Synergy with other closely-related sectors such as automotive is expected to accelerate the development of novel material solutions. Moreover, novel ways to look at the use of pressurized vessels not only as containers but as structural part of the aircraft will help reducing related weight and volume penalties (e.g. design aircraft considering the tanks as an integral structural component).

Some of the above technologies require a significant amount of fundamental research such as new materials for H_2 storage (in cryogenic, high pressure or as improved hydrogen storage powerpastes), bioengineering materials, biological surfaces, but others are at the stage to be developed for specific targets, e.g. dynamic polymers for reusable components, waterborne coatings, anti-icing. Intensive and dedicated research on the above three domains during the coming 20 years with both fundamental and applied research should lead to significant tangible developments.

5.7. Physics based artificial intelligence for structures, materials, and flight physics

Designing an aircraft is multidisciplinary in nature. It can also be viewed as a cyber-physical collaborative development. Thus, embedding Artificial Intelligence (AI) in this process has created some new fields in such as material informatics, digital materials, smart robots for automatic fibre placement and 3D printing, generative design and topology optimisation for optimal manufactured structures, acceleration of aero-structural coupling through reduced order modelling, loads computation through physics informed neural networks and multi-scale approach for virtual coupon and aero-structures testing. Linking AI and physics is viewed crucial for the future of aerospace. The technologies help distributed engineering teams to rapidly reach design decisions whilst drastically reducing simulation, testing, and costly experiments.

Technology description and potential

Machine Learning (ML) has, historically, played a significant role in aircraft design, primarily by approximating expensive physics-based numerical simulations. It can also lead to a smart automated design of aero-structures, e.g. pylon, engine etc…, with radical design space exploration or be an enabler for the concept of digital twin of the full aircraft establishing a natural processing between sensors and simulation. A recent revolution has been the successful application of Deep Neural Networks (DNN) and Deep Learning (DL), in fundamental research of various fields including flight physics and structures/materials.

One challenge in design and manufacturing is to drastically accelerate the CAD-CAE-3D printing path. New tools such as generative design and ML topology optimisation can help engineers to print directly optimal structure under manufacturing constraints. Steered Automated Fibre Placement enables highly-automated manufacturing of large-scale complex parts from carbon fibre rein-forced plastics, achieving tailored structures and materials reusability. AI is also assisting the digital twin updating process, thereby including uncertainty quantification, and enabling health/condition monitoring purposes. The physics-based AI will require 15 years of long-term research to achieve TRL6 for aircraft design tasks.

The technology is the enabler of a digital transformation of main pillars of the aeronautical supply-chain: design, certification, and manufacturing. The huge technology potential of physics physics-based AI will help to reach lighter, smarter and more versatile aircraft. We expect that aircraft development times can be halved, with reductions in testing of 70%, and up to 90% of simulations could be saved. Hence, the economic value of the technology is very high. An important impact will be on OAD/MDO level, making it a strong enabler of electric and hydrogen flight.

Research demands, complexity and associated risks

The central challenges in applying AI methods to aerospace are: how to ensure robustness, interpretability, scalability, and efficiency? Materials informatics, for example, is at very low TRL, because this area is truly complex, computationally extremely demanding, and not directly applicable to industry. The application of this approach will have significant impact in materials discovery, e.g. high entropy alloys or hybrid composites, and thus by snowball effects to aircraft structures. The technology of digital or architectured materials, e.g. for a morphing structure, is a very promising technology that receives significant research funding e.g. by NASA. The resulting lattice (often built by ML) can exhibit the same stiffness, but with less than one-thousandth of the density of existing materials. Start-up companies in Artificial Intelligence for Engineering are slightly more mature. They offer deep-learning-based solution dedicated to Computer Assisted Engineering. These technologies should be combined with Knowledge Based Engineering in order to take care of model consistency and synchronisation for complex and distributed design tasks, allowing distributed teams speed up R&D cycles. While there is a growing interest to use machine learning for creating new materials and structures there is still a missing path of including eco-design constraints in the process. Fundamental knowledge on Life Cycle Analysis and Environmental Impact are existing but, the lack of aerospace industries experience in sustainable development leads to significant technology risk. The technology risks can only be reduced by strategic long-term research action including a reasoned high-performance computing strategy.

5.8. Sustainable manufacturing and end of life of aircraft

The environmental impact caused by aircraft is typically linked to their operation stage. However, in order to prevent problem shifting, i.e. creating unwanted environmental consequences in other life cycle stages, it is essential to consider the whole life cycle of the aircraft when developing strategies to reduce the environmental impact of aircraft. In this regard, simultaneous innovations in the manufacturing and end-of-life (EoL) stages are necessary, with emphasis in the following areas: (i) Methods supporting structural Design for Disassembly and Recycling (DfDR); (ii) Reversible Joining

Techniques; (iii) Closed-Loop Recycling Technologies; and (iv) Approaches for Zero Material Waste Manufacturing.

Technology description and potential

Firstly, disassembling plays a key role in enabling efficient repair, reuse, remanufacturing and recycling of aircraft structures. For it to be effective and economically sound, disassembling and EoL-strategies need to be incorporated in the design phase (DfDR), which is not current industrial practice (TRL 3). Secondly, reversible joining technologies, i.e., those which can be disassembled on demand without jeopardizing safety of the structure, are of great importance in this vision. Currently, aircraft structural joints are non-reversible as they are based on mechanically fastening using permanent rivets and bolts. Contrarily, welded joints are reversible by nature. In particular, welding techniques for polymer composites have experienced quite intensive development during the recent decades leading to a handful of technologies with different readiness levels. The reverse “un-welding” technologies are however at TRL 2-3. Thirdly, technologies to support closed-loop recycling of the aircraft body and structure as well as to enable zero material waste during manufacturing are essential. Technologies to recycle carbon fibre material, especially relevant to new-generation aircraft, have just recently been started for development (TRL2-3). Recent studies have shown that recycled fibres have a high market and potential in comparison to the use of virgin fibres in composite materials.

The expected outcome is moving from the current linear approach to a circular aircraft life in which the main design drivers become safety, weight, cost and environmental impact. Such a scheme would aim at the continuous use of resources and the elimination of waste and emissions through reuse, repair, remanufacturing, refurbishment and recycling.

Research demands, complexity and associated risks

Promising approaches for achieving closed-loop recycling scenarios of composite materials are besides mechanical recycling, pyrolysis and solvolysis of fibres, or, alternatively, fragmentation and re-melting of thermoplastic composites. Finally, in the area of zero waste manufacturing generative manufacturing is one enabler. With additive manufacturing (AM) becoming a competitive manufacturing process for low to medium production volumes, productivity becomes an increasingly relevant research area, as regulatory agencies and customers demand more eco-efficient life-cycles of products.

Out of the topics described above, the development of reversible joining and of closed-loop recycling technologies involve the higher level of complexity and risk. Main risks are inability to disassemble without damage to the structure and inability to consistently achieve high quality reused or recycled products. Intensive 5 to 10 year of research and development work should minimize those risks. The approaches presented above are expected to have a very positive effect on resource usage, economic value of the aircraft, recycling, and end of life. DfDR strategies may lead to modular structures with positive impact on MRO operations and enabling “plug and play” aircraft series. They might however lead to a potential increase in the number of joints and, hence, their impact on the weight of the aircraft, fuel consumption and emissions should be closely monitored.

6. Conceptual Aircraft Design

6.1. Introduction

The technologies discussed in the previous are typically motivated by a figure of merit (efficiency, weight, emissions, etc.) on their functional or modular level. In addition to their individual merits, the impact at vehicle level encompasses more than simply reducing the airplanes drag, weight or fuel volume. Assessing the impact of these new technologies also requires considering their impact on the airplane system as a whole. For example, a drag-reducing device may increase the empty weight of an airplane or its power consumption, reducing the beneficial effect it has on the overall energy consumption and increase noise and emissions. Airplane design methods can be utilized to quantify the impact of new technologies in a holistic way and assess the technology impact on vehicle level.

Looking at design activities within an airplane OEM like Airbus, three phases can be distinguished: conceptual design, preliminary design, and detailed design. In the context of this chapter, the term “Airplane Design” refers to the conceptual design phase. In this phase, the vehicle is designed in an iterative process involving all relevant disciplines: aerodynamics, structures, propulsion, weight, stability and control, performance, and costs. Methods to perform these conceptual design activities are described in well-known textbooks and are being taught at universities across the world. The iterative, multi-disciplinary process of designing an airplane is also captured in a variety of software tools that exist in industry, academia, and research institutes. These so-called Overall Airplane Design Tools are often employed to investigate the impact of new technologies or new airplane configurations. They typically require a simple desktop computer to execute and are able to synthesize an airplane design in a matter of minutes to hours. While sophisticatedly implemented, the core of these methods typically still relies on relatively old empirical data (weight, drag, mass) stemming from previous aircraft designs, which also form the basis for so-called handbook methods. Therefore, academic and research institutes have strived to include more physics-based analysis methods to estimate the relation between the airplane’s geometry and its weight, its aerodynamic properties as well as the effect of the installed propulsion system.

To produce aircraft that have a substantially lower climate impact, the question arises whether todays Airplane Design practices are still sufficient for the challenges of tomorrow. With an increased focus on the impact of commercial aviation on global-warming as well as on the noise and emissions around airports, do we have the necessary skills and tools to assess these aspects properly, in particular for novel airplane concepts for which empirical data does not exist? How are the aspects of noise taken into account, particularly regarding its societal impact? These are some of the aspects that have traditionally not been part of the Airplane Design process described in the previous paragraphs.

This chapter presents how the Airplane Design field should develop in the near future to holistically assess the impact of new aviation technologies. The research that is needed in this field aims to bring new disciplines and higher-fidelity analysis methods to the iterative design loop at conceptual-design level. In this manner, we would be able to assess new technologies with a reduced level of uncertainty. A so-called *Extended Holistic Assessment* is proposed, which relies on two main developments:

1) The **extension** of technology assessment with new methods to include:
    - Environmental impact: climate, local emissions, noise, and cost
    - Airplane operational aspects: routes, speed, altitude, fleet, maintainability

2) The **evolution** of tools and methods with a focus on:

- Impact quantification of radically new airplane configurations
- Multidisciplinary Design Optimization including multi-fidelity analysis
- Parametric modelling of airplane geometry and its relation to design
- Uncertainty quantification of technology metrics and analysis methods

6.2. Holistic assessment – the core of airplane design

The holistic assessment of new technologies or configurations has always been at the core of Airplane Design research. While keeping the top-level airplane requirements (TLARs) constant, Airplane Design studies can be performed to assess the impact of a new technology on vehicle-level performance metrics. Traditionally, they have been confined to weight, operating cost and fuel consumption, quantities that are computed straightforwardly. From an industry point-of-view, the long-standing quest for maximum performance has been superseded by a need for a "balance" between performance, life-cycle cost, reliability and maintainability, and operational efficiency. But as environmental concerns are becoming more important, the term "holistic" might be expanded to more disciplines to fully capture the impact of design decisions. What we wish to avoid is that we are overlooking opportunities that would mitigate the noise and climate impact because they are not reflected in our tool set.

Local environmental impact of aviation is driven by the landing and take-off (LTO) emissions as well as the fly-over noise around airports. While these aspects are important in societal discussions regarding the expansion of airports or increase in number of flights, they are often not considered in the conceptual design phase of commercial airplanes. This is partly due to the high computational cost and complex geometric input that is required for the noise prediction models. To remedy this, it is proposed to include fast and reliable noise analysis methods that are compatible with other disciplinary models in the conceptual design process. Such noise prediction methods should be able to generate new performance metrics such as fly-over noise and should be able to simulate noise abatement approach procedures. Technologies that impact the flight profile of an airplane in the vicinity of an airport (i.e., wind milling propellers to allow steep decent) could then be evaluated properly. In addition, when coupled to actual approach and climb trajectories in airport vicinities, the impact of new technologies on community noise or the number of awakenings in night flights could be evaluated around airports.

Operating cost has been a notorious design driver for many, if not all, commercial airplanes and it is anticipated that this is not likely to change in the near future. As described before, new elements as i.e. the price of carbon emissions through taxation are likely to motivate aviation to reduce carbon emissions via various potential energy carrier scenarios (c.f. chapter 3). To consider those in operating cost models poses three main challenges. First of all, cost modelling is difficult to perform outside the industrial domain due to a lack of publically available cost data. The methods to predict nonrecurring and recurring cost for the manufacturer are based on legacy data and require a valid quantification of a large amount cost components in order to make a realistic cost prediction. The same can be said for the operating costs, which comprises many distinct aspects and again are dependent on a lot of different parameters that are difficult to capture. Therefore, cost modelling can still be considered an Achilles heel of the holistic assessment. Secondly, the cost of fuel is challenging to predict (see chapter 3). Finally, if technologies are incompatible with existing infrastructure (batteries, hydrogen) there are additional costs to be included in the analysis: distribution cost, storage cost, and operational costs. Improving cost modelling in conceptual design is therefore important to assess the impact of taxation and subsidy policies that governments might employ to direct the industry towards climate neutrality.

6.3. The effect of airplane operations on airplane assessment

As anthropogenic climate change is a slow process and hardly influenced by the design of a single vehicle, measuring the impact of new technologies needs to be assessed at fleet level and over the operational life of the vehicle. While top-level requirements determine the limits of what an airplane can do, typical operation of an airplane happens relatively far away from those limits. It is therefore of interest to include a representative airline route network and traffic schedule to assess the climate impact of a future fleet of airplanes. This would allow the inclusion of range, longitude, and season variations on the short-term and long-term climate impact. Other operational aspects that are important to include are the flight altitude and corresponding flight speed. With fleet-level and operational-life aspects included, one can also use Airplane Design methods to study the effect of the top-level requirements on some of the key performance metrics. As is well known, relaxing the mission range requirement and reducing the cruise Mach number can significantly reduce weight, operating cost, and energy consumption of a vehicle.

In conceptual airplane design, the payload and mission specifications drive the energy consumption of the airplane. Typically, a (set of) mission profile(s) is prescribed that the airplane needs to fulfil. These mission requirements typically translate to a payload-range diagram that communicates which combinations of payload and range can be flown with the designed airplane. The payload-range diagram is therefore an important output of the design process as it gives a clear indication of the potential productivity of the airplane outside of the specified payload and range combination(s). Based on empirical data, the cruise altitude is often added to the mission specification as we know quite well at which altitude turboprop and turbofan airplanes operate most efficiently.

Taking the environmental effects into account, both in terms of LTO emissions, noise, and global-warming impact, then the state-of-the-art method might not be sufficient. For example, the formation of cirrus clouds is dependent on the atmospheric state and therefore on the flight altitude, the location on earth and the season. This has led to the idea that, in order to reduce the climate impact of aviation, airplanes need to fly lower and slower. However, this does not yet account for the seasonal and geographical variations. Furthermore, flying lower and slower also implies that more energy is required to perform the prescribed mission, that the mission time is longer, and that either more airplanes or an equal number of larger airplanes are required to fulfil the worldwide demand for air travel. This, in turn, would lead to more LTO emission and noise production around airports.

This example demonstrates that operational aspects should become part of the design process. In an ideal situation, the design process comprises mission design parameters, airframe design parameters and engine design parameters. Furthermore, the analysis methods that are employed in the design chain should be able to assess the effect of off-design operations on environmental performance metrics such as radiative forcing, LTO emission and LTO noise. To include the effect of operational parameters on the overall aviation system, a system-of-systems approach is required. Rather than designing a single airplane, the airplane is part of a fleet, and the impact of design decisions are measured on fleet level, rather than airplane level. Furthermore, by varying both mission design variables and engine design variables, studies can be conducted into the effect of different sustainable aviation fuels.

One advantage of the inclusion of such a system-of-systems approach would be the ability to evaluate the effect of taxation or subsidy policies. It should be kept in mind that the aviation industry is highly cost driven and that it is likely that (global) pricing policies for fuel need to be adopted to nudge the industry towards using sustainable aviation fuels. If air travel using conventional kerosene is made more expensive through taxation, how should airplanes be designed to keep operating cost low? What should the mission look like? What is the best propulsion system for this airplane? If more refined taxation policies are instigated that tax the global warming impact, rather than carbon emissions, what is then the answer to these questions? In summary, the system-of-system approach would allow researchers to investigate the possible impact of policy scenarios. In turn, policy makers could use the results of these studies to aid their decision on how to shape policies that push the aviation sector in the right direction, while keeping it affordable for the public to fly.

Including mission design variables as well as fleet design variables in the design process is clearly desirable. However, it also comes with its own challenges. The first one is that the number of design variables can easily grow very quickly if mission design variables are added. Speed and altitude are the simplest to add, but that still constitutes a two-dimensional flight profile. If geographical and seasonal effects are to be included as well, than a route network is needed as well as information on the predicted flight frequency on that network over the service life of the airplane. Secondly, fleet analysis requires information of the market potential of the airplane design, its service lift, the replacement rate, etc. Each and every one of these aspects brings design variables to the problem. Secondly, the analysis of off-design mission scenarios can quickly become a time-consuming effort. Both aspects can dramatically increase the computational time of the design synthesis problem, making it unfeasible to use in the conceptual design phase. Reducing the multi-variable operational and fleet design problem is therefore advised in order to have an acceptable computational time as well as a manageable design space.

Rather than assessing technologies at vehicle level, long-term research is needed to enable a system-of-systems approach that includes the analysis of operational parameters as well as fleet parameters. This would allow airplane design studies to predict the environmental impact of possible policy scenarios combined with new technologies or configurations.

6.4. Radically new energy-efficient airplane configurations

Civil transport airplanes have largely looked the same over the last seven decades. We have come to know this configuration as the “tube-and-wing” configuration. Variations on this configuration have been limited to wing position (high vs. low wing), engine position (fuselage vs. wing), tail configuration (low tail, cruciform tail, or T-tail), and landing-gear integration (mounted on the wing or on the fuselage). If we limit our assessment to turbofan-powered airplanes introduced in the last two decades, we see one dominant configuration: two engines hanging under the wing, a low wing with the landing-gear integrated into its Yehudi and a low tail. The advantages of this configuration are so abundant that it is safe to state that this is what civil aviation has evolved to. Despite the fact that all previous efforts to find an alternative configuration have been unsuccessful, it is a broadly-shared vision the we should keep on looking beyond the tube-and-wing configuration to further improve the energy efficiency of our airplanes. Previous studies have indicated that alternative configurations show this potential.

Research should keep on exploring the merits of other configurations. First and foremost, because of the fact that the tube-and-wing configuration is reaching a maturity level where we do not expect more improvement in energy-efficiency. With the computational tools of today, industry is able to refine the airplane design to such an extent that, within the constraints of the regulations, the airplane is as efficient as possible. While airplanes have been typically optimized to minimize operating cost, this design goal almost coincides with the goal of minimal energy consumption or minimum climate impact. Of course, technologies such as high-bypass-ratio engines and composite structures allow airplanes to become more efficient, but these technologies could work equally well on alternative configurations. If more energy-efficiency is required to reduce the impact of aviation, we also have to look for unconventional alternatives.

Unconventional airplanes have been proposed since the beginning of aviation. Many of them are a variation on the tube-and-wing theme. One can think of forward-swept wings, over-the-wing engines, or truss-braced wings. Each of these configurations has its merits and drawbacks but still fundamentally relies on a pressurized tube to comfortably house the passengers and their luggage. However, for large airplanes the size of the airplane compared to the size of the average human being becomes so large, that passengers can be comfortably accommodated in the wing. This idea, which is also relatively old, is based on two fundamental premises: 1) this leads to a lower ratio between wetted area and useable volume and 2) the lateral distribution of payload weight reduces the structural weight of the airplane. Practical applications of these premises are found in pure flying-wing airplanes, such as the Flying V and the blended-wing-body airplane. Because these unconventional configurations stir up very diverse questions, it is evident that research, particularly at academic institutions and research centres, is warranted to answer these.

On the other hand, as history has proven that the tube-and-wing configuration can actually be applied in practice, unconventional configurations that still use a tubular fuselage also need further studying. Particularly, the integration challenges that stem from technology advancement deserve our attention. This includes, but is not limited to, the integration of hybrid-laminar flow control, the integration of hydrogen fuel tanks, or the integration of ultra-high bypass-ratio or open-rotor engines. Each of these technologies requires the conceptual designer to think about configurational aspects of the tube-and-wing airplane and how this affects all cross-disciplinary aspects.

So, while the present-day regulatory framework as well as financial constraints on the R&D budget of manufacturers hamper the introduction of an unconventional airplane configuration, this does not mean research should be aimed at advancing the tube-and-wing configuration. Rather, new ways to improve the tube-and-wing airplane should be followed, by making subtle changes to the configuration to further improve it. However, also the more fundamental benefits that could be reaped from an unconventional configuration such as a flying wing or a blended-wing body should not be neglected.

In conclusion, more short-term research is needed into radically new airplane configurations such as flying wings and blended-wing-body airplane because of their inherent benefits that warrant exploration, especially in academia and research centres.

6.5. The role of multi-disciplinary design optimization

Designing an airplane is by definition a multi-disciplinary activity. Design handbooks typically present a cyclic multi-disciplinary analysis process, which converges after a number of iterations. The field of multi-disciplinary design optimization (MDO) has formalized this approach such that design variables are altered by an algorithm to minimize a predefined objective function subject to a set of constraints. By implementing this MDO process in a computer, optimal airplane designs can be produced without the interference of a design engineer, although a team of disciplinary expert is still required to define the MDO problem, to set it up and to monitor, interpret and check the results. MDO also allows a multi-level approach: more refined analysis methods that analyse an aspect of the airplane in more detail or with higher fidelity are introduced where required as the design progresses. The assumption is that more refined analysis methods (also known as “higher-fidelity methods”) reduce the uncertainty of the multidisciplinary analysis result by including more physics or first principles rather than empirical or low-fidelity methods and thereby increase the confidence in the performance metrics which are predicted at the end of the design cycle. Due to their automation, MDO approaches also lend themselves to trade studies.

While theoretically this works flawlessly, MDO has its limitations. The starting point (or baseline) of the optimization process as well as the parameterization and thus the choice of the design variables determines, to a large extent, the outcome of the problem. For example, optimizing a tube-and-wing airplane for minimal fuel burn does not yield a blended-wing-body airplane. In order to compare the two configurations, two different sets of design variables need to be defined: one set of design variables that describe the geometric attributes of a tube-and-wing airplane, while another set describes a blended-wing-body airplane. From that we can deduce that the airplane designer is still important in setting up the MDO problem: selecting and parameterizing the baseline in terms of design variables, setting up the disciplinary models, selecting and coupling the disciplinary analysis methods, and choosing the optimization algorithm.

Secondly, the more refined (or “higher fidelity”) methods in one discipline are not necessarily properly matched to the level of refinement in another discipline. For example, assessing the drag of a transonic wing requires a very refined geometry model of the wing if an aerodynamic solver is employed that can capture aerodynamic effects such as shock waves. If such a refined analysis is combined with a rudimentary geometry description, the result of the optimization process is not representative for the aerodynamic performance of that wing. Balancing the individual disciplinary methods in terms of their “fidelity” is therefore important. Choosing the right fidelity is therefore left to the designer. However, artificial intelligence (AI) could play a role in this process in the future.

While MDO cannot replace the airplane designer, it can help the designer in assessing the impact of innovative technologies. In conceptual design, MDO enables the design team to better explore the design space that is too complex to be managed (>15 airframe design variables, >10 propulsion design variables, >5 operations design variable). While benefits of a technology can be measured with a multi-disciplinary analysis, optimization part shows the designer the potential and the possible trades for the technology. Then, the most promising or robust one can be selected. Also for preliminary and detailed design MDO is an asset to really find the best design point according to industry criteria. This traceable way of generating mathematically optimized designs makes the MDO approach also suitable for scientific publications. Therefore, MDO is a valuable tool to assess the impact of a new technology and to perform trade studies.

If we compare how we envision MDO to be used in conceptual (and preliminary) design and how it is used in the aviation industry today, there is still a large discrepancy. The first barrier to MDO adoption is the required knowledge of computer science. The successful implementation of an MDO process in a computer or a network of computers is largely dependent on the programming skills of the developer. While the developers are often trained aerospace engineers, they do not necessarily have the skills and the knowledge to setup this process in a robust manner. Vice versa, computer scientists do not possess knowledge of the design process or airplane attributes to effectively judge the validity of outcomes. Thus, MDO is a highly collaborative effort of overall aircraft design experts, disciplinary experts, MDO experts, and IT experts.

A second barrier lies in the distribution of tools and knowledge between several disciplines. While less relevant for conceptual design, in the preliminary design phase the design process is more often distributed between various entities within a company or between various companies when subcontractors are involved in the design process. Currently this is done in a fairly traditional way: the designer prepares the required input for all the disciplines and determines budgets or targets: e.g. a weight budget, a cost budget, an energy budget or a loads target. This is typically done in the form of a Design Database (DDB). With the input from the designer, each of the disciplinary entities refine the design and perform the required analysis to show that they stay within the budget constraints or targets. The result is looped back to the designer that uses that input to make an updated version of the design. Formalizing this approach requires each entity to be connected to a workflow and have tools and methods that are fully compatible with a digital equivalent of the DDB. In addition, subcontractors might not want to share their proprietary design and analysis methods making it more challenging to introduce MDO in the preliminary design process.

While much research into algorithms has made it possible for MDO to be used effectively at conceptual-design level, the implementation of MDO in larger problems where more refined analysis methods are employed still encounters implementation barriers and requires substantially larger computing facilities. Therefore, long-term research is needed to investigate how to implement MDO in an industrial environment in a way that allows disciplinary experts to stay in control, while still taking part in the automated design optimization process in an efficient manner.

6.6. Parametric modelling of airplane geometry and its relation to design

There is no other vehicle where shape and performance are as strongly coupled as in an airplane. The external shape determines how much lift and drag is produced at any combination of speed, altitude, and inflow angle. The shape also determines to what degree the airplane can be controlled or how stable it is. Furthermore, the internal geometry affects how much volume is available for the structure, the systems, the payload, and the energy carrier. The structural weight of the airplane (see also the following chapter) has a double dependency on the geometric properties: first through the external shape affecting the aerodynamic loads and secondly through the internal shape that determines the available volume for the structure. Engine and airframe noise also have a strong dependency on the external geometry of the airplane: leading edge radius, size of the landing gear strut, tire dimensions, and so on. This demonstrates that in order to estimate the impact on energy consumption, emissions and noise, the generation of airplane geometry is an important pillar of airplane design.

The state-of-the-art in conceptual airplane design does not use very advanced geometry descriptions. While three-dimensional modelling in conceptual design has become more commonplace, the function of geometry modelling is usually limited to representing the external geometry of the airplane. While this gives the designer valuable insight into how the airplane looks like, it is not an integral modelling step in the design process. It is also not customary to query the geometric model of the airplane in order to derive shape-related information. In addition, the internal and external geometry are usually not coupled. For example, the geometric model of a wing box is usually modelled as a box structure with rectangular cross section while the external wing surface is curved. These simplifications are typically justified in the conceptual design phase as the analysis methods are relatively crude and not sensitive to small changes in geometry.

The limited use of geometry modelling in conceptual design can, however, present a fundamental limitation to airplane innovation. The absence of good geometry modelling limits the successful implementation of analysis methods that rely on geometry information for accurate results. As desktop computers become faster, simple numerical tools for the assessment of aerodynamic and structural properties are within reach of conceptual design. However, these methods require computational geometry: a geometry that can be automatically discretized in small elements, such that it can be fed to a variety of analysis methods. While automated discretization methods have existed for a long time, the computational geometry is still not embedded in the conceptual airplane design processes. This implies that physics-based analysis methods cannot be successfully employed in the conceptual design phase because the computational geometry is simply not part of the modelling chain. This also means that multi-fidelity analysis (where one progressively increases the “fidelity” of the analysis method as the design progresses) is not possible. This hampers particularly innovations in the airframe design that go beyond the limitations of empirical analysis methods. These include almost all recently proposed novel airframe configurations: the truss-braced wing, the blended-wing body, the Prandtl-Plane, and the Flying V. Each of them present unique, geometry-dependent attributes that directly affect their aerodynamic, structural and noise properties.

To improve the airplane design process and allow configurations other than tube-and-wing and technologies to be properly assessed, geometry modelling and analysis should become part of the design process. Not only as an output of the process but as an integral part of the process. It is desired to have a single geometry of the airplane that can be queried by all disciplines in the design process: aerodynamics, structures, weight, noise, etc. Furthermore, the geometry should also be allowed to be used in a multi-fidelity design process. For example, it should allow the wing to be modelled as a one-dimensional beam as well as three-dimensional box structure. Finally, as the external geometry interfaces with the airflow, it would be desirable to impose curvature continuity over the surface as well. This would yield an excellent starting point for the aerodynamic design. If such geometry modelling would be implemented in a multi-disciplinary design process, it could greatly enhance the assessment of new airplane configurations.

The challenge with geometry definition is that the more requirements one poses on the geometry the more variables are needed to describe that geometry. While a lifting surface in conceptual design can be constructed by defining a handful of design variables, describing a computational geometry in three-dimensional space requires many more. Each of these variables, in turn, affects the performance of the vehicle and therefore the design synthesis problem can grow quite rapidly out of hand due to the intractable number of variables. Therefore, a balance needs to be stricken between the computational requirements on the one hand and the number of design variables on the other hand. Efficient parameterization of a geometry plays an important role in finding that balance. What is equally important is that airplane designers have good knowledge about defining geometry. Therefore, graduate-level courses on geometry modelling, parameterization and computational geometry might help in filling the knowledge void that is currently exists.

In summary, geometry modelling and analysis should take a more significant role in the design of future airplanes. To balance the number of design variables with geometric design freedom, medium-term research is needed to conceive efficient forms of geometry parameterization suitable for conceptual airplane design.

6.7. Uncertainty quantification in airplane design: The challenge of predicting weight

The minimization of airplane weight has been one of the main focuses of aircraft designers. However, weight estimation is often more art than science. While physics-based weight prediction methods have been developed to estimate the weight of the primary structure of the fuselage and lifting surfaces, the weight of other components still largely relies on empirical methods. This makes the weight estimation for unconventional configurations particularly difficult. While useful, these empirical methods are often based on weight data of aircraft that were designed more than fifty years ago. With manufacturers keeping the weight data of state-of-the-art airplanes close to their chest, it is difficult for research institutes and academia to use reliable weight data to synthesize an airplane design. Secondly, there is an absolute lack of reliable weight data of new technologies such as hybrid-electric power train sub-systems, superconductive systems, liquid-hydrogen components and sub-systems, etc. This lack of reliable weight data hampers the proper assessment of new aviation technologies at vehicle or aviation level.

For industry the lack of available weight data does not need to be a problem as they can work with available weight data from their latest products in order to make sure the relative weights are correctly represented in the airplane's weight break-down. They could even employ artificial-intelligence techniques to construct elaborate weight sensitivity methods that rely on a large database of weight data all the way to part level. In other words, while the research community might not have the perfect weight estimation methods available, this does not preclude the assessment of new aviation technologies as long as the aleatory uncertainty in the weight estimation method is taken into account when presenting the performance metrics.

This also touches on the question whether research institutes and academia should perform studies to improve the empirical weight prediction methods. Particularly, when this research would involve scouring through detailed weight reports from industry (assuming they would be made available). Only when a scientific contribution can be made, would it justify the use of research money to improve knowledge on weight estimation. The same argument can be made for further research into cost estimation methods (see above).

On the other hand, more research should be performed on the uncertainty quantification of the analysis methods (including weight estimation) and how that transpires into the technology assessment. When combined with MDO, this can lead to a more robust assessment of technologies. While epistemic uncertainty in new technologies is often included in Uncertainty MDO (UMDO), the aleatory uncertainty in the prediction methods is usually neglected. So rather than improving our weight estimation methods, research should focus on how to quantify these uncertainties and propagate them to the airplane performance metrics. This allows us to gain insight in the uncertainty of the impact of a new technology due to the lack of knowledge as well as due to the unknown accuracy of our analysis methods. To advance the field of UMDO, long-term research is required covering the entire analysis chain, including the extensions that have been proposed in the preceding chapters.

7. Conclusions and Outlook

The analysis of the preceding chapters shows that a change towards a carbon-free aviation with significantly reduced climate impact does require more than a simple replacement of fossil fuels. Instead, alternative fuels plus new aircraft technologies and concepts, customized to their individual mission requirement are the only way to combine requirements on environmental impact and economic viability.

Significant advancements of a broad range of technologies in flight physics, energy storage and conversion as well as materials and structures will be needed. These enable transformation of aviation to cope with the societal objectives of using renewable energy sources for sustained air travel with commercial aircraft, and of employing circular life cycles of aircraft. It turns out that the identified technologies represent important keys for a competitive aircraft industry to develop and produce viable aircraft in the future. We are convinced that the associated research needs cannot be satisfied until the end of the present decade, rather time lines that span 15 years or even more are envisaged to advance the majority of technologies to a technology level of at least TRL 6.

The roadmap towards technology readiness should build on the following elements:

- Research into new aviation energy carriers has to be combined with configuration concepts studies. Both should allow for new radical solutions in terms of on-board energy storage, conversion and distribution as well as unconventional configurations such as flying wings and blended-wing-bodies.

- Energy density, efficiency and weight remain the governing parameters on subsystem levels for technology assessment. Energy carriers and conversion systems which do offer significant emission reduction (e.g. electric and hydrogen based flying) need further significant improvement in specific energy/power-to-weight ratio.

- Even with an optimistic outlook for the next decades, the way for such technologies can only be paved by significant reduction of the energy demand of future aircraft by radical weight and drag reduction measures.

- Traditional analysis methods for propulsion systems (including the energy carrier) on aircraft level need to be extended to include fast and reliable noise analysis methods, methods to assess emissions and methods to predict the radiative forcing.

- Assessing future technologies on energy systems, vehicle level and aircraft operation requires a system-of-systems approach, which includes the energy carrier production and distribution system as well as mission and fleet parameters for a holistic approach.

- Life-cycle based cost modelling needs to be improved to enable the assessment of new technologies from production during full life operation and maintenance plus external effects of political measures like tax policies on all emissions (CO_2, NO_X, contrail formation, noise, etc.)

- It will not be possible to explore the relevant physics of fluids, energy systems, material and structures solely by using simulations built on first principles. Therefore, experimentation in ground-based test facilities must be employed. Because of the complex interactions involved among the basic research disciplines there is a strong need for technology demonstrators with subscale and scale models.

- Numerical simulation that support multidisciplinary analysis and optimisation on subsystem level up to full aircraft design tools must be seamlessly integrated with Artificial Intelligence and a comprehensive Knowledge-Based Engineering approach to deal with design complexity, various sources of uncertainty, and lack of knowledge and experience about suited system topologies.

- Cross fertilisation by technological progress in the fields of e.g. automotive, materials, electronics, production and process engineering should be fostered by dedicated means of long-term funding.

- Considering the estimated potentials and economic effects of enabling technologies (energy carriers, conversion and aircraft technologies) for sustainable aviation, a wider range of different aircraft concepts is expected. One solution will not fit to all missions from regional to long range. Rather, there should be sourcing and courage to develop optimal solutions while carefully assessing the benefits of scalability.

- Public funding to comply with the identified research needs should follow a strategic long-term plan, focussing on those technologies with strong estimated impacts. The funding agencies must avoid embarking on unproductive funding cycles, where research projects over short periods of e.g. 3 years must promise unrealistic technology advancements in order to be successful.

Herausgeber
Niedersächsisches Forschungszentrum für Luftfahrt
Technische Universität Braunschweig
Hermann-Blenk-Str. 42
38108 Braunschweig
Telefon +49 531 391-9821
nfl@tu-braunschweig.de
www.tu-braunschweig.de/nfl

Redaktion
Jens Friedrichs/Rolf Radespiel/Henri Werij/Roelof Vos