The Energy-Efficient Aircraft of the Future: A Long-Term Perspective

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Executive Summary

With the goal of drastically reducing aviation's climate-impact footprint, and even achieving a net-zero aviation system by 2050, the aviation stakeholders face enormous challenges. While it is clear that these goals can only be achieved through the use of renewable and sustainable energy sources such as sustainable aviation fuels (SAF) and green hydrogen, there will be limitations in their availability, as well as significantly increased fuel cost associated with this energy transition. The challenges arise from the investments required for renewable energy production capabilities, infrastructure and logistics, as well as higher recurring costs due to increased production costs of SAF and hydrogen. Therefore, targeted measures to significantly enhance the energy efficiency of the air transport system are essential, addressing both transport operations and aircraft design.

In this paper, the authors focus on the latter, examining how much aircraft efficiency can be further enhanced to support these goals. To this end, various technological options are discussed with a balanced approach, considering both their potential and the challenges associated with significantly improving energy efficiency. Based on our findings we outline a pathway for achieving a reduction of 50% or more in the energy consumption of future aircraft.

In the broad field of aircraft technologies, those are highlighted that promise the highest saving potentials in aerodynamics, airframe structures, aircraft control, propulsion systems and aircraft systems, also allowing for the derivation and assessment of promising aircraft configurations. This is complemented by identifying key enablers, namely multi-disciplinary optimization, changes in aircraft certification and revised operational constraints.

The authors identify the following key technologies as candidates for viable integration into future classes of large transport aircraft well before 2050:

Aerodynamic efficiency needs to be improved through a balanced approach, combining viscous drag reduction with the reduction of induced drag. The concepts of viscous drag reduction techniques through laminar flow control are well understood but only partially demonstrated at sufficient levels of technology readiness. They will provide the highest leverage for viscous drag reduction if applied on all aerodynamic surfaces, including ideally the fuselage, for which mature solutions are still lacking. However, to fully leverage the potential, exploitation will require advances and changes to the wing design, compliant high-lift devices and the actuation and control system. Especially the latter will go hand in hand with increasing the wingspan of future aircraft to further reduce the induced drag. This will require advanced structural concepts, fully utilizing the potentials of carbon fibre composite (CFRP) structures, and advanced flight controls allowing for active load control. However, the constraints imposed by actual infrastructure standards at airports interfere with

the full exploitation of aircraft with significantly higher spans than currently employed. This may be overcome by the adaptation of airport standards or by integrating new technical means like folding wingtips in future aircraft.

Airframe structures will be key enablers for further significant weight reductions, but also functional capabilities not achieved with classic designs. For this, the authors consider it essential to fully utilize the capabilities and features of CFRP materials in a thoroughly integrated and consistent manner. Due to the special characteristics of carbon fibre–based structures, some essential design requirements that were introduced to allow fail-safe designs in metallic structures are no longer valid. If suitable design requirements were adapted to the physical properties and characteristics of the material and the structural design, significant weight reductions and tailored functionalities, e.g. in the control of structural loads and flutter, would be possible.

Active control of the aircraft in combination with advanced systems technologies will be the key enablers to allow for functionalities like active alleviation of gust loads, manoeuvre loads and even flutter control to substantially reduce aircraft weight, and to allow the realization of wings with extremely high aspect ratios. Additionally, they may contribute to allowing new or enhanced synergies in the utilization of energy on board the aircraft. Especially if we consider hydrogen as one promising sustainable fuel option for aviation, a series of changes will be required on the systems side, including fuselage-integrated and insulated tanks, hydrogen-handling and safety systems and thermal and water management. This will also make it possible to take advantage of additional synergies, especially with new concepts for thermal management utilizing hydrogen as a coolant and along with water, integrated in hybrid architectures comprising fuel cells and gas turbines.

More synergistic approaches will also allow for enhanced efficiency in the field of propulsion integration. New engine concepts with an ultra-high bypass ratio or open propulsors will benefit from integration where the stronger aerodynamic coupling of the airframe aerodynamics with the propulsion flow needs to be deliberately controlled. One potential technology in this field is boundary layer ingestion (BLI), which could help to reduce the adverse effects of viscous drag on the fuselage to enhance overall propulsive efficiency. The use of process water for hydrogen-based aircraft enables significant NOx reductions as well as efficiency improvement in the core engine.

Integrating the different technologies into a specific aircraft configuration will eventually show the integrated potential, as synergies may be utilized more or less and integration penalties may be more prominent in some combinations than in others. We also point out that top-level aircraft requirements and also varied concepts of operations with altered cruise speed and cruising altitude, as well as novel routing concepts, can have significant impacts on overall aircraft performance and need to be carefully reviewed and probably adapted for future transport networks and operations. While radically changed aircraft configurations show some specific advantages, the authors still consider an advanced tube and wing configuration as promising for achieving maximum reductions of energy consumption.

In order to quantify the identified potentials, an exemplary, yet very promising combination of technologies is provided for a future short- and medium-range (SMR) configuration and compared to a reference aircraft with an A350 technology level. The saving potentials are presented in detail, given the mutual interactions being key for some technologies to unfold their potential. The authors predict physically and technically sound potentials for energy savings well beyond 50%. Even considering additional uncertainty margins used to cover present uncertainties in the technology assumptions, those savings sum up to more than 40%.

Based on the findings presented in the paper, the authors highlight the urgent need to strengthen targeted measures to foster the identified technologies in a comprehensive and coordinated manner. Only such measures will facilitate technology maturity ready for an insertion into future products well before 2050. Boosting aircraft efficiency is seen as a key enabler to achieve the climate targets and allow for sustainable growth in the aviation sector.

The full paper is released online by the DGLR:

https://www.dglr.de/informieren/publikationen/the-energy-efficient-aircraft-of-the-future/

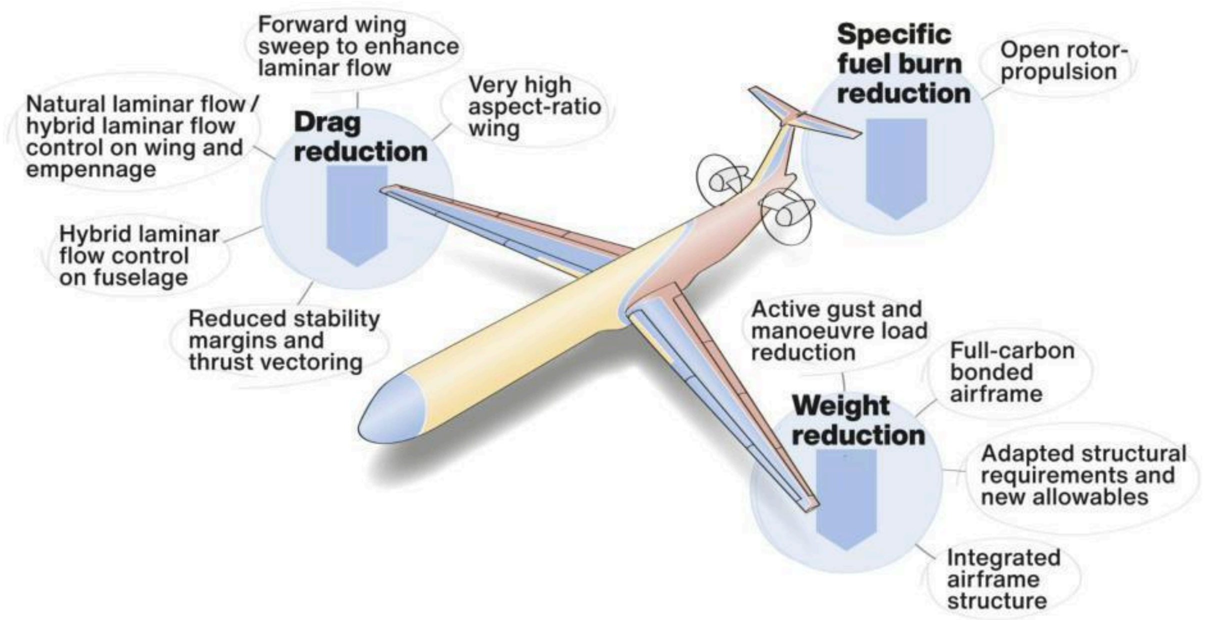

Figure 1: Key building blocks on the way to the energy-efficient aircraft of the future