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Most Promising Technologies and Aircraft Concepts for Environmental Performance Improvements: A Systematic Review

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Abstract. A systematic review of the most promising technologies and aircraft concepts for reaching climate-neutral aviation is presented, based on a technology scouting for classification and benchmarking of their environmental performance. In a first step, a heuristic approach is used to analyse existing technology roadmaps on reducing environmental impact. The main levers commonly identified are technology advancements, operational measures, sustainable aviation fuel and demand management. The aircraft technologies from the aviation roadmaps are classified in a technology taxonomy in the categories aerodynamics, structural, systems and propulsion technologies and the entry-into-service is visualised in technology roadmaps. In a second step, an overview and categorisation of recent developments in advanced and disruptive (regional, short/medium and long-range) aircraft concepts is compiled. Environmental performance improvements can reach up to 40-50% (kerosene fuel burn and CO_2) and 70% (NO_X) compared to older reference aircraft, with reductions dependent on reference aircraft age. Hydrogen combustion offers zero CO_2 while hydrogen fuel cells offer zero CO_2 and NO_X emissions. Different architectures are used for various ranges: Blended wing body and tube and wing (long-range), tube and wing (regional), and box-wing, double-bubble, strut-braced wing and tube and wing (short/medium range). While it is not possible to attribute a single reduction potential to a single technology feature, the most promising fuels are kerosene (conventionally, or in combination with batteries or fuel cells), sustainable aviation fuel and hydrogen. From the propulsion concepts, innovative turbofans (e.g. ultra-high bypass ratio turbofans) and innovative engines (e.g. hybrid-electric fans) had large improvements. In the field of aerodynamics, most applied technologies are high aspect ratio wings, riblets and laminar flow control, furthermore most concepts applied composite materials. For some aircraft concepts the climate impact was measured using climate metrics like ATR100 or GWP100, revealing trade-offs between fuel burn and climate impact or NO_X emissions.

Introduction

The aviation sector moves towards climate neutral aviation, with the goal of reaching Net Zero CO_2 emissions in 2050 [1, 2, 3]. Therefore, technological advancements are needed to reduce fuel burn and the resulting emissions. In Europe, Clean Aviation will contribute to Europe's climate neutrality by developing and implementing aircraft new technologies [4]. The concepts of a hybrid electric regional aircraft and short/medium range aircraft, both with a tube and wing architecture, have the overall target of a 30% CO_2 emission reduction compared to an aircraft with 2020 state-

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of-the-art technology. A hydrogen-powered aircraft, either with H_2 direct combustion or a fuel cell-powertrain, would lead to 100% in-flight CO_2 reductions. The objective of the Clean Aviation project CLAIM is to translate these goals into tangible (climate) metrics and recommend an assessment methodology. As an input for a performance assessment of Clean Aviation-like aircraft concepts, a technology scouting has been performed to classify and benchmark technologies and aircraft concepts in terms of environmental performance, providing guidance for future research and deployment efforts.

In this paper the most promising aircraft technologies for emission savings are investigated by reviewing recent technology roadmaps [5]. Additionally, it compares the potential of sized aircraft concepts with different architectures and utilised technologies on an aircraft basis and linking the improvement potential to the utilised technologies [6].

Methods

A literature research was conducted to identify key trends and developments in aircraft technologies. The scouting of technology roadmaps comprised roadmaps, aviation strategies, pathways and projections from international authorities, government agencies and (non-) governmental associations. The roadmaps[1] and the mentioned technologies are classified along a defined taxonomy, to enable a fast analysis and comparison. The categories are: aerodynamics, propulsion, systems, structural, architecture/concepts, air traffic management (ATM) and (Aero) Acoustics. Information is collected on the entry-into service, interdependencies, technology readiness level (TRL), market segment, estimated market penetration and considered benefits. The results are saved in a technology database which enables the analysis and comparison of the different technologies, the identification of more progressive and conservative sources, key technologies and technology groups.

In a second step, a structured literature review on advanced and disruptive aircraft concepts was performed, considering research programs, research papers and commercial developments.

For an aircraft concept to be included in this assessment, its environmental performance must be defined relative to a reference aircraft. This can be determined through indicators such as fuel burn reduction, CO_2 or NO_X emissions, or an overall climate impact evaluated using dedicated climate metrics. The concepts were then categorised by study context, aircraft class, aircraft architecture, fuel/energy source, propulsion concept, aerodynamic concepts, and structural concepts. The collected data was analysed to provide insights into the potential environmental improvement of these advanced and disruptive aircraft concepts.

Results

All roadmaps recognise current challenges in aviation with the overall goal to decouple future growth from emissions and their resulting climate effects. The main levers are technology advancements, consisting of fuel efficiency increase and a shift towards zero carbon technologies, operational measures, SAF deployment and demand management. Without economic measures, net zero CO_2 emissions will not be reached within the sector by 2050. Non-CO_2 emissions are mostly only incorporated as a future goal and more mitigation measures are needed to reach net zero climate impact of aviation.

Through an in-depth analysis of the technologies, a database of 117 technologies, architectures, and concepts was established. Some technologies are specific to individual market segments, while others can be applied across multiple aircraft types. The technology references (if given) also vary from technologies from the year 2000 and technologies about to enter service or currently in service. Generally, there is an agreement on which type of future aircraft concepts are needed, however the expected entry-into-service (EIS) date varies:

- Sub-regional zero-carbon electric aircraft (EIS 2029-2030)

[1] The list of investigated roadmaps can be found in the CLAIM D3.1 report [5].

- Regional aircraft (hybrid electric EIS 2029-2040 or zero-carbon EIS 2036-2040)
- Narrow body aircraft (ultra-efficient EIS 2033-2040 or zero-carbon EIS 2042-2050)
- Wide body aircraft (ultra-efficient EIS 2042-2050 or zero-carbon EIS 2050)

The key technology groups are hybridisation and electrification, sustainable aviation fuel (SAF) upscaling, (liquid) hydrogen aircraft enabling technologies (direct combustion, fuel cell propulsion), ATM and operational technologies, and knowledge and research needs (especially for non-CO_2, fuel characteristics and operations).

Along with the most frequently mentioned technologies, technology roadmaps were developed. An example[2] for the group ‘Propulsion Technologies’ is given in Figure 1, where the new technologies are matched with the future aircraft type that they could be deployed on and an estimation of the entry-into-service (EIS) is given.

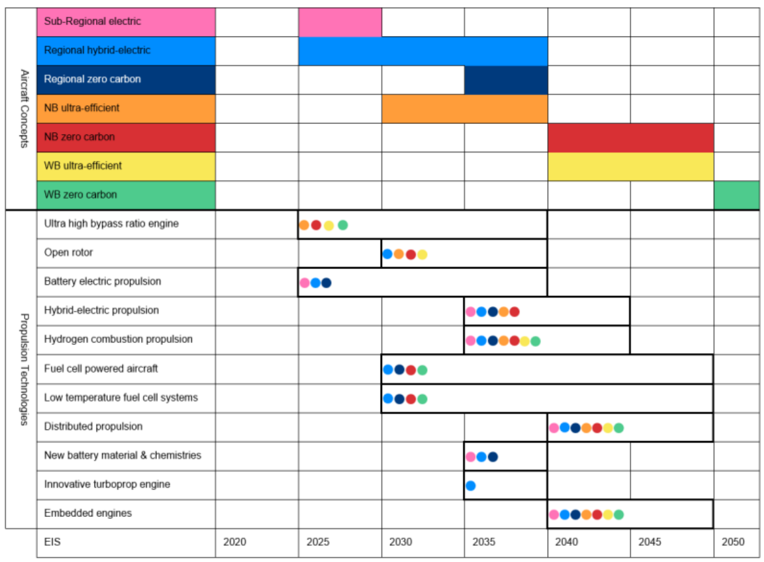

Figure 1: Roadmap for propulsion technologies

In the second step, 161 disruptive or advanced aircraft concepts[3] were found and analysed with respect to climate impact parameters fuel burn, CO_2 emissions, NO_X emissions and other climate metrics. The reported kerosine fuel burn reductions were up to 40-50% compared to traditional reference aircraft (EIS before 2015). Smaller gains were observed compared to state-of-the-art reference aircraft (EIS between 2015 and 2025), and even smaller gains compared to future reference aircraft (EIS after 2025). This is due to the fact that the more recent or future reference aircraft already include technology advancements with the connected benefits in fuel burn reductions. For some aircraft concepts, the fuel burn even slightly increases which stems from a trade-off with other climate effects.

The overview of CO_2 emission reductions in Figure 2 looks similar as the kerosene fuel burn reductions, because for aircraft concepts that only use kerosene or SAF[4] (and potentially batteries) as fuel, the reduction of kerosene fuel burn equals the reduction of CO_2. However, hydrogen aircraft stand out, as they lead to a 100% CO_2 reduction potential.

[2] More roadmaps for aerodynamic, system, structural and ATM technologies can be found in the CLAIM D3.1 report [5].
[3] The list of investigated aircraft concepts can be found in Appendix B of the CLAIM D3.2 report [6].
[4] Tank-to-wake emissions of SAF are taken into account, not considering well-to-tank CO_2 reductions and a possibly higher energy content of SAF.

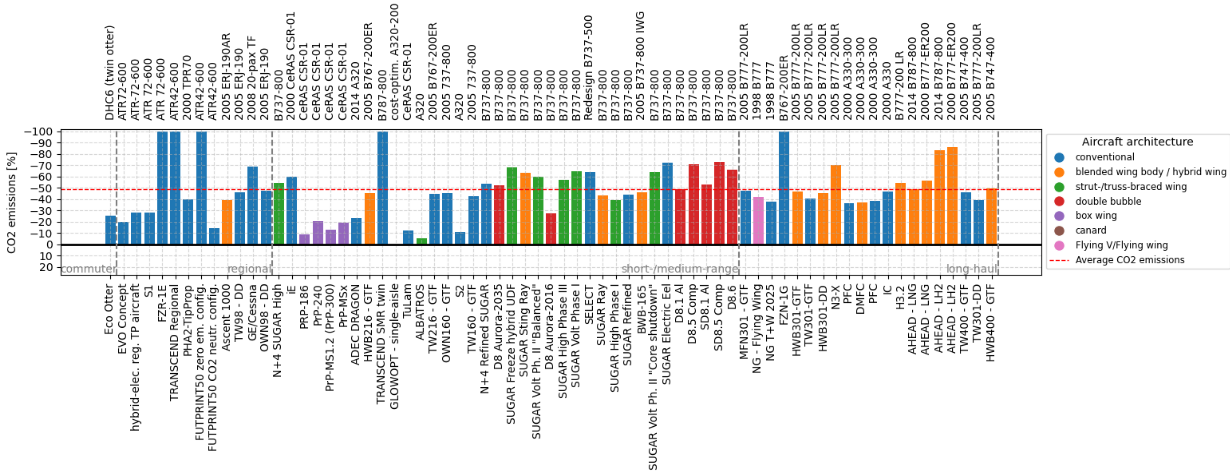

Figure 2: CO_2 emissions compared to traditional reference aircraft (EIS before 2015)

For NO_X emissions, reductions up to 70-80% were found compared to traditional reference aircraft (EIS before 2015). A plausible explanation for the high reduction values is that the NO_X reductions were a specific target for a subset of the investigated aircraft concepts. A few concepts lead to higher NO_X emissions due to trade-offs with CO_2 emissions.

It is hard to attribute general emission reductions to specific aircraft technology features and architectures. Some concepts apply only one or a few new technologies while other concepts have the intention to include a large number of technologies that are realistic for a future EIS. The aircraft concepts with several technologies are conceptualised to explore the possibilities of environmental impact reduction or to assess the integration and interaction of the different technologies. The relationship between the aircraft architecture and kerosene fuel burn reduction potential is complex, as multiple factors have an influence, such as energy carrier, aerodynamics, propulsion and structural advanced technology. From the overview, e.g. in Figure 2, it is not possible to identify one specific aircraft architecture that clearly leads to higher environmental performance improvements. One can observe that the blended wing body aircraft architecture and tube and wing architecture are mostly used for long-range aircraft and that commuter and regional aircraft mostly use a tube and wing architecture. For short/medium range aircraft more different aircraft architectures are explored such as tube-and-wing, box-wing, double-bubble or strut-braced wing aircraft architectures.

To identify promising technologies heat maps are used, an example is given in Figure 3. The heat map shows which technologies are utilised on which aircraft concepts and in which combinations the technologies are deployed. The metric, either kerosene fuel burn, CO_2 emissions or NO_X emissions, is visualised in a colour scheme, which is identical for each concept(/row), as it is not possible to attribute a single reduction potential to a single technology feature.

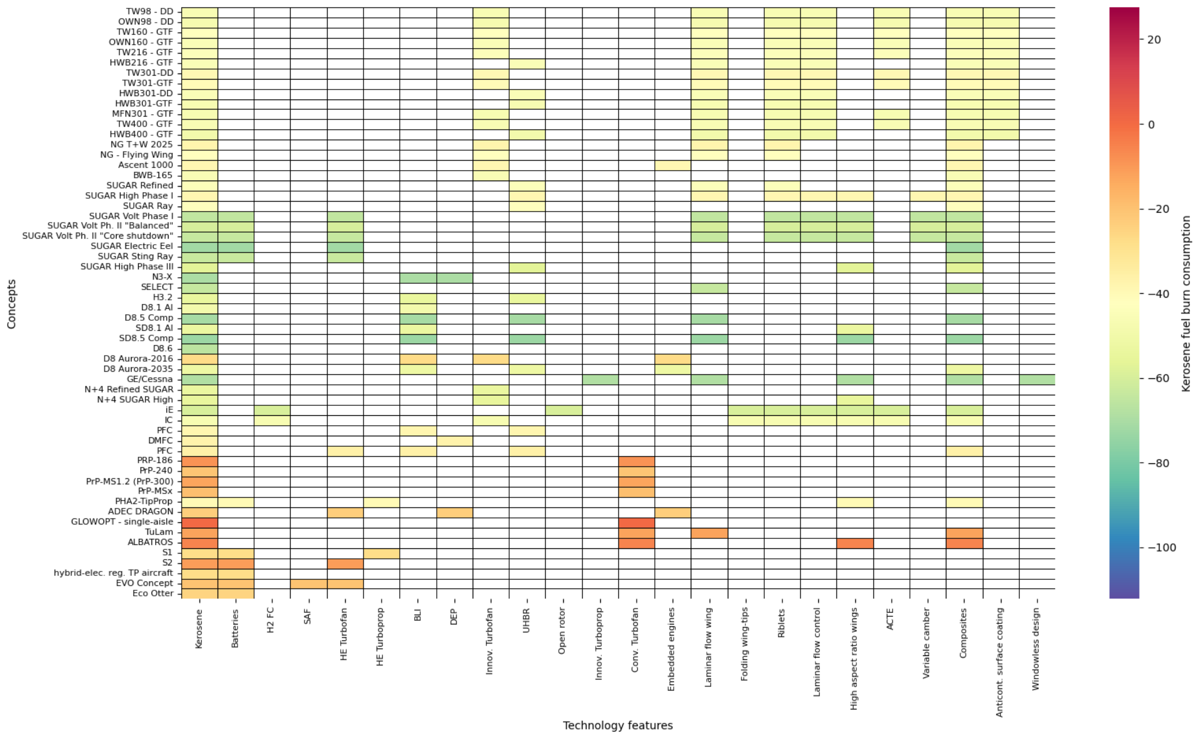

Figure 3: Heat map of the effect of technology features on fuel burn consumption compared to traditional reference aircraft (EIS before 2015)

The most promising fuels include sustainable aviation fuel (SAF) and hydrogen, while even kerosene-powered aircraft (either conventionally, or in combination with batteries or fuel cells) showed significant performance improvements. From the propulsion concepts, innovative turbofans (such as ultra-high bypass ratio turbofans), innovative engines (e.g. hybrid-electric fans) and to a certain extend the aero-propulsive concept of boundary-layer ingestion (BLI) had large improvements. For regional concepts, the hybrid electric powertrain enables distributed electric propulsion. In the field of aerodynamics, most applied technologies are high aspect ratio wings, drag reduction (e.g. riblets for skin friction drag reduction) and laminar flow control which can be well combined with high aspect ratio wings. In terms of structural technologies, the most concepts applied composite materials. Some concepts even include improvements in operations and from air traffic management (ATM) in their environmental reduction potential.

Discussion

Some of the roadmaps are more conservative whereas others are more progressive in the estimations. The entry-into-service window of a technology can be large or vary according to the source. Older sources, and the most progressive ones even foresee the EIS of some technologies in the timeframe 2025-2030 which seems questionable with today's knowledge.

The energy carrier strongly influences the CO_2 and NO_X reduction potential with hydrogen and batteries reducing CO_2 emissions by 100%. Purely battery-electric concepts were beyond the scope of this study, as they are currently hindered by the substantial weight penalty and energy density constraint of batteries.

The data of aircraft concepts was derived from conceptual studies in which usually low-fidelity methods are used. This leads to uncertainties, which can only be reduced during later design stages.

For some aircraft concepts the climate impact was measured with a climate metric such as ATR100 or GWP100. In some cases, trade-offs between total climate impact and fuel burn (with resulting CO_2 emissions) or between NO_X emissions and fuel burn reduction (either kerosene or hydrogen) occurred, which can lead to the deterioration of one assessment value while another one is optimised.

The here presented technology scouting of the most promising aircraft technologies served as an input for a performance assessment of Clean Aviation-like aircraft concepts, using the climate metrics ATR100 and EGWP100, showing how climate metrics can be used to benchmark and monitor new aircraft concepts and technologies [7]. Furthermore, this systematic review can provide guidance for future research and deployment.

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