D3.4: Know-how and capability gaps for aeronautical technology in Europe

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Abstract

This document represents the final output of Task 3.6. It addresses the current state of knowledge and capability gaps in Europe related to hydrogen and hybrid-electric propulsion technologies. Stating from CLAIM knowledge, it identifies the current limitations in predicting both CO_2 and non-CO_2 environmental impacts—including air quality effects—of future short/medium-range (SMR) and regional aircraft concepts. The first part of the report, based on CLAIM project activities, maps these gaps across three key technological layers: energy carriers, propulsion systems, and aircraft architectures. The second part reviews current European numerical and experimental capabilities and outlines the major remaining technological and integration challenges, particularly those affecting aircraft design and performance. Finally, the report provides key recommendations to improve the accuracy of environmental performance assessments, emphasizing the need for enhanced modelling tools, targeted experimental validation, and the early integration of environmental indicators into aircraft design processes.

Keywords

Technology assessment, Gaps, Know-how, CO2, non-CO2

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Acronyms and AbbreviationsKeine Indexeinträge gefunden.

Acronym / Abbreviation	Description / Meaning
ATM	Air Traffic Management
BFFM2	Boeing Fuel Flow Method 2
BWB	Blended Wing Body
EED	Engine Emissions Databank
EI	Emissions Indices
HER	Hybrid-Electric Regional
ICAO	International Civil Aviation Organization
LTO	Landing and take-off
PEMFCs	Proton Exchange Membrane Fuel Cells
RQL	Rich-Burn, Quick-Mix, Lean-Burn
SAF	Sustainable Aviation Fuel
SMR	Short-to-Medium Range
SOFC	Solid Oxide Fuel Cells
TLAR	Top-Level Aircraft Requirements

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1. Introduction

Clean Aviation Joint Undertaking will contribute to Europe's climate neutrality by 2050 by developing and implementing new and more environmentally friendly technologies in the aeronautic sector. In Clean Aviation's Strategic Research and Innovation Agenda 2035, future aircraft concepts with advanced technologies and the projections of environmental performance improvements are described. For instance, a hybrid electric regional aircraft concept and a short-/medium range aircraft concept, both with a tube and wing configuration, have the overall target of 30% CO_2 emission reduction and up to 86% with SAF.

In the frame of the project "Clean Aviation Support for Impact Monitoring" (CLAIM), Task 3.6 "Know-how and capability gaps for aeronautical technology in Europe "aims at providing both a review of current European capabilities in numerical modelling and experimental testing as well as identifying the remaining challenges for hydrogen and/or hybrid-electric propulsion systems technologies.

The first part of the deliverable, based on CLAIM project activities, identifies the knowledge gaps associated with predicting CO_2 and non-CO_2 environmental impacts—including air quality effects—of future aircraft concepts, with a focus on short/medium-range (SMR) and regional configurations across three technological levels: energy carrier, propulsion system, and aircraft architecture. The second part presents a review of current European capabilities in numerical modeling and experimental testing related to these technologies, and highlights the remaining challenges in their development and integration, particularly those impacting aircraft design and operational readiness. The final part consolidates the findings and formulates a set of key takeaways to improve the accuracy of environmental performance predictions, with recommendations for both modeling and experimental strategies from the early stages of conceptual design

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2. Scope and Approach

2.1. Scope

The primary objective of this report is to support the development of advanced aircraft concepts by:

- Identifying areas of uncertainty related to both CO_2 and non-CO_2 effects.
- Pinpointing potential levers to reduce these uncertainties.
- Ultimately, enhancing the accuracy of environmental performance predictions for these concepts from the early stages of conceptual design.

The scope of this deliverable is fully aligned with the activities of the CLAIM project, which are structured into two main streams:

- WP2: CO_2 and non-CO_2 impact modelling.
- WP3: Technology and concept studies, including scouting and research facility analysis.

Particular emphasis is placed on gaps and the lack of studies concerning CO_2 and non-CO_2 effects predictions (including air quality impacts) for future aircraft configurations. This focus specifically targets short/medium-range (SMR) and regional aircraft concepts, involving hydrogen and/or hybrid-electric propulsion systems.

Although non-CO_2 modelling and climate impact assessments are not the central focus of this report, they are addressed in terms of:

- Key input requirements for climate models and air quality models especially in terms of aircraft emissions details for all flight phase. Depending on the energy carrier and propulsion systems, the importance of the various species may vary.
- Knowledge gaps related to specific effects, such as contrail formation linked to unconventional aircraft architectures.

Following the identification of these gaps, the report proposes computational and/or experimental strategies to reduce those uncertainties, considering the current state of numerical and experimental capabilities in Europe.

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2.2. Approach

To achieve this objective, the approach has been structured into the following steps:

- Collect comprehensive information on gaps in CO_2 and non-CO_2 emissions prediction for future aircraft, with a focus on short/medium-range (SMR) and regional concepts—particularly those involving hydrogen and/or hybrid-electric propulsion.
- Cluster and analyse these identified gaps based on specific technology choices and the different levels of aircraft system elaboration (such as energy carrier, propulsion system, and aircraft architecture).
- Propose targeted strategies to enhance the knowledge base, including computational and/or experimental studies, taking into consideration the current landscape of numerical and experimental capabilities available in Europe.

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3. Gaps associated to technology regarding CO_2 and non – CO_2 effect (CLAIM)

3.1. Technology scope and clustering

The gaps are collected for aeronautical technologies applicable to regional and SMR aircraft with a specific focus on advanced hydrogen and hybrid-electric technologies.

The clustering is made depending of the different levels of aircraft system elaboration

- **Energy carrier level**:

Regarding energy carrier level, the different possibilities that will be considered are:

  - Kerosene, SAF and blends especially applicable for SMR
  - Kerosene, SAF or blends associated to batteries applicable for both Regional and SMR
  - LH2 (fuel cells) with/without batteries especially applicable for Regional
  - LH2 (combustion) especially applicable for SMR

- **Propulsion level**:

Regarding propulsion level, the different possibilities are the following:

- Turboprops and their evolution especially applicable for Regional
  - In terms of internal improvement (such as new combustion systems)
  - In terms of energy carrier (H2) and energy carriers' combination with hybridization
- Turbofans and there evolution especially applicable for SMR
  - In terms internal improvement (such as new combustion systems)
  - In terms of more radical change with evolution such as UHBR or OpenFan solution
  - In terms of energy carrier (H2) and energy carriers' combination with hybridization

- **Aircraft level**:

Regarding aircraft level, the different possibilities are more open as depending of the energy carrier and propulsion combination could lead to significant redesign of conventional aircrafts. For instance, when using H2, the cylindrical tanks will too thick to be integrated into the wings and solutions could lead to either tube and wing extension (with stretch fuselage to accommodate the H2 tank) or even Blended Wing Body architectures (BWB).

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Nevertheless, two main clusters can be identified (based on in D3.2 report [3]):

- Tube and wing and their evolutions
- Radical concepts

3.2 Gaps review

First, a systematic analysis of all the CLAIM deliverables has been conducted with the objective to collect all on gaps in CO_2 and non-CO_2 emissions prediction on aircraft side. In a second phase additional sources of information were added in order to both investigate some of the gaps more in details.

Reminder (from D2.4 report [4]):

- Aviation has a direct impact on climate through its CO_2 emissions. However, as aviation releases its emissions at high altitude, the other engine emissions such as water vapour, NOx or soot also affect the atmosphere radiative forcing, directly or through complex atmospheric processes like contrail formation or chemical reactions with other atmospheric species
- In addition, non-CO_2 emissions have a direct impact on local air quality on and around airports, with potential health issues. Aircraft activities, especially at landing and take-off cycles, generate a large amount of harmful air pollutants, among which nitrogen oxides (Nox), sulfur dioxide (SO2), carbon monoxide (CO), hydro-carbons (HC), unburned or partially combusted hydrocarbons also known as volatile organic compounds (VOCs) and black carbon (BC)

Usually, building inventory of emissions to assess non-CO2 effects at fleet and air traffic level, the primary source of data is the ICAO engine certification database. This records emissions index for CO, Nox, unburned hydrocarbon and nvPM mass and number. These emissions are measured at ground, on isolated engines on test bed, with no other off-takes and loads than those necessary for engine basic operation, for operation regimes representative of the landing and take-off cycle (LTO – take-off, climb, approach and taxi/idle). As stated in D2.4, at the starting point of any assessment of non-CO_2 effects is a precise knowledge of aircraft emissions.

Reminder (from D3.2 report [3]):

Many ongoing research projects have been and are currently conducted regarding existing advanced/disruptive aircraft concepts/architectures. Commonly expected technology benefits cover CO_2 effects due to a reduction in fuel burn, weight, drag or an increase of lift characteristics, noise benefits as well as alternative fuel/ energy compatibility. Among the outcomes one can highlight:

- SAF employment named as one of the largest potentials for climate effect mitigation
- Energy carrier strongly affects the CO2 reduction potential. Concepts that utilize hydrogen combustion, hydrogen fuel cells, a combination of both or a combination with batteries, stand out for achieving 100% reduction

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- For Nox emissions (similar to CO2 emissions), aircraft which make use of solely a hydrogen fuel cell are considered to have a 100% reduction in Nox emissions. With hydrogen combustion on the other hand, still some Nox emissions (or even higher Nox emissions) are produced

Nevertheless, from the analysis of all research projects a major limitation can be identified that is quantifications for non-CO2 benefits is not often performed and, in that case, it mainly concerns NOx reductions. In addition, it should be noted that mostly the LTO Nox reductions are given, while sometimes also the cruise NOx emission value is given.

Energy carrier level

Energy carrier level is directly connected to all the emissions species of interest for the CO2 and non-CO2 assessment.

The prediction of engine emissions is significantly impacted by uncertainties related to the composition of conventional jet fuel, Sustainable Aviation Fuels (SAFs), and hydrogen. These uncertainties stem from the inherent variability in fuel properties, limitations in current modeling and measurement techniques, and the complex atmospheric interactions of emitted species

Regarding conventional fuel, aircraft emissions are dependent on the composition of the fuel used, including its hydrogen-to-carbon (H/C) ratio, aromatic content, and sulfur content [4]. These properties can vary significantly even within the boundaries allowed by fuel standards.

Regarding SAF, their introduction adds a new layer of variability to fuel properties, as their chemical composition can differ substantially from fossil kerosene, particularly in aromatic and sulfur content. SAFs, especially those like HEFA-SPK with lower aromatic content, generally lead to reduced non-volatile particulate matter (nvPM) mass and number emissions **Fehler! Verweisquelle konnte nicht gefunden werden.**. However, a key uncertainty is that beyond a certain level of soot reduction, the total number of ice crystals formed in contrails does not necessarily decrease [4]. This is attributed to the "emerging contribution" of volatile particles (e.g., sulfuric acid, organics) and electric charges from secondary engine emissions acting as condensation nuclei in low-soot regimes.... The exact role and characterization of these secondary emissions (e.g., organics beyond global unburned hydrocarbons) remain open questions and areas of active research.
For both drop in fuel, models predicting the effect of fuel composition on nvPM emissions have shown discrepancies and "limitations" when compared to measured data, particularly for smaller turbofan engines.

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Propulsion level

As indicated earlier, the primary source of data is the ICAO engine certification database that records emissions index for CO, Nox, unburned hydrocarbon and nvPM mass and number for a set of engines (turbofans and turbojets).

ICAO (International Civil Aviation Organization) tables are extensively used for predicting engine emissions at trajectory or fleet levels due to their role as a primary and comprehensive source of standardized emission data. The ICAO Engine Emissions Databank (EED) is the most extensive source of quantitative information for engineering analysis of aircraft engine emissions as it records certified emission indices (EIs) for key pollutants and is continuously updated with contributions from manufacturer [1]. This database therefore serves as the primary source for building emission inventories to assess non-CO2 effects at both fleet and air traffic levels.

Nevertheless, that information suffers from limitations and sometimes lacks data depending on the energy carrier and propulsion systems combination considered in this deliverable.

First, the ICAO databank primarily contains emission indices for turbojet and turbofan engines only, specifically those with thrust ratings greater than 26.7 kN [1]. This results in a significant lack of data for smaller turbofan engines (those with thrust below 26.7 kN), as they are unregulated for gaseous and particulate emissions, and their data is largely absent from public databases. In addition, there is a difficulty in assessing exhaust emissions from turboprop and turboshaft engines due to the absence of industry data for these types [1]. Moreover, these engines often operate outside the typical pressure-ratio and fuel flow ranges found in the ICAO database, sometimes falling entirely off its bounds.

Secondly, the certification data are derived from a limited number of tests (typically 3 new engines) performed under specific atmospheric conditions and at a fixed altitude. Therefore, the ICAO databank lacks information for cruise emissions, requiring these to be reconstructed using modelisation.

In terms of modelisation of emissions at trajectories levels, some gaps can slot be highlighted

First, this data is collected at ground level on isolated engines for the Landing and Take-Off (LTO) cycle, not for cruise conditions. This necessitates reconstructing cruise emissions using transposition methods, which can introduce inaccuracies. While transposition methods like Boeing Fuel Flow Method 2 (BFFM2) work reasonably well for conventional (RQL type) burners for NOx, they are more uncertain for lean-burn combustors for which no validated or agreed method is published [4].

Still regarding cruise estimating non-volatile particulate matter (nvPM) is even more uncertain than NOx due to a lack of reliable in-flight data for validation.

LTO emissions of nvPM mass and number are not as well understood as NOx LTO emissions due to greater uncertainties in sampling and measurement procedures

For low-soot emissions (e.g., with SAFs or lean-burn combustors), other emissions like volatile particles (sulfuric acid, organics) and electric charges are suspected to play a significant role in contrail formation, but these are not fully characterized in current certification processes.

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Measurements are lacking regarding lean burn combustion and very low soot emissions situations

There is a need for characterization of organics concentration and properties for aviation engines, as only a global measure of unburned hydrocarbons is currently provided in the certification process

Regarding Ground-Level emissions, comparisons between ICAO LTO emissions and those predicted using actual flight data often show large discrepancies, particularly for CO and HC. The interpolation of emission indices at low engine speeds (idle mode), corresponding to very low fuel flows, is not trivial and can lead to inaccuracies or undetectable errors if extrapolated linearly.

Regarding SAFs, they significantly reduce life-cycle CO2 emissions and can mitigate non-CO2 climate impacts due to their generally low aromatic and sulfur content, but several gaps remain in their emissions prediction.

While they generally reduce nvPM mass and number emissions, the decrease in soot emissions beyond a certain level is not a guarantee that ice crystal number in contrails will decrease. Other volatile particles may contribute to contrail formation when soot is drastically reduced.

In addition, while SAFs lead to lower emissions of complex unsaturated hydrocarbons like aromatics and polycyclic aromatic hydrocarbons (PAHs), a global characterization of organics concentration and properties for aviation engines is needed, as the certification process only provides a global measure of unburned hydrocarbons

The issue of the relation between fuel composition, emissions, and ice crystal formation is undergoing intensive research and is still open. Secondary emissions, such as organics, sulfuric acid, and potentially nitric acid, are suspected to play a role in contrail formation, especially with low-soot fuels. These are not fully characterized in current certification processes

While hydrogen utilization can reduce NOx, CO, and HC emissions compared to kerosene31, and CO2 emissions significantly, it introduces its own set of prediction challenges. While new combustion techniques are expected to reduce NOx emissions by up to 99.8% for hydrogen-powered jet engines [8], the ICAO databank's transposition methods (e.g., BFFM2) are more uncertain for modern lean-burn combustors that might be used with hydrogen [4]. Hydrogen combustion produces significantly more water vapor (2.55 times as much) than kerosene engines.

While this can lead to optically thinner contrails and potentially lower climate impact due to less soot, the net radiative effect of these phenomena is still uncertain and requires in-depth additional studies

Studies show that while CO and HC emissions can be unchanged in most cases at wide operating ranges, some findings reveal a slight increase in CO production under lean primary zone and less residence time conditions, particularly when hydrogen injection is around 4 % [7]

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Last, the assumption is that advanced hydrogen management and combustion technologies will result in "minimal unburnt H2 emissions" [6], but practical strategies for capturing or neutralizing any unburnt hydrogen are necessary.

Eventually engine designs like hybrid-electric aircraft, established emission prediction models may not be reliable. Current predictive databases are based on conventional turboprop and turboshaft engines, which may not be representative for hybrid-electric systems as these aircraft could operate under uncommon conditions, such as very low thermal power output or reduced fuel flow during specific flight phases [2]. This highlights limitations and uncertainties of current emission prediction models when applied to such "off-design" operating regimes. There is a need for reliable and high-resolution predictive emission models for these configurations.

Aircraft level

At aircraft level, when designing a new aircraft concept, the objective to combine and connect several design capabilities in order to size any concept fulfilling a given set of TLAR. Among relevant disciplines, propulsion (and associated system) and its impact on the overall architecture is of major importance. As indicated in [3], most of all research projects on new concepts analysed do not often perform the evaluation for non-CO2 benefits.

Like for the others levels, non-CO2 assessment at aircraft levels can suffer from uncertainties, depending on the energy carrier, propulsion systems combination and aircraft architecture.

In general, OAD (Overall Aircraft Design) tools typically consider 2D trajectories with conventional atmospheric conditions, which prevents accurate estimation of non-CO_2 emissions (add reference to fast OAD). To reduce these uncertainties, some approaches have been developed [9] that couple aircraft design-level tool to 4D trajectory tool and simplified contrail modelling tool. This allows for the consideration of realistic ATM (Air Traffic Management) trajectories and weather data. These approaches have successfully enabled more accurate estimations of CO_2 emissions, but they remain limited in estimating non-CO_2 emissions due to the lack of detailed emissions data for future propulsion architectures. Including an extension of OAD tools to consider trajectories and weather data therefore seems essential for any future aircraft concept assessments at the ATM level

Another limitation of new concepts is the probable modifications of architectures in order to gain improvements on fuel consumption [3]. Actually, different architecture types are under study: even if most of them feature a conventional tube-and-wing architecture, more radical ones, such as blended-wing-body or hybrid-wing body concepts were considered. Even for tube-and-wing some evolutions are envisaged in line with propulsion like the introduction of ultra-high bypass ratio engines (UHBR), open rotor / unducted fan engine, boundary layer ingestion engine (BLI), hybrid-electric turbofan, or even, distributed electric propulsion. Moreover, when considering new energy carrier such as LH2, the overall architecture of the aircraft is bound to evolve to accommodate tanks. Usually, the studies are performed during conceptual studies where low fidelity methods are used, e.g. because many variants need to be explored and only few details are known. This leads to uncertainties in the results in terms of performances and therefore emissions.

In addition, regarding contrails formation, studies have demonstrated the impact of engine installation effects on two-dimensional simulations of the initialized vortex regime [10]. Recently,

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some RANS calculations have observed the formation of new vortex structures in the wake when the engine position was modified. Therefore, contrails formation process based on conventional concept studies may not apply to these new concepts, especially considered the relative evolution of engine, wing and HTP locations [11][12].

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4. Numerical and experimental Know How (Review papers)

This chapter aims at providing an overview of the recent and current activities in terms of numerical and experimental activities regarding hydrogen and hybrid-electric propulsion technologies with a focus on regional and SMR aircraft categories.

4.1 Hydrogen (combustion)

Hydrogen is recognized as a versatile energy carrier with high specific energy density that can contribute to a decarbonized energy future. Its utilization in gas turbine engines for aircraft has the potential to reduce NOx emissions, improve fuel efficiency, and increase range while significantly decreasing pollutants such as carbon monoxide.

Modelisation

Modelling efforts are crucial for understanding and optimizing hydrogen combustion and its integration into aircraft systems. This effort covers all the range from propulsion to aircraft design level.

Propulsion level

Most of the activities of modelisation focus on combustor design. For instance, Cranfield University, under the ENABLE-H2 project, has conducted extensive numerical studies (using RANS and LES) on micromix combustors for hydrogen and has plans for experimental validation [13]. These studies include NOx emissions predictions and investigations into the impact of injector geometrical design parameters on hydrogen micromix combustion characteristics. Other computational simulations demonstrate the efficacy of Lean Fully Premixed (LFP) combustors in reducing unburnt fuel, aligning with the goal of zero-unburnt fuel in hydrogen-powered aviation [6]. In addition, some studies have explored the impact of hydrogen blends on engine performance and emissions, finding the feasibility of hydrogen in gas turbines to be viable [14] while some studies have investigated 100% premixed hydrogen combustors at gas turbine conditions using detailed chemistry [13].

The other topic of modelisation deals with thermodynamic cycle calculation and performance programs development. For instance, German Aerospace Center (DLR) uses a performance program (DLRp2) within the Gas Turbine Laboratory (GTlab) for multidisciplinary simulations of gas turbines at different levels of detail, including hydrogen applications [15]. Tools like GasTurb and TURBOMATCH are widely used in research and industry for hydrogen-adapted engine code development and validation [13].

Aircraft level

At aircraft level, modelling efforts for systems integration related to hydrogen combustion aircraft are highly multidisciplinary, encompassing detailed simulations of individual components and their complex interactions within the overall aircraft design.

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Conceptual studies frequently focus on overall aircraft design (OAD) to understand how the significantly larger volume of liquid hydrogen (LH2) tanks impacts the airframe [16]. Geometrical, material, and thermal models are used to design tanks that satisfy insulation, center of gravity (CG), and power constraints, often guided by detailed equations [6]. Associated topic is the modeling addresses boil-off in hydrogen storage by considering effective thermal insulation strategies and tank configurations [6], [17].

Thermal Management Modeling is also a field of modelisation as Engine-integrated heat exchangers (HEX) are critical components for fuel conditioning (heating cryogenic hydrogen before combustion) and for recovering waste heat from various engine parts, exploiting hydrogen's cryogenic nature and high specific heat capacity [15], [17].

OAD tools have also to be adapted for hydrogen combustion in order to design associated concepts. The DLR research project EXACT (Exploration of Electric Aircraft Concepts and Technologies, 2020–2023) developed new aircraft types, including short- and medium-haul aircraft with hydrogen direct combustion using turboprop and turbofan engines [18]. In, ONERA's GRAVITHY Project some modelisation have been conducted in order to identify solutions for technical issues inherent in aeronautical hydrogen use and quantify their overall impact on commercial transport aircraft design. It focuses on Small/Medium Range (SMR) aircraft and studies both traditional Tube and Wing (T&W) and more advanced Blended Wing Body (BWB) configurations [16]. In another project, flight optimization system (FLOPS) and Gasturb simulation tool have been employed to predict the economic and design viability of hydrogen as a fuel for long-range aircraft, analysing bending weight calculation as fuel weight increases [14].

Experimental

Regarding the field of experimental studies, it is also quite advanced with tests ranging from combustion chamber to flight tests.

Propulsion level

Several lab or ground demonstrators for hydrogen combustion in gas turbine engines are currently being developed or tested.

For instance, FH-Aachen research developed a non-premixing micro-mix combustor design to prevent flashback issues and premature combustion. This design achieved an almost 80% reduction of NOx emissions compared to kerosene by introducing thousands of uniformly distributed diffusing flames [17]. In addition, Cranfield University is planning experimental validation in a newly developed test rig for this concept [17].

In another study, a hydrogen-fueled micro gas turbine unit has been researched and tested, demonstrating NOx reduction. The combustor and fuel trains were modified for operation with hydrogen blends [14]. In Clean Sky 2 project LEAFINNOX , a novel combustor concept based on the Lean Azimuthal Flame has demonstrated 100% hydrogen operation [17]. These efforts aim to address challenges like NOx emissions and combustion stability, and to develop necessary engine modifications.

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In parallel, some studies are focusing on safety with the UK Health and Safety Laboratory conducted unignited tests with LH2 spills to imitate hose line failure during tanker refuelling, showing flammable gas cloud behaviour [13].

Aircraft level

Hydrogen combustion has been studied and tested since decades. In the 1950s–60s, the NACA (now NASA) conducted a flight test of a modified B-57 bomber as part of Project Bee, which assessed the potential of liquid hydrogen [16], [17], [30],. This involved a J57 turbojet modification for the B-57 bomber. More , in the 1980s, the TU-155 project in the Soviet Union reported the flight test of a Tu-155 aircraft, which was converted to operate on hydrogen, with an NK-88 engine modification [16] [17], [30],.

Since that period, major engine manufacturers are actively studying hydrogen combustion. Rolls Royce has completed the first phase of a demonstrator program with successful ground tests of a hydrogen-adapted AE 2100 engine [17]. Pratt and Whitney initiated the HySIITE project to develop hydrogen combustion with steam injection to achieve significant NOx reduction [17]. GKN Aerospace is leading the H2JET project to develop hydrogen gas turbines for single-aisle aircraft by 2035 [17]. CFM International partnered with Airbus to modify a GE Passport turbofan for a demonstrator program [17], [30]. Finally, MTU Aero Engines is working on Project 'WET Engine' for SAF and hydrogen-compatible engines [17]

More recently, in order to assess the impact of hydrogen combustion on contrails, Airbus Blue Condor tests involved an Arcus-J glider with a hydrogen-modified engine[1]

4.2 Hybrid electric (fuel cell)

The use of hydrogen fuel cells in hybrid electric aircraft presents a significant number of technological challenges, ranging from the fundamental properties of hydrogen and the fuel cell system itself to their complex integration within an aircraft's design and broader infrastructure.

Modelisation

Propulsion level

A key research area concerns the engine and propulsion system modeling. For instance, a thermodynamic model has been developed to evaluate the feasibility and performance of high-performance Solid Oxide Fuel Cell (SOFC) / Gas Turbine (GT) hybrid power systems for electric aviation [6]. This model has been validated against NASA's SOFC model, demonstrating potential for high fuel-to-electricity conversion efficiencies.

In parallel, numerous studies are dedicated to the design and implementation of Energy Management Systems (EMS) for fuel cell-powered Unmanned Aerial Vehicles (UAVs) [26] A tool was specifically created for the preliminary design of hybrid fuel cell propulsion systems for regional aircraft, encompassing both sizing and energy management aspects [26].

[1] https://www.airbus.com/en/newsroom/stories/2023-11-contrail-chasing-blue-condor-makes-airbus-first-full-hydrogen-powered

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Fuel cell propulsion systems necessitate a novel electrical architecture system to efficiently distribute and control power [17]. For instance, the HASTECs (Hybrid Aircraft: academic reSearch on Thermal and Electrical Components and Systems) project developed a parametric model for individual propulsion components within an advanced serial hybrid electric propulsion system [21]. This model covers electrical, mechanical, and thermal aspects for sizing and evaluating losses and weights, with a focus on optimizing the propulsive system.

Aircraft level

In Europe, the IMOTHEP project (Integrated Methodology for OAD and TEchnologies for Hybrid Electric Propulsion) performs an integrated assessment of hybridization potential by investigating various aircraft configurations and their powertrain architectures [24]. Although primarily focused on thermal hybrid propulsion, IMOTHEP also conducted a simplified evaluation of fuel cell systems, sometimes combined with other energy storage, for regional aircraft configurations, aiming to assess their total mass and gravimetric energy density [24]

More recently, the HASTECs models (described in previous paragraph) have been integrated with FAST-OAD software to create a new OAD process [21]. This coupling aims to provide a multidisciplinary design that integrates electrical, aerodynamic, and structural considerations with greater fidelity, allowing for a broader exploration of the design space for various aircraft topologies, including turboelectric, serial-hybrid, and full-electric concepts

Another integrated tool, the THEA-CODE (Tool for Hybrid-Electric Aircraft Conceptual Design) has been developed an in-house design software used for the conceptual design of hybrid-electric aircraft, supporting both conventional and unconventional airframe configurations, such as box-wing designs [29]. This tool incorporates modules for aerodynamics, engine sizing, mission analysis, and weight estimation, operating within an iterative cycle to achieve convergence on maximum take-off weight (MTOW).

Lastly, a methodology has been developed to assess emissions and performance tradeoffs for retrofitted SOFC and hydrogen-powered aircraft [6]. This framework integrates a flight profile module, an H2 tank configuration module, and an emissions module to model alternative fuel emissions. It also includes a lifecycle emissions assessment and a mission implementation cost analysis for comprehensive comparison of different power sources.

Experimental

From experimental point of view, several activities are on-going on fuel cells stream.

Propulsion level

To study hybrid-electric aircraft utilizing fuel cells, various lab and ground experimental means are currently under development and investigation. These efforts are crucial for validating the technology and addressing the associated challenges before broader implementation.

Hydrogen fuel cell systems are being evaluated in dedicated laboratory settings. Experiments are performed on fuel cells both on their own and as part of a parallel hybrid configuration to assess their viability as an energy source for Unmanned Aerial Vehicles (UAVs) [29]. For instance, the Centre for Aerospace Research (CfAR) has developed a Hybrid Test Bench as an experimental propulsion rig to test hybrid propulsion solutions [29].

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Research and development involve designing and testing efficient cooling systems for fuel cell components and the overall electric architecture, particularly for managing low-grade internal heat release [22].

In addition, some laboratories are focusing on superconducting technologies that integrate with hydrogen fuel cell systems, focusing on managing heat loads on the fuel line to maintain efficiency and operating integrity [17]

Regarding ground demonstrators, The National Research Council of Canada (NRC) Aerospace Research Centre (ARC) is developing the Hybrid-Electric Aircraft Testbed (HEAT), an airborne electric propulsion demonstrator platform that includes qualification testing of its electric propulsion and energy storage systems [23]. More recently, in June 2023, in the frame of ZEROe project, Airbus announced the successful test campaign of the hydrogen fuel cell system, which reached its full-power level of 1.2 megawatts ZEORe project[2].

Aircraft level

To study hybrid-electric aircraft using fuel cells, several flying demonstrators are currently under development or have already undergone flight tests, showcasing the integration of fuel cell technology into propulsion systems.

The LH2-powered HY4 aircraft is highlighted as the world's first hydrogen-electric experimental aircraft, designed by H2FLY and certified for passenger flights [28]. It first took off in 2016 and has since made significant technological advancements in hydrogen-electric propulsion systems for aviation [17], [28]. This aircraft has been actively used for ground demonstrations as well [28] and was tested in flight achieving a range of 1500 km and a maximum speed of 200 km/h with an 80 kW electric motor [26]

Other demonstrators were developed such as the Antares DLR-H2: This aircraft serves as a flying test bed for the development of aircraft fuel cell systems [17]. Another fuel cell demonstrator is developed in HyFlyerproject, based on a 6-seater Piper Malibu M350 [17].

Another demonstrator, Universal Hydrogen's Dash8-300, has been developed with one engine replaced by a hydrogen fuel cell propulsion system [17]. In addition, ZeroAvia has successfully demonstrated a modified 19-seat Dornier aircraft, where one engine was replaced with a 600kW low-temperature Proton Exchange Membrane Fuel Cell (LT-PEMFC) system [17]. This project aims to bring a 19-seat commuter aircraft with a 450+ km range into service [18].

More in future, Airbus has plans to perform a flight demonstration of a megawatt-class fuel cell propulsion system by 2026 on its A380MSN1 test aircraft. If successful, this system could potentially power a 100-passenger, 1000 nautical mile concept [17].

[2] https://www.airbus.com/en/newsroom/stories/2024-01-first-zeroe-engine-fuel-cell-successfully-powers-on

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4.3 Hybrid electric (batteries)

Current hybrid electric aircraft concepts primarily target regional and smaller aircraft categories, due to the energy density limitations of batteries

Modelisation

Modelization activities for studying hybrid-electric aircraft with batteries are ongoing at various levels, including batteries themselves, hybridization strategies, system integration, and overall aircraft design

Propulsion level

Regarding propulsion level, batteries are already a topic of study for several aspects.

First, studies are conducted on batteries performance. Indeed, batteries, particularly Lithium-ion batteries, are widely used and their performance (gravimetric energy density (BED), volumetric energy density (VED), and gravimetric power density (PD)) have to be modelled [19]. Researchers are also investigating potential breakthrough solutions like lithium–sulfur (Li–S) and lithium–oxygen/lithium–air (Li–O2) batteries, which exploit the high specific capacity of lithium-metal anodes to increase BED [19].

Then safety and thermal management also concentrate modeling efforts. They focus on addressing safety aspects related to thermal management of battery packs, which are crucial for certification. This includes cooling and monitoring of battery pack temperature to prevent overheating [19]. Advanced materials like solid electrolytes are under investigation to reduce thermal runaway, and improvements in thermal management systems are sought to extend battery life [19].

Regarding operational constraints, specific research is trying to enable battery cycling life and charge/discharge rates compatible with aircraft usage, including on-ground procedures and infrastructure. This involves developing adequate battery check, maintenance, and/or refurbishment procedures synchronized with aircraft maintenance schedules [24].

At a system level, architectures aspects are explored where modeling includes various hybrid-electric powertrain architectures such as serial hybrid, parallel hybrid, serial–parallel hybrid, and turboelectric [19]. Here power management strategies are of interest as a key focus is on modeling power management strategies to determine how power is split between thermal and electric sources during different flight phases [15],[19]. Approaches like HASTECS project allow to design advanced serial hybrid electric propulsion system with parametric models for each propulsion component, integrating physical phenomena across electrical, mechanical, and thermal fields to size and evaluate device losses and weights [21].

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Aircraft level

At aircraft level, like for fuel cells stream, methodologies are being developed for the conceptual design and sizing of hybrid-electric aircraft, integrating various disciplinary tools into a workflow. This involves determining aircraft geometry, weights, and aerodynamic characteristics [15], [21]. For instance, tools like THEA-CODE (Tool for Hybrid-Electric Aircraft Conceptual Design) are used for conceptual design of hybrid-electric aircraft with conventional or unconventional airframes [19]. The FAST-OAD software (from ONERA and ISAE Supaero) is also used to analyse propulsion-airframe integration [21]. Multi-objective optimization problems are formulated to simultaneously optimize conflicting objectives like fuel consumption and flight range/duration for hybrid aircraft design [20].

Experimental

Propulsion level

A crucial area of experimental activity is the detailed modelling of battery safety, which implicitly requires extensive testing [24]. Experimental studies are therefore conducted on thermal runaway of lithium-ion batteries, specifically investigating fully charged and overcharged batteries under adiabatic and side-heating conditions [23]. Addressing safety aspects related to battery pack thermal management is vital for aircraft certification [19]. Some studies focused on other related aspects to ensure battery products meet the specific requirements of aviation in terms of operating conditions [24]. Research is also promoted for battery integration, including multifunctional/structural batteries, which implies testing their performance and structural integrity [24].

Some dedicated test bench such as the Hybrid-Electric Aircraft Testbed (HEAT) project, is developed by the National Research Council of Canada (NRC) Aerospace Research Centre (ARC), to serve as an airborne electric propulsion demonstrator platform. Its primary goal is to acquire knowledge, experience, and capabilities related to electrified aircraft propulsion [23]. Other test bench are dedicated to verify Simulation tools that predict the performance of electric components [19].

Aircraft level

Several flying demonstrators have been developed to study hybrid-electric aircraft using batteries as an energy source, alongside conventional combustion engines, excluding fuel cell applications. These demonstrators range from small-scale unmanned aerial vehicles (UAVs) to larger aircraft concepts [20].

Key flying demonstrators and projects include:

Small-Scale UAVs as academics initially focused on this sector to demonstrate the feasibility of hybrid electric technology.

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Regarding larger concept, examples include hybrid aircraft such as EcoEagle concept. Developed by Embry-Riddle Eagle Flight Research Center, this light airplane was designed with a hybrid electric system for the NASA's Green Flight Challenge in 2011. It combined a 40-horsepower (30 kW) electric motor with a 115-horsepower (86 kW) internal combustion engine [20]. Another concept is Diamond Aircraft DA36 E-Star, presented as the "world's first serial hybrid electric aircraft" [20]. The Ampaire EEL, featuring a "parallel hybrid" configuration, was also unveiled as a demonstrator [20].

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5. Remaining Challenges at technology level and supply chain (Review papers)

5.1 Remaining Technological developments

Hydrogen (combustion)

Regarding hydrogen combustion stream, a few areas of improvement can be identified

One of these area deals with the design of engine and combustor. There is a need for further detailed design studies, including simulation and testing, of different combustor technologies and heat exchanger configurations. These are crucial for novel fuel and thermal management systems and alternative engine cycles [14]. The precise space and mass requirements for heat exchangers cannot yet be accurately rated, necessitating more accurate methods for future calculations [15]. Additionally, the boundaries for fuel temperature concerning the combustion chamber, piping, and overall fuel system are not yet clear.

Another key feature is the need of advanced materials and manufacturing processes. Research, analysis, and testing of materials that are tolerant to cryogenic conditions and hydrogen, as well as those that can withstand very high temperature gradients, are critical for engine-integrated heat exchanger development [14]. Material challenges also extend to resisting hydrogen-induced corrosion and high temperatures, especially for additive manufacturing parts, and understanding hydrogen embrittlement [6].

Last, technological improvement studies are required for fuel system architecture. Substantial work is still required for the detailed design and testing of cryogenic fuel system architectures for aircraft [17]. A review of safety and certification related to hydrogen venting is also necessary.

Hybrid-Electric Aircraft (Batteries and Fuel Cells)

General for Hybrid-Electric

Several topics of interest for future studies can be identified for hybrid electric aircraft in general

First topic concerns the electric systems part. For instance, the feasibility of high voltage electric cabling remains a critical issue, with existing guidelines not easily extrapolating to kilovolt ranges. Research is ongoing to limit or eliminate partial discharges in DC distribution systems [22]. In a similar way, protection devices with reduced size and fault arc detection systems for active protection are major gaps in power distribution [24]. The breaking capacity of such devices for aviation conditions is not yet achieved [22].

The second topic deals with thermal management aspects. Designing a light yet highly efficient cooling system is crucial for the feasibility and performance of hybrid aircraft, especially given the low-grade internal heat release (up to a few hundred degrees Celsius) from electric components, making heat dissipation challenging [22]. Waste heat utilization and the design of integrated thermal management systems (TMS) with minimal mass and drag impact is a significant research gap [17]. Safety aspects related to the thermal management of battery packs and fuel cells are critical for certification [29].

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A third crucial topic are the testing and certification aspects. Infrastructure for testing and certifying hybrid electric propulsion systems is required [24]. Efforts are also needed to develop simulation, characterization, and verification tools for electrical components [24].

Last, studies at overall aircraft design level are required for new concepts. Refining and broadening concept analysis is still required to determine if hybridization will truly benefit emissions reduction for commercial aircraft, and under which technological assumptions [22].

Fuel cells focus

As far as fuel cells are concerned, some need for specific studies can be highlighted.

Thermal management is more crucial for this choice of system. Given fuel cell efficiencies (50-70%), thermal management and waste heat recovery are critical for determining overall system efficiency [17]. For instance, controlling the heat output of Solid Oxide Fuel Cells (SOFCs) in confined aircraft spaces is crucial, as current thermal management can restrict power output to levels too low for medium-sized aircraft [6].

Another specific topic is the choice of fuel cells technology, especially SOFC. Actually, the integration of SOFCs into aircraft systems is considerably less explored and commercialized compared to Proton Exchange Membrane Fuel Cells (PEMFCs) [6]. Fuel cells may also require longer maturation times, potentially beyond 2030, due to safety and redundancy issues [24].

Batteries focus

Batteries choice come with its own specific fields of improvement.

First topic is connected to the specific energy estimation. Actually, there is major uncertainty regarding the projection of specific energy for aviation batteries, which is a main enabler for parallel hybrid systems [24]. Research needs to focus on more ambitious and aggressive technology developments for battery specific energy [22].

Another key aspect are the performance indicators. Many performance indicators, such as continuous fast charge/discharge capabilities and cycle life, are not yet well assessed, and application-specific electrochemical formulations and cell designs may be needed [22]. Specific research is required to enable battery cycling life and charge/discharge rates compatible with aircraft usage, including on-ground procedures and infrastructure [22].

A third point concerns thermal aspect. New materials and advancements in thermal management systems are needed to reduce cell thermal runaway and extend battery life [29]. Passive cooling solutions for battery stacks also highlight critical areas for improvement [23]

A fourth aspect deals with maintenance handling There is a need for adequate battery check, maintenance, and refurbishment procedures synchronized with aircraft maintenance schedules while mitigating obsolescence [22].

Last, certification of batteries is still an important topic [22].

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5.2 Supply chain perspectives

The transition to hydrogen and hybrid-electric aircraft presents several significant supply chain challenges, affecting both the availability and integration of necessary technologies and infrastructure. Only the ones related to aircraft design and operation are recalled below.

Hydrogen Combustion and Fuel Cell Aircraft

Hydrogen-powered aircraft, whether using direct combustion or fuel cells, face distinct supply chain challenges primarily related to hydrogen production, storage, distribution, and airport infrastructure:

Regarding hydrogen production aspects, the majority (approximately 96%) of global hydrogen production currently relies on fossil fuels (e.g., natural gas, coal), which contributes to substantial emissions [25], [18]. Only a small portion, about 4%, comes from water electrolysis [25]. The transition to low-carbon or green hydrogen is crucial, with targets of 70% low-carbon by 2030 and 100% by 2050 [18]. However, green hydrogen, produced via electrolysis using renewable energy, remains significantly more expensive compared to grey hydrogen [25], [14].

The extraction process requires significant energy inputs, especially for renewable electricity-driven electrolysis [25]. Space limitations for large-scale production facilities (e.g., electrolysis) can also be a challenge at airports [27].

Regarding hydrogen storage, hydrogen must be liquefied (LH2) for practical aviation use, requiring chilling to below -253°C [30]. This necessitates the development of specially insulated tanks and next-generation fuel distribution systems [30], [14]. In addition, challenges include managing boil-off to align with fuel consumption and developing effective thermal insulation to mitigate weight concerns [6]. Hydrogen embrittlement, where atomic hydrogen makes high-strength metals brittle, poses a significant risk to the structural integrity of fuel tanks and pipelines [26]. While material-based storage (e.g., metal hydrides, chemical storage) is being researched, it currently has a low Technology Readiness Level (TRL) [17], [26].

Last but most important point from operational point of view deals with hydrogen distribution and airport infrastructure.

The current infrastructure for hydrogen production, transportation, and storage is inadequate, requiring substantial investments in pipelines, storage facilities, and refueling stations [25], [14].

At airports, hydrogen must be delivered in gaseous or liquid form, which is a significant change in operating conditions with implications for infrastructure, capital investment, operational practices, and safety [27]. For instance, if hydrogen arrives in gaseous form, a liquefier is needed on-site [27]

For distribution within airports, new hydrant systems running parallel to existing Jet A-1 systems would be required [27]. Transporting the same amount of energy requires four times more trucks for liquid hydrogen compared to Jet A-1 due to its larger volume [27]

In addition, safety during refueling is paramount, with leakage management being a top priority to avoid hydrogen gas concentrations, which may alter turnaround procedures [27] The refuelling process alone is linked to several threat sources, with large leaks being the most common due to human factors [28].

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Hybrid-Electric Aircraft (Batteries)

For Hybrid Electric Aircraft (Batteries), the supply chain challenges primarily revolve around the batteries themselves, their integration into aircraft systems as well as the operational aspects.

Current battery technologies are still under development to meet the required power and energy density, weight, safety, and reliability for commercial aircraft [26], [24] The low gravimetric energy density (BED) of batteries is a main obstacle, limiting electric propulsion to smaller aircraft and raising uncertainties in development [19].

Like for hydrogen, the operational aspects are challenging. Batteries require fast charging cycles and longer lifetimes compatible with aircraft usage and ground procedures [24]. There are also challenges related to the available volumes for battery installation and the need for quick and easy mounting, removing, and swapping of battery packs to minimize ground downtime [19].

Last, adequate battery check, maintenance, and refurbishment procedures are needed, synchronized with aircraft maintenance schedules, while also mitigating obsolescence [24].

At that stage of development, both battery-electric and hydrogen-based propulsion systems for aircraft face substantial challenges across the entire supply chain, from raw material sourcing and production to storage, distribution, infrastructure development, and integration into aircraft and airport operations.

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6. Take away points for non -CO2 assessment improvements (CLAIM and Review papers)

This last part aims at highlighting the main take away points related to CLAIM topics in order to enhance the accuracy of environmental performance predictions for the aircraft concepts from the early stages of conceptual design.

6.1 Modelisation

Modelisation aspects need to be improved in order to increase the accuracy of the overall assessment process

- Improve current emission extrapolation methods and extend them for new energy carrier aspects

Existing emission extrapolation methods, such as BFFM2, are mainly suited for conventional engines and show limitations when applied to lean-burn combustors, SAF use, or hydrogen technologies. They lack accuracy for cruise conditions and also ground-Level emissions and do not account for secondary emissions like organics or sulfuric acid, which become relevant in low-soot scenarios. Current certification processes also provide insufficient detail on these emissions. Hybrid-electric architectures, with low or varying thermal engine loads, introduce additional complexity that current models cannot capture. To improve prediction accuracy, these methods must be extended to cover non-standard regimes, alternative fuels, and new energy carriers

- Increase High-Fidelity Modelling of Complex Propulsion Systems

The growing complexity of aircraft propulsion—especially in hydrogen combustion and hybrid-electric systems—requires higher fidelity in performance modelling at aircraft level. Hybrid-electric aircraft involve intricate interactions between various domains, including electrical, mechanical, thermal, aerodynamic, and structural systems. Achieving complex modelling is essential to integrate and analyze these multidisciplinary couplings with greater fidelity, which is not possible when components or systems are decoupled. Advanced modeling is needed to account for complex electrical phenomena that are often overlooked in low-fidelity models, such as partial discharges. Similarly, the thermal management of numerous distributed heat sources from electrical components throughout the airframe. For hydrogen combustion, extensive modifications are required for engine components, including fuel injection systems and combustion chamber designs. In addition, high-fidelity modeling of tank design, insulation (e.g., multi-layer insulation for cryogenic conditions), and boil-off rates is critical. The design and integration complexity of cryogenic storage, distribution, and fuel conditioning systems must therefore be rigorously modelled. The integration of higher fidelity models for those complex propulsion systems allows for a greater fidelity in incorporating and analyzing the intricate electrical, aerodynamic, and structural couplings present in aircraft. It will enable o greater

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flexibility in defining the aircraft's topology, mission performance, and even wing design, which is crucial for optimizing these advanced aircraft concepts.

- Integrate Climate and Air Quality Impacts into Design KPIs

To support sustainable aircraft design, climate impact indicators and local air quality effects should be embedded into key performance indicators (KPIs) used in early concept evaluations. Traditionally, fuel burn and CO_2 have dominated performance metrics; however, non-CO_2 effects such as contrails, NOx-induced ozone, and particulate matter must also be accounted for. Compared to current design process at conceptual level, adding this KPIs will require specific extensions. For instance, coupling aircraft design-level tool to 4D trajectory tool able to consider weather data as well as realistic ATM (Air Traffic Management) seems compulsory. Another aspect to be considered will be the effect of new architectures (including the impact of engine installation effects) on the behaviour of wake contrails formation. Additionally, the environmental footprint around airports—where populations are exposed to emissions like NOx and soot—should be considered in the process in order to reduce the uncertainties on pollutant emissions during LTO phases. This integrated view ensures that aircraft concepts are not only fuel-efficient but also aligned with broader environmental goals.

- Implement Uncertainty Propagation throughout the Design Chain

To improve the reliability of non-CO_2 impact assessments, it is essential to implement uncertainty propagation methodologies from the earliest stages of aircraft design. This includes characterising uncertainties in fuel properties and uncertainties in emissions values at engine level (especially in cruise condition). But considering more complex and integrated complexity aircraft propulsion, most of the technology inputs still suffers from uncertainty. For instance, the technological development of batteries for aeronautical applications is exposed to numerous uncertainties and, regarding hydrogen combustion, there is still uncertainties on the performance of different combustor technologies and heat exchanger configurations. These uncertainties can affect the aircraft weight and performance estimation but also the emissions predictions. Therefore, they must be systematically propagated through propulsion system behaviour and performance predictions, particularly for novel architectures. By enabling the propagation of these uncertainties up to climate impact models, designers can better understand how technology choices may influence environmental outcomes across a range of realistic scenarios.

6.2 Experimental

Regarding experimental activities the main objective should to provide accurate information to improve the modelisation aspects highlighted in previous paragraph.

- Improve Emission Extrapolation Methods and Extend for New Energy Carriers

To strengthen emission modeling, especially for cruise conditions and non-conventional fuels, a variety of experimental efforts are needed. Lab-scale combustion tests can help characterise the influence of fuel properties—such as aromatic content, sulfur content, or hydrogen purity—

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on primary and secondary emissions. Ground engine tests across a wide range of operating conditions, including low thrust and idle, are essential to build a more representative emissions database, particularly for lean-burn combustors and engines running on SAF or hydrogen.

Eventually, flight tests, will play a crucial role in validating extrapolated emissions (e.g. from BFFM2-type methods), and are especially needed for non-volatile particulate matter (nvPM) and volatile emissions under cruise conditions. These measurements will allow models to be recalibrated and extended to cover new propulsion–fuel combinations and low-soot regimes.

- Increase High-Fidelity Modelling of Complex Propulsion Systems

The complexity of future propulsion systems—such as hydrogen combustion and hybrid-electric architectures—requires an experimental foundation to support higher-fidelity modelling.

At the lab level, component testing is essential: fuel injection behaviour for hydrogen, heat exchanger performance, or electrical system responses under high-altitude conditions (e.g. partial discharges, thermal runaway risks). Ground-based integration tests are also critical to validate coupled powertrain systems involving mechanical, electrical, and thermal subsystems. This is particularly important for hybrid-electric configurations, which must account for dynamic interactions and power-sharing logics.

In-flight testing will help validate these models under realistic mission profiles, capturing transient behaviour, power fluctuations, and the system's ability to meet performance demands during different flight phases.

- Integrate Climate and Air Quality Impacts into Design KPIs

To support the integration of climate and air quality impacts into aircraft design metrics, experiments must extend beyond traditional emissions measurements.

More ground-based monitoring near airports can help quantify the real-world impact of NOx and soot emissions during LTO cycles, which is necessary to better inform local air quality models.

In parallel, flight tests with instrumentation capable of measuring contrail properties—such as optical thickness, particle size, and ice number—are required to validate contrail formation models, especially for new fuels and propulsion types.

- 4. Implement Uncertainty Propagation Throughout the Design Chain

Uncertainty propagation requires a solid understanding of how key variables fluctuate throughout the design and operation of aircraft systems.

Lab tests are needed to characterise the performance dispersion of new technologies like batteries or fuel cells under aerospace-relevant conditions. Ground testing of engine and propulsion systems under varied inputs can help quantify how performance changes across configurations or operational settings.

Flight campaigns, meanwhile, can be used to capture real-world system variability (e.g., thermal behaviour of hybrid-electric architectures) and compare predicted versus observed emissions and performance.

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7. SUMMARY

This report has identified and analysed the key gaps, challenges, and opportunities for improving the prediction of environmental impacts—both CO_2 and non-CO_2—of future aircraft concepts, with a specific focus on short/medium-range and regional configurations using hydrogen and hybrid-electric propulsion systems. Based on CLAIM activities and an extensive literature review, the findings show that both modelling and experimental capabilities must evolve to address the complexity introduced by these new technologies. On the modelling side, priority areas include extending emission extrapolation methods to account for alternative fuels and low-thrust operations, improving high-fidelity modelling of integrated propulsion systems, incorporating climate and air quality indicators into early design KPIs, and implementing uncertainty propagation across the design chain. These needs are mirrored on the experimental side, where targeted lab, ground, and flight tests are essential to validate and refine models, including real-world performance of hybrid and hydrogen-based systems. Strengthening the link between experimental data and predictive models will be critical to improving the robustness of environmental assessments and enabling informed design decisions from the earliest stages of conceptual development.

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