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Towards sustainable regional aviation: Environmental potential of hybrid-electric aircraft and alternative fuels

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A B S T R A C T

The aviation sector needs to reduce its environmental impacts, like climate change and air pollution. New hybrid-electric aircraft concepts may contribute to abating part of these impacts. But to what extent and under which conditions? This study addresses these questions in the context of regional aviation and identifies technologies and concrete actions required for more environmentally sustainable aviation. The environmental impacts of emerging hybrid-electric aircraft configurations deployed in 2030, 2040, and 2050 have been comprehensively quantified using prospective life cycle assessment. The entire life cycle of the conventional and hybrid-electric aircraft configurations was encompassed, covering various technologies and systems like batteries, fuel cells, hydrogen, and selected alternative aviation fuel (AAF) systems. For these elements, detailed life cycle inventories stemming from primary data, literature, and prospective environmental databases were used, and uncertainty was evaluated. Results showed that hybrid-electric aircraft with Li-ion batteries appear as a promising transition technology in the short-term while aircraft propelled by fuel cells using hydrogen from electrolysis yield important environmental benefits relative to conventional aircraft in longer time horizons. In contrast, the studied AAFs present little or no environmental benefits when considering environmental impacts holistically, demonstrating the need to revise existing AAF frameworks and incentives globally. Environmental burden-shifting from flight emissions in conventional aircraft systems to airport operations and aircraft manufacturing in hybrid-electric aircraft is also observed in the results, thus calling for strengthened support to airports in their sustainability management and increased integration of ecodesign practices in future aircraft design and development.

1. Introduction

Flight tracking data for 2019 indicate passenger transport represented 89 % of the CO_2 (carbon dioxide) and NO_x (nitrous oxide) emissions of flights transiting through civil platforms, emitting 903 Mt. (megaton) CO_2 and 4 Mt. NO_x (Aviation Week Network, 2023). Short flights under 600 nautical miles (nmi) (1111 km) represented 18 % of these emissions globally and 55 % of the number of flights, meaning that regional aviation (aircraft usually accommodating <100 passengers) accounts for a reasonable part of airport noise and air pollution (Aviation Week Network, 2023). Therefore, mitigating the impacts of short-range flights is environmentally relevant and needed to achieve the sector sustainability goals (ATAG, 2021; Epstein and O'Flarity, 2019; ICAO, 2022; Zaporozhets et al., 2020). For short-range missions under 600 nmi, new hybrid-electric aircraft technologies have been advanced to potentially reduce the climate change (CC) impacts of regional aviation (Gnadt et al., 2019; Schäfer et al., 2018; Su-ungkavatin et al., 2023; Zaporozhets et al., 2020). The potential of hydrogen hybrid-electric aircraft configurations is a key consideration in the development of sustainable aviation despite its technical challenges of hydrogen storage (Hoelzen et al., 2022; Kapoor et al., 2017). However, to encourage a transition towards the lowest possible environmental

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burden, it is crucial to assess the environmental impacts of these innovative aircraft configurations through comprehensive environmental sustainability assessments, such as life cycle assessments (LCAs) (Hellweg et al., 2023).

Life cycle thinking has become a key complementary tool in decision and policy-making (Sanyé-Mengual and Sala, 2022). LCA is an ISO-standardized methodology that comprises four mandatory steps, which are interdependent and iterative: goal and scope definition, life cycle inventory (LCI) analysis, life cycle impact assessment (LCIA), and life cycle interpretation (ISO, 2006a, 2006b). Two of the main strengths of LCA lie in its capability to quantify multiple environmental impacts and to do so in a life cycle perspective, i.e., including all activities from the necessary raw materials extraction through production and operations of the technological systems up to their recycling and ultimate end-of-life (Hauschild et al., 2017).

Until now, LCA has been applied to aviation systems in scientific literature and beyond (Rupcic et al., 2023). However, most aircraft LCAs focus solely on climate change impacts and present a low level of detail and transparency (Rupcic et al., 2023). The carbon footprint of hybrid-electric aircraft is thus often performed in literature based on preliminary design outputs such as hybridization degree, energy requirements, fuel consumption, and weight (Barke et al., 2022; Johanning and Scholz, 2014; Melo et al., 2023; Ribeiro et al., 2020; Scholz et al., 2022). This limited the interpretation of these rough carbon footprints, which indicated that hybridization would perform better than conventional aircraft for a given mission but did not allow for hotspot analysis due to a lack of technical specifications of the power train technology and the coarse granularity of the impact assessment. The possibilities to improve the design to reduce the impacts have thus been limited. In addition, part of the aircraft system life cycle is often missing or incompletely covered in hybrid-electric aircraft LCA literature: airport systems are such an example, although their relevance may be important due to the change in infrastructure that electricity and hydrogen supply systems entail (Ratner et al., 2019; Siddiqui and Dincer, 2021). Finally, multiple environmental impact indicators, beyond mere carbon footprints, should be considered when assessing the environmental sustainability of aircraft systems to pinpoint tradeoffs between environmental problems and avoid burden shifting from one impact to another in further decision-making (Rupcic et al., 2023). Overall, these limitations and gaps in past LCA studies in the field make existing LCA results insufficient to comprehensively address comparisons between hybrid-electric and conventional aircraft systems from a future-oriented perspective and provide meaningful recommendations to stakeholders in the aviation sector.

Additionally, LCA methodology is conventionally static and relies on existing data regarding processing practices and current efficiencies (Sohn et al., 2020). To provide recommendations to decision-makers regarding the sustainability of future aircraft solutions, it is essential to address the data limitations linked to the novelty of the technologies and the issue of dynamic modeling of future environmental impacts and thus perform so-called prospective LCA (Sacchi et al., 2022; Thonemann et al., 2020; Thonemann and Schulte, 2019). Prospective LCAs are applied to assess the environmental impacts of mature and immature technologies at a future point in time by using, e.g., upscaling technologies and updated LCI background databases (Thonemann et al., 2020). Past studies have considered the prospective change under the narrow-sighted lens of the fuel system only, for example, varying the greenhouse gas (GHG) emission intensity of the electricity grid in line with government pledges and considering multiple hydrogen production pathways (Bicer and Dincer, 2017; Gnadt et al., 2019; Siddiqui and Dincer, 2021). Thus, the future changes in industrial background systems, such as electrification, efficiency gains, and technology maturation, have not been modeled in such studies. As a result, the questions of when hybrid-electric aircraft technologies become available, under which technical specifications, and with which associated environmental impacts have remained unanswered.

This study contributes to bridging these gaps in the environmental sustainability assessment of hybrid-electric aircraft systems by performing a prospective LCA that can yield an environmental sustainability roadmap to decision- and policy-makers in the aeronautic sector. The specific goals of the study are to (i) quantify the environmental impacts of emerging hybrid-electric aircraft technologies, with uncertainty characterization, in three time horizons, namely 2030, 2040, and 2050; (ii) compare the environmental performance of hybrid-electric aircraft configurations with conventional aircraft using either kerosene or AAF; and (iii) provide recommendations to aviation stakeholders and policy-makers for a more sustainable transition in the context of regional aviation. This study builds on the GENESIS project of the Clean Sky 2 program (https://www.genesis-cleansky.eu/) and concentrates on 50-PAX regional short-haul aircraft systems (termed "GENESIS aircraft" in the following) (Marciello et al., 2023; Thonemann et al., 2023a, 2023b). The ATR42 regional jet was hence chosen as a reference aircraft, and the aircraft, airport, and fuel systems were considered from cradle to grave.

In the following sections, we will delve into the details of our study, beginning with Section 2, where we outline the methods and materials employed, followed by Section 3, where we present our results and engage in a comprehensive discussion; Section 4 will provide insightful recommendations tailored for policy- and decision-makers in the aviation industry, and finally, in Section 5, we will conclude our paper while offering a forward-looking perspective.

2. Methods and materials

2.1. Overall assessment methodology

Five hybrid-electric aircraft configurations were evaluated based on batteries and/or fuel-cell technologies and identified alternative aviation fuels as technically viable by 2050 (Marciello et al., 2023). For each time horizon, the prospective LCI, a collection of all inputs, outputs, and emissions (ISO, 2006a), was based on primary data and from scientific literature elaborated in partnership with industry experts (Thonemann et al., 2023a, 2023b). The environmental impacts were quantified using the IMPACT World+ methodology (Bulle et al., 2019) and the computational framework Brightway2 for more transparent and reproducible results (Mutel, 2017).

2.2. Aircraft configurations

Based on a design exploration and technology foresight analysis for regional hybrid-electric aircraft, different aircraft designs considering the technology readiness level and the potential sustainability benefits of emerging aircraft technologies were derived fulfilling the top level aircraft requirements (TLAR) outlined in Table 1 (Marciello et al., 2023).

The different aircraft configurations (cf. Fig. 1 and Appendix A) considered are for (i) the short-term time horizon, gas turbine (GT, also called conventional) and gas turbine with battery (GT-bat), (ii) the medium-term, gas turbine (conventional), GT-bat, and proton exchange

Table 1
Top level aircraft requirements for the aircraft design developed in the GENESIS project and taken from Marciello et al. (2023). Additional abbreviations: knots true airspeed (KTAS), nautical miles (nmi).

Description	Value	Unit
Design range	600	nmi
Typical range	200	nmi
Time to climb (design mission)	13	min
Cruise speed	295	KTAS
Take-off field length	<1200	m
Landing field length	<1200	m
Design payload	4750	kg
Maximum takeoff mass	<24,000	kg

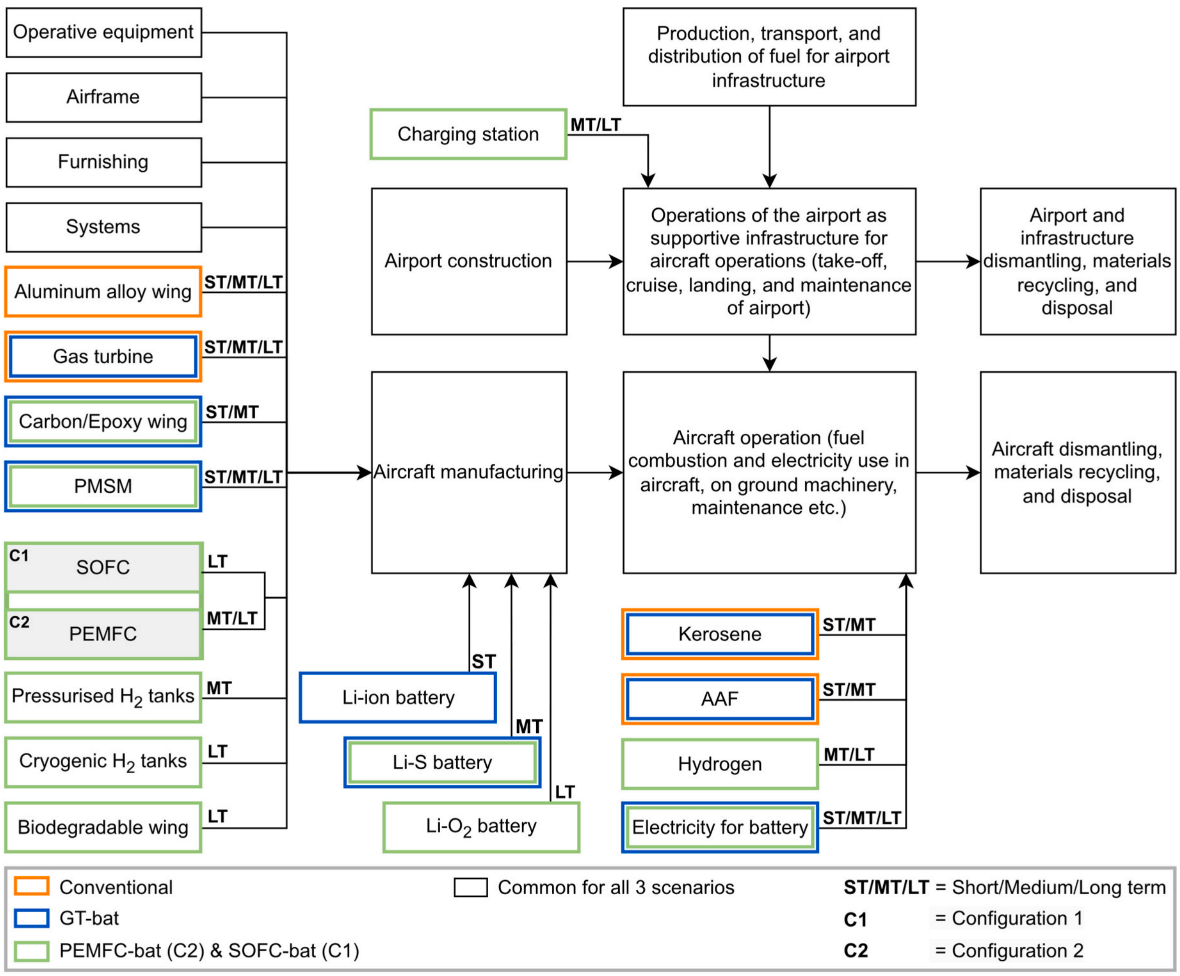


Fig. 1. System boundaries for all analyzed aircraft configurations, including gas turbine (also called conventional), gas turbine and battery (GT-bat), proton exchange membrane fuel cell and battery (PEMFC-bat), and solid oxide fuel cell and battery (SOFC-bat). Substitution of kerosene with alternative aviation fuels (AAF) is also considered. Components present in all configurations, such as airframe or furnishing, are indicated as boxes with black outline, though differences in, e.g., weight and material composition can occur. A variation in the outline color indicates flows differing between configurations, while multiple colors indicate that a flow appears in several configurations. The SOFC-bat and PEMFC-bat configurations are equivalent, except for the fuel cell, indicated by "C1" and "C2". Additional abbreviations: hydrogen (H_2), lithium (Li), oxygen (O_2), permanent magnet synchronous motor (PMSM), sulfur (S).

membrane fuel cell and battery (PEMFC-bat), and (iii) the long-term; gas turbine (conventional), PEMFC-bat, and solid oxide fuel cell and battery (SOFC-bat).

2.3. Scoping of the assessment

The functional unit (FU), which is the basis for a fair comparison across aircraft systems, is defined as the air transportation of 50 passengers in a regional class aircraft over 200 nmi (370 km) (typical mission) from and to a regional airport in Europe in the years 2030 (short-term), 2040 (mid-term), and 2050 (long-term). The adopted reference flow is thus a flight with the GENESIS aircraft on a typical mission for each configuration and time horizon. For comparison across means of transport, the main results are also presented per passenger and per kilometer (noted "passenger.kilometer" or "pkm" in the following), although distances may not be functionally equivalent (while aircraft can fly more or less directly, trains, cars or buses may be constrained by topography, leading to higher distances to reach a same destination). A cradle-to-grave approach covering all processes or activities within each aircraft configuration (cf. Section 2.2) is illustrated in Fig. 1.

2.4. Data collection and system modeling

Different data sources were used for the LCI datasets, which compile the input and output flows of all activities in the aircraft life cycle systems, such as energy, material, waste, emissions, and resources (Saavedra-Rubio et al., 2022). LCI data for the specific aircraft technologies and systems (defined as "foreground system") mainly stem from Thonemann et al. (2023a), which provides a large number of time-differentiated LCI datasets for different aircraft technologies built from primary data collection at industrial sites, reviews of scientific literature and existing LCI databases. These datasets enable the modeling of all considered hybrid-electric aircraft configurations for each time horizon and include quantified uncertainty information that allows for uncertainty analyses (cf. Section 2.7).

The premise framework was used to account for the prospective aspect of the background systems, which include all supporting systems independent from the aircraft systems, like electricity supply or waste management systems (Sacchi et al., 2022). The premise framework uses integrated assessment models (IAMs) and manipulates the unit processes from the LCI databases ecoinvent 3.8 cut-off (Wernet et al., 2016) to reflect prospective changes in the background system, e.g., changes in electricity production over time (Sacchi et al., 2022). In this study, the selected IAM scenarios reflect the Shared Socioeconomic Pathway 2 (SSP2) for each time horizon using the regional model of investments and development (REMIND) (Aboumahboub et al., 2020). Nationally determined contributions (NDC) were chosen as the default climate policy scenario (also called baseline in the following), translating to a global mean surface temperature increase of ~2.5 °C (use of other scenarios was also explored for sensitivity analysis; see Section 2.6 and Section 2.7). This approach leads to temporally differentiated LCI models for background systems for 2030, 2040, and 2050. The matching of background LCI datasets with the aircraft-specific LCI datasets (foreground activities) is documented in a GitHub repository (Thonemann and Dudka, 2023), where linkages between appropriate activities reflecting the deemed product, technology, and geographical region were sought. Moreover, the LCI characterization, LCIA, and uncertainty analysis were computed using the Python package Brightway2 (Mutel, 2017). This open-source package allows transparent analysis documentation and enhances the reproducibility of the results.

2.5. Impact assessment

The environmental impact assessment was conducted by considering a large spectrum of environmental problems, such as climate change, particulate matter impacting human health, chemical releases impacting ecosystems, water use, or land use impacts, to name a few (see complete list in Table 2). Eighteen different impact categories were encompassed, leading to damages to ecosystems, human health, and natural resources (defined as areas of protection).

To characterize these impacts, i.e., translating pollutant emissions and resource use into potential impact indicators, the LCIA methodology IMPACT World+ (Bulle et al., 2019) was used. At the time of the study, it was one of the most up-to-date and consistent methodologies available in the LCA field. Where shorter-term (0–100 year time horizon) and long-term impacts (0–500 year time horizon) were differentiated in the methods (relevant for some impact categories, e.g., climate change), only shorter-term impacts were considered due to the uncertainties embedded in the long-term impact characterization (relevant for the following impact categories; CC, marine acidification, freshwater ecotoxicity, and human toxicity damages).

The assessment results were interpreted at both the midpoint and endpoint level. Indicators at endpoint level quantify damages to the areas of protection, whereas midpoint-level indicators are positioned somewhere along the cause-effect chain, from a pollutant emission or resource extraction to the eventual damages. While the former indicators bear more environmental relevance than the latter, they are associated with larger model uncertainty. Due to the reduction of indicators (from 18 to 3), the assessment at the endpoint level also allows for solving potential trade-offs between environmental problems observed at the midpoint level. Hence, assessment at both levels is relevant and was considered in the current study.

2.6. Scenario definition

The effect of three modeling choices on the results was investigated: the CC scenario used for building the prospective LCI database, the use of AAF, and the mission range. Table 3 provides an overview of the investigated scenarios with changed parameters.

The CC pathway and mitigation/adaptation trajectories are expected to affect the environmental performance of hybrid-electric aircraft, for instance, due to the influence of the GHG emission intensity of the electricity grid (Rupcic et al., 2023). Therefore, this study compared the environmental impacts of the aircraft scenarios with different shared socioeconomic pathway (SSP) scenarios by adjusting the environmental database ecoinvent 3.8 using the premise framework (see Section 2.4) (Sacchi et al., 2022; Wernet et al., 2016). The baseline scenario assumes that the committing States will implement their nationally determined contributions to mitigate CC (SSP2-NDC); a global mean temperature

Table 2
Environmental impact categories covered in the current assessment (based on Impact World+ LCIA methodology (Bulle et al., 2019)).

Environmental impact category	Indicator (midpoint level)	Units	Link to areas of protection (endpoint level)
Climate change	Radiative forcing as global warming potential (GWP100)	kg CO2eq.	- Human health (HH in disability-adjusted life year, DALY) - Ecosystems quality (EQ in potentially-disappeared fraction of species over area and time, PDF.m^2.year)
Fossil and nuclear energy use	Primary energy content	MJ dep.	Natural resources (NR) – not covered
Ozone layer depletion	Ozone depletion potential	kg CFC-11 eq.	HH
Particulate matter formation	Number of deaths normalized using PM2.5 as reference substance	kg PM2.5 eq.	HH
Photochemical oxidant formation	Tropospheric ozone concentration increase	kg NMVOCeq.	HH
Human toxicity, cancer and non-cancer effects [CTUh]	Comparative toxic unit for human health	CTUh	HH
Ionizing radiation	Human exposure efficiency relative to C14	Bq C14eq.	HH
Freshwater acidification	Change of pH in receiving ecosystems	kg SO2eq.	EQ
Terrestrial acidification	Change of pH in receiving ecosystems	kg SO2eq.	EQ
Freshwater ecotoxicity	Comparative toxic unit for ecosystems	CTUe	EQ
Freshwater eutrophication	Increase in phosphorus mass discharged to freshwater	kg PO4eq.	EQ
Land occupation	Land occupation impacts on biodiversity	m2eq*yr	EQ
Land transformation	Land transformation impacts on biodiversity	m2eq.	EQ
Marine eutrophication	Increase in nitrogen mass discharged to seawater	kg Neq.	EQ
Mineral resources use	Material competition scarcity	kg dep.	NR (not covered)
Water scarcity	Water scarcity accounts for both human and ecosystems needs	m^3eq.	HH, EQ

Table 3
Defined scenarios for the scenario analysis addressing three key aspects: sensitivity to climate change scenarios, inclusion of indirect land use change impacts, and longer mission range. Abbreviations: alternative aviation fuel (AAF), climate change (CC), integrated assessment models (IAM), indirect land use change (ILUC), nationally determined contribution (NDC), nautical miles (nmi), shared socioeconomic pathway 2 (SSP2). PkBudg500 is a scenario in line with the Paris Agreement.

Scenarios	IAM scenario for LCI background database	AAF	Mission	Time horizon
Baseline	SSP2-NDC	Market mix	200 nmi	2030, 2040, 2050
CC pessimistic	SSP2-Base	Market mix	200 nmi	2030, 2040, 2050
CC optimistic	SSP2-PkBudg500	Market mix	200 nmi	2030, 2040, 2050
AAF-ILUC	SSP2-NDC	Market mix with ILUC	200 nmi	2030, 2040, 2050
Long mission	SSP2-NDC	Market mix	600 nmi	2030, 2040, 2050

increase is estimated to be ~2.5 °C at the end of the century. The “CC pessimistic” and “CC optimistic” scenarios (cf. Table 3:) follow a business-as-usual trajectory with no climate policy (SSP2-Base: +3.5 °C) and a development driven by sustainable practices while respecting the Paris Agreement (SSP2-PkBudg500: 1.2–1.4 °C), respectively.

The use of AAF to substitute kerosene in conventional and hybrid-electric aircraft configurations was also tested, owing to its strong policy focus and potential environmental relevance (scenario “AAF-ILUC” in Table 3:). AAFs, which include different alternative fuels (including the so-called “sustainable aviation fuels” (ICAO, 2021)), are expected to abate >60 % of the CO_2 emissions of air transportation globally thanks to the carbon removal that occurs during the feedstock cultivation for biomass-based fuels or carbon capture strategies for electro-fuels (ICAO, 2022). The AAF was modeled as a market mix based on processes available in the premise databases. The fuels added to the market mix were selected in line with the EU sustainable aviation fuel (SAF) mandates and the EU sustainability criteria, which specify the biofuel/electro-fuel market shares and the kg-CO_2-eq/MJ targets in 2030, 2040, and 2050 (EC, 2021). None of the biofuels for which a process existed in premise matched the EU sustainability criteria of −65 % of the kg-CO_2-eq/MJ amount, so the fuels with the closest carbon intensity were chosen. The AAF market mix processes were hydroprocessed esters and fatty acids synthetic paraffinic kerosene (HEFA-SPK) derived from palm oil and Fischer-Tropsch (FT) fuel from direct air capture with hydrogen produced by electrolysis and wood gasification (see LCI files in the GitHub repository (Thonemann and Dudka, 2023)). However, the carbon footprint of such AAF is highly dependent on modeling the carbon flows, particularly the inclusion of indirect land use change (ILUC) induced by crop cultivation displacement (Schmidt and De Rosa, 2020; Schmidt et al., 2015). In the baseline scenario, biodiesel AAF was assumed to be carbon neutral; hence, the carbon capture during crop cultivation compensated for the carbon emissions from fuel burn. In the AAF-ILUC scenario, a penalty of 0.61 kgCO_2-eq/kg of refined palm oil was included due to the ILUC (Schmidt and De Rosa, 2020). This penalty was considered valid for the selected biodiesel process because palm oil production can be considered a global market; thus, the ILUC value represents average market displacements (Schmidt et al., 2015). Finally, the effect of the mission range on the results by considering a design mission (600 nmi) for which LCI data are available was also tested (i.e., “long-term” scenario; Table 3:) (Thonemann et al., 2023a, 2023b).

2.7. Sensitivity and uncertainty analysis

The uncertainty in the results and, consequently, the robustness of the comparisons of aircraft configurations depends on the uncertainty of the LCI data, LCIA method, and modeling choices (Huijbregts, 1998; Huijbregts et al., 2001). The current assessment includes characterization of the uncertainty in the LCI data and the influence of three critical modeling choices (choice of IAM scenario, use of AAF, and mission length) but does not account for the uncertainty in the LCIA methods, as quantified overall uncertainty information is not available for all impact categories in a consistent way (Chen et al., 2021; Laurent et al., 2020).

A Monte Carlo analysis of the LCI data of the foreground system was conducted to quantify the uncertainty related to the LCI data quality. The minimal number of iterations required increases with the number of flows in the datasets and entails a significantly increased computation time (Heijungs, 2020). The number of iterations was optimized and set to 500 based on the minimum number of runs required for the fuel cell configurations (datasets with the highest amount of flows and thus the highest required amount of iterations) (Oberle, 2015). LCI data statistical distributions were derived from the uncertainty data provided in the LCI files (Thonemann et al., 2023a, 2023b). Most of the LCI data is accompanied by a pedigree matrix, used to specify a log-normal distribution for these parameters, similar to the procedure used in ecoinvent (Weidema et al., 2013). An appropriate uncertainty range was available for a few processes, in which case a triangular distribution was assumed if not otherwise specified. It was assumed that the uncertainty was unknown for the remaining processes; therefore, no variability was included.

3. Results and discussion

3.1. Comparison across aircraft configurations (baseline scenario)

Overall environmental damage assessment. Accounting for the LCI uncertainty, all hybrid-electric aircraft configurations (kerosene fuels, electricity, and hydrogen as fuels) were found to reduce the damages to ecosystems quality compared to conventional aircraft for all time horizons (see Fig. 2). In the short- and medium-term, with a probability of 75 % and >95 %, the GT-bat hybrid configuration shows less impact on EQ than the conventional aircraft and performed worse than the PEMFC-bat in the medium-term with a likelihood of 75 %. However, hybridization had no advantage when considering the damage to human health (see Fig. 2, second row). In 75 % of the simulations, the PEMFC-bat aircraft performed environmentally worse than the conventional aircraft in the medium- and long-term for all damages. The SOFC-bat aircraft comparison with other configurations in the long-term was inconclusive due to higher uncertainty causing the interquartile ranges of human health damage scores to overlap. Nonetheless, the SOFC-bat aircraft performed similarly to the conventional aircraft in 50 % of the simulations (see Fig. 2). Overall, these findings show that hybrid-electric aviation alternatives tend to be environmentally advantageous compared to conventional aircraft for all time horizons, particularly hydrogen aircraft configurations in the medium and long terms, provided that their impacts on human health are mitigated.

Damages to ecosystem quality. With regard to ecosystem quality, climate change, land use occupation and transformation (LUo and LUt), and terrestrial acidification (TA) contributed together to >90 % of the damage for all time horizons (Fig. 3A). The reduction of CC obtained with the hybridization appears sufficient to compensate for small increases in LUt and LUo. The main processes contributing to LUo and LUt are the airport building construction and the photovoltaic electricity used to charge the batteries (GT-bat, PEMFC-bat, SOFC-bat), with LUo predominantly resulting from the buildings (55 %) and LUt from the expansion of renewable energy capacity (50 %). Kerosene combustion and airport building construction were the main causes for the EQ damage of conventional aircraft, via terrestrial acidification.

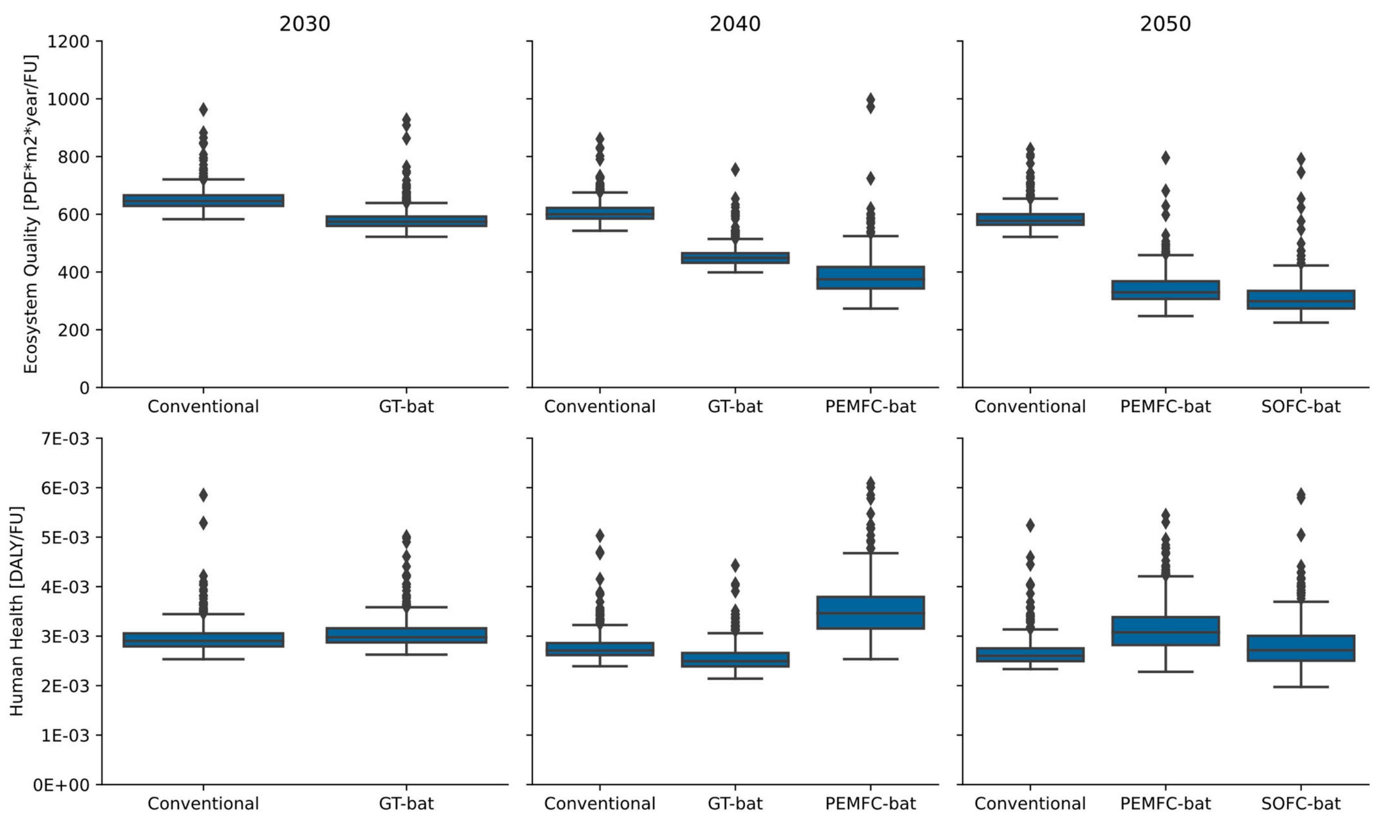
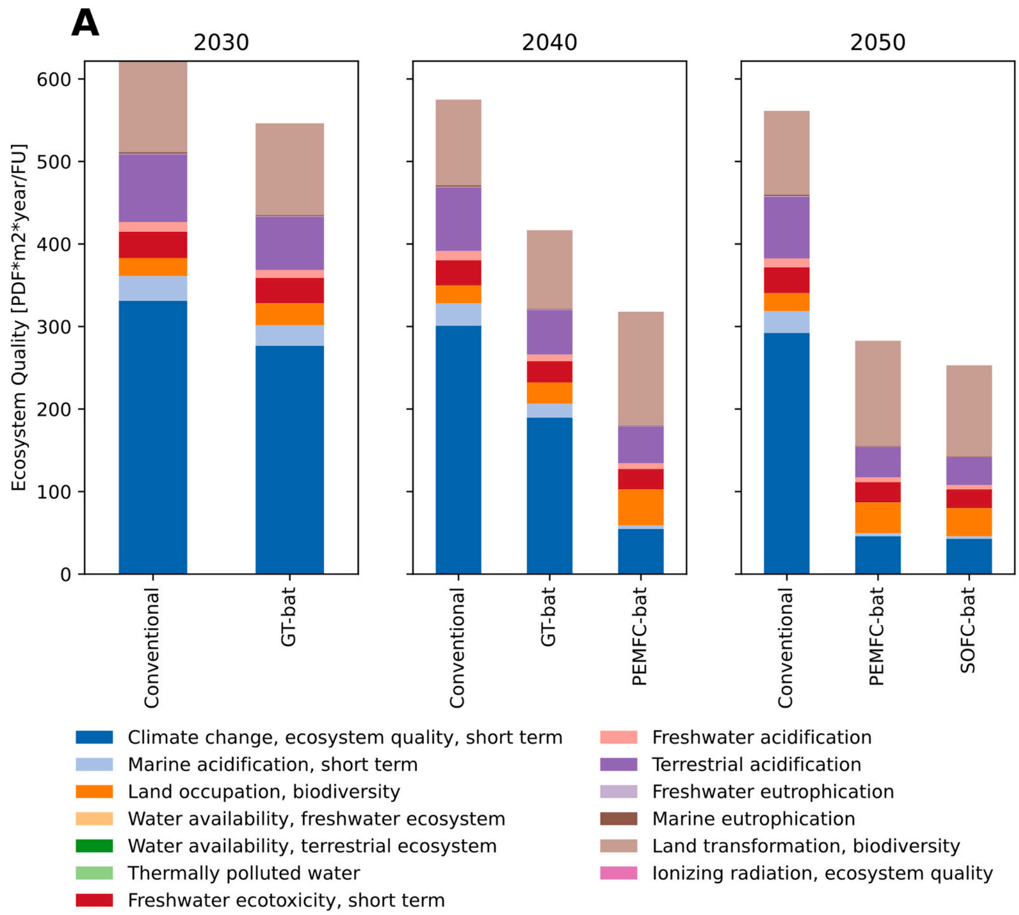


Fig. 2. Impact assessment results (damages to ecosystems quality and human health) comparing different hybrid-electric regional aircraft configurations and conventional aircraft (kerosene) across three time horizons (2030, 2040, and 2050). The boxplots represent the distributions for each configuration obtained via Monte Carlo analysis ($n = 500$, seed =35). The extremities of the boxplot and the central line represent the interquartile range and the median of the damage scores, while the whiskers illustrate the 95 % confidence interval. Individual dots represent outliers. Y-axis ranges were limited for visibility reasons to [0,1200] and [0,7E^{-3}] respectively for EQ and HH. The same figure including all outliers is shown in Appendix A Fig. A.1, and all Monte Carlo results can be retrieved from Appendix B. Additional abbreviations: disability-adjusted life years (DALY), functional unit (FU), gas turbine with battery (bat) aircraft (GT-bat), potentially disappeared fraction of species (PDF), proton exchange membrane fuel cell and battery (PEMFC-bat), solid oxide fuel cell and battery (SOFC-bat).



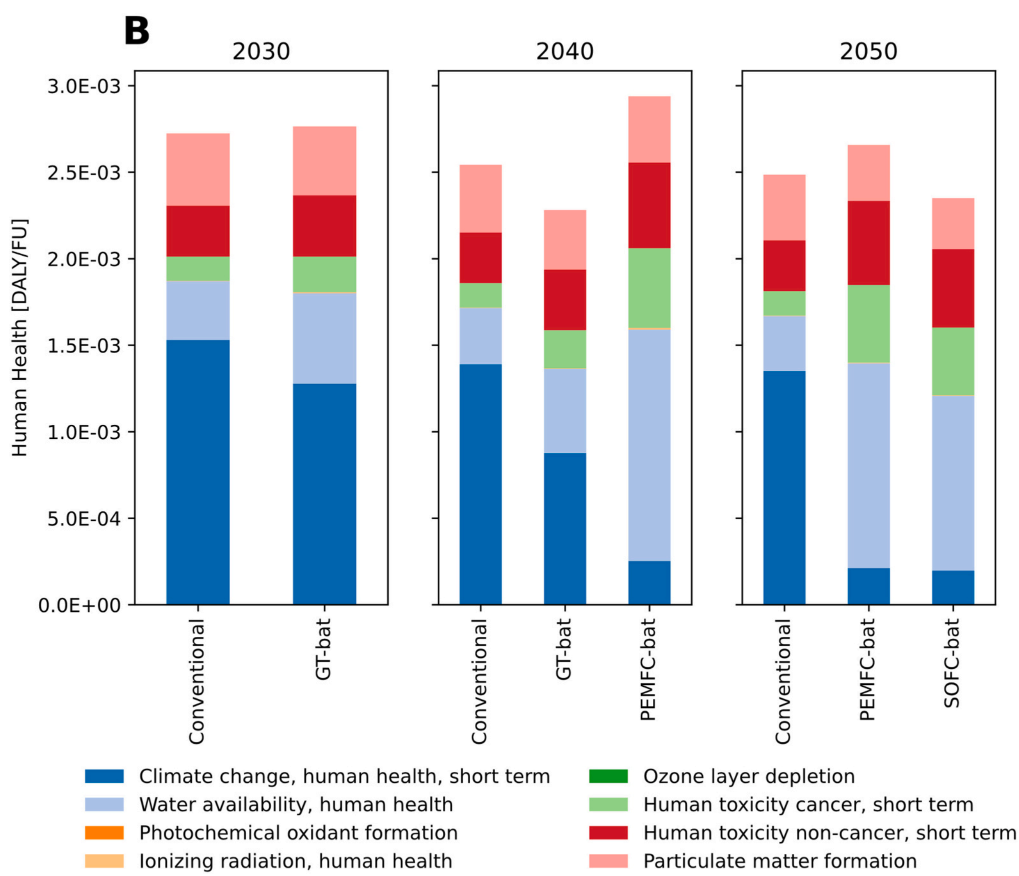


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Fig. 3. Individual environmental impact contribution to damages to A) ecosystem quality and B) human health for the baseline scenario for all analyzed configurations and time horizons (2030, 2040, and 2050). The stacked bar plots are based on deterministic results that can be retrieved in Appendix B. Abbreviations: disability-adjusted life years (DALY), functional unit (FU), gas turbine with battery (bat) aircraft (GT-bat), potentially disappeared fraction of species (PDF), proton exchange membrane fuel cell and battery (PEMFC-bat), solid oxide fuel cell and battery (SOFC-bat).

Damages to human health. CC, water use (WU), particulate matter formation (PM), and human toxicity carcinogenic and non-carcinogenic (HTc, HTnc) contributed the most to human health damages across all time horizons, with a large increase of WU damage (Fig. 3B). Overall, hybridization considerably reduces the damage of CC and its relative importance in the total damage. It occurs because kerosene is partially substituted by renewable electricity or low-carbon hydrogen in hybrid-electric aircraft configurations. Reducing CC can therefore benefit both EQ and HH, justifying a strong focus on this impact category. Nonetheless, the CC impact reduction achieved with hybridization was insufficient to compensate for the increase in WU damage (Fig. 3B). In the long term, WU impacts resulted from the indirect WU embedded in the electricity demand for hydrogen production and liquefaction, the airport use, and the PEMFC-bat production (approx. 55 %, 28 %, and 6 %, respectively). This tendency is also found in the SOFC-bat configuration, although the SOFC-bat production represented a higher share of the WU damage to HH (14 %). The impacts of the water used for the electrolysis and liquefaction yielded relatively small contributions with approx. 11 % and 19 % of the WU damage to HH. Nonetheless, using freshwater for hydrogen production in water-stressed areas may be problematic, and alternative water sources in these regions should thus be investigated (Beswick et al., 2021).

Trade-offs between fossil/nuclear energy use and resource use. The midpoint impact scores associated with fossil and nuclear energy use, mineral resource use, water scarcity, and LUo and LUt, are presented in Table 1 in Appendix A. Results are similar to the ones observed at damage level, with overall decrease of impacts over time for all configurations (see above). Yet, trade-offs were observed between fossil and nuclear energy use on one side, and mineral use, and water and land use, on the other. While conventional aircraft performed worse than the hybrid-electric aircraft configurations in the former category, hydrogen aircraft configurations were found to perform worse than the conventional aircraft for mineral, water, and land resource use. This is caused by the use of more renewable systems in hydrogen aircraft systems (e.g., photovoltaics): as the energy source is shifted from fossils use towards more renewables, fossils-related impacts (e.g., climate change, fossils use, etc.) tend to decrease while other impact categories like minerals use may remain or even increase due to the equipment manufacturing (Laurent et al., 2012).

Comparison of results with literature findings. The impact assessment results are partially concordant with existing literature, even though past studies often focused on the fuels only and rarely included a prospective dimension. Results in Fig. 2 and Fig. 3 reveal that aircraft configurations with hydrogen from electrolysis and electric aircraft (with renewable electricity) lead to lower magnitudes in the impacts caused by greenhouse gas, sulfur oxide (SO_x), and NO_x emissions (e.g., climate change, acidification, etc.) than conventional propulsion, as also found by Siddiqui and Dincer (2021). However, Siddiqui and Dincer (2021), which assessed the environmental impacts of aviation fuels, did not find a significant increase in ecotoxicity. In the current assessment, hydrogen aircraft were observed to lead to higher human health impacts (relative to conventional aircraft), partly due to higher toxicity from chemical releases in the systems; this is also in line with Siddiqui and Dincer (2021).

3.2. Key drivers of environmental impacts

Fig. 4 illustrates the contributions of life cycle stages to damages to ecosystems (Fig. 4A) and human health (Fig. 4B) for all aircraft configurations and time horizons. The relative life cycle stage contributions vary slightly over time for the conventional aircraft configuration, with the combustion stage having expectedly the largest shares of around 52 % (EQ) and 47 % (HH). Kerosene production (27 % and 16 % for EQ and HH, respectively) and airport operations (20 % and 36 % for EQ and HH, respectively) are the other key drivers of the impacts. Manufacturing conventional aircraft is relatively negligible with about or <1 % contribution for EQ and HH damages.

For the hybrid-electric aircraft configurations the results slightly differ, although the most relevant contributing life cycle stage for the GT-bat configuration remains the combustion stage. Overall, the share from the fuel supply and combustion tends to decrease over time (− 7–8 %), while the airport operations, electricity generation, and aircraft manufacturing gain larger contribution to the total damage (see Fig. 4). This can be explained by the increasing hybridization when moving from short-term to long-term perspective, causing subsequent reduction in fossil fuels and increased demand for electricity and battery capacity needs. Unlike for conventional aircraft, aircraft manufacturing becomes a relevant source of impacts, amounting to 5–8 %.

Fuel cell-driven hybrid-electric aircraft configurations follow the same pattern regarding the key drivers to EQ and HH damages, although, in the absence of major combustion impacts, a much larger impact share is attributable to the airport operations (ca. 60–67 % across all configurations and time horizons), aircraft manufacturing (ca. 8–14 %) and electricity generation (ca. 17–18 %).

Considering the breadth of the represented aircraft configurations, these findings tend to demonstrate that airport operations and aircraft manufacturing can be expected to become increasingly relevant in the environmental burden of future aircraft systems. While the current policy focus is primarily directed to abating flight emissions from conventional aircraft design, a relative burden shifting towards the aircraft production, particularly the necessary emerging technologies like batteries or fuel cells, and more importantly, towards the airport operations is expected to occur. This trend calls for stakeholders to anticipate such future shifts and fully include these systems in future policy making concerning sustainability (e.g., reinforced ecodesign of aircraft, airport-wide policies, etc.).

3.3. Scenario analysis

A scenario analysis was conducted to evaluate the potential influence of modeling assumptions (see Section 2.6). Environmental impact distributions (considering the Monte Carlo analysis results) when considering different CC scenarios are provided in Fig. 4 and for different AAFs in Fig. 5.

Relatively modest influence of CC scenario on impact results. The CC scenario modestly influenced the distribution of the environmental impacts by shifting the interquartile ranges but without modifying the aircraft configuration ranking analyzed in Section 3.1 (cf. Fig. 2). Considering the CC trajectories in the order of increasing temperature increase (PkBudg500, NDC, Base), the impacts tend to reduce for each configuration. The comparative advantage of hybridization increased when the CC mitigation improved from the pessimistic to the baseline scenario, as the difference in EQ and HH damage between hybrid-electric and conventional aircraft configurations increased (Fig. 5). This is due to the electrification of the industry and the higher share of renewable energy in the electricity grid factored in the baseline scenario modeled in the premise database (Sacchi et al., 2022). However, the impact distribution between the baseline and optimistic CC scenarios remained similar. In the premise database, the renewable energy share in 2050 continues to increase from the baseline to the

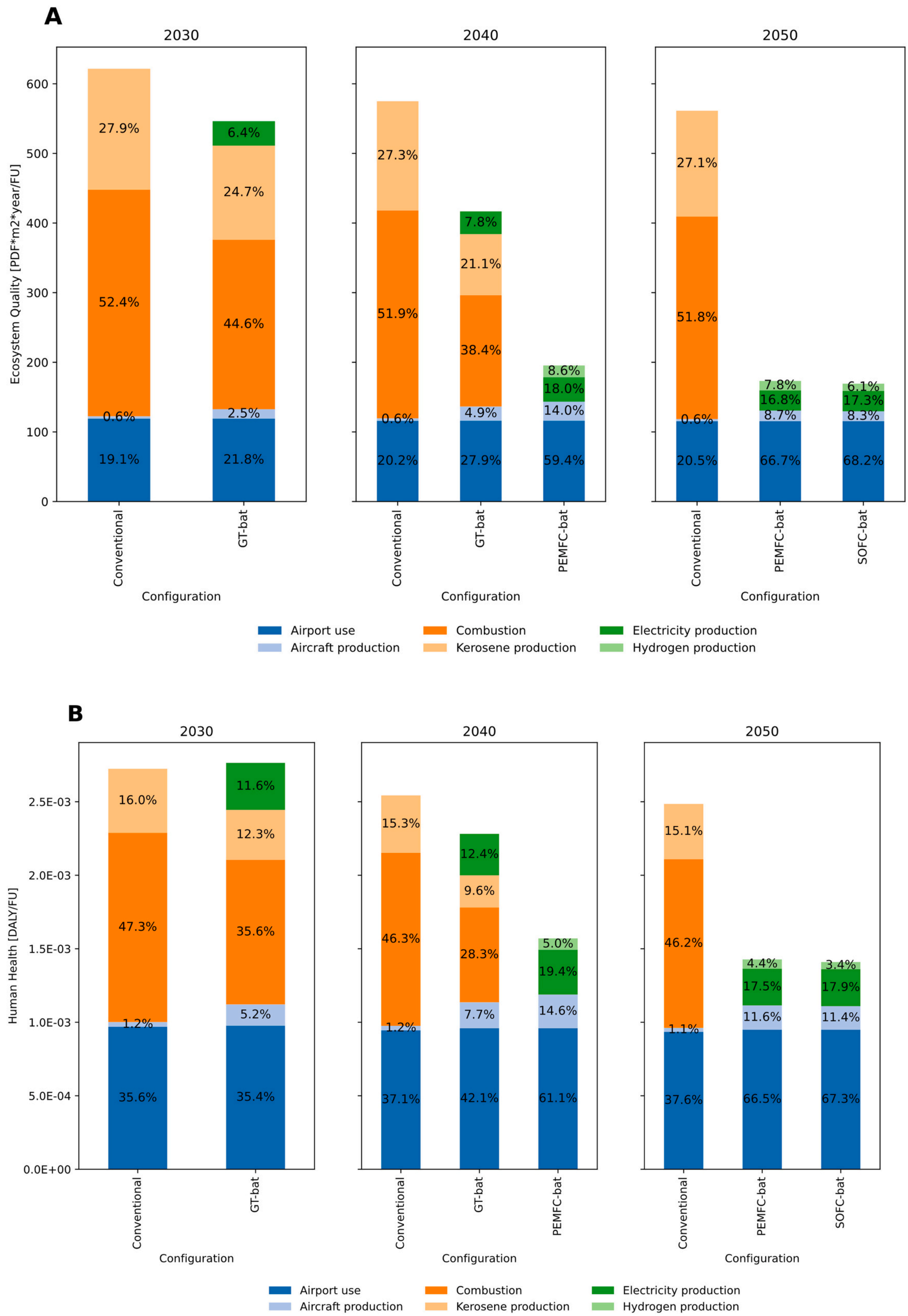

Fig. 4. Environmental impact contributions from different life cycle stages or elements of the aircraft system based on the baseline scenario and deterministic results for damages to A) ecosystem quality and B) human health. Results are based on deterministic values and are shown as absolute values with indications of the represented percentage on the bar plots. The deterministic results can be retrieved in Appendix B. Abbreviations: disability-adjusted life years (DALY), functional unit (FU), gas turbine with battery (bat) aircraft (GT-bat), potentially disappeared fraction of species (PDF), proton exchange membrane fuel cell and battery (PEMFC-bat), solid oxide fuel cell and battery (SOFC-bat).

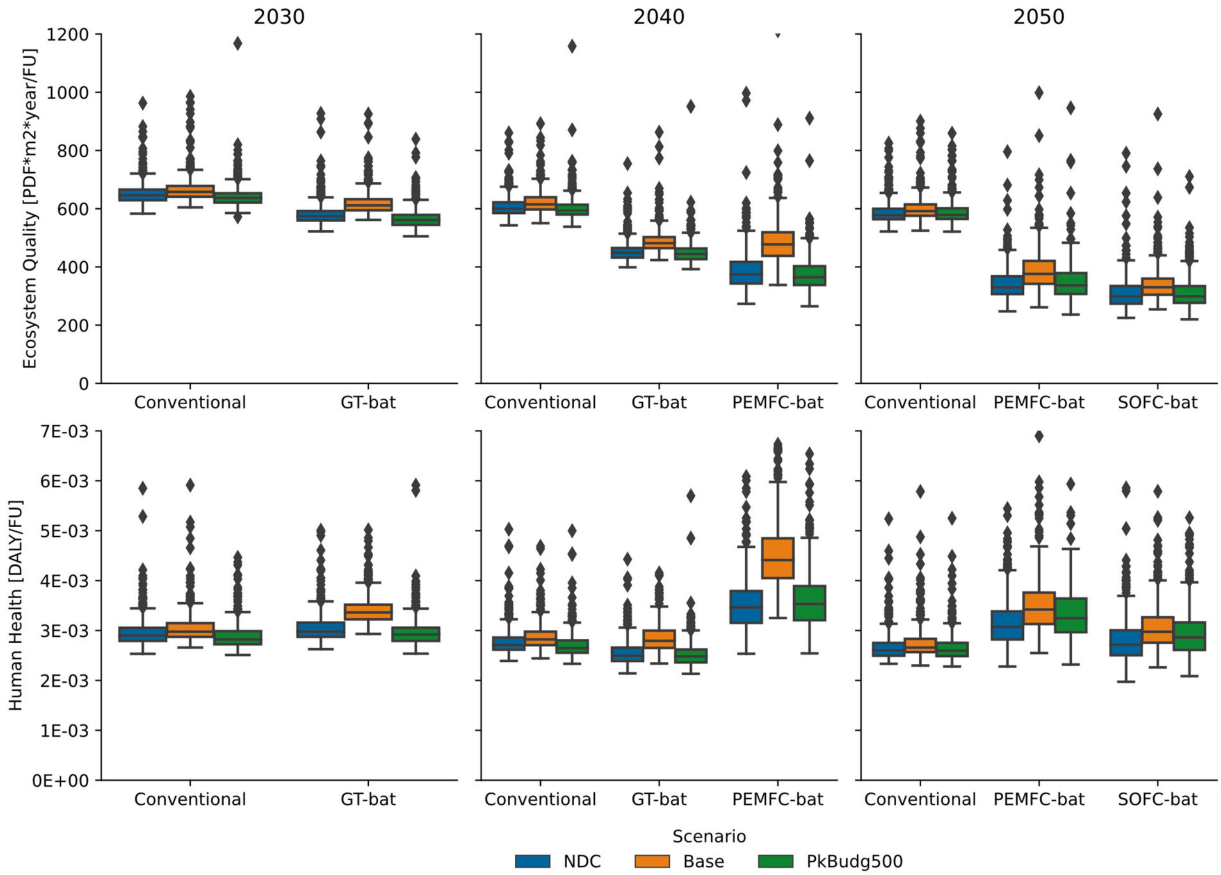

Fig. 5. Sensitivity analysis of environmental impact assessment results (damages to ecosystems quality and human health) for all tested regional aircraft configurations and time horizons considering three different SSP2 scenarios: NDC (baseline scenario), Base (pessimistic climate change (CC) scenario), and PkBudg500 (optimistic CC scenario). The boxplots represent the distributions for each configuration obtained via Monte Carlo analysis ($n = 500$, seed =35). Y-axis ranges were limited for visibility reasons to [0,1200] and [0, 7×10^{-3}] respectively for ecosystem quality and human health. The same figure including all outliers is shown in Appendix A Fig. A.2, and all Monte Carlo results can be retrieved from the Appendix B. Additional abbreviations: disability-adjusted life years (DALY), functional unit (FU), gas turbine with battery (bat) aircraft (GT-bat), potentially disappeared fraction of species (PDF), proton exchange membrane fuel cell and battery (PEMFC-bat), solid oxide fuel cell and battery (SOFC-bat).

optimistic CC scenario; however, the CC impact reduction is associated with an increase in other impacts such as land use, ionizing radiation, ozone depletion, and terrestrial ecotoxicity (Sacchi et al., 2022). This is observed in Fig. 3 with a decrease in climate change and increased land use impacts in the ecosystem quality damage.

AAF overall does not show environmental benefits. As illustrated in Fig. 6, scenarios with AAF caused the greatest damages to human health and ecosystems quality in all time horizons and configurations, except for the GT-bat with AAF, which had overlapping impact distribution with the PEMFC-bat configuration. While the substitution of kerosene by AAF supports the decrease of CC impacts, it leads to increases in other relevant environmental impacts like water scarcity or land occupation (see Appendix B). The palm fruit cultivation and, to a lesser extent, the syngas production are thus the key drivers for impacts from AAF production, particularly water use and land use impacts, which counter-balanced the reductions in CC impacts when assessing environmental damages. When factoring in the ILUC, the use of AAF was logically found to yield even larger environmental impacts due to the additional CO_2 emissions resulting from the increase in agricultural land demand to sustain palm oil for food systems (see Fig. 6) (Schmidt and De Rosa, 2020). This result is aligned with AAF studies focused exclusively on CC, which found higher impacts for AAF, which were first-generation biofuels derived from food crops (Kolosz et al., 2020; Prussi et al., 2021; Zhao et al., 2021). Given the weight of feedstock cultivation in the total environmental impacts, these findings call for revoking AAF derived from food crops and recently converted land from the list of potentially sustainable aviation fuel alternatives to kerosene in international frameworks such as CORSIA (ICAO, 2021; Prussi et al., 2021), even when the blend includes a large share (28 %) of low-carbon electro-fuel as in the long-term time horizon (see Fig. 6). More promising environmental impact results might be achieved using AAF derived from urban, agricultural, and oil wastes (HEFA-SPK and FT processes) since their generation could be considered burden-free (Baumeister and Leung, 2021; Su-ungkavatin et al., 2023). However, the restricted availability of such feedstock calls into question the viability of using AAF at a large scale (Ueckerdt et al., 2021), especially when considering that hybridization yields better environmental performance.

Environmental benefits of hybridization remain with longer mission. The environmental impacts of the different aircraft configurations were simulated for a longer mission of 600 nmi. (see Fig. A.4 in Appendix A). The ranking of the configurations noted in Section 3.1 remains unchanged. The benefits of the hybrid-electric aircraft over the conventional one for EQ damages were larger than for shorter missions, and so was the increased HH damages. For longer missions, due to a longer cruise phase, the effect of the kerosene substitution by electricity and hydrogen is stronger than for shorter ones. These results, therefore, suggest that hybridization is worthwhile to reduce environmental impacts for any mission between 200 and 600 nmi as long as human health damages are mitigated (see Section 3.1).

Global sensitivity analysis. Following the results of the global sensitivity analysis (results can be retrieved from Appendix B), conducted in accordance with Cucurachi et al. (2022), only sensitive

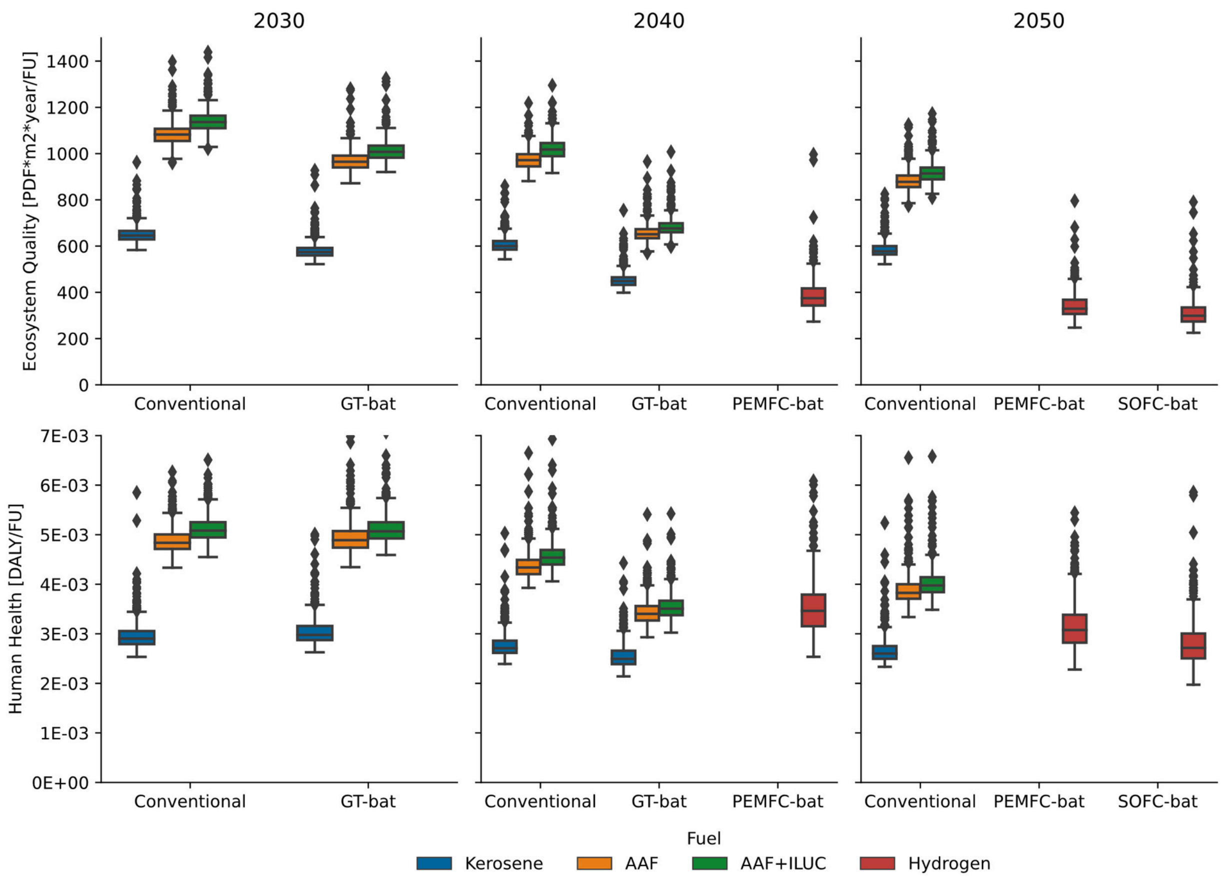

Fig. 6. Sensitivity analysis of environmental impact assessment results (damages to ecosystems quality and human health) for all regional aircraft configurations and time horizons considering substitution of kerosene by alternative aviation fuel (AAF) with and without indirect land use change (ILUC) considerations. The boxplots represent the distributions for each configuration obtained via Monte Carlo analysis ($n = 500$, seed =35). Y-axis ranges were limited for visibility reasons to [0, 1500] and [0, 7E^{-3}] respectively for ecosystem quality and human health. The same figure including all outliers is shown in the Appendix A Fig. A.3, and all Monte Carlo results can be retrieved from the Appendix B. Additional abbreviations: disability-adjusted life years (DALY), functional unit (FU), potentially disappeared fraction of species (PDF), proton exchange membrane fuel cell and battery (PEMFC-bat), solid oxide fuel cell and battery (SOFC-bat).

contributors ($\delta \geq 0.1$) are identified for the conventional aircraft configurations when considering the impacts on EQ and HH. It is apparent that the treatment of solid waste from terminals, direct CO_2 emission during fuel combustion, tap water production for use in airports, and kerosene production are sensitive coefficients in the analysis. In order to reduce uncertainties, it is relevant to decrease uncertainty in the data collection of those activities.

3.4. Comparison with other modes of transport

Aligned with the current assessment, a typical regional aircraft mission corresponds to the transportation of 50 passengers over 370 km (equaling 18,520 passenger.km), which could be achieved in a reasonable time by train or road transportation in most regions. Modal substitution might not be possible everywhere, for instance, in remote areas, such as the north of Scandinavia, or where the rail and road infrastructure is insufficient. Nonetheless, for contextual purposes, the prospective environmental impacts of a typical mission, fulfilled by the different aircraft configurations evaluated in the current study or by alternative modes of transport, were assessed and compared; see results in Fig. 7. The assessment considered the supporting infrastructure and indirect impacts from electricity generation, including the prospective approach for the alternative mode of transport (rendered possible by the use of premise database (Sacchi et al., 2022)), which was selected as an average train in Italy (purely powered by electricity, based on a European electricity mix), an average global train (based on a weighted average of existing trains globally, out of which a share of 85 % is diesel-powered), and an average global coach (diesel-based average coach on a global scale). The methodological details behind these assessments and comparisons are available in Appendix A. As noted in Fig. 7, it is important to note that the comparisons made considering the FU may not be fully equivalent since aircraft can optimize traveling distances while train and road transportation modes are dependent on the topography and may be subject to larger distances when transporting passengers between two given points. Another consideration is the varying levels of technology forecast for the three transport modes. Technology was forecasted to different extents when comparing the aircraft processes established in this study with the ones taken from premise. Technology forecast variations are also present within premise itself (Sacchi et al., 2022). However, using this approach was deemed the most appropriate within the study.

Results in Fig. 7 indicate that traveling with a conventional or a GT-bat aircraft fueled by AAF is associated with similar CC impacts to when traveling via a coach or a high-speed diesel train in the short-term. However, the lowest CC impacts remain by electric trains, provided that the electricity grid mix relies on renewables and is associated with low GHG emissions. For instance, the Italian train relies on a grid mix that embeds a GHG emission intensity of 43 gCO_2-eq/kWh (compared to the 293 gCO_2-eq/kWh for the global average) and is associated with 2–3 times lower GHG emissions than AAF-fueled aircraft in the short-term (ca. 5–6 times for conventional aircraft).

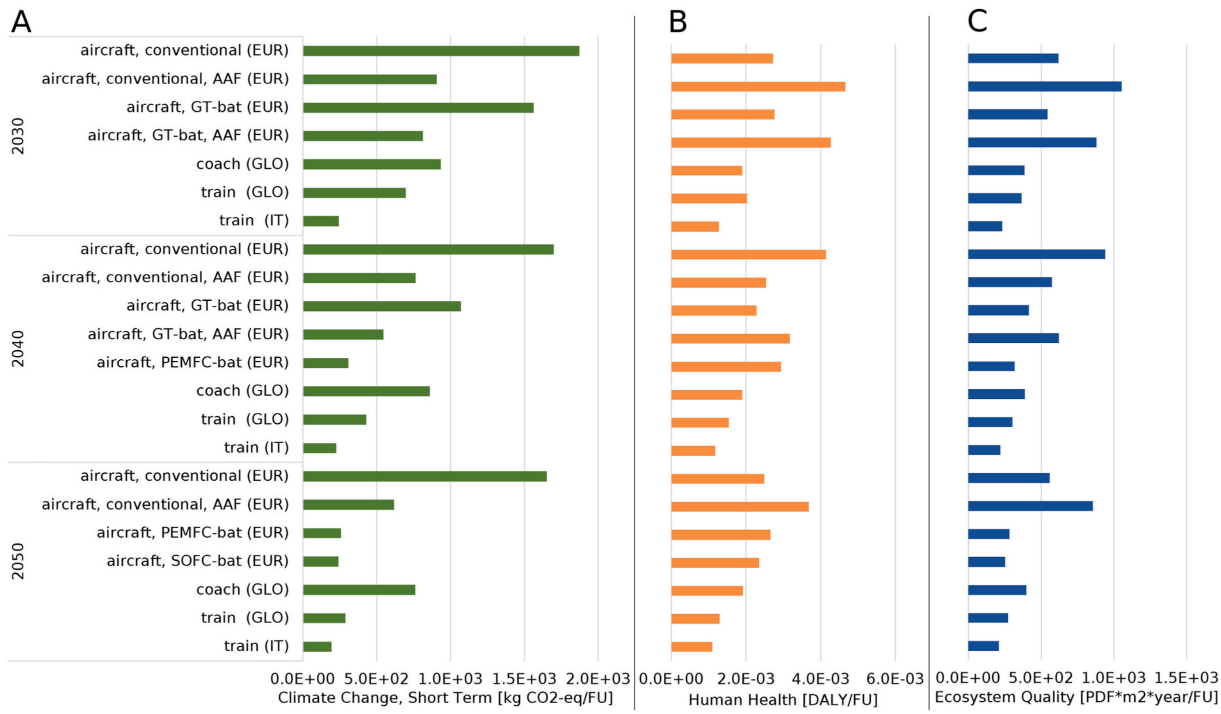

Fig. 7. Environmental impact indicator results for A) climate change impacts, B) total human health damages, and C) total ecosystem quality damages from the transportation of 50 passengers over the distance of the typical mission (200 nmi) with different modes of transport (taken as functional unit, FU). Abbreviations: alternative aviation fuel (AAF), disability-adjusted life years (DALY), European Union (EUR), gas turbine with battery (bat) aircraft (GT-bat), global average (GLO), Italy (IT), potentially disappeared fraction of species (PDF), proton exchange membrane fuel cell and battery (PEMFC-bat), solid-oxide fuel cell and battery (SOFC-bat). Note that the comparisons across different transport modes are indicative and do not consider the possible differences in distances effectively traveled to fulfill a service of being transported from point A to point B (e.g., due to topography constraints).

Interestingly, the medium- and long-term perspectives may change the relative environmental burden of the regional hybrid aircraft compared to trains and coaches. In the medium-term, hybrid-electric aircraft (PEMFC-bat, GT-bat with AAF) performed better than coaches but retained higher environmental impacts than trains. In the long-term, hydrogen-driven aircraft (PEMFC-bat, SOFC-bat) showed competitive CC impacts compared to trains and coaches.

However, when looking at a broader spectrum of environmental problems and assessing EQ and HH damages, trains and coaches still performed environmentally better than hybrid-electric aircraft (Fig. 7B). It should be noted that the total EQ damages of hydrogen-driven aircraft are comparable to those of trains in the long-term perspective, in contrast to the results for total HH damage, where aircraft still retain high impact values (see Section 3.1). Similar results are obtained for the design mission with a flight length of 600 nmi (cf. Appendix A for detailed results).

From this rough comparison, the conclusion favoring rail is consistent with the literature quantifying the direct GHG emissions of rail and air transportation substitution, although the relative impact difference between the transportation modes can be reduced in a long-term perspective. As indicated in previous sections, an important focus should lie on reducing the human health damages from future hybrid-electric aircraft; addressing this aspect may render some aircraft configurations competitive with other modes of transport in specific contexts. As noted above, the above comparison is made in a general way, without considering an actual specific transport service between two points, and it did not consider the passenger shift between the modes of transport and their complementarities (Baumeister and Leung, 2021). Hence, although the overall trend is not expected to change, unlocking hybrid-electric aircraft configurations, as assessed in the current study, may bring regional aircraft to be competitive in cases where it is not at present.

3.5. *Limitations*

Although the study provided unprecedented prospective modeling of the environmental impacts of regional aviation that can support robust results, several methodological limitations should be highlighted and be the source of further research.

The uncertainty analysis only included the quality of the LCI data, the CC background scenario (e.g., influencing the electricity grid mix), and the ILUC modeling. The uncertainty of the background database and the uncertainty of the LCIA method were not included (Chen et al., 2021; Huijbregts, 1998; Huijbregts et al., 2001). To implement this, information on the uncertainty of the prospective LCI datasets and the characterization factors is needed. Climate non-CO_2 effects of, e.g. water vapor, have not been studied as the GWP of water vapor in lower altitudes (regional airliners usually fly below 12,000 km) seem to be negligible as reported in Fuglestvedt et al. (2010). However, these GWPs are associated with high uncertainty.

The conclusions are valid for the regional aircraft class, as the model is based on the reference aircraft ATR42. Moreover, the hybrid-electric aircraft configurations in scope are technically viable for routes up to approximately 600 nmi (Rupcic et al., 2023). Globally, different classes of aircraft served journeys up to 600 nmi, with narrow-body aircraft representing 65 %, regional jets 14 %, and widebody aircraft 7 % of the CO_2 emissions in 2019 (Aviation Week Network, 2023). Therefore, the potential GHG abatement obtained by substituting conventional aircraft with hybrid-electric aircraft at the global fleet scale is limited (Epstein and O'Flarity, 2019). Future research could investigate the technical feasibility and the environmental impacts of hybridization for narrow-body aircraft.

Other AAF feedstock and conversion routes should be explored to assess further the impacts of drop-in fuels. AAF blends have been restricted to fuels whose production processes were available in premise, i.e., first-generation biofuel (HEFA-SPK from palm oil) and FT e-fuels from direct air capture and hydrogen from wood gasification and electrolysis. Second-generation AAF from waste such as used oils or energy crops could yield a different result than the ones presented in Section 3.1. For this, new, forward-looking LCI datasets are needed. Moreover, the ILUC scenarios only included the effect of food crop displacement in terms of CO_2, while the land occupation and transformation displacement were not modeled. Therefore, the ILUC scenario only partially reflects the impacts of indirect land use, and the damage is underestimated.

4. Recommendations for policy- and decision-making in the aviation sector

The prospective LCA performed in the current study enables to draw recommendations to aviation stakeholders, airport managers, and transport policy-makers for fostering a more sustainable regional aviation and enhancing the relevance of sustainability assessments applied to aviation. These are summarized in the following:

- *Echoing the lack of consistent and broadly encompassing study in literature, aviation stakeholders, including industry and policy-makers, should broaden the scope of the ambitions associated with the environmental sustainability of future aircraft.* As demonstrated in the current study, climate change is a key driver to damages to human health and ecosystems quality. However, it is essential that the large spectrum of environmental problems, beyond climate change, is addressed and integrated into policy-making and sustainability targets, thus covering relevant aspects like biodiversity losses and chemical pollution (Hellweg et al., 2023). In the current assessment, climate change, respiratory impacts from particulate matter, mineral resource use, water use, land use, terrestrial acidification, and toxicity impacts from chemical releases are key environmental problems to consider in future LCA studies of aircraft systems.
- *While the environmental relevance of the aircraft flight operations decreases over time, that of other activities in the aircraft life cycle becomes predominant, particularly in relation to airport operations and aircraft manufacturing.* Water use and land use impacts from airports were thus found to contribute to nearly half of the total damages to human health or ecosystems quality for hydrogen-based aircraft, and several other impacts (e.g., toxicity of chemical releases on ecosystems and human health) were driven by the airport construction stage, stemming from electricity embedded in building materials or metals (copper, aluminum) extraction and processing. Likewise, aircraft manufacturing is expected to become increasingly environmentally relevant because of the increasing demand for emerging technologies, like batteries or fuel cells, which are found to be impact-intensive. Such identified trends, therefore, call for initiatives within the aviation sector to target those specific systems. For example, the integration of ecodesign measures could be strengthened, including when addressing emerging technologies, e.g., optimizing production and recycling of particular elements, like batteries or fuel cells, improving buy-to-fly ratios for key materials in production, etc. With regard to airports, implementation of sustainability actions should be facilitated; circular economy initiatives targeting material efficiency, circularity of building materials, and direct water use reduction (or recirculation) could thus be streamlined to support airports in decreasing their environmental footprints in the medium- and long-term.
- *Out of the tested aircraft configurations, the assessment shows that adopting hybrid-electric aircraft technologies while phasing out kerosene can bring potentially important environmental benefits to short-range aviation.* Overall, hybridization could reduce between 15 % (GT-bat in the short-term) and 83 % (H_2 aircraft in the long-term) the damages to ecosystems quality and human health from climate change. In the medium- and long-term, hydrogen aircraft appeared as the preferred technological track among the analyzed aircraft configurations, provided their human health damages are mitigated. Reducing these damages may be achieved by tackling impacts from water consumption, particulate matter, and chemical releases primarily stemming from the large energy and water demand in hydrogen production. The design and development of these technological configurations, along with their further improvement potentials, should therefore be prioritized when addressing the transition of regional aviation towards more sustainability.
- *The assessed AAF, particularly those derived from food crops in blend with electro-fuels, did not appear as an environmentally viable solution to substitute kerosene, leading in some cases to increased environmental impacts.* This calls into question current schemes regarding the so-called sustainable aviation fuels (SAF), for which revisions may be warranted. Existing incentives for AAF development, e.g., EU SAF mandates and carbon offsetting and reduction schemes for international aviation (CORSIA), should thus carefully expand the defined sustainability criteria to avoid shifting the environmental burden from climate change to other impact categories, such as land use or water use, or simply prevent inadvertent increase of climate change impacts (e.g., first-generation biofuels). Ignoring such recommendations runs the risk of diverting investments to unsustainable AAF systems, away from more relevant alternatives to develop, like hydrogen propulsion (ICAO, 2021). To reframe AAF development, restrictions in terms of feedstock types may be useful to account for the variability of AAF environmental performances, e.g., banning food-crop feedstock and prioritizing AAF derived from waste or residue materials. Given the limited availability of AAF associated with acceptable environmental performances, a prioritization within the aviation sector could be developed. In such a setting, acceptable AAFs should be routed to hard-to-abate segments, where there is little or no alternative to AAF, such as long-haul aviation (Ueckerdt et al., 2021).
- *The competitiveness of regional aviation relative to other transport modes like electric trains may occur in specific situations and under conditions that further reductions in specific environmental damages (*e.g., *human health) are addressed.* In the long-term perspective, pending additional efforts to lower specific impacts, the hydrogen-based regional aircraft could bring the environmental performances of regional air transport to a sufficiently low level that may become a relevant alternative to road or electric rail transportation in specific cases. Competitive air transport may thus occur in areas with topographical constraints, for example, where flying would allow a direct route instead of a convoluted route that would embed larger environmental impacts by road, train, or ferry (e.g., traveling over ecosystems preserved areas, areas with relief, etc.).

5. Conclusions and outlook

A prospective LCA was performed to identify environmentally preferable regional aircraft configurations in 2030, 2040, and 2050. The environmental impacts of flying with conventional aircraft were compared to those of various hybrid-electric aircraft configurations employing emerging technologies of batteries and fuel cells. The impacts of the fuel systems, including AAF, kerosene, and electricity, and the impacts of the airport systems were included as part of the aircraft life cycle system and were thus analyzed. The uncertainty introduced by the LCI data quality, climate change scenarios, and AAF modeling choices were analyzed to gauge the robustness of the conclusions.

In the long-term perspective, the hybrid-electric aircraft configuration using fuel cells and hydrogen as fuel appeared promising, provided that the high impacts obtained for human health damages are mitigated. Improvement potentials could come from gains in energy and water efficiency in the hydrogen supply chain and in the airport operations, from strengthening building material circularity in the airport construction, and from developing further the ecodesign of the fuel cells. In contrast to the promising hydrogen-based technologies, the assessed

AAFs were found to reduce CC impacts at the cost of greater damage to human health and ecosystems quality. Hence, the assessed drop-in fuels were not identified as sustainable solutions for short-range flights. In the short- and medium-term, hybridization with Li-ion and Li—S batteries may be regarded as transitioning solutions towards commercial hydrogen aircraft, but alternative modes of transport for trips up to 600 nmi generally caused less environmental impacts than flying (per passenger-kilometer traveled). Based on these findings, a number of recommendations were developed for policymakers and aviation stakeholders at large. A major one is to invite these decision-makers to prioritize efforts on securing the viability of hydrogen aircraft, additionally supporting the technological development of green hydrogen production.

Across the assessment performed in the study, climate change impacts were found to be insufficient to represent the environmental burden of regional aviation as other relevant environmental problems were identified with large contributions to this burden, including water use, land use, toxicity of chemical releases on human health and ecosystems, respiratory impacts from particulate matter and mineral resource use. This calls for including a large array of environmental impact categories into future environmental assessments of aviation systems. Going beyond the current assessment, more research is needed to conduct a similar evaluation of environmental impacts in other segments of the aviation sector, in particular for the long-haul flights that are responsible for a large share of total GHG and air pollutant emissions globally. The current study and its prospective LCI/LCA approach should thus be used as a starting point, and could potentially be expanded to benchmark the results against sustainability goals, like those of the Paris Agreement or the ones set by the International Civil Aviation Organization.

CRediT authorship contribution statement

Nils Thonemann: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation and data curation, Writing original draft, Writing review and editing, Visualizations, Supervision, Project administration **Eleonore Pierrat:** Conceptualization, Methodology, Validation, Formal analysis, Investigation and data curation, Writing original draft, Writing review and editing, Visualizations, Supervision, Project administration **Katarzyna Maria Dudka:** Methodology, Software, Validation, Formal analysis, Investigation and data curation, Writing original draft, Writing review and editing, Visualizations **Karen Saavedra-Rubio:** Conceptualization, Investigation and data curation **Anna Lia S Tromer Dragsdahl:** Investigation and data curation, Writing original draft, Writing review and editing, Visualizations **Alexis Laurent:** Conceptualization, Writing review and editing, Supervision, Project administration, Funding.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

All data, the code used to produce the results, the uncertainty analysis, and the figures are available on a GitHub repository (Thonemann and Dudka, 2023) https://zenodo.org/record/8250228.

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Appendecies. Supplementary data

Appendix A contains additional figures, tables, and method explanations, and Appendix B contains five result files in an Excel format. Additionally, all data, the code used to produce the results, the uncertainty analysis, and the figures are available on GitHub repository https://zenodo.org/record/8250228. Supplementary data to this article can be found online at https://doi.org/10.1016/j.spc.2024.01.013.

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