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Environmental impacts in the civil aviation sector: Current state and guidance

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ABSTRACT

The aviation sector contributes to environmental problems like climate change, resource depletion, and air pollution. We perform a systematic literature review of life cycle assessment studies to map the environmental impacts in the sector and provide methodological recommendations. The sector is divided into cross-cutting systems, namely aircraft, fuel and propulsion systems, and airports. Our review results confirm the sector's focus on climate change impacts. The mitigation strategies rely mostly on reducing CO_2 emissions during aircraft operations, like implementing sustainable aviation fuels and prospective technologies or decreasing aircraft weight with lightweight components. We use review analyses to identify and discuss knowledge gaps, such as the assessment of noise impacts or non-CO_2 flight emissions. Finally, aviation-specific recommendations are provided to LCA practitioners and aviation stakeholders with respect to data transparency and harmonization of results. Research needs, such as the development of characterization factors, are recommended to developers of life cycle impact assessment methods.

1. Introduction

Global aviation contributes to climate change through various activities, in particular, the aircraft operations stemming from burning fossil fuels in aircraft engines on-ground or in the upper troposphere (Lee et al., 2021). The gases and particles emitted directly at those levels, such as carbon dioxide (CO_2), nitrogen oxides (NO_x), soot, and sulfate aerosols, alter the chemical composition of the atmosphere, hence leading to increased radiative forcing and contribute to climate change (Lee et al., 2021). Thus, aviation has been reported to emit 2.4% of all human-induced CO_2 emissions, accounting for 12% of total transportation emissions yearly and 4% of observed human-induced global warming today (Klöwer et al., 2021; Planès et al., 2021).

Hybrid and electric propulsion, as well as alternative aviation fuels (AAF), have gained significant attention over the last few years as they may provide ways to curb climate change impacts stemming from aviation and the reliance on fossil fuels (SRIA, 2020; ICAO, 2019a). Potential greenhouse gas (GHG) emission reductions of 25% and 63% by 2050 have been reported to be achievable through technological improvements, including electric propulsion (for short-haul flights) and fossil fuel substitution (Zaporozhets et al., 2020). Low-carbon synthetic kerosene can be used in long-haul flights and thus is expected to drive CO_2 emission reductions by 2050

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Nomenclature

Abbreviations

AAF	Alternative aviation fuels
AIC	Aviation induced cloudiness
APP	Aqueous phase processing
APU	Auxiliary power units
ASTM	American Society for Testing and Materials
ATJ	Alcohol to jet
BTF	Buy-to-fly
CC	Climate change
CFRP	Carbon-fiber-reinforced polymers
CHJ	Catalytic hydrothermolysis jet
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
EIO-LCA	Economic Input-Output Life Cycle Assessment
EQ	Ecosystem quality
FE	Freshwater eutrophication
FET	Freshwater ecotoxicity
FWC	Freshwater consumption
FT	Fischer-Tropsch
FD	Fossil depletion
FPMF	Fine Particulate Matter Formation
FAA	Federal Aviation Administration
GAV	Ground access vehicles
GHG	Greenhouse gas
GSE	Ground service equipment
HC	Hydrocarbons
HDCJ	Hydrotreated depolymerized cellulosic jet
HEFA	Hydroprocessed esters and fatty acids
HH	Human health
HTL	Hydrothermal liquefaction
HTc	Human toxicity cancer
HTnc	Human toxicity non-cancer
HVAC	Heating, ventilation, and air conditioning
ICAO	International Civil Aviation Organization
IR	Ionizing radiation
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCIA	Life Cycle Impact Assessment
$\mathrm{LH_2}$	Liquefied hydrogen
LNG	Liquefied natural gas
LTO	Landing and take-off
LU	Land use
LUC	Land use change
LTAG	Long-term aspirational goal
ME	Marine eutrophication
MD	Metal depletion
MET	Marine ecotoxicity
MRO	Maintenance, repair, and overhaul
NR	Natural resources
PAHs	Polycyclic aromatic hydrocarbons
PED	Primary Energy Demand
PM	Particulate matter
POFe	Photochemical Ozone Formation ecosystems
POFhh	Photochemical Ozone Formation human health
SAF	Sustainable aviation fuels
SIP	Synthesized iso-paraffins
SOD	Stratospheric Ozone Depletion
STJ	Sugar to jet
TA	Terrestrial Acidification

TE	Terrestrial Ecotoxicity
UAV	Unmanned aerial vehicle
Units	
Pkm	passenger-kilometer representing the transport of one passenger by a defined mode of transport (road, rail, air, sea, inland waterways, etc.) over a distance of one kilometer
tkm	ton-kilometer representing the transport of one ton of freight by a defined mode of transport (road, rail, air, sea, inland waterways, etc.) over a distance of one kilometer
Wh/kg	Watt-hour per kilogram expressing the density of energy in batteries and capacitors
$W\ m^{-2}$	Watt per square meter (W/m^2 or $W\ m^{-2}$) expresses the intensity of radiation in watts over a square meter surface
gCO_2eq/kWh	grams of carbon dioxide equivalent per kilowatt-hour of electricity generated, reflecting the climate change impact intensity associated with electricity generation

(ICAO LTAG, 2022).

Besides its contribution to climate change during aircraft operations, the aviation sector is responsible for other environmental problems through the aircraft's supportive systems (e.g., airport and fuel production) and the rest of its value chain, for example, aircraft manufacturing and disposal. Noise pollution, scarce metal use (e.g., due to special alloys from cobalt or chromium), or toxicity impacts from released chemicals are examples of impacts that potentially cause damage to human health, ecosystems, and depletion of natural resources (Héroux et al., 2015; Rupcic et al., 2022). The growing demand for air transportation thus calls for an effective tool that can comprehensively quantify those environmental problems and help design solutions that enable environmentally sustainable growth in the air transportation sector.

Life cycle assessment (LCA) can be such a tool. It is an ISO-standardized (ISO 14044) and widely used methodology to quantify all relevant environmental and health impacts from goods or services occurring in their life cycle perspective, i.e., from raw materials extraction through manufacturing, use, and up to recycling and disposal (ISO, 2006). The methodology is iterative and includes four mandatory phases: goal and scope definition, life cycle inventory analysis (LCI), life cycle impact assessment (LCIA), and life cycle interpretation. Iterative loops of the phases ensure the accuracy of the systems model and processes (JRC-IES, 2010).

Several studies have tackled the environmental problems of the aviation sector and its systems, and a number of reviews have also been conducted in recent years (Calisir et al., 2020; Greer et al., 2020; Kolosz et al., 2020; Schmidt et al., 2018; Trevisan and Bordignon, 2020). Calisir et al. (2020) provided an overview of existing LCA studies on aircraft and its components, including unmanned aerial vehicles (UAVs), but excluded fuels and airports from their scope. The studies focused on AAF, generally through compiled carbon footprints. They, however, rarely addressed other environmental impacts and often disregarded several relevant fuel types or propulsion alternatives, like liquid hydrogen, battery systems, or power-to-liquid fuels (Kolosz et al., 2020; Schmidt et al., 2018). Greer et al. (2020) examined environmental sustainability metrics and methods applied to airports, although excluding the potentially relevant impacts from on-ground aircraft operations (e.g., taxiing) from their studies' scopes. Sector-scale studies have also been conducted, although they have focused on inventorying specific emissions like selected flows of air pollutants (SO_2, NO_x, CO, PM10) and GHGs for freight and passenger transportation in the US, without impact assessment (Chester and Horvath, 2009; Facanha and Horvath, 2007). Nevertheless, the sector-scale studies provided a perspective of the most influential contributors to total life cycle emissions of CO_2 and NO_x, with tailpipe emissions from fuel combustion being the main driver, followed by fuel production (Chester and Horvath, 2009; Facanha and Horvath, 2007). All these studies carry important limitations in scoping the aviation sector, often being too narrow to provide an overarching picture and/or, when addressing environmental problems, restricted to only evaluating climate change impacts. To enable a complete overview of environmental hotspots in the aviation sector that could provide relevant support to its stakeholders, a yet-missing coverage of all potential environmental problems across the entire sector's system life cycle is required.

To tackle this gap, we perform a comprehensive critical review of published LCA and other environmental studies conducted within civil aviation, where we aim to: (i) identify, critically evaluate, and discuss their main environmental findings and methodological practice; (ii) provide methodological guidance for LCA practitioners in their application of LCA to the civil aviation sector; and (iii) elaborate recommendations to stakeholders within the sector based on key learnings from the review. We adopted a multi-level approach to meet these objectives and address the sector comprehensively. After defining and categorizing the civil aviation sector in Section 2, Section 3 summarizes the review approach. Results of the review are presented in Sections 4-7, with report findings for each scoped system, complemented by recommendations to stakeholders in the field in Section 8.

2. Scoping of the civil aviation sector

The civil aviation sector can be divided into three overarching systems, namely (i) aircraft, (ii) fuels, and (iii) airports. Each system can be assessed individually, with different life cycle perspectives (i.e., cradle-to-gate and cradle-to-grave, Fig. 1A) and life cycle stages (e.g., operation) as shown in Fig. 1B. In the following subsections, the scoping of each system is addressed, detailing the respective life cycle stages and different interactions the systems have with each other. In the use/operation stage, the systems cannot be mutually excluded due to their strong interactions and dependence on each other, see Fig. 1B.

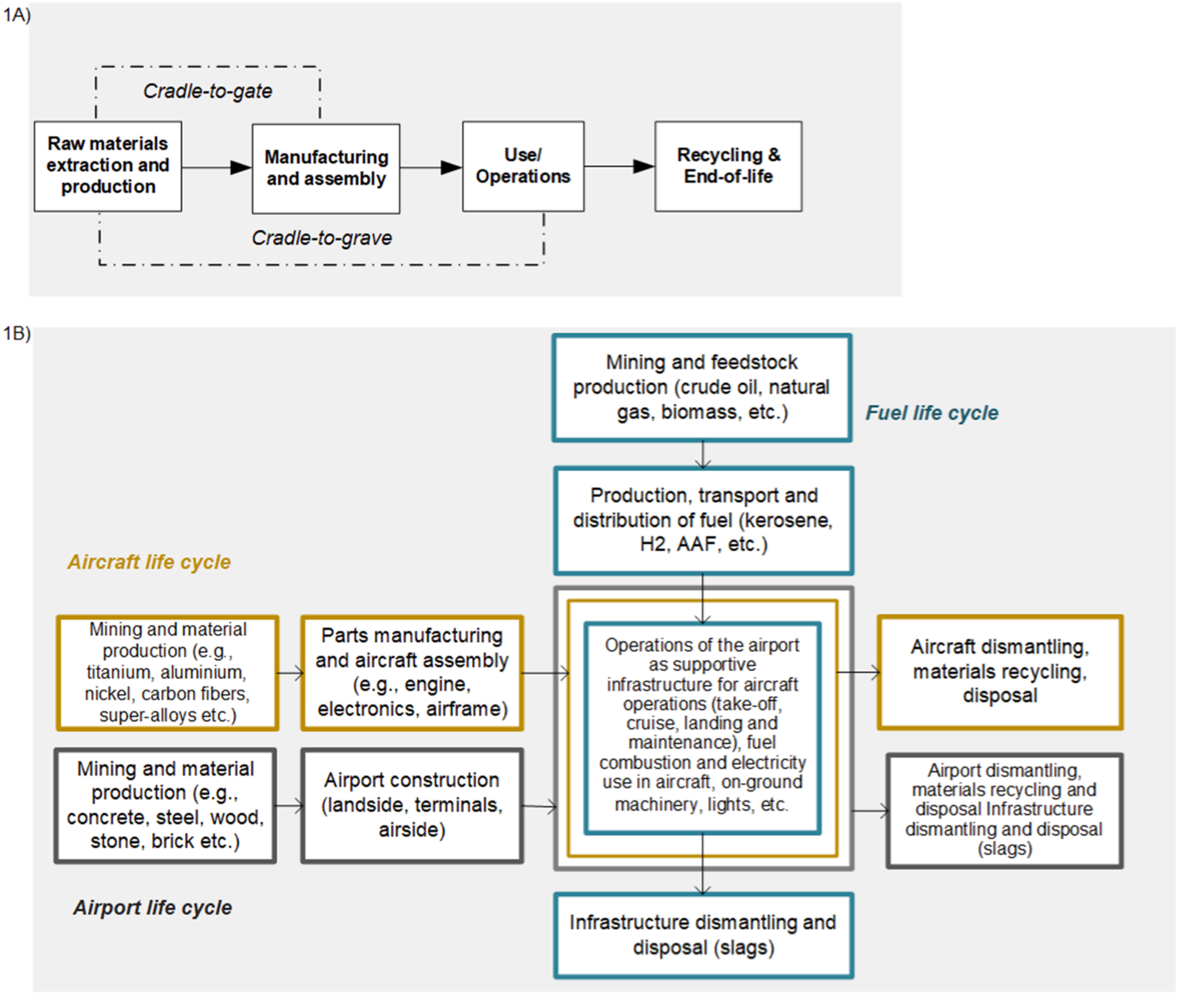

Fig. 1. Detailed overview of the civil aviation sector and its systems; life cycle stages with cradle-to-gate and -grave perspectives (A), and detailed representation of the life cycle of each system with an illustrative example of the interactions and dependencies between the systems, e.g., the operational stage in which aircraft, airport, and fuel systems overlap (B). The color coding represents the three aviation sector systems: yellow for aircraft, blue for fuel and electricity, and grey for airport systems. Note that fuel and electricity are used in all life cycle stages of both aircraft and airport systems, but here we highlight the cross-cutting aspects during the operations due to fuel combustion.

2.1. *Aircraft system*

Aircraft can be classified between the lighter-than-air (balloon, airship) and heavier-than-air aircraft (airplane, rotorcraft, ornithopter, glider, kite) (ICAO, 2003). Table S1 in Appendix A shows an overall aircraft classification by modes, such as speed, engine, wings, and payload.

The life cycle of an aircraft starts with the raw material stage, which accounts for mining different raw materials and producing intermediate products like super alloys (see boxes marked in dark grey in Fig. 1B). The machining of the aircraft components (blisks for turbofan engines, seats for the interior, navigation systems, etc.), their transport, and the final aircraft assembly are part of the manufacturing stage. Following the differentiation done by Pierrat et al. (2021), component processing can be divided into four modules: electronics, systems (auxiliary power unit, fluids and waste, interiors, etc.), engines, and airframes. The manufacturing stage ends with a fully tested and assembled aircraft ready for use or operation. The operations/use stage of an aircraft can be roughly divided into two parts: i) the flight mission and ii) the maintenance, repair, and overhaul (MRO). The flight mission profile includes numerous phases, which can be defined with different levels of detail; it covers the taxi-out, takeoff, climb, cruise, descent, landing, and taxi-in. The taxi-out and -in, together with landing and takeoff under 914 m (3,000 ft) are often regrouped within the landing and take-off (LTO) cycle (ICAO, 2010). The aircraft MRO includes all activities performed during the operational stage to ensure the continued airworthiness and safety of the aircraft. MRO includes light maintenance (e.g., daily checks before departure, routine inspections) and heavy maintenance (e.g., engine and system wear checks and repairs, major defect rectification, technology upgrade, etc.) (SKYbrary, 2022). A number of external activities that support the flight missions and MRO should also be considered as cross-cutting elements, including on-ground infrastructures, on-ground energy supply systems, etc. At the end of their lifetime (typically above 30 years), civil aircraft enter the “recycling and end-of-life” stage, where they are decommissioned with specific parts being recycled while others undergo other waste treatment options (incineration or landfill). Conventional aircraft and all-electric/hybrid propulsions share similar structures but differ in fuel storage and propulsion systems. Due to the system boundaries defined in the reviewed studies, and the comparison with other fuels, we clustered the LCAs of electric and hybrid-electric aircraft and alternative aviation fuels.

2.2. *Alternative aviation fuels and propulsion systems*

Electric propulsion supplies power and thrust to the aircraft with electric motors driven by a generator, itself supplied by liquid/gaseous fuels (e.g., kerosene or hydrogen) and/or batteries. As illustrated in Fig. 2, three main architectures are typically considered: hybrid-electric (with a battery system, mounted in series or parallel), turboelectric (without battery), and all-electric (batteries only) (Epstein and O’Flarity, 2019; Schäfer et al., 2019; Zaporozhets et al., 2020). Promising liquid fuels for hybrid designs are compressed or liquefied natural gas (LNG) and compressed or liquefied hydrogen (LH_2) (SRIA, 2020). Nonetheless, these alternative technologies are incipient and are expected to be mature enough to enter the market by 2050 (SRIA, 2020).

AAF are categorized into drop-in fuels, e.g., synthetic or biofuels, and non-drop-in fuels, e.g., LNG or liquid and gaseous hydrogen (Perea-Moreno et al., 2022; SRIA, 2020). Non-drop-in fuels can be burned in a modified gas turbine and deliver power to the engine or be converted into electric energy in hybrid electric configurations (Fig. 2). Thus, needing modifications on the conventional propulsion system e.g., batteries, electric power train, and LH_2 requires specific cryogenic storage (SRIA, 2020).

The main advantage of drop-in fuels is that they have similar properties to petroleum derivates and are compatible with conventional propulsion systems. In the context of the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) programme, the International Civil Aviation Organization (ICAO) has defined criteria for all drop-in fuels produced after 2024 to frame Sustainable Aviation Fuels (SAF) based on quantitative GHG emissions reduction targets and qualitative guidelines related to land use, air quality, biodiversity, and water resources preservation (CORSIA, 2021; ICAO, 2022). Therefore, the SAF are a subset of drop-in AAF which meet the sustainability criteria. Until now, the main alternative jet fuels found in the literature (Fig. 3) include hydroprocessed esters and fatty acids (HEFA), hydrotreated depolymerized cellulosic jet (HDCJ), Fischer–Tropsch (FT) jet, hydrothermal liquefaction (HTL) jet, alcohol-to-jet (ATJ) fuel, sugar-to-jet (STJ) fuel also called synthesized *iso*-paraffins (SIP), and aqueous phase processing (APP) jet fuels. The latter can be considered as a secondary pathway to STJ fuel, catalytic hydrothermolysis jet (CHJ), co-processed HEFA, or FT jet (co-processing). Depending on the pathway, the blending percentage varies from 5% to 50% with conventional jet fuel (ICAO, 2021). Only HEFA, FT, ATJ, STJ, CHJ, and co-processing were approved by the American Society for Testing and Materials (ASTM) as of 2020 (ASTM, 2021). HEFA, FT, ATJ, and STJ have been flagged as sustainable alternatives (i.e., SAF) to jet fuel A. The production of drop-in AAF using the FT process requires a carbon source as input, such as fossil fuels (e.g., coal, natural gas), CO_2 captured from the atmosphere, municipal solid waste, or biomass (e.g., agricultural waste, vegetable oil, lignocellulosic biomass, herbaceous crops) (Schmidt et al., 2018). Most SAF production is expected to rely on biomass carbon sources (ICAO, 2021).

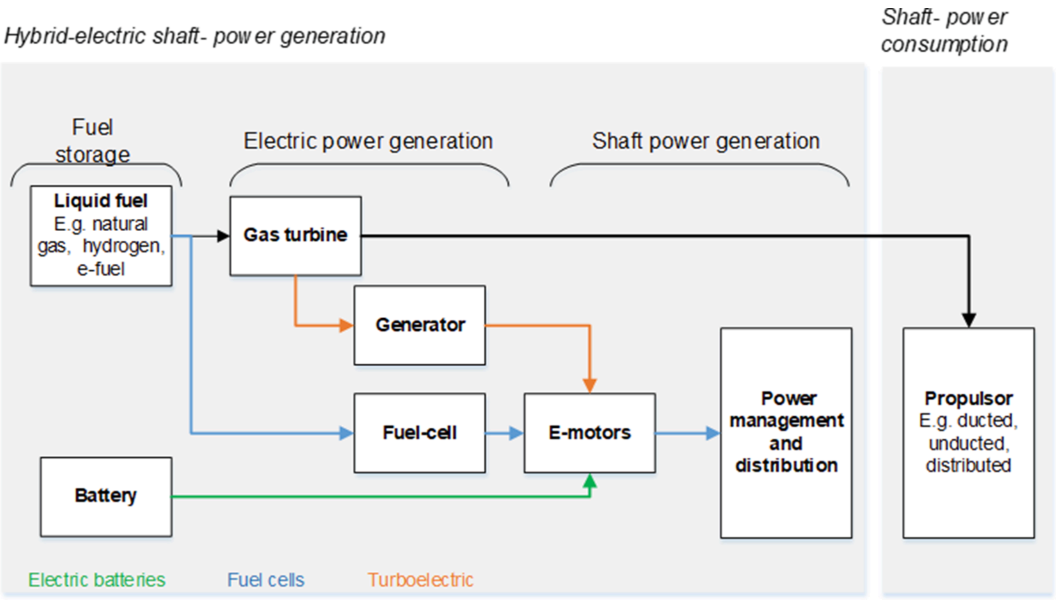

Fig. 2. Hybrid electric propulsion configurations (adapted from Pornet et al., 2015).

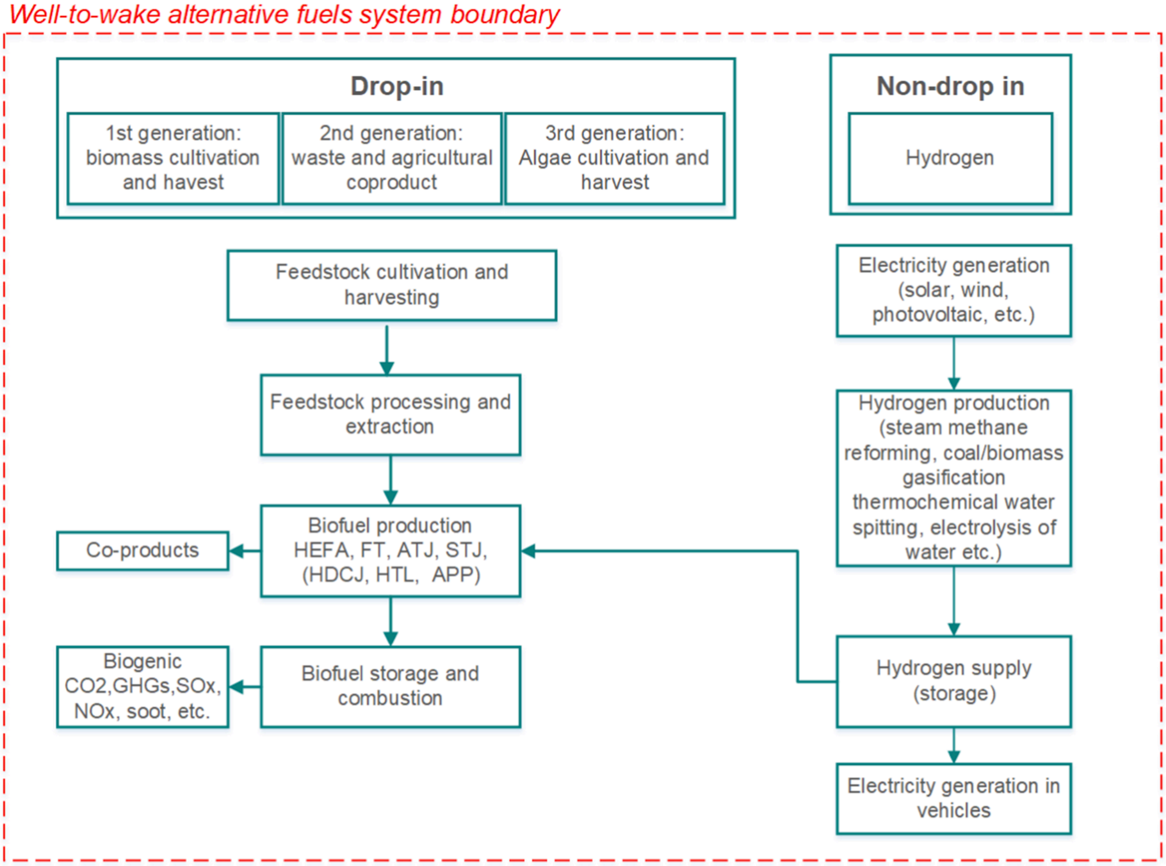

Fig. 3. Well-to-wake alternative aviation fuels system boundaries for drop-in fuels produced from different biomass sources and for hydrogen (taken as an example of non-drop-in fuels). Hydrogen can be used in biofuel production (i.e., dotted arrow), e.g., through the Fischer-Tropsch pathway, or directly, to power an electric motor or turbine in vehicles (vertical straight arrows). Acronyms: Hydro-processed esters and fatty acids (HEFA), hydrotreated depolymerized cellulosic jet (HDCJ), Fischer–Tropsch (FT) jet, hydrothermal liquefaction (HTL) jet, alcohol-to-jet (ATJ) fuel, sugar-to-jet (STJ) fuel also called synthesized *iso*-paraffins (SIP), and aqueous phase processing (APP) jet fuels.

2.3. Airport system

The airport’s life cycle can be seen in Fig. 1B. It is similar to that of a small city, where its production and end-of-life stages relate to the construction of the buildings and infrastructures (e.g., runaways) and their final decommissioning and waste management, respectively. The use stage includes the operation of the airport infrastructure and all the activities conducted in it and associated with the airport’s functioning, such as ground and airside operations. Typically airports can be divided into three main parts: landside, terminals, and airside – see Fig. 4 (Janic, 2011). The landside corresponds to all the infrastructure giving access to the airport and, if owned by the airport, can sometimes include activities such as energy generation and water and waste treatment (Greer et al., 2020). The terminals mainly receive and manage the flow of passengers, while the airside, which includes, for example, runways and taxiways, is delimited from the terminals by the presence of aircraft operation security protocols. Fuel supply can be part of the airside/landside, depending on whether or not it is owned or controlled by the airport. It is important to highlight that air traffic management systems, such as Terminal Radar Approach Control (TRACON), should be considered in the scope of the civil aviation sector if placed outside of the airport to account for its environmental contributions. However, it was disregarded in this review, assuming a small contribution compared to other systems.

3. Identification of LCA studies and review criteria

To find relevant literature, a systematic literature review (SLR) was conducted up till March 2022. Following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) approaches by Fink (2020) and Zumsteg et al. (2012), we divided the search terms into two different domains. The first domain focuses on environmental impact assessment and included keywords like “sustainability”, “life cycle assessment”, “LCA”, “life cycle impact assessment”, “LCIA”, or “environmental impact”. The second domain captures the civil aviation sector and its systems, covering the three main systems categorized in Section 2, i.e., aircraft, aviation fuels and propulsion systems, and airports. We excluded agriculture airplanes, rotorcrafts, lighter-than-air (LTA), private jets,

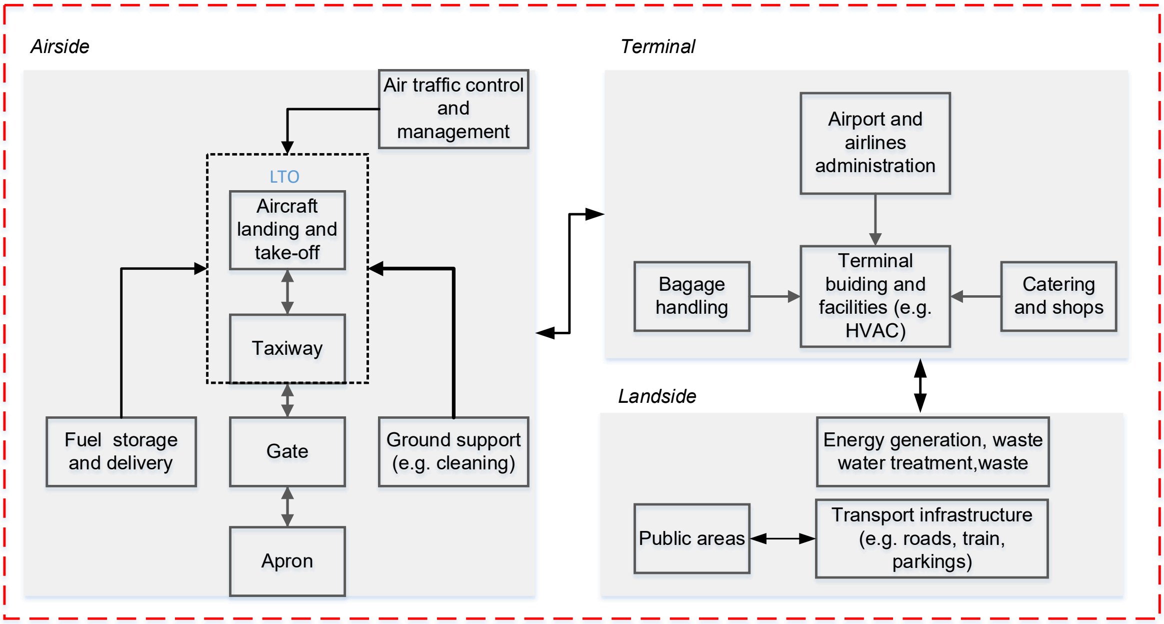

Fig. 4. Classification of the airport systems main elements, including airside, terminals, and landside. Acronyms: landing and take-off (LTO), heating, ventilation, and air conditioning (HVAC) (adapted from Greer et al., 2020; Janic, 2011).

and any kind of military aircraft (manned or unmanned). Unmanned aerial vehicles (UAVs) with civil applications were included and results are presented in Appendix A. A detailed overview of the keywords, temporal coverage, and type of studies considered for the current review can be found in Table S2, Appendix A.

Queries were made in the search engines Scopus (https://www.scopus.com/home.uri) and Google Scholar (https://scholar.google.com). In addition, bibliographies of selected literature were cross-checked to ensure maximal coverage. Due to the presence of many articles in the field of aviation fuels and propulsion systems, as well as in the domain of airports, the review was concentrated on recent peer-reviewed literature published after 2015, while literature prior to this date was captured through the consideration of existing critical reviews (Greer et al., 2020; Kolosz et al., 2020; Schmidt et al., 2018). A minimum criterion for inclusion of a study was that at least one impact category was assessed (e.g., climate change impacts expressed in equivalent mass unit of (CO_2eq.)). Studies presenting inventories of emissions and resources without an impact assessment (energy or individual flow of emissions of CO_2, CH_4, or NO_x,), including those in reports from aviation organizations (e.g., ICAO LTAG, 2022 feasibility report) were recognized as important contributions to discussion but were disregarded from the review of LCA studies. An exception to this rule was sector-scale assessments, where the lack of studies, including impact assessment, compelled the inclusion of studies looking into GHGs and air emissions only to substantiate the discussion (see Section 4). By following this approach, a total of 61 peer-reviewed scientific articles were retained. These are further described in Sections 4-7, and a full overview of the retained studies is documented in Appendix B.

4. Sector-scale environmental findings

No studies performing a full environmental impact assessment could be found at the scale of the entire aviation sector. The closest sector-scale studies to the criteria of the review are the studies which presented only selected emission flows of air pollutants (SO_2, NO_x, CO, PM10) and GHGs for freight and passenger transportation in the US (Chester and Horvath, 2009; Facanha and Horvath, 2007). They followed a hybrid approach using Input-Output (IO) analysis combined with LCA (EIO-LCA), albeit with no impact assessment. All life cycle stages were included, except for the end-of-life stage, which was disregarded due to a lack of data.

Selected air pollutants (SO_2, non-operational NO_x, and CO) have been reported to stem from direct (aircraft manufacturing) and indirect (extraction and refinement of copper and aluminim) electricity requirements. Activities such as fuel production, the use of diesel trucks to transport materials, aircraft manufacturing, and airport ground support equipment, have been found to cause 2.6–8.5 times higher CO ground emissions (30–180 mg/passenger-kilometer) compared to aircraft operation emissions (Chester and Horvath, 2009; Facanha and Horvath, 2007). However, values for those emissions should be considered with caution. Since the documentation of this data, the efficiency of internal combustion engines and the availability of cleaner fuels (e.g., low-sulphur diesel) are expected to have increased (CLEC, 2019).

Considering these studies, at the sector level, up to 94% of total life cycle emissions of CO_2 and NO_x were found to be dominated by tailpipe emissions from direct fuel combustion, both in freight and passenger transport. Fuel production is shown as the second largest contributor to total emissions, followed by vehicle and infrastructure construction and operation (Chester and Horvath, 2009; Facanha and Horvath, 2007). Airport infrastructure and ground operations have been found to account for the smallest share of GHG emissions

(3%) of all GHGs per passenger kilometer (pkm) or tonne-kilometer (tkm) for cargo (Chester, 2008; Facanha and Horvath, 2007). It is worth noting that the aforementioned studies have focused on the aviation sector within the US. Hence, their results may be different in other countries, e.g., by a different electricity grid mix supporting manufacturing processes.

In studies using process-based approaches at the sector level, the contribution of aircraft manufacturing to the sector's GHG emissions was found to range between 1 and 3% (Pierrat et al., 2021; Trevisan and Bordignon, 2020). The emissions are associated with the largest aircraft module producers (i.e., airframes and engines) due to the manufacturing activities' high energy and resource consumption (Pierrat et al., 2021).

More sector-scale studies with a full global scope, when addressing the aviation sector, are needed to better evaluate the

Table 1
Overview of retrieved LCA studies applied to civil aircraft, with a focus on kerosene-fueled civil aircraft, materials, and components.

Object of study	*Functional unit and system boundary*	*Impact coverage* [a]	*Source*
A320 aircraft	Not specified, only unit passenger-kilometer mentioned Cradle-to-grave	FD, CC, POFe, POFhh, HTc TA, TE, FWC, IR, FPMF, MET, LU, FET, SOD, FE, ME, HTnc, MD, HH, EQ, NR	(HOWE ET AL., 2013)
A330-200 aircraft	Not specified, only unit passenger-kilometer mentioned Cradle-to-grave	FD, CC, POFe, POFhh, HTc TA, TE, FWC, IR, FPMF, MET, LU, FET, SOD, FE, ME, HTnc, MD, HH, EQ, NR	(DALLARA ET AL., 2013)
Airbus A320-200 aircraft	Not specified, only unit passenger-kilometer mentioned Cradle-to-grave	FD, CC, POFe, POFhh, HTc TA, TE, FWC, IR, FPMF, MET, LU, FET, SOD, FE, ME, HTnc, MD, HH, EQ, NR	(JOHANNING AND SCHOLZ, 2014)
Theoretical all-composite aircraft structure based on Boeing 787 Dreamliner vs. *aluminum alloy structure*	Not specified, only unit tonne-kilometer mentioned Cradle-to-grave	FD, CC, POFe, POFhh, HTc TA, TE, FWC, IR, FPMF, MET, LU, FET, SOD, FE, ME, HTnc, MD, HH, EQ, NR	(TIMMIS ET AL., 2015)
Fleet of 78 different passenger capacity aircraft t	Not specified, only unit passenger-kilometer and seat-kilometer mentioned Cradle-to-grave	FD, CC, POFe, POFhh, HTc TA, TE, FWC, IR, FPMF, MET, LU, FET, SOD, FE, ME, HTnc, MD	(COX ET AL., 2018)
CeRAS aircraft based on A320-200	Moving a passenger over one kilometer with an Airbus A320 aircraft running on drop-in fuel (e.g., kerosene, biofuel) with a standard lifespan Cradle-to-grave	FD, CC, POFe, POFhh, HTc TA, TE, FWC, IR, FPMF, MET, LU, FET, SOD, FE, ME, HTnc, MD, HH, EQ, NR	(FABRE ET AL., 2022)
Aluminium alloy 2024, carbon fiber reinforced epoxy resin (CFRP), and GLARE (glass fiber/Al laminate used by Airbus in A380)	Not specified, only unit tonne-kilometer of freight mentioned Cradle-to-grave	FD, CC, POFe, POFhh, HTc TA, TE, FWC, IR, FPMF, MET, LU, FET, SOD, FE, ME, HTnc, MD, HH, EQ, NR	(RAJENDRAN ET AL., 2012)
CRFP	1-tonne waste CFRP entering the waste treatment processes Gate-to-grave	PED, CC	(LI ET AL., 2016)
CRFP	1 kg of CFRP waste treated from a composite part Gate-to-grave	CC, HH, EQ, NR	(WITIK ET AL., 2013)
Nickel production from ferronickel ore	1 kg of nickel contained in the nickel product at the factory gate Cradle-to-gate	PED, CC, AP, EP, POF	(MISTRY ET AL., 2016)
Aluminium ingot	1 kg of primary aluminium ingot at the factory gate Cradle-to-gate	AP, FD, EP, CC, ODP, POF	(NUNEZ AND JONES, 2016)
Steel slabs	Production of 1,000,000 tons of solid steel slabs Cradle-to-gate	FD, CC, POFe, POFhh, HTc TA, TE, FWC, IR, FPMF, MET, LU, FET, SOD, FE, ME, HTnc, MD	(RENZULLI ET AL., 2016)
Cargo aircraft elevator	Medium size cargo aircraft elevator Cradle-to-gate	CC, HH, EQ, NR	(CALADO ET AL., 2019)
Integrated rotor for aircraft (blisk)	Manufacturing of functional high-pressure compressor blisk made of Ti6Al4V alloy with a 220 mm tip radius and a final weight of 3.7 kg with a maximum cycle time of 87 h Cradle-to-gate	FD, CC, POFe, POFhh, HTc TA, TE, FWC, IR, FPMF, MET, LU, FET, SOD, FE, ME, HTnc, MD	(RUPCIC ET AL., 2022)

[a] LCIA methods use different names for impact categories. Here we use ReCiPe classification of impact categories (see full table of methods used by each study in Appendix A, Table S3). Primary Energy Demand (PED), Fossil Depletion (FD), Climate Change (CC), Photochemical Ozone Formation ecosystems (POFe), Photochemical Ozone Formation human health (POFhh), Human Toxicity cancer (HTc), Terrestrial Acidification (TA), Terrestrial Ecotoxicity (TE), Freshwater Consumption (FWC), Ionizing Radiation (IR), Fine Particulate Matter Formation (FPMF), Marine Ecotoxicity (MET), Land Use (LU), Freshwater Ecotoxicity (FET), Stratospheric Ozone Depletion (SOD), Freshwater Eutrophication (FE), Marine Eutrophication (ME), Human Toxicity non-cancer (HTnc), Metal Depletion (MD), Human Health (HH), Ecosystem Quality (EQ), Natural Resources (NR).

environmental hotspots of the sector. These should be accompanied by a systematic inclusion of a life cycle impact assessment to quantify all potentially relevant environmental problems (e.g., climate change, land use, water use, chemical pollution, etc.) (Hauschild, 2005).

5. Aircraft systems

As observed in Table 1, several LCA studies have been performed at the level of the whole aircraft or sub-aircraft system (i.e., specific technologies or components). In the following, after summarizing subsection (5.1), the findings of LCA studies are addressed per life cycle stage to enable a detailed analysis of reported hotspots.

5.1. Overview of civil aircraft life cycle

The focus and scope of the retrieved LCA studies vary, see Table 1. Generally, cradle-to-grave LCA studies addressing the entire aircraft life cycle, focused on a specific model of aircraft, such as the Airbus A320-200, the theoretical all-composite Boeing 787, or a specific fleet of aircraft (Cox et al., 2018; Dallara et al., 2013; Fabre et al., 2022; Johanning and Scholz, 2014; Timmis et al., 2015). The other studies, which adopted a truncated life cycle scoping (cradle-to-gate perspective), typically focused on material extraction and production or the end-of-life of materials used in the aircraft (Li et al., 2016; Mistry et al., 2016; Nunez and Jones, 2016; Renzulli et al., 2016; Rupcic et al., 2022; Scelsi et al., 2011; Witik et al., 2013). In addition to having different focus areas, these studies were applied using different LCA methodological choices, with a variety of LCIA methods used, modeling perspectives or LCA software (e.g., SimaPro, GaBi); see Table 1 and Appendix A, Table S3. Therefore, the results of the studies could not be directly compared, although their analyses were made in the below subsections. Detailed guidance specific to the methodological conduct of LCA is additionally reported in Section 8.

5.1.1. Materials and aircraft manufacturing

Raw materials extraction and production, together with aircraft manufacturing, contribute to less than 1% of the aircraft life cycle emissions of GHGs (Dallara et al., 2013; Howe et al., 2013; Pierrat et al., 2021). The raw material extraction and production stage has been found to be dominant over aircraft manufacturing due to the high energy requirement and resource intensity of mining activities (Eckelman et al., 2014; Paraskevas et al., 2016; Pierrat et al., 2021; Priarone et al., 2016; Rupcic et al., 2022). Wing and engine components have been found to yield the highest impact on GHGs proportional to mass, while implementation of CFRP in aircraft components have been proven to provide up to 20% reported savings in weight and fuel during the operational stage of aircraft (Dallara et al., 2013; Timmis et al., 2014).

Energy generation is known to be the main driver of several impact categories in the raw materials and manufacturing stages, e.g., fossil depletion, climate change, and photochemical ozone formation (Nunez and Jones, 2016; Renzulli et al., 2016; Rupcic et al., 2022). Besides associated high energy consumption, mining activities have been found to contribute to other relevant impact categories, such as metal depletion and freshwater consumption (e.g., from extraction processes such as leaching), as shown in the manufacturing of aircraft blisk components (Rupcic et al., 2022).

Due to extreme conditions such as high operating temperatures and shear forces, aircraft components are usually made with high-precision and purity materials (Eckelman et al., 2014). Those special requirements can lead to high metal resource use during manufacturing and are typically captured by the buy-to-fly (BTF) ratio, which is a metric expressing the ratio of a given material input mass over the output mass of the final part. It can be as high as 23:1, as is the case for the integrated rotors for aircraft made of Ti-Al-V alloys (Rupcic et al., 2022). In this example, manufacturing thus generates approximately 68 kg of available metal per one blisk; these scraps are often discarded or undervalued depending on the country's or company's waste management practices. For aluminium, titanium, and steel products, the BTF ratio has been reported to amount to 5:1, 10:1, and 16:1, respectively (Pierrat et al., 2021; Rupcic et al., 2022). This indicates the need for adapted waste management practices, including optimizing scrap recycling. Moreover, these results highlight the need for more holistic approaches to impact assessment rather than scarcity-based approaches that only consider lithosphere stocks in relation to resource use. The loss of resource accessibility should also be taken into account when accounting for lithosphere and anthropogenic stocks (Owsianiak et al., 2022).

The machining of special materials or components may also lead to unusual patterns in the LCA results when assessing aircraft manufacturing. Taking the example of rotor production, cobalt, which constitutes the machining tools, was observed to drive toxicity-related impact categories (chemical releases impacting human health and ecosystems) and metal depletion (Rupcic et al., 2022). As a result, capital goods could be directly responsible for these impacts, rather than the products themselves. While capital goods have sometimes been omitted from LCA studies, e.g., waste management, it is still important to include them by default in the system boundaries when assessing aircraft component manufacturing (Laurent et al., 2014).

LCA studies comparing different aircraft material alternatives have shown the importance of adequately integrating the material functionality into the functional unit (i.e., quantitative measure to ensure fair comparisons between alternatives in LCA, instead of directly comparing materials based on mass, e.g., kg of aluminium vs. kg of titanium (Scelsi et al., 2011; Timmis et al., 2014). A given component made of steel that becomes substituted by a new one made of carbon fibers may lead to a largely decreased mass for a same functionality (Scelsi et al., 2011). Comparison based on a mass ratio of 1:1 is therefore misleading between these materials.

The environmental benefits of a newer component may be reflected through a break-even point analysis, i.e., the distance that is traveled by aircraft before the lighter materials, which carry more burdens during their production, become environmentally preferable, for example, in the cases of aircraft fuselage and structural tubes (Scelsi et al., 2011; Timmis et al., 2014). In the tube component, comparisons between steel and CFRP reported higher emissions for CFRP tubes in all stages but the operation stage (Scelsi et al., 2011). When considering climate change impacts, the break-even point for replacing steel components with CFRP was achieved already after five hours of flight (3,600 km) (Scelsi et al., 2011). The trend in these results, which reflect a low payback time, is in line with Timmis et al. (2015), who found a break-even point of between 75 and 210 h for an integrated aluminum and CFRP fuselage. Even with higher energy consumption in the manufacturing stage, CFRP has thus been found to be an environmentally preferable option compared to aluminum or steel choices of material when considering climate change impacts from an aircraft life cycle perspective.

If the LCA approach is applied in the early stage of aircraft design to explore lightweight components, the potential reduction in fuel emissions has been reported to reach up to 53% (Calado et al., 2019). Alternatives to energy-intensive production of synthetic resins (epoxy, phenolic) that are currently used in CFRP, are composites made with bio-fibers, such as flax and ramie, which have lower energy demand for the same functionality (Bachmann et al., 2017). However, they are reported to have high flammability and reduced mechanical properties. Therefore, their use in the aviation sector is limited to applications such as interior or secondary structures (Bachmann et al., 2017). Bachmann et al. (2017) also pointed out the need to account for differences in material properties, degradation during service, or region-specific influences when comparing materials used in aviation.

With respect to the LCA studies investigating the whole aircraft life cycle, the majority of environmental impacts are reported to stem from the operation stage, particularly during the cruise flight, due to the kerosene fuel combustion (Cox et al., 2018; Dallara et al., 2013; Howe et al., 2013). Although not all relevant environmental impact categories are shown in these studies (e.g., mineral and metal availability, land use, etc.; see Table 1), these results are consistent with the few studies performed at the sector level (see Section 4). Manufacturing and end-of-life have been found to contribute less than 1% to total GHG emissions, and the results of those stages, especially aircraft disposal and recycling benefits, were not sufficiently addressed in comparison to aircraft operation or fuel production, with the exception of novel CFRP (Cox et al., 2018; Dallara et al., 2013; Fabre et al., 2022; Li et al., 2016; Scelsi et al., 2011; Timmis et al., 2014; Witik et al., 2013).

5.2. *Aircraft operations*

5.2.1. *Flight operations*

The magnitude and intensity of aircraft operating emissions depend on many factors, such as aircraft weight, flight distance, engine efficiency, payload, and flying altitude. A strong relationship between aircraft size and impact per passenger-kilometer was found in multiple studies. Larger aircraft and longer flights (>400 passengers) are found to have lower GHG emissions per passenger-kilometer in contrast to small aircraft flying short distances, which use more energy and produce more GHGs during the operational stage (Cox et al., 2018). Older aircraft traveling shorter distances are found to contribute the most to NO_x emissions and unburned hydrocarbons due to lower engine efficiency (Cox et al., 2018). A major part (90%) of aircraft emissions in the operation stage (and total aircraft life cycle emissions) occurs during the cruise phase of the flight at an altitude of several kilometers above sea level (Grobler et al., 2019; Cox et al., 2018; Dallara et al., 2013; Fabre et al., 2022; Johanning and Scholz, 2014). Those emissions include notably CO_2, NO_x, SO_x, hydrocarbons (HC), CO, particulate matter (PM), soot, water vapor, and indirect effects such as aviation-induced cloudiness (AIC), which might eventually lead to damages on ecosystems and human health. NO_x, CO_2, and AIC have been reported to contribute to 97% of total health damage per unit of fuel burned (Grobler et al., 2019). Moreover, the sensitivity to PM2.5 was found to differ depending on the region, e.g., with 57% and 64% higher for the population in Europe compared to Asia and North America, respectively (Quadros et al., 2020).

Johanning and Scholz (2014) introduced the effect of altitude-dependent emissions of NO_x and condensation trails (contrails) generated by the cruise stage of jet aircraft in LCA and explored to what extent life cycle impact assessment methods consider them. Existing LCIA methodologies do not enable a consistent characterization of these aircraft emissions and cloudlines during the cruise phase (Huijbregts et al., 2017; Verones et al., 2020). Until now, the two studies by Cox et al. (2018) and Johanning and Scholz (2014) remain the only attempts at addressing this gap within LCA. Cox et al. (2018) developed global warming potentials (GWP) for several non-CO_2 emissions based on Fuglestvedt et al. (2010), including aircraft ice clouds forming around the emitted soot particles and developing into persistent contrails or contrail cirrus, together named AIC (Kärcher, 2018). The application of these new characterization factors for climate change impact assessment shed light on the relative impact distribution, with a direct contribution from CO_2 emissions estimated at 60%, while contributions of ca. 35% were found for AIC, 3–4% for water vapor and 0.5–2% for NO_x emissions (with high uncertainty) (Cox et al., 2018). Although requiring more investigation, AICs have recently been associated with a change in effective radiative forcing of $+0.06$ [0.02–0.10] $W.m^{-2}$ over the 1750–2019 period, hence showing relevance when compared with a total anthropogenic effective radiative forcing estimated at 2.71 [1.96–3.48] $W.m^{-2}$ in that period (Lee et al., 2021; IPCC, 2021). According to Lee et al. (2021), the current net aviation effective radiative forcing is driven by AICs (>50%), CO_2 (ca. 30–35%), and NO_x (ca. 15%). Moreover, the importance of combined non-CO_2 climate impacts from aviation has been confirmed by a recent study conducted by the European Union Aviation Safety Agency (EASA), which calls for the development of future policy options to address the non-CO2 climate impacts of aviation (EC, 2020). The use of alternative aviation fuels, such as low aromatic compounds, might provide important reductions in cirrus cloud formations. Voigt et al. (2021) have reported a potential reduction of 50–70% in soot and ice number concentrations, thus leading to decreased impacts on climate change compared to the use of fossil fuels. However, more studies are needed to confirm this projection. In addition to in-sector measures (technology, operations, and fuels), improving flight performance by formation flying could contribute to CO_2 emission reductions, as reported by ICAO LTAG (2022).

Nevertheless, further research is required to consistently develop characterization factors for the high-altitude non-CO_2 emission flows and enable their systematic inclusion in LCA applied to aircraft, covering both climate change and stratospheric ozone depletion impacts as well as other potential environmental impacts.

5.2.2. *On-ground operations*

Impacts of aircraft operations also occur at ground level during the LTO phase. Although rarely addressed, ground-level emissions from fossil fuel combustion lead to problems like those of other transportation modes, i.e., through potential contributions to human health and ecosystem damages from particulate matter and other chemical releases. Noise may also be an issue. These aspects covering on-ground operations and the LTO phase are covered with more depth in Section 7, along with the airport-related impacts.

5.2.3. *Maintenance, repair, and overhaul*

Overall, there is a lack of literature investigating the impacts of aircraft maintenance, repair, and overhaul (MRO). No LCA study portrays in detail the environmental impacts of aircraft maintenance. Existing life cycle inventory (LCI) databases, like ecoinvent, which encompasses ca. 20,000 process LCI datasets, do not cover aircraft maintenance in their air transportation processes (Wernet et al., 2016). The few estimations of GHG and air pollutant emissions that can be found in the LCA literature are highly uncertain due to major assumptions made at the level of the entire sector or aircraft (Chester, 2008). Chester (2008) thus, accounted for maintenance at the sector level, selecting the EIO-LCA sectors that covered lubrication and fuel change, battery repair and replacement, chemical milling, parts cleaning, coating application, painting, aircraft engine, and parts manufacturing. Under these assumptions, maintenance was found to represent up to 1.8% of an aircraft's life cycle energy requirements for the aircraft Embraer 147, Boeing 373, and Boeing 747. The use of specific chemicals for MRO processes and checks at the airport may also be a potentially important source of impacts like chemical pollution or eutrophication (O'Connell, 2018). Future LCA studies should therefore try to include MRO aspects wherever possible. When doing so, new component manufacturing, remanufacturing, repair materials and processes, and associated MRO waste management (e.g., recycling, landfilling, incineration, reuse, etc.) should be addressed for all aircraft elements that typically require heavy maintenance, e.g., airframe, engines, electric drives, landing gears, etc. (Keivanpour et al., 2017). The use of emerging technologies and processes, such as additive manufacturing, should also be explored owing to their low material wastage, relative gains in maintenance time and costs, and relatively low emissions and resources (energy, materials, and water requirements) compared to conventional manufacturing processes (Madhavadas et al., 2022).

5.3. *Recycling and end-of-life*

Waste management options for aircraft include reuse, materials downcycling, incineration, and landfilling/dumping in places with low humidity to prevent corrosion before re-using the parts again (e.g., deserts) or locations close to airports (Ribeiro and De Oliveira Gomes, 2015; Zhao et al., 2020). Currently, the recycling of aircraft materials is favored, and closed-loop recycling of aerospace alloys for reuse in the aerospace industry has started to emerge (Eckelman et al., 2014). Such practice avoids the production of primary alloys and was found to reduce the costs and GHG emissions from raw material production (Eckelman et al., 2014). An explorative recycling project led by Airbus (i.e., Process for Advanced Management of End-of-Life Aircraft PAMELA) thus showed that more than 85% of the weight of aircraft materials could be reused as secondary parts or sold for material recovery (PAMELA, 2012). However, Asmatulu et al. (2013) showed in the example of five US local aerospace recycling companies that only 20% of the aircraft scrap materials are currently recycled.

Compared to emissions released for primary alloy production, emissions from recycling processes are reported to be low (0.4–3.2% of primary production for metals and 10% for CFRP) (Eckelman et al., 2014; Witik et al., 2013). Important impact benefits can thus be achieved for emission-based environmental impacts and resource use. Rupcic et al. (2022) also found that in the case of titanium 6/4 alloy, alloy-to-alloy recycling (compared to hazardous waste treatment with macro encapsulation) can lead to climate change impact reductions of up to 52%. However, the market value for recycled titanium alloys is approximately 30% lower than other aerospace super-alloys (such as Nickel or Cobalt based) (Eckelman et al., 2014). Aircraft metals are usually downcycled because of expensive and energy-intensive recycling processes and constrained markets due to quality requirements, as is the case for Ti alloys (Eckelman et al., 2014; Rupcic et al., 2022; Takeda et al., 2020).

A similar trend is observed for carbon fibers, for which the preferred disposal option remains landfilling over incineration and recycling, due to the lack of market incentives, e.g., high costs and/or GHG emissions associated with incineration and mechanical recycling (Scelsi et al., 2011; Witik et al., 2013). Even with modern incineration plants with energy recovery from waste, landfills still have been found to yield lower CO_2 emissions (Witik et al., 2013). Lower environmental impacts in landfilling scenarios, compared to other options, have additionally been found in the few LCA studies addressing aircraft waste management (Li et al., 2016; Timmis et al., 2015; Witik et al., 2013). This can be explained by the slow degradation rate of carbon fibers, with just 1% over the first 100 years and only 26% for longer time periods (Witik et al., 2013). Besides carbon fibers, the assumption of zero leakages in the landfilling scenarios considered in these studies for other materials can be questioned as emissions from landfills do occur, e.g., slow leaching of heavy metals over several decades or centuries (Bakas et al., 2015; Witik et al., 2013). Moreover, although robust and operational methods and databases are still lacking to assess these long-term emissions from metals and carbon fibers, the inclusion of these types of impacts should be done wherever emission inventories can be developed.

Overall, there is a need for more LCA studies exploring and assessing the impacts of aircraft at the end of their operations, including their potential decommissioning and the transportation, reuse, recycling, and/or further waste treatment of the different parts. Despite the potentially large benefits brought by aircraft recycling and the end-of-life stage, little data on the matter currently exists in the public domain and within the LCA field.

6. Alternative aviation fuels and propulsions

Following the general pattern within the aviation section, the studies addressing aviation fuels and propulsion systems focus strongly on assessing climate change impacts, and only a few have covered other environmental impacts.

6.1. Hybrid electric propulsion and non-drop-in fuels

All LCA studies, which focused on alternative propulsion systems, compared the potential impacts on climate change of conventional versus electric propulsion systems, including all-electric, hybrid electric, and turboelectric aircraft (see classification in Section 2.2), combined with well-to-wake production of the alternative fuels (Bicer and Dincer, 2017; Gnadt et al., 2019; Ratner and Yuri, 2019; Schäfer et al., 2016). Three additional studies compared battery technologies' impacts from the cradle to the grave (Barke et al., 2020; Ekener et al., 2018; Ribeiro et al., 2020). In general, all-electric and hybrid-electric aircraft studies included the electricity or the alternative fuel production and use in the system boundaries, but only two studies included the battery pack life cycle (Ribeiro et al., 2020; Afonso et al., 2021). The studies pointed out that (hybrid) electric propulsion yields lower climate change impacts than conventional propulsion for shorter-range missions (up to approximately 1000 km) and maximum payloads corresponding to 190 passengers for electricity, gas, and hydrogen fuels (Gnadt et al., 2019; Bicer and Dincer, 2017; Schäfer et al., 2019). The benefits of shorter range for hybrid and all-electric aircraft results from trade-offs between the weight and volume of the propulsion system and the corresponding aircraft range (Gnadt et al., 2019). Given the current best available technologies, battery configurations are heavier, and liquid hydrogen storage occupies more volume than conventional kerosene propulsion systems (Bicer and Dincer, 2017; Gnadt et al., 2019; Schäfer et al., 2016). For example, a configuration with an all-electric aircraft with a payload of 180 passengers has been estimated to lead to minimal climate change impact for a mission range between 555 km and 1,296 km depending on the battery-specific energy density (Gnadt et al., 2019). To enable such aircraft configurations, Gnadt et al. (2019) have emphasized that a major increase in battery-specific energy densities with values of 800 Wh/kg and above is required. Slightly lower densities, e.g., ca. 600 Wh/kg, have also been estimated for smaller configurations of regional class aircraft, i.e., with a shorter mission range and 50–90 passengers (Hansson et al., 2018; Ribeiro et al., 2020). Therefore, all-electric and hybrid electric aircraft with batteries require a battery technology breakthrough as none of these technologies have reached the market yet and still require further research (Hansson et al., 2018).

Barke et al. (2021) analyzed eight potential battery systems for short-range aircraft, finding that lithium-sulfur batteries are the most promising technology from an environmental perspective (Barke et al., 2021). These results should be taken with caution as the study by Barke et al. (2021) built upon demonstrated battery performances with none of the battery systems exceeding 300 Wh/kg energy density, and none of the systems encompassing future chemistries like solid-state batteries or lithium-oxygen batteries. Hansson et al. (2018) found that lithium-air and zinc-air batteries have much higher life cycle emissions (GHG emissions, NO_x emissions, water, and energy consumption) due to a higher material demand than those of current lithium-sulfur and lithium-ion battery alternatives. However, Hansson et al. (2018) did not define a functional unit to compare similar technologies in their study.

Moreover, the climate change mitigation potential of electric/hybrid propulsion highly depends on the environmental impact intensities of the electricity grid mix and/or the liquid fuel production, as shown in Table 2. For an all-electric aircraft, the GHG emission intensities associated with the electricity production mix directly drive the climate change impact performances (Gnadt et al., 2019; Ratner and Yuri, 2019). Gnadt et al. (2019) for instance, showed that an all-electric 180 passengers aircraft equipped with a 1,200 Wh/kg battery would outperform the climate change impacts of conventional aircraft for a mission range of 926 km in 2030 under a high renewable energy scenario in the USA (Gnadt et al., 2019). In this scenario, the NREL projects an electricity grid mix of 330 gCO_2eq/kWh. However, with an electricity grid mix mainly relying on coal (i.e., "business as usual" scenario with 380 gCO_2eq/kWh in 2050), the climate change break-even point would be attained before 2050 only in cases of a battery energy density above 1,200 Wh/kg.

Table 2
Overview of climate change impact results retrieved from the three reviewed studies addressing different non-drop-in fuel alternatives.

Fuel (source of fuel/energy)	*Reported score*	*Reference flow*	Source
Methanol (natural gas)	1.30	$kgCO_2eq$/tkm	(Bicer and Dincer, 2017)
Ethanol from ethylene	1.09	$kgCO_2eq$/tkm	(Bicer and Dincer, 2017)
Kerosene	1.05	$kgCO_2eq$/tkm	(Bicer and Dincer, 2017)
Liquid natural gas	0.85	$kgCO_2eq$/tkm	(Bicer and Dincer, 2017)
Ammonia	0.21–1.08	$kgCO_2eq$/tkm	(Bicer and Dincer, 2017)
Liquid hydrogen (steam methane reforming)	0.01–0.19	$kgCO_2eq$/tkm	(Bicer and Dincer, 2017)
Liquid hydrogen (natural gas)	7.00	$kgCO_2eq$/tkm	(Ratner and Yuri, 2019)
Liquid natural gas	2.00	$kgCO_2eq$/tkm	(Ratner and Yuri, 2019)
Kerosene	1.50	$kgCO_2eq$/tkm	(Ratner and Yuri, 2019)
Renewable electricity (wind)	0.22	$kgCO_2eq$/tkm	(Ratner and Yuri, 2019)
Liquid hydrogen (steam methane reforming)	0.20	$kgCO_2eq$/tkm	(Ratner and Yuri, 2019)
Liquid hydrogen (renewable electricity)	0.10–0.50	$kgCO_2eq$/tkm	(Ratner and Yuri, 2019)
Electricity grid mix USA 2015 (battery-pack specific energy of 800Wh/kg)	0.091 [a]	$kgCO_2$/pkm	(Schäfer et al., 2019)

[a] Only aircraft CO_2 emissions from the operation are included (Schäfer et al., 2019).

For hybrid-electric aircraft, liquid hydrogen (LH_2) and liquefied natural gas (LNG) were the most cited liquid alternative fuels. Less cited relevant alternative fuels were ethanol, methane, and ammonia (as hydrogen carrier) (Bicer and Dincer, 2017). LNG did not show clear environmental benefits in terms of climate change impacts compared to kerosene (Bicer and Dincer, 2017; Ratner and Yuri, 2019). LH_2 aircraft caused fewer climate change impacts than LNG and kerosene-fueled aircraft when produced from renewable electricity or steam methane reforming (Table 2). Only specific LH_2 production pathways, i.e., from hydropower, geothermal sources, and coal gasification with carbon capture, performed systematically better than kerosene for climate change, metal and mineral resource depletion, and stratospheric ozone depletion impact categories, although other impact categories did not follow this trend, such as freshwater ecotoxicity or land use, for which results were contrasted (Bicer and Dincer, 2017; Ratner and Yuri, 2019). Notwithstanding, the current hydrogen production relies mostly on natural gas extraction (Ratner and Yuri, 2019). Thus, if the LH_2 production routes remain unchanged, hybrid aircraft using hydrogen fuel cells might cause more climate change impacts than conventional aircraft.

Based on the reviewed literature, the comparative advantage of electric and hybrid propulsion systems in terms of climate change impacts can be traced to three intertwined factors: (i) the aircraft mission profile, (ii) the type, storage capacity, and weight of the energy storage solution (e.g., batteries), and (iii) the GHG emission intensities associated with the alternative fuel production and combustion. Given the short mission ranges of electric aircraft, the potential of these technologies to mitigate climate change impacts at the sector level is limited. Short-haul flights represent a small portion of global air transportation CO_2 emissions with approximately 12% of GHG emissions resulting from flights shorter than 750 km, while 57% come from flights longer than 6,500 km (Epstein and O'Flarity, 2019; Zaporozhets and Synylo, 2017). Moreover, short-haul flights might be in direct concurrence with other transport modes, which may have significantly lower climate change impacts per passenger-kilometer or ton-kilometer, like high-speed trains or road vehicles (Epstein and O'Flarity, 2019; Facanha and Horvath, 2007; Jiang et al., 2021; Baumeister and Leung, 2021). Hence, prospective LCA studies are needed to explore the environmental impacts of future hybrid electric aircraft (regional class), integrating technology foresight for the battery systems and their projected energy densities to match top-level aircraft requirements (e.g., range and payload). Eventually, such studies could support determining aircraft configurations that may become technologically viable in short-, medium- and long-term perspectives and allow for anticipating their future environmental impacts, so they can be mitigated during the aircraft design phase. Moreover, including the interactions between air transportation with other transport modes in LCA studies would support the design of policies that effectively reduce the climate impacts of transportation at sector level (Jiang et al., 2021; Thonemann et al., 2020).

6.2. *Fossil fuel substitution by drop-in fuels in conventional propulsion*

Drop-in fuels, also commonly termed alternative aviation fuels, are alternatives to petroleum-derived fuels that can substitute them without major modifications of current equipment and infrastructures (Section 2.2). Multiple studies have investigated the relative environmental impacts of different drop-in fuels. Gathering some of them, two comprehensive reviews focused on the well-to-wake

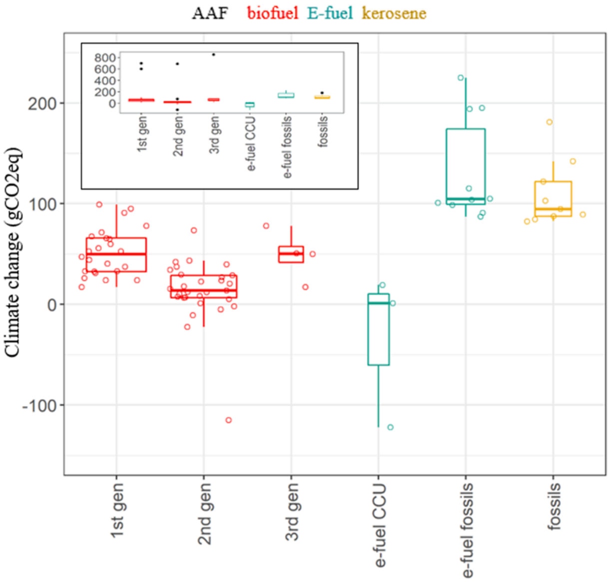

Fig. 5. Indicative comparison of well-to-wake average climate change impact of 1 MJ of conventional and alternative aviation fuels from LCA literature reviewed in this study (n = 15, raw data available in Appendix C). The black dots in the insert represent the outliers, and the boxplot width in the main figure represents the number of data points. CCU: carbon capture and utilization’ 1st gen: first generation biofuel’ 2nd gen: second generation biofuel’ 3rd gen: third generation biofuel, e-fuel fossil: electro-fuels using a fossil carbon source, e-fuel CCU: electro-fuels using CCU as a carbon source, AAF: alternative aviation fuels (insert).

impacts of alternative jet fuels and feedstock biomass on climate change (Kolosz et al., 2020; Schmidt et al., 2018). Covering the literature up to 2015–2017, these studies were complemented in the current review by 13 more recent studies assessing the climate change impacts of different fuel alternatives (see Appendix B, C). Fig. 5 and Table 3 show an indicative comparison of well-to-wake climate change impact intensities of different AAFs. Table 3 presents averaged values for other impact categories (including outlier data identified in Fig. 5).

The AAFs derived from fossil feedstock (petroleum, natural gas, and coal), even with carbon capture, resulted in climate change impacts higher than kerosene (Bicer and Dincer, 2017; Chiaramonti and Nogueira, 2017; Kolosz et al., 2020; Ratner and Yuri, 2019; Schmidt et al., 2018; Siddiqui and Dincer, 2021).

The biofuels, categorized into three groups or generations, showed a mixed picture (Fig. 5). First-generation biofuels, which are produced from food crops, lead to similar or slightly lower impact intensities than conventional fuels, with a mean of approximately 50 g-CO_2eq/MJ (see Fig. 5, without outliers) (Kolosz et al., 2020; Prussi et al., 2021). Concerning second-generation biofuels, which result from different types of non-food biomass, climate change impact intensities can vary depending on the accounting methods (e.g., handling of the process multi-functionality via system expansion or allocation when the biomass is a by-product); and the considered land use scenarios (Rojas-Michaga et al., 2022; Kolosz et al., 2020; Prussi et al., 2021; Schmidt et al., 2018; Zhao et al., 2021b). Depending on these parameters, second-generation biofuels can reduce 50% of GHG emissions on average compared to conventional fuels (Fig. 5, without ouliers). The variability of the climate change impacts associated with first- and second-generation biofuels depends on the in- or exclusion of land use change (LUC) carbon emissions associated with biomass production and the fuel conversion technology. Lower climate change impacts are typically obtained for crop cultivation on existing agro-pastoral land, and higher for cultivation on woodland due to deforestation (Zhao et al., 2021b). In addition, the competition of first-generation biofuels with food production (e.g., corn, palm oil, sugarcane, soy feedstocks) may cause indirect land use change (iLUC) to maintain food supply, which can overall yield a substantial increase in CO_2 emissions (Rojas-Michaga et al., 2022; Prussi et al., 2021; Zhao et al., 2021b). The feedstock (e.g., corn, soy) and the fuel conversion pathway (e.g., HEFA, FT) also influenced the climate intensity of feedstock conversion pathways. The approach used to allocate climate change impacts to the AAF in multi-functional processes is another source of intra-category variability (Appendix C). This modeling choice was not always reported explicitly in the reviewed studies, yet energy allocation and system expansion are commonly used. In other impact categories, second-generation biofuels used in aviation also mitigate high environmental impacts observed with first-generation biofuels, which is the case for water use (surface and groundwater) or land use (Cox et al., 2018; Kolosz et al., 2020; Table 3).

Finally, third-generation biofuels derived from algae biomass did not show clear benefits with respect to climate change impacts (Fig. 5). Most studies concluded that algae-derived jet fuel might have larger emission intensities than conventional jet fuel, although causing less LUC and ecotoxicity-related impacts than other biomass-based AAFs (Kolosz et al., 2020, Table 3). Possible reasons are that the fuel production pathways for algae feedstock show lower technology readiness (e.g., hydrotreated depolymerized cellulosic jet, hydrothermal liquefaction jet, see Fig. 3) and have higher capital expenditure than other first- and second-generation feedstocks (Kolosz et al., 2020).

As another option to conventional fuels, electro-fuels can be relevant AAFs. Electro-fuels using CO_2 captured from the air or biogenic sources (marked as “e-fuel CCU” in Fig. 5) have been reported to offer significantly smaller climate change impacts on average, compared to reference conventional jet fuel (Fagerström et al., 2022; Rojas-Michaga et al., 2022; Schmidt et al., 2018). Rojas-Michaga et al. (2022) work, which should be replicated for confirmation, even found that AAF produced with a bioenergy with carbon capture and storage system can yield net carbon capture (negative value in Fig. 5). In contrast, electro-fuels using fossil carbon as feedstock performed poorly with 50% more CO_2eq/MJ than kerosene (Schmidt et al., 2018, Kolosz et al., 2020, Fig. 5). The total gains obtained from electro-fuels (from fossil and non-fossil CO_2) at the sector level are estimated between 30% in 2030, assuming 100% renewable electricity, and 50% in 2050 (Ueckerdt et al., 2021; Wise et al., 2017). In addition to climate change, these AAFs have comparatively low impacts on land and water use impact categories, with less than 1% of the well-to-wake water footprint (Table 3) and land requirements of biofuels (Falter and Pitz-Paal, 2017; Schmidt et al., 2018). For electro-fuels as well as for any AAF requiring an external source of hydrogen, the environmental benefits of the production pathways are strongly influenced by the availability of the so-called green hydrogen, meaning hydrogen produced using renewable electricity sources and water (Fagerström et al., 2022; Siddiqui and Dincer, 2021; Ueckerdt et al., 2021). For instance, the Fischer-Tropsch jet, Sugar to Jet, and hydrotreated depolymerized

Table 3
Well-to-wake average environmental impacts of 1 MJ of AAF using energy content allocation from the LCA literature reviewed in this study (n = 15)[a].

Fuel generation	*CC (gCO_2eq)*	*WU (L)*	*LU (m^2.yr)**	*FE (kg Peq)**	*PM (kg PM)**	*FET (CTUe) **	*HT (CTUh)**
1st gen	1.26E+02	5.52E+01	2.21E+01	2.95E+01	NA	5.20E-10	NA
2nd gen	5.19E+01	1.72E+02	6.15E+00	5.96E+00	−3.40E-01	5.20E-10	9.55E-06
3rd gen	3.06E+02	1.18E+01	6.90E+00	1.00E+01	NA	4.20E-10	NA
e-fuel (all)	1.11E+02	NA	NA	NA	NA	NA	NA
e-fuel CCU	1.02E+01	9.2E-1 L	8.66E-07	NA	NA	NA	NA
e-fuel fossils	1.32E+02	NA	NA	NA	NA	NA	NA
Fossils	1.13E+02	NA	NA	NA	NA	NA	NA

[a] Detailed references are available in Appendix C. Stars “*” indicate one single reference (in the case of Kolosz et al. (2020)). Impact categories are indicated with the following acronyms. CC: climate change, WU: water consumption, LU: land use, FE: freshwater eutrophication, PM: particulate matter, FET: freshwater ecotoxicity, HT: human toxicity.

cellulosic jet fuels all use hydrogen in the process, which can be supplied by an external source or by the process itself. The H_2 production process is indeed particularly energy-intensive, and its environmental performances are largely dependent on the possibility of securing renewable energy sources (Fagerström et al., 2022; Ueckerdt et al., 2021).

Based on the reviewed LCA studies, AAFs of second-generation, derived from herbaceous energy crops or forestry and agricultural residues, and electro-fuels using carbon capture (direct air capture, bioenergy carbon capture, and storage) seem to present the most beneficial pathways for AAF production in terms of climate change mitigation potential. First-generation biofuels do not appear as a viable alternative at scale due to competition with food crops. More research is needed to confirm the potential of third-generation biofuels and e-fuels with CCU as fewer studies focused on these AAFs and the technology readiness levels are lower than for other AAFs (e.g., HEFA, FT). Moreover, the second generation biofuels may not be sufficient to meet the growing demand because feedstock availability is constrained by the number of agricultural by-products, municipal waste, and the availability of anthropized unproductive land. A study by ICAO estimated that only 10% of the demand in 2035 could be supplied by second-generation biofuels, while 23% would be first-generation AAF (ICAO, 2019a; Zhao et al., 2021a). In this case, 40% and 23% of the iLUC emissions associated with AAF production were evaluated to occur in Brazil, Malaysia and Indonesia, thus potentially contributing to major deforestation and biodiversity damage in these countries (Zhao et al., 2021a; ICAO, 2019a).

Nonetheless, the values presented in Fig. 5 are only indicative of the relative performance of different AAFs due to differences in the processes included in the system boundaries and LCA assumptions. Therefore, the values should be interpreted focusing on ranges and trends. A more accurate comparison would require performing a *meta*-analysis to recalculate harmonized carbon intensities. Such analysis was considered out of scope and requires full transparency of the LCI data, which is not (yet) systematic in LCA practice (Saavedra-Rubio et al., 2022). This is, however, disregarding the non-CO_2 emissions during aircraft operations and other environmental problems. As discussed in Section 5.3, non-CO_2 emissions are currently not assessed in most LCA studies and may alter the relative climate change impact potentials of specific AAFs (Ueckerdt et al., 2021). Being largely understudied, trade-offs with other environmental problems, like land use, water demand, and water quality issues, might also be present and nuance such a tendency. For example, only a few studies have included other environmental impact categories in their assessment (Appendix B) (Falter and Pitz-Paal, 2017; Kolosz et al., 2020; Schmidt et al., 2018; Siddiqui and Dincer, 2021). No study assessed the impacts of water use on the environment following the water footprint ISO-standard recommendation (ISO 14046, 2016). To clarify whether trade-offs exist, future LCA studies should be performed with complete coverage of environmental problems and not just focus on GHG emissions and climate change (ICAO, 2019a; Zhao et al., 2021a).

7. Airports

This section largely builds upon the comprehensive review of airport sustainability studies from Greer et al. (2020), which covers publications up to 2019. It was complemented by 14 additional scientific studies published after 2015 (see Appendix B). The main findings of these studies are described below, distinguishing the impacts of the aircraft landing and take-off (LTO) cycle (Section 7.1) from the impacts stemming from ground operations and terminal operations (Section 7.2).

7.1. Aircraft landing and take-off (LTO) cycle

Aircraft LTO takes place in the airside of the airport (Fig. 4) at the intersection of the aircraft and airport systems (Fig. 1B) (Akdeniz, 2022; Ashok et al., 2017; Greer et al., 2020; Yim et al., 2015). A summary of past findings from airport studies assessing airside operations and aircraft LTO are reported below.

Airside operations typically increase the concentrations of nitrogen oxides (NO_x), sulfur oxides (SO_x), CO_2, and hydrocarbons (HC) in the vicinity of airports (Ashok et al., 2017; Bendtsen et al., 2021; Simonetti et al., 2015). Most emissions occur during the aircraft LTO cycle (Greer et al., 2020), and their associated climate change and human health impacts are mainly influenced by the aircraft type, engine model, and taxiing time (Akdeniz, 2022; Ashok et al., 2017; Bendtsen et al., 2021). Fuel type is currently not a relevant parameter since nearly all aircraft operate with petroleum-based fuels. However, deploying different fuel alternatives and propulsion systems may lead to this parameter becoming largely influential (see Section 6).

As a result of these airfield activities, the surrounding human population and ecosystems located outside the airport might be exposed to air pollutants and other chemical releases, such as polycyclic aromatic hydrocarbons (PAHs), ozone, or particulate matter (Ashok et al., 2017; Bendtsen et al., 2021; Yim et al., 2015). Air pollution is one of the leading risk factors for disease burden, and Yim et al. (2015) estimated that population exposure to aviation-attributable PM2.5 and ozone results in 16,000 (90% CI: 8,300–24,000) premature deaths per year. 87% of deaths are found to be caused by PM2.5, with 25% of those emissions occurring during LTO (Yim et al., 2015). At the airport site, exposure to these air pollutants mostly occurs on the airside. It may particularly affect the workers managing on-ground operations, like luggage transport and loading or refueling, and, to a much lesser extent due to a lower exposure time, passengers boarding/disembarking aircraft (Greer et al., 2020). Different ways to limit these impacts exist, such as the electrification of the on-ground transportation systems, electric taxiing or single-engine taxiing of the aircraft, and gate-hold time adjustment (Akdeniz, 2022; Ashok et al., 2017). For example, holding the aircraft at the gate for up to 25 min to avoid congestion can reduce the impacts on human health from taxiing emissions by 35%, as demonstrated at Detroit Airport (Ashok et al., 2017).

In addition to air emissions, impacts also arise from the noise generated by aircraft during their LTO cycles. Noise annoyance has been a poorly assessed impact category in LCIA despite its multiple impacts on human health, with no LCA study having quantified its impacts. The challenge in incorporating noise in impact assessment is the additivity principle necessary for life cycle assessment. In the case of noise, this is an aggregation of sound emissions across all life cycle stages of the product (Heijungs and Cucurachi, 2017).

Previous studies have explored the assessment of these impacts in LCA, but the operationalization of noise impact assessment and its full integration within the LCIA framework is yet to be established (Cucurachi et al., 2012; Cucurachi and Heijungs, 2014; Greer et al., 2020; Zaporozhets and Synylo, 2017). Although studies observing noise-related incidences cases, such as hypertension, sleep disturbance, negative effects on the human metabolism, cardiovascular system, and potential cognitive impairment in children exist, the assessment of noise caused by aviation sector needs further investigation (Nguyen et al., 2023; Kim et al., 2022; OECD, European Union, 2020).

Based on the reviewed literature, the impacts of air pollution and noise annoyance are prominent issues related to aircraft LTO. With the forthcoming introduction of AAF, these impacts from air emissions and noise are overall not likely to be mitigated, although a strong dependency on the type of fuels may arise, as mentioned above. Different air emissions in terms of compositions and intensities occur between H_2-fuelled, all-electric, and biofuel powered aircraft. Similarly, noise reductions may be achieved with electric and hybrid aircraft, as shown by Schäfer et al. (2019). When assessing such fuel and propulsion system changes at the airport site, LCA analysts and decision-makers at large need to consider the risk of potential burden-shifting (Laurent et al., 2012). For example, all-electric aircraft (or electrification of the on-ground support operations) may dramatically reduce air emissions at the airport site but may lead to increases in air emissions – and associated damages to human health and ecosystems – outside the airport, e.g., near a potential coal-fired power plant that would supply the necessary power. Likewise, trade-offs and burden-shifting may occur between environmental problems. For example, increasing the engine bypass ratio to reduce noise or reducing the takeoff thrust to curb air pollution may imply hampering fuel efficiency and thus increase NO_x and CO_2 emissions, eventually contributing to higher climate change impacts (Ashok et al., 2017; Graham et al., 2014). A combination of technological improvements in engines and changes in operation routines at airports might be a way forward to reduce noise and CO_2 and NO_x emissions altogether, although the assessment approach should be extended to cover other environmental problems like land use or water use impacts (Graham et al., 2014; ICAO, 2019a). In this approach, indoor exposure (e.g., passengers in terminals, workers at airports, surrounding population) and outdoor exposure (workers on the airfield, surrounding population) inside and outside the airport site should be considered in the impact assessment. Furthermore, the system boundaries of the study should be carefully determined to address the goal and scope of the study and properly capture the interlinkages and dependencies of the three systems (i.e., airport, aircraft and fuel) during the use stage to avoid the burden shifting to other systems and prevent overlooking other contributing activities. To date, LCA studies that undertake such holistic scoping in the assessment of airports remain to be conducted.

7.2. *Ground operations and airport infrastructure*

In addition to the LCA study by Butt et al. (2021), and excluding the studies by Blanca-Alcubilla et al. (2020), Farré et al. (2022), and Guignone et al. (2022), nearly all the retrieved LCA studies from (Greer et al., 2020) have focused exclusively on airfield pavement (Magnoni et al., 2016; Said and Al-Qadi, 2019; Shen et al., 2016; Wang, 2016; Yang and Al-Qadi, 2017).

The airport pavement studies typically compare two or more solutions for new pavement construction or pavement rehabilitation, which consists of adding or replacing material in the existing pavement structure (e.g., structural overlays, in-place recycling). The relative impact results and the associated choice of permanent or conventional (incl. rehabilitation) pavements were found to depend mainly on the following parameters: the pavement design, the thickness of the layers, the inclusion of recycled aggregates, and the use of warm asphalt instead of hot asphalt (Greer et al., 2020). As an example of the last-mentioned, the study by Shen et al. (2016) compared heated pavement systems (HPS) with conventional pavement using traditional snow and ice removal systems. Traditional removal systems and electrically heated pavements had the highest impacts on climate change, and HPS using geothermal energy heat pumps with high COP had the lowest. In addition, results showed that snow rate and duration were the main parameters influencing energy consumption and, thus, the GHG emissions for HPS. For traditional systems, snow duration was the only parameter influencing energy consumption, which hints that traditional systems could outperform HPS using geothermal energy heat pumps or natural gas at intense snowfall rates (Shen et al., 2016). Nevertheless, the LCA studies on airfield pavements can hardly be comparable due to differences in the goal and scope definitions across studies, e.g., the studies by Wang, (2016) and Yang and Al-Qadi, (2017) both assessed and compared the environmental impacts of different materials used in the construction of airfield pavement, from raw material extraction to its construction excluding end of life. Yet only Wang, (2016) included the maintenance life cycle stage (concrete repair every eight years for runaway pavements). Hence, future studies should seek alignment; in that effect, the extensive guidelines for applying LCA to airfield pavements released by the FAA could provide a useful basis for harmonization (Butt et al., 2019).

An additional LCA study has focused on the use of waste glass in cement production for airport buildings (Guignone et al., 2022). Other studies investigated ways to reduce climate change impacts from terminals and ground operations through water, waste, and energy management (Akyüz et al., 2020; Blanca-Alcubilla et al., 2020; Farré et al., 2022; Greer et al., 2020; Mancinelli et al., 2021). Compared to aircraft emissions, ground service equipment (GSE), auxiliary power units (APU), and ground access vehicles (GAV) servicing the airside contribute to a lesser extent to air pollution, albeit not negligibly (Greer et al., 2020). Yang and Al-Qadi (2017) estimated that on the airside of Beijing Capital International Airport, 13%, 17%, 26%, 2%, and 38% of NO_x, CO, VOC, SO_2, and PM2.5 emissions, respectively, come from ground operations. Nonetheless, ground operations and landside emissions are seldom considered in sustainability studies (Greer et al., 2020). According to Akyüz et al. (2020) and (Greer et al., 2020), approximately 70% of the energy consumption (excluding fuels for aircraft and including electricity and fuels for GSE) at an airport is attributable to terminal buildings, being the terminal heating, ventilation, and air conditioning (HVAC) systems the ones with the highest energy demand. Climate change impacts from the HVAC systems are typically proportional to the annual number of passengers and seasonal temperatures and depend on the energy source, e.g., electricity grid mix composition (Akyüz et al., 2020; Mancinelli et al., 2021). Other initiatives have been advanced to curb climate change impacts, including the electrification of diverse on-ground systems (e.g., aircraft gates, GSE, urban waste collection systems) as long as the electricity grid mix can be associated with low impacts (see also Section 7.1) or the implementation of circular economy solutions, e.g., reduced energy consumption, reusable catering tableware, etc. (Blanca-Alcubilla et al., 2020; Farré et al., 2022; Greer et al., 2020). In addition to climate change impacts, other environmental issues result from airport operations, such as land use, water use (consumption and degradation), and chemical pollution (Greer et al., 2020). These impacts have rarely been addressed in past studies, although LCIA methods exist for most of those impacts. The difficulty in accessing and collecting life cycle inventory data, for which the requirements for an airport assessment can be assimilated to that of a city, may explain this important gap. In complement to the recommendations made in Section 7.1, future studies should therefore seek to gather such data and develop LCIs for different elements of an airport, so it may unlock the conduct of holistic LCA studies and enable gauging the overall environmental burdens and detailed hotspots of airport life cycles (see also Section 7.1).

Table 4
Recommendations directed to LCA practitioners to improve LCA practice in the aviation sector. Guidance is divided between all four phases of the LCA methodology.

GOAL & SCOPE	LCI	LCIA	INTERPRETATION
o Clear definition of functional unit (FU), appropriate for the system under study. As examples: - Aircraft-level assessment may require to include functionalities (depending on goal and scope) like load factor, number of flight cycles, flight hours, and the description of an average flight cycle (Cooper, 2003) - Sector-level assessment may require defining a FU conditioned by the air transport demand (similar to energy sector-level assessments; see (Laurent et al., 2017) - Component- or material-level assessments (e.g., for eco-design) should require careful consideration of the functionalities within the aircraft operations to enable fair comparisons (Furberg et al., 2022) o Delimiting the system boundaries considering the whole life cycle of all three systems (airport, aircraft, and fuels) outlined in Section 2 as starting points (to avoid burden-shifting from one life cycle to another). Transparent justifications of potential exclusions should accompany the delimitation (e.g., demonstrating consistency with the goal of the study, removal of life cycle stages in comparative assertions should provide evidence that these are identical for all compared alternatives), and handling of multi-functional processes (e.g., system expansion/substitution, allocation).	o Establish the practice of reliable, transparent, and representative LCI data communication. Guidance, as developed by Saavedra-Rubio et al. (2022) should be used. o Determine approaches if LCI data need to be concealed, like averaging, proxies, or aggregation, as a last resort (Kuczenski, 2019). If LCI data can only be published partly, a non-disclosure agreement (NDA) should be signed initially to clarify what and in which resolution data might be disclosed, or when the LCI data cannot be disclosed, reviewers with full access to the LCI data should be instated to ensure quality. o Aligned with the scoping phase (data requirements), comparisons between technologies of different maturity should include representative LCI datasets that consider upscaling and learning curves (Thonemann et al., 2020). In prospective LCA, prospective LCI background databases, such as the premise developed by Sacchi et al., 2022, should be used. o Include systematic quantification of data quality via the pedigree matrix and uncertainties, e.g., ranges, distributions, or uncertainty factors associated with LCI data (Muller et al., 2016)	o Perform an impact assessment (instead of just an inventory of pollutants, GHG emissions, or resources) to account for the relative potencies of the emission/resource flows. o Systematic inclusion of all environmental impact categories to avoid burden-shifting from one environmental problem to another. (If environmental impact coverage is truncated, as per the goal and scope definition, it is important to (i) transparently justify and document the reduced impact coverage, and (ii) adapt and document the interpretation of the results accordingly, e.g., with no overstatement))	o Ensure that all interpretation steps are applied. The guidance that builds and complements ISO 14044 should be used (Laurent et al., 2020). The steps include: - Perform completeness check. - Perform consistency check. - Perform sensitivity check, including sensitivity (e.g., allocation principles or substitution for fuels) and uncertainty analysis (e.g., global sensitivity analysis) (Kim et al., 2021). This approach can allow for (i) testing the robustness of the results and identifying the most influential sources of uncertainties and (ii) quantifying potential variability and sensitivity to different scenarios. - Identify significant issues (closely tied to the run of sensitivity and uncertainty analyses, but not only; cf. (Laurent et al., 2020) - Draw conclusions, limitations, and recommendations concerning the study's goal and account for uncertainties and sensitivities identified/tested. It should include transparent documentation of what the study cannot answer, where relevant. o *Outside the scope of the interpretation phase:* Ensure communication is appropriate to the target audience, and use communication visuals (Gavankar et al., 2015; Hollberg et al., 2021).

Table 5

Recommendations directed to LCA method developers for increasing the relevance and robustness of LCA studies in the aviation sector. Guidance is provided for each LCA phase, except for the goal and scope definition phase, as it is not relevant.

LCI	LCIA	INTERPRETATION
o Develop guidance for assessing large-scale studies and future changes, including prospective perspectives to reflect technological development over time and consequential LCI modeling to consider a change-oriented viewpoint (Ekvall et al., 2016; Laurent et al., 2020) o Development of modular LCI datasets to support LCA applications within the aeronautics sector (as a possible way to circumvent data gaps and confidentiality issues), with a focus on: - *Aircraft systems*: focus on airframe material production and airframe production, special alloy production (incl. new manufacturing processes, e.g., additive), assembly, decommissioning, recycling, and end-of-life (aircraft-specific treatment; different scenarios to explore) - *Alternative aviation fuels and propulsion*: Focus on (i) AAF, incl. potential iLUC aspects, (ii) H_2 production and storage, covering all potential pathways of grey, blue, and green H_2 as well as storage alternatives (liquid, cryogenic); and (iii) battery technologies (incl. emerging like Li-S, Li-O_2). Investigate potential changes, e.g., emissions, in propulsion mode and behavior resulting from the use of AAF and other fuels. - *Airport*: focus on LCI for airside activities as well as on creating consumption-based, module-based LCI for terminals/buildings and landside similar to LCI requirements for an urban area (incl. onsite activities as well as activities outside the airport resulting from consumption of commodities and services in the airport). o Improve data availability and accessibility of environmental data by, e.g., using application programming interfaces of flight tracking services or open environmental data provided by global sensor networks. o Approaches for inventory data gap filling proposed by Zargar et al., 2022, like data-driven, mechanistic, or future inventory modeling using, e.g., artificial neural networks, process simulations, or learning curves.	o Advance LCIA methods to address the following problems: - Develop characterization factors (CFs) for altitude-differentiated emissions from aircraft operations, incl. water vapor (relevant for H_2 fuel) and other non-CO_2 emissions (e.g., NO_x, soot) impacting climate change and, where also relevant, stratospheric ozone depletion - Further refine CFs for AICs based on work by Cox et al. (2018) and research outside LCIA. Potential differentiation according to climate and altitude in the CFs should be explored. - Develop CFs for noise damage to ecosystems and human health (incl. spatial differentiation), building on previous works by Cucurachi and Heijungs, (2014). This impact is particularly relevant concerning the LTO cycle of aircraft and when assessing airports. - Develop CFs for toxicity-related impacts (chemical releases damaging human health and ecosystems), particularly for emissions specific to the aeronautics sector (e.g., special alloy production processes). Consensus-based USEtox could serve as a starting point, although further research to better address inorganics is needed (Fantke et al., 2021; Fantke et al., 2017). The toxic impact categories are relevant for any considered systems since nearly all processes are associated with chemical releases (e.g., aircraft manufacturing, biofuel production, fossil fuel combustion, and metal recycling). - Continue development of CFs to assess better mineral/metal use and accessibility based on dissipation and accounting for different anthropogenic stocks (products in use, product in hibernation, like in landfills) and lithosphere (Owsianiak et al., 2022). Materials criticality should also be included (Graedel et al., 2015; Schrijvers et al., 2020). This impact category is particularly relevant (but not only) to addressing aircraft manufacturing, recycling, and end-of-life. - Model missing impact pathways for comprehensively assessing water use damages to ecosystems, human health, and resources, accounting for both consumption of water (extraction from surface water and groundwater, and modeling of green water scarcity) and its degradation (contamination by direct and indirect pollutant releases, e.g., pesticides) (Pierrat et al., 2022). This impact category is particularly relevant (but not only) when assessing SAF production. - Strengthen the assessment of land use damages to biodiversity as well as to ecosystem services, covering physical changes to vegetation cover and land (e.g., fragmentation, degradation) as well as to soil (e.g., compaction, erosion). This impact category is particularly relevant (but not only) when assessing SAF production. o In the above, systematically quantify the uncertainty associated with the developed CFs (Verones et al., 2020).	o Additional research is needed to make uncertainty assessments (propagated through LCI and LCIA), combined with spatial differentiation, fully operational for practitioners o *Outside the scope of the interpretation phase:* Guidelines for good practices in communicating and visualizing LCA results specific to aeronautics can be developed similarly to Hollberg et al. (2021)

8. Methodological recommendations

Tables 4 and 5 gather a number of recommendations explicitly addressing the application of the LCA methodology and identifying research needs for its further development and have been compiled from the review and analyses developed in Sections 4-7. The recommendations in both tables are subdivided into the LCA phases and target LCA practitioners and LCA method developers. They are complemented in the following by overarching points directed at these target groups and aviation industry stakeholders at large.

To ensure the robustness of the LCA studies, reliable, case-specific, and detailed LCI datasets are needed. The GREET model https://greet.es.anl.gov/ (GREET Aviation Module Instruction Manual, 2022) and the ecoinvent database (Wernet et al., 2016) were commonly used to quantify the air emissions from aircraft flights and LTO in the reviewed studies. Additional model references for calculating toxic air pollutants from aircraft LTO can be found in Kurniawan and Khardi (2011). Important LCI gaps remain to cover all aspects of aircraft systems. In this context, data accessibility is essential, and aviation industry stakeholders must engage voluntarily in sharing information, which can support developing such LCI datasets so that they may be used to support other LCA studies in the field. When performing an LCA for external purposes, practitioners are encouraged to clarify early, e.g., via a non-disclosure agreement, which data can be published and which data must be concealed due to their sensitive nature. LCA method developers are called upon to develop procedures and approaches that may allow adapting original confidential datasets so other practitioners can reutilize them. This adaption can be achieved through data averaging, the use of proxies, and/or data aggregation, all of which should be transparently documented in a reviewable scheme in close cooperation between the LCA practitioner and the industry stakeholders involved (Kuczenski, 2019). Industrial stakeholders, jointly with LCA method developers, should additionally explore options for blockchain-based LCI to secure and transmit LCI data within the aviation supply chain while allowing for a trustworthy assessment (Lin et al., 2021). It is important to note that such recommendations are not limited to LCI datasets but should also be followed when addressing sustainability reporting of aircraft manufacturers and airports (Saavedra-Rubio et al., 2022).

As described in earlier sections, gaps exist in assessing specific environmental impacts, and practitioners need to keep updated on new developments so these can be integrated when conducting comprehensive LCA. In such integration, practitioners should take particular care to ensure consistent coupling between LCI and LCIA flows, i.e., matching the LCI elementary flows (emission or resource consumption of a substance) and their detailed features (e.g., location, emission compartment, or archetype) with the corresponding characterization factors in LCIA. Specific guidance exists in this field, including approaches and steps to address gaps or inconsistencies (Verones et al., 2020). The LCI-LCIA connection issues have recently been subject to attention in the LCA community, and concerted efforts within the UNEP Life Cycle Initiative's Global LCA Data network (GLAD) and Global Guidance for Life Cycle Impact Assessment Indicators (GLAM) flagship projects are currently taking place to address them (Edelen et al., 2017; Life Cycle Initiative, 2022; Sanyé-Mengual et al., 2022).

Finally, a crucial cross-cutting aspect of LCA is the characterization of uncertainties (Verones et al., 2020). Although necessary research has emerged in the past years, additional research is still needed to enable entirely consistent, systematic, and quantified uncertainty assessments in LCA studies that can integrate uncertainty propagation through all LCA phases (Kim et al., 2021; Igos et al., 2019). Guidance for addressing them in the interpretation phase may be found in Laurent et al. (2020), who provide overarching recommendations for conducting the LCA interpretation phase.

9. Conclusion

The goal of net zero emissions policies, set to be achieved by 2050, is to minimize CO_2 emissions in the atmosphere from all sectors, with high importance set on transportation. The review results show that the aircraft life cycle CO_2 emissions are dominated by tailpipe emissions from direct kerosene fuel combustion during the operation stage of civil aircraft, followed by fuel production. The most currently-promising kerosene substitutes for reducing climate change impacts seem to be second-generation biofuels and electro fuels using carbon capture technologies. Hybrid-electric and electric aircraft performed better than conventional aircraft when the alternative fuel and electricity GHG emissions were low. The importance of non-CO_2 emissions and indirect impacts from emissions of NO_x and AIC, respectively, has been recognized. Noise annoyance and air pollution are important environmental issues from airport operations, although there is little quantitative information on life cycle noise emissions due to methodological limitations. In order to enable informed decisions on the impacts of the civil aviation sector and to support both practitioners and method developers, comprehensive recommendations are provided to ensure (i) comparability of results by e.g., clearly defining the FU and system boundary, (ii) increased transparency and availability of LCI data, and (iii) advancement of LCIA methods to fill gaps in impact assessment of aviation activities including, e.g., altitude-differentiated impacts.

CRediT authorship contribution statement

Lea Rupcic: Conceptualization, Methodology, Investigation, Resources, Data curation, Formal analysis, Writing – original draft, Writing – review & editing, Project administration. **Eleonore Pierrat:** Methodology, Investigation, Formal analysis, Writing – original draft, Writing – review & editing, Conceptualization. **Karen Saavedra-Rubio:** Investigation, Writing – original draft, Formal analysis, Conceptualization, Writing – review & editing. **Nils Thonemann:** Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Supervision. **Chizoba Ogugua:** Investigation, Writing – original draft, Data curation. **Alexis Laurent:** Writing – review & editing, Supervision, Funding acquisition, Formal analysis, Conceptualization.

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.

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Appendices A–C. Supplementary material

Supplementary data, containing the scope of the review, identification of the studies, supportive materials for Section 5, and environmental findings for unmanned aerial vehicles (UAVs) can be found in Appendix A. List of reviewed publications can be found in Appendix B, and supplementary material for alternative aviation fuels and propulsions in Appendix C. Data are also fully available on the Zenodo repository; https://doi.org/10.5281/zenodo.7180085". Supplementary data to this article can be found online at https://doi.org/10.1016/j.trd.2023.103717.

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