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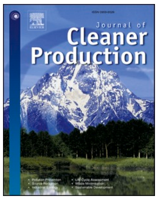

Prospective life cycle inventory datasets for conventional and hybrid-electric aircraft technologies

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ABSTRACT

Hybrid-electric aircraft represent a promising solution for the urgent need to decarbonize short-haul flights and bolster aviation sustainability. Nevertheless, the realization of hybrid-electric aircraft demands rigorous environmental impact analysis, given the substantial investments, time, and research required for technology development. This study offers a comprehensive life cycle inventory spanning the years 2030, 2040, and 2050 for both conventional and hybrid-electric aircraft configurations. Our inventory datasets are meticulously constructed through a systematic approach, ensuring data harmonization by drawing upon scientific literature, industry expertise, and primary data sources. This extensive dataset encompasses all pertinent systems necessary to model the environmental footprint of flights covering distances ranging from 200 to 600 nautical miles, utilizing a 50-passenger aircraft with the ATR42 as a reference model. Additionally, we furnish supplemental data for end-of-life considerations and uncertainty analysis. The systems under examination include the airframe, powertrain, power electronics and drives, batteries, fuel cells, hydrogen onboard storage, airport infrastructure, and battery charging stations. Notably, the carbon footprint of conventional aircraft aligns with data from the ecoinvent v3.8 database; however, our provided datasets are more than tenfold more detailed and incorporate a forward-looking perspective. These meticulously curated life cycle inventories can be amalgamated to simulate the potential environmental ramifications of conventional aircraft powered by kerosene or alternative aviation fuels, hybrid-electric aircraft utilizing battery technology, and hybrid-electric aircraft employing hydrogen as a fuel in conjunction with batteries. In this context, our findings play a pivotal role in nurturing the development of technology roadmaps that prioritize environmental sustainability within the realm of regional aviation.

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1. Introduction

As the transportation sector continues to evolve rapidly, with significant advancements in emerging technologies, there is a pressing need to transition away from conventional, fossil-based fuels towards more sustainable alternatives (Kallbekken and Victor, 2022). Batteries, alternative aviation fuels (AAF), and hydrogen (H_2) fuel cells have emerged as promising solutions to curb the climate change impacts of traditional transportation systems (Afonso et al., 2023). However, to ensure that this shift to emerging technologies is environmentally beneficial, it is imperative to conduct comprehensive sustainability assessments, such as a Life Cycle Assessment (LCA) (Thonemann et al., 2020).

LCA is a widely accepted methodology that quantifies the potential environmental impacts of products and systems across their entire life cycle, from raw material extraction to end-of-life (EOL) disposal (ISO, 2006a, 2006b). It enables decision-makers to make informed choices by providing a holistic view of the environmental performance of different technologies. However, when it comes to the application of LCA to transportation systems involving batteries, alternative fuels, and H_2 fuel cells, significant gaps exist within the current state-of-the-art prospective LCA (pLCA) framework (Sacchi et al., 2022; Thonemann et al., 2020).

The first gap arises from the limited availability of Life Cycle Inventory (LCI) datasets specific to emerging technologies associated with aviation systems (Rupcic et al., 2023). LCI datasets are compilations of input and output flows, including both intermediary flows (e.g., products, materials, processed energy, waste, etc.) and relevant elementary flows (emissions and resource consumption flows) associated with the provision of one unit of product, technology or service (Saavedra-Rubio et al., 2022). Existing LCI databases, such as the ecoinvent LCI database, do not adequately capture the material needs, the manufacturing processes, the usage performance, let alone potential EOL treatments of future technologies of batteries, H_2 fuel cells, and other alternative fuels (Wernet et al., 2016). Within the literature, studies remain to assess direct fuel combustion emissions (Prussi et al., 2021), compare powertrains (Sarathy et al., 2022) or fuels (Rosenfeld et al., 2019), and limiting aviation transition pathways to certain types of alternatives (Sacchi et al., 2023) Consequently, LCA practitioners face challenges in accurately assessing and comparing the environmental footprints of these emerging technologies taking a full life cycle perspective. Furthermore, while some LCI data can be found in the literature, the inconsistency and lack of transparency hinder reliable analysis and decision-making (Rupcic et al., 2023).

The second gap stems from the absence of a prospective dimension in available LCI datasets. LCI databases predominantly focus on retrospective dimensions, providing insights into the environmental impacts of present technologies (van der Giesen et al., 2020). However, it is essential to anticipate and address potential environmental impacts to ensure the sustainability of emerging technologies in aviation systems. By integrating a prospective dimension into LCI datasets, LCA can offer valuable foresight and aid in making informed decisions considering potential environmental consequences (Steubing et al., 2023).

This study addresses these gaps by providing LCA practitioners with robust and comprehensive LCI datasets. These LCIs can be used to assess the environmental impacts of emerging aviation technologies and beyond, such as batteries, alternative fuels, and H_2 fuel cells, in LCA studies. Our approach utilizes a recently developed LCI data collection framework (Saavedra-Rubio et al., 2022) to compile and offer complete access to a wide array of technologies, both present- and future-oriented. This study primarily focuses on aircraft systems for a short-haul, regional class, and 50 PAX; it was part of a project for gauging the environmental impacts of hybrid-electric aircraft systems (project GENESIS within the Clean Sky 2 program; https://www.genesis-cleansky.eu/). Furthermore, the provided LCI datasets may be adapted for other transportation systems, including battery and fuel cell manufacturing for electric vehicles in road transport systems.

Our research seeks to enable a more accurate and holistic assessment of the environmental sustainability of evolving aviation systems. Through the integration of comprehensive and transparent LCI datasets, as well as the incorporation of a prospective dimension, we aim to support decision-makers in identifying sustainable pathways and minimizing the environmental impacts associated with the adoption of emerging aviation technologies.

2. Material and method

2.1. LCI dataset-building methodology

The methodology adopted to build the LCI datasets relies on the detailed guidance provided by Saavedra-Rubio et al. (2022), who developed a stepwise approach to collect LCI data and structure it into LCI datasets with the help of a generic LCI data collection template (Fig. 1A). Owing to their technology spans, the generation of the LCI datasets in the current study can thus be regarded as a wide operationalization of the LCI data collection framework by Saavedra-Rubio et al. (2022).

Primary data were collected throughout the Clean Sky 2 project GENESIS, which gathered several technology-specific experts from academia and industry (cf. Section 2.2 for an overview of technology coverage). The LCI data collection template developed by Saavedra-Rubio et al. (2022) was utilized to ensure harmonization and transparency across the different datasets concerning LCI data reporting (Step 1 in Fig. 1A). For each technology-specific LCI dataset, the generic template was adapted with specific processes and flows pertaining to different elements of the technology life cycle. Iterations were then performed with technology experts to progressively fill in the thus-customized LCI template with primary data and perform verification and checks of the data (Step 2 in Fig. 1A; see also Saavedra-Rubio et al. (2022) for further details). After the evaluation was performed and uncertainty characterized (Step 3 in Fig. 1A), consistent LCI datasets were obtained.

2.2. Overview of technologies addressed

The generated LCI datasets covered technologies required to explore different aircraft configurations and technology advances in energy supply and storage for three time horizons. Technology foresight assessments and analyses of top-level aircraft requirements were conducted in the GENESIS project to identify relevant energy technologies in 2030 (short-term), 2040 (medium-term), and 2050+ (long-term) time horizons (see Marciello et al. (2023) and Meindl et al. (2023a)). Propulsion systems in scope include internal combustion engines (ICE, with the supply of conventional or AAF), batteries, fuel cells, and a combination of those (Marciello et al., 2023). An overview of the different technology configurations for each time horizon is provided in Fig. 1B.

To provide an exhaustive dataset for each configuration, LCIs for specific aircraft systems (aircraft, fuels, or airport) and their components were established following the LCI building approach described in Section 2.1. The combinations of the generated LCI datasets for each configuration are also shown in Fig. 1B. A life cycle perspective was adopted within each LCI dataset, covering all key processes from raw materials extraction, manufacturing, and use up to the final EOL. Data regarding life cycle stages are included directly in each respective LCI dataset (see Sections 2.3.1-2.3.7). Weights and material composition within the datasets vary for each time horizon and configuration.

2.3. Detailed LCI modeling for each technology

This section briefly describes the LCI modeling associated with each key technology or component of the aircraft, airport, and fuel systems. More specifically, LCI modeling is described for the airframe (see section

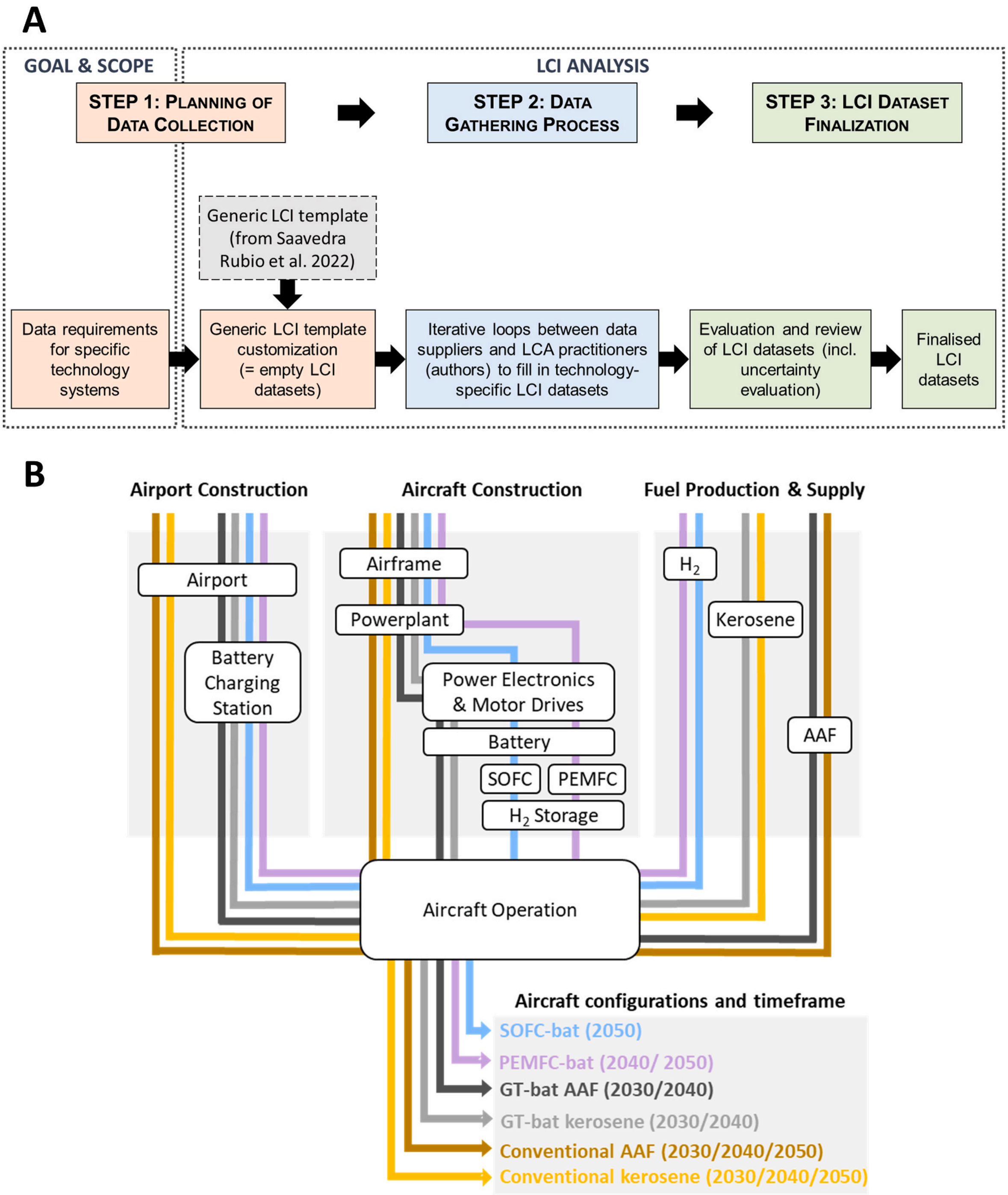

Fig. 1. **A.** Life cycle inventory (LCI) dataset-building methodology (adapted from Saavedra-Rubio et al. (2022)). Only the goal and scope definition and LCI analysis phases of the life cycle assessment (LCA) methodology are illustrated. The final LCI datasets feed into the system modeling and further impact assessment (not represented in the figure as outside the study scope). **B.** Overview of the aircraft configurations for which LCI datasets are provided (shown in white boxes). Each configuration is represented by a color that indicates which database belonging to the airport, aircraft, or fuel systems is to be included when assembling the inventory. Weights and material composition within the files vary for each time horizon (AAF = Alternative aviation fuel, bat = Battery, GT = Gas turbine, H_2 = Hydrogen, PEMFC = Proton exchange membrane fuel cell, SOFC = Solid oxide fuel cell). Please see the repository at https://doi.org/10.5281/zenodo.8155003 for further details on each technology. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

2.3.1), powertrain (see section 2.3.2), power electronics and drives (see section 2.3.3), battery systems (see section 2.3.4), fuel cells and H_2 storage systems (see section 2.3.5), fuel systems (see section 2.3.6), and airport systems (see section 2.3.7).

2.3.1. *Airframe*

The airframe is the main structural component of the aircraft, encompassing the fuselage, undercarriage, empennage, and wings. It includes systems, interiors, and operative equipment. Airframe components were manufactured based on the mass breakdown provided by the aircraft's preliminary design (Marciello et al., 2023; Nicolosi et al., 2022). LCI data for materials and energy requirements were derived from literature sources (Annamalai and Puri, 2006; Baroutian et al., 2013; Fabre et al., 2022; Lopes, 2010; Orefice et al., 2019, 2020; Wernet et al., 2016; Yang et al., 2021); additional details are available in Appendix.

Energy consumption and emissions related to airframe manufacturing were estimated by multiplying the mass of the airframe components by the energy requirement and emissions per unit of component mass (Airbus, 2022). Wing materials were considered, while no prospective changes were made for other airframe components. The wings were assumed to be made of aluminum alloy for conventional aircraft. In hybrid configurations, carbon fiber reinforced composite (CFRP) was used for the wings, resulting in lighter weight (Johanning and Scholz, 2014). In the long-term scenario, advanced biocomposites were used for the wings, increasing their weight (Ramachandran et al., 2023).

The airframe was assumed to operate for 20 years, with an average of six typical daily missions covering 200 nmi (370.4 km) each. Aircraft maintenance was not considered in the LCI modeling.

At the end of the airframe's life, dismantling and recycling of the structural components took place. Based on the Airbus Pamela project, waste treatment methods such as material recovery, incineration, and landfill were employed in varying proportions for each structural material and component (Lopes, 2010).

2.3.2. *Powertrain*

The aircraft powertrain comprises all the necessary components to generate the required thrust for take-off, climb to the desired cruise altitude, and maintain the selected design speed during the cruise phase. It encompasses the power electronics, drives, energy storage, and propulsion systems. Section 2.3.3 focuses on the LCI of power electronics and drives, including electric motors. The energy storage system varies based on the configuration, as illustrated in Fig. 1B. For this study, we differentiate between internal combustion engines (ICE) and hybrid-electric systems utilizing batteries and/or H_2. Battery- and H_2-based systems are addressed separately in Sections 2.3.4 and 2.3.5, respectively. Below, we describe ICE systems; additional details regarding the LCI modeling can be found in Appendix.

For all ICE configurations, turboprop engines are employed as the preferred propulsion system due to their technical and economic advantages (Gudmundsson, 2022; Torenbeek, 1982). Specifically, the adopted technology involves free-turbine three-spool turboprop engines (Di Stasio, 2022). This choice offers various technical benefits, including increased overall pressure ratio, enhanced engine efficiency, and compatibility with AAF (Di Stasio, 2022). Anticipated advancements in engine materials and manufacturing techniques are considered, such as the utilization of nickel-based single-crystal superalloys for turbine disks and blades in the short- and medium-term and transitioning to SiC ceramic matrix composites in the long-term (Greitzer et al., 2010).

Regarding the manufacturing of ICE, the energy consumption and water usage for producing the turboprop engine were estimated based on corporate data from Airbus, similar to airframe production (section 2.3.1 (Airbus, 2022),). The material composition for each component was derived from a compilation of literature sources (see details in Appendix). Material losses were estimated using buy-to-fly (BTF) ratios obtained from various references, ranging from 1.5 for the ceramic matrix to 30 for aluminum and titanium alloys for propeller hubs (Aerospace Manufacturing, 2010; Kobryn et al., 2006; Lambert, 2011; López De Lacalle et al., 2016; Mohd Yusuf et al., 2019).

The LCI data of the powertrain's usage stage includes direct emissions from fuel combustion during flights encompassing major greenhouse gases and air pollutants such as NO_x, CO, hydrocarbons, CO_2, H_2O, and SO_2. The emissions were estimated using the methodology by Di Stasio (2022). Assuming a 20-year lifetime, consistent with the airframe, the LCI data were scaled based on the total mass determined by the preliminary design, resulting in reduced material and energy requirements. The medium- and long-term improvements in engine design and materials were incorporated into the model to simulate lower fuel consumption and emissions during flight. After the powertrain reaches the end of service, it is dismantled. Following industry practices, the engine, the gearboxes, and the propellers are assumed to be reused, while the fuel system elements are either reconditioned and reused or recycled (IATA, 2022; Towle et al., 2004; Zhao et al., 2020).

2.3.3. *Power electronics and drives*

Power drives transfer the energy from the energy-generating to the energy-consuming components, while power electronics manage the conversion between analogic current (AC) and direct current (DC) as well as the adjustment of the voltage level between the battery, fuel cell, high-voltage onboard network and the low-voltage onboard network in the aircraft. The power drives technology chosen was permanent magnet synchronous machines (PMSM) because permanent magnets increase the overall power density of the electric machines, which is desirable for aviation applications (Meindl et al., 2023b). The modeling details of the power electronics and drives are documented in Appendix.

The manufacturing of the power electronics (relevant for all configurations except ICE; see Fig. 1B) included a motor drive inverter, a battery DC-DC converter, a DC-AC grid inverter, and an isolating DC-DC converter for the low-voltage supply (Meindl et al., 2023b). Fuel cell DC-DC converters and generator drive AC-DC inverters were used exclusively for fuel cell and ICE-battery configurations. The materials and energy inputs used in the LCI of both power electronics and drives were scaled from the inventory of an automotive power electronic inverter unit and traction machine published in (Nordelöf et al., 2018, 2019). The scaling was done proportionally to the physical design constraints and expert assessments of the power electronics and traction machines. The lifetime of the power electronics and traction machines was assumed to be 15 years without replacing parts. A new traction machine was designed, simulated, and constructed for medium- and long-term hybrid configurations (see details in Appendix). LCI data of the power electronics were generated based on expert estimates for future converters and the Nordelöf model, using simulations to determine the power modules and essential components of a converter in percentage (see Appendix).

The EOL of the inverters and the converters were assumed to be partly recycled, with 90% recovery of the copper and aluminum content; circuit boards were considered to be recycled at a rate of 65%.

2.3.4. *Battery systems*

The battery system includes the battery and the charging stations. Separate LCI datasets were created for the battery manufacturing, EOL, and charging station due to the different availability of specific data for each part.

2.3.4.1. Battery manufacturing. Lithium-ion (Li-ion), lithium-sulfur (Li-S), and lithium-air (Li-air) batteries were considered relevant battery technologies (Varzi et al., 2020). Li-ion batteries offer high energy density, low self-discharge rates, and long lifespan, making them a popular choice for many applications (Nitta et al., 2015). Li-S batteries have the potential to provide high energy densities and low costs thanks to the high theoretical capacity of sulfur and its abundance (Ma et al., 2021). However, challenges such as low cycle life and poor stability still need to be addressed before mass commercialization. Li-air cells would potentially unlock high energy densities up to 1700 Wh/kg (Girishkumar et al., 2010). However, Li-air batteries still face challenges, such as low electrical efficiencies, low discharge C-rates, and low lifetimes (Imanishi and Yamamoto, 2019). The specifications of the considered batteries are represented in Table 1, and the modeling details of the LCI are summarized below and detailed in Appendix.

The LCI of battery manufacturing covers the main components of the batteries: casing, battery management systems, and battery modules (including battery cells). The Li-ion batteries were dimensioned using the Batpac model and literature to meet the energy requirements of the powertrain and specify the battery pack mass (Porzio and Scown, 2021).

Table 1
Overview of the battery technologies manufacturing and use characteristics.

Components of the battery cell	Li-ion	Li-S	Li-air
cathode	NMC 811	graphene-sulfur composite	air (O_2)
anode	graphite-silicone	lithium metal	lithium metal
electrolyte	LiPF6 as salt, ethylene carbonates as solvent	[Li10Ge (PS6)2]	$LiClO_4$ in solution of tetraethylene glycol dimethyl ether
specific energy of the battery pack (Wh/kg)	285	672	994

Considering future improvements, the battery cell mass was assumed to represent 80% of the total mass in 2030 and 90% in 2040 and 2050 (Löbberding et al., 2020). The material composition for each battery cell chemistry was based on literature sources and published LCIs (Barke et al., 2023; Nelson et al., 2011; Wang et al., 2020). The mass of the remaining components was extracted from Yuan et al. (2017), and similar material distribution was assumed for the Li-S and Li-air batteries. The energy demand for producing the battery was estimated from the literature (Crenna et al., 2021; Deng et al., 2017, 2019; Romare and Dahllöf, 2017; Wang et al., 2020).

During the use stage, the battery packs are recharged between flights, which is realistic because the battery charging time was not considered to exceed 45 min. The battery's lifetime ranged between 2.5 and 3 years of continuous operation. However, they are only used for part of the flights due to their limited energy storage capacity. Hence, 10% of the modules should be replaced during the aircraft's lifetime.

2.3.4.2. Battery end-of-life. The battery EOL was modeled based on the processes and operational data of a Li-ion battery treatment factory, with a capacity of 2000 kg battery/year, located in Germany and operated by ACCUREC-Recycling GmbH. All assumptions used to build the LCI datasets are documented in Appendix and summarized below.

The recycling processes of the Li-ion and Li-S batteries included the battery pack dismantling, the pyrolysis of the battery modules, and a multistep mechanical treatment. Primary data from the recycling facility were used to model ancillary material input, energy demand, and the material composition of the active material fractions for Li-ion recycling. The recycling process of Li-air batteries was assumed to be similar but without pyrolysis. The primary data from the Li-ion recycling process were rescaled to populate the LCI datasets of the Li-S and Li-air batteries.

Subsequently, to recycle the batteries, the active material fractions and the battery casing were assumed to be further treated so that critical metals could be partially recovered. Based on experts' opinions from the metal recycling sector, aluminum and nickel are thus assumed to be 95% recovered and copper 90% recovered. To reflect the progress of the recycling processes in the future, more aluminum and 95% of lithium were assumed to be recovered in 2040 and 2050. Despite including metal recovery, the recovery processes were not modeled in the LCI dataset due to lack of data.

2.3.4.3. Battery charging station. Fast charging stations for aircraft are yet to be developed and made available. Therefore, in the absence of detailed knowledge, the Combined Charging System (CCS) standard limits for electric vehicles were used as starting point, which is the preferred charging standard in Europe and North America (Abogdallah, 2023). In all time horizons, the charging station was designed to charge hybrid aircraft with batteries in 45 min (Meindl et al., 2023a, 2023c). The progress of technology was modeled assuming a functioning at 600 V and 500 kW in 2030 and 1200–1300 kW in 2040 and 2050 (Meindl et al., 2023a).

The assumptions for the LCIs of the manufacturing included all the main components, including casing, display unit, power module AC/DC, power module DC/DC, and transformer are documented in Appendix. The energy and material demand for the power modules were rescaled from the same dataset used for the power electronics and drives LCI datasets (see Section 2.3.3). The mass of the other components was derived from the characteristics of an existing high-power, fast charging station from ABB (ABB, 2022), which was dismantled and analyzed at component level (see Appendix).

The modeling of the use stage was made assuming 5 charging stations, including 1 spare in case of a defect, to fulfill the need of the airport (Section 2.3.7 for details about this airport) and charge a hybrid aircraft in 45 min. The charging station EOL was assumed to include recycling relevant materials and components (e.g., metals from housing, plugs, transformers), while the remaining fractions were modeled as landfilled (Carlen et al., 2011).

2.3.5. Fuel cells and hydrogen supply systems

The fuel cell (FC) systems for an H_2-fueled aircraft consist of fuel cells and an H_2 tank. The aircraft's powerplant includes battery and FC systems (see Fig. 1B). FCs convert the chemical energy of H_2 into electrical energy by reacting it with oxygen from the air. Two promising technologies, proton exchange membrane FCs (PEMFC) and solid oxide FCs (SOFC), have been studied (Ho et al., 2014). This article briefly describes each technology and discusses H_2 storage systems. More information can be found in Appendix.

2.3.5.1. Proton exchange membrane fuel cells. A generic PEMFC system was defined for medium- and long-term aircraft configurations. Proton Motor Fuel Cell GmbH provided the preliminary design based on their expertise, resulting in 2 FC plants with 4 FC systems each. The aircraft had a total number of 16 PEMFC stacks, providing 1180 kW within the medium–term and 1273 kW within the long-term. The PEMFC stack included 400 cells with a gravimetric power density of 4.56 kW/kg and a lifetime of 10,000 operating hours. Details of the LCI dataset for the PEMFC plants are documented in Appendix.

For the PEMFC manufacturing LCI, technologies used in heavy-duty road transport applications were referenced to optimize volume and weight. The PEMFC used a coated membrane with perfluorinated polymer and sulfonic acid groups coated with platinum and iridium. Material composition, mass, electricity, heat, and water demand were determined using expertise from Proton Motor Fuel Cell GmbH and data from existing PEMFCs on the market. The bill of materials, water and energy inputs, and waste for the production of chemical constituents (e.g., polytetrafluoroethylene, perfluorosulfonic acid, carbon nanotubes) in the FC cells were modeled using ecoinvent data and literature (Wang et al., 2020; Weber et al., 2018; Wernet et al., 2016). However, energy demand for some components was not included due to lack of data (e.g., FC cells assembly, load cables). The LCI model included partial information on chemical production plant facilities based on literature. Realistic assumptions were made for the medium- and long-term PEMFC systems based on previous developments, with conservative and progressive bounds.

The LCI of the use stage included cooling fluids and water vapor emissions associated with H_2 combustion during flight. Water vapor emissions were calculated based on the energy demand, PEMFC systems conversion efficiency, H_2 energy density, and H_2 combustion stoichiometry.

The LCI for EOL was replicated by Stropnik et al. (2019). Metallic parts had material recovery ratios ranging from 76% (platinum) to 96% (aluminum). Recyclable polymers were also treated for material recovery, while other materials were incinerated with energy recovery.

2.3.5.2. Solid oxide fuel cells. The SOFC functions similarly to the PEMFC but uses nonporous "solid ceramic" electrolyte, such as zirconium oxide stabilized with yttrium oxide, and operates at high temperatures (600–1000 °C) (Akinyele et al., 2020). It can achieve an electrical efficiency above 60%, approaching the theoretical thermodynamic efficiency of 75% (Akinyele et al., 2020).

For the long-term aircraft configuration, two independent SOFC plants with a power density of 1.875 kW/kg were used (Lemoine et al., 2023). Each SOFC plant consisted of 6 SOFC stacks, with a replacement rate of 0.1 unit/year during the aircraft's lifetime. Detailed information on the LCI modeling and underlying assumptions can be found in Appendix.

The LCI dataset for the SOFC plant manufacturing included all the main components, such as the fuel cell stack, air system, fuel flower, heat exchanger, and power electronics (DC/DC and AC/DC converters). The power density of the SOFC stack in 2050 was assumed to reach 2.5 kW/kg. The mass distribution of the stack (75%) versus the other components (25%) was estimated based on the ratio of their power densities. The chemistry of the SOFC stack was chosen to meet the technical requirements with an anode made of nickel oxide and yttrium-stabilized zirconia, a cathode of lanthanum alloys. The composition, energy, and water demands for manufacturing were derived from literature and rescaled according to the required power density (2.5 kW/kg) and total power output of the SOFC plants (2480 kW) (Mehmeti et al., 2018; Scataglini et al., 2015). The LCI of power DC/DC and AC/DC modules were rescaled from the same dataset used in the power electronics and drives LCI (Nordelöf et al., 2019).

Similar to the PEMFC use stage, the LCI dataset for the SOFC included the water vapor emissions associated with the H_2 combustion during flight.

The SOFC EOL was not covered due to the absence of recycling technology. Recycling strategies for lanthanum manganite and steel may hold promise in minimizing environmental impacts and resource waste (Valente et al., 2018).

2.3.5.3. Hydrogen tanks. In this study, MAHYTEC SAS, an H_2 storage system manufacturer, designed H_2 tanks to meet the aircraft requirements (Marciello et al., 2023). The LCI datasets were derived from scientific literature and onsite production facility data (capacity of 500 tanks/year in 2022). More details about the LCI modeling are available in Appendix.

For medium-term FC systems, H_2 was stored in a gaseous, compressed form at 700 bar (see Fig. 1) using a " type V″ tank made of CFRP with a capacity of 2.432 m^3 (Air et al., 2023). The tank's LCI dataset included the mass of CFRP and fiber fraction calculated based on the tank volume and wall thickness required for 700 bar of compressed H_2. In the long-term, advancements are expected to enable liquid H_2 storage in a cryogenic tank (Lemoine et al., 2023; Marciello et al., 2023). Therefore, smaller tanks with capacities of 1.04 and 1.34 m^3 for the SOFC and PEMFC configurations, respectively, were used, along with insulation to maintain the H_2 at −253 K. The additional components, ancillary materials, waste flows, and energy requirements for manufacturing were derived from primary data obtained from the production facility and literature (Colozza, 2002; Zheng et al., 2018).

Four tanks were required to store the H_2 during aircraft operations, and the refueling time was estimated to be 1 h. In the long-term configuration with liquid H_2, 100 kg of coolant was also considered. The EOL of the tank was modeled based on expert judgment from experts of MAHYTEC SAS. The CFRP components were assumed to be recycled up to 70%, with the epoxy matrix separated from the carbon fibers, which would be reused for applications with lower mechanical property requirements. The steel parts were assumed to be 100% recycled.

2.3.6. *Fuel systems*

The fuel systems required in the configurations include electricity, kerosene, drop-in alternative aviation fuel (AAF), and kerosene. LCI datasets were developed only for H_2 production and supply because other databases provide LCI for conventional fuels, alternative fuels, and electricity production. Prospective LCIs for electricity, synthetic kerosene, and kerosene production are available in the ecoinvent database adjusted to 2030, 2040, and 2050 using the premise framework (Sacchi et al., 2022; Wernet et al., 2016).

In this study, H_2 production is considered using a plant with a total capacity of 200 MW and 50 tons per day. The plant consists of 10 alkaline electrolyzers with a capacity of 20 MW each. The electrolyzer stacks are assumed to have a lifetime of 60,000–90,000 operational hours (Delpierre et al., 2021). The H_2 is then liquefied onsite by cooling it below −253 °C to increase its volumetric density by 80% compared to the gaseous state. H_2 supply occurs on demand, and without storage at the airport, transportation needs increase over time. Trucks transport the H_2 to the airport 48.8 km away in the Netherlands. Assumptions, LCI modeling, and data sources used for the H_2 production and supply are available in Appendix.

The LCI dataset for H_2 production includes electrolyzers, liquefaction plants, and truck manufacturing. Electrolyzers manufacturing LCI data were derived from literature sources and scaled proportionally to the nominal power (Lotrič et al., 2021; Valente et al., 2018). Liquefaction plant manufacturing LCI data were directly taken from Stolzenburg and Mubbala (2013). Liquid tankers were modeled as trailer trucks and a tanker. The trailer production and H_2 transport assumed the use of 32 metric tons trailers of EURO6 class, while the tanker had a capacity of 4300 kg of LH2. LCI data for trailer production were adapted from an existing ecoinvent process (Wernet et al., 2016), while LCI data for tanker production were retrieved from literature (Choi et al., 2022).

H_2 production involves 10 alkaline electrolyzers with a capacity of 20 MW each, assuming a lifetime of 60,000–90,000 operational hours. The LCI dataset for H_2 supply includes data for the operation of the electrolyzers and liquefaction (Sakas et al., 2022; Stolzenburg and Mubbala, 2013). Energy and water consumption, as well as other factors, are considered.

At the end of the electrolyzer's life, it is dismantled and recycled. Material types and masses resulting from dismantling are estimated, and a proposed treatment aims to optimize environmental benefits. Metals and thermoplastics are recycled, ceramics are landfilled, and fluorescent lamps are reused.

2.3.7. *Airport systems*

Airports support air transport and, throughout their different areas, serve aircraft, passengers, cargo, and surface vehicles. The activities and infrastructure associated with aircraft landing and take-off are accommodated by the airside area, while other supporting activities occur on the landside, e.g., infrastructure giving access to the airport, local wastewater treatment, and parking facilities (Greer et al., 2020). Lastly, terminals and buildings handle passengers, baggage, and freight connecting the landside with the airside area (IATA, 2015; Nagarajan and Parthasarathi, 2018; Young and Wells, 2011). The airport dataset considered in this study represents the construction, use, and decommissioning of a regional airport in Europe, based on primary data and expert assumptions from Rotterdam the Hague Innovation Airport (RTHA) in the Netherlands, which surface area covers 220 ha (see Appendix).

The airport LCI is divided into landside and airside areas, with the terminals included in the latter (Meindl et al., 2023a). The materials used for the airport constructions are based on expert assumption and Spielmann et al. (2007) and then rescaled for RTHA using the airport plant. The lifetime of the airport foundation layer is assumed to be 100 years, while the buildings and reinforced concrete pavement are assumed to have a 33.33-year life span.

The LCI dataset for the airport operations includes ground vehicles and ground power units for serving the airside, consumable materials, and energy for the airside and terminal operations. The water, energy, and deicing fluids consumption and the waste generation reflect the operations of the airport in one year using 2019 airport data. The LCI dataset is built upon the assumptions used by Spielmann et al. (2007) and rescaled with the data collected from Rotterdam the Hague Innovation Airport (RTHA) (see Appendix for details).

At the EOL, the airport decommissioning consists of removing the apron, taxiway, and runways and disposing of the concrete in a landfill (Spielmann et al., 2007).

2.4. Evaluation of uncertainties

Uncertainty about LCI data quality was collected for all datasets using a semi-quantitative approach, as described in the LCI data collection stepwise guidance (Saavedra-Rubio et al., 2022). To quantify data variability, the data provider was invited to give information about the statistical distribution of specific LCI parameters (e.g., min, max). If no more than one data point was available, the uncertainty on the LCI parameter was described by filling the pedigree matrix, which provides scores from 1 to 5 for data reliability, completeness, temporal correlation, geographical correlation, and technological correlation (Funtowicz and Ravetz, 1990; Hedbrant and Sörme, 2001; Kennedy et al., 1996; Weidema and Wesnæs, 1996). These scores can be used to derive parameter distributions, e.g., log-normal distribution, mean, and standard deviation, as done in all processes of the ecoinvent database (Weidema et al., 2013). Additionally, if an expert estimate is given for a specific data point, the uncertainty of this data point is assessed with the approach by Laner et al. (2016). These uncertainty factors can then support sensitivity analysis, e.g., with Monte Carlo simulations. Therefore, the uncertainty information associated with each LCI dataset is consistent with the background database ecoinvent (Wernet et al., 2016).

3. Results and discussion

3.1. Datasets and comparison with other LCIs

Table 2 shows an overview of the LCI datasets established. These component LCIs can be combined, as indicated in Table 1, to form an inventory for a given configuration and time horizon. Each LCI dataset is assigned an ID specific to the configuration and time horizon and is openly available in the Zenodo repository “Prospective Life Cycle Inventory Datasets for conventional and hybrid electric aircraft technologies” at https://doi.org/10.5281/zenodo.8155003 (Thonemann et al., 2023).

The datasets required for each configuration are provided with an ID number (format: Time Horizon - file number). The LCI files can be found in the SI with the corresponding IDs. For each dataset, the number of covered intermediary and elementary flows is shown in parenthesis, with a total for each configuration at the bottom of the table. Each dataset file includes details regarding the resource extraction, manufacturing, and EOL stage details. The use stage of the aircraft is documented for either kerosene, AAF, or H_2 within the powerplant file. The use of the airport is documented in the airport file.

In this study, each aircraft configuration is represented by inventories covering 432 to 976 elementary or intermediate flows indicated as a total at the bottom row of Table 2. The specific number of covered flows for each LCI dataset is shown below the ID number (Table 2). In comparison, the ecoinvent aircraft equivalent dataset, which was scaled for LCA studies such as the work of Cox et al. (2018), shows a much lower granularity with only 17 inputs from the technosphere and 23 substance emissions to the biosphere for the short-haul aircraft. The present study, therefore, contributes to increasing tenfold the level of details of our LCI datasets compared to existing LCI available to LCA practitioners.

While assumptions and references are partially provided for the ecoinvent process, another major concern is that the inventory is given on an overarching material mass percentage basis for the whole aircraft with no further specification or differentiation into aircraft components. The same limitation is present in other aircraft LCAs, such as the work of Fabre et al. (2022). The study of Lopes (2010) presents details regarding the parts of the aircraft structure, with a transparent inventory divided into the engine, landing gear, fuselage, and stabilizer components, and covers a total of 78 flows for the aircraft, where the EOL is also considered. In this study, the work of Lopes (2010) was further detailed component-wise, and the overall span of the dataset was extended to account for gaps regarding processing energy and other non-structural aircraft components. Comparing the number of flows in previously published LCIs (17 and 78 flows) with our LCIs (432 flows), we found that our LCIs enable modeling an aircraft with 5–10 times more details. The advantage of subdividing the inventory into systems and sub-components enables the identification of hotspots and allows to scale or reuse the datasets for technologies with similar properties.

3.2. Validity check of the LCI datasets

Owing to the prospective nature of the LCI datasets and the emerging technologies embedded in them, few comparable LCIs are available to check our datasets. Comparisons with alternative sources were made where possible to realize plausibility checks. These were mainly focused on climate change impacts to estimate whether the carbon footprint of the generated LCI datasets was consistent. Climate change impacts are typically associated with well-covered substance emissions, and the relative reliability of the impact results can support consistency checks (Laurent et al., 2015, 2020).

The carbon footprint was calculated considering a load factor of 80%

Table 2
Overview of component LCI datasets with an ID number and number of covered flows in parenthesis. Please see the repository at https://doi.org/10.5281/zenodo.8155003 for further details on each technology.

	Component	Short-term		Medium-term			Long-term		
		ICE	ICE + Bat	ICE	ICE + Bat	PEMFC + Bat	ICE	SOFC + Bat	PEMFC + Bat
Aircraft	Powerplant	ST-01 (215)	ST-02 (271)	MT-01 (213)	MT-02 (267)	MT-03 (79)	LT-01 (204)	LT-02 (92)	LT-03 (84)
	Airframe	ST-03 (80)	ST-04 (68)	MT-04 (80)	MT-05 (80)	MT-06 (80)	LT-04 (80)	LT-06 (80)	LT-05 (80)
	Power Electronics and Motor Drives		ST-05 (240)		MT-07 (247)	MT-08 (192)		LT-08 (210)	LT-07 (210)
	Battery		ST-06 (38)		MT-09 (50)	MT-10 (43)		LT-10 (51)	LT-09 (78)
	Battery EOL		ST-07 (36)		MT-11 (33)	MT-12 (31)		LT-12 (25)	LT-11 (25)
	Fuel Cells					MT-13 (157)		LT-14 (66)	LT-13 (143)
	H_2 storage onboard					MT-14 (23)		LT-15 (17)	LT-16 (17)
Airport	Airport	ST-08 (61)	ST-08 (61)	MT-15 (61)	MT-15 (61)	MT-15 (61)	LT-17 (61)	LT-17 (61)	LT-17 (61)
	Battery Charging Station		ST-09 (91)		MT-16 (93)	MT-16 (93)		LT-18 (82)	LT-18 (82)
H_2	H_2 production & supply					MT-17 (145)		LT-19 (146)	LT-19 (146)
Total flows covered		432	881	430	976	904	421	830	926

Abbreviations: ICE: internal combustion engine, bat: battery, PEMFC: proton-exchange membrane fuel cell, SOFC: solid oxide fuel cell, ST: short-term, MT: medium-term, LT: long-term.

(i.e., 40 passengers with 95 kg each) and using the premise framework combined with ecoinvent v. 3.8 for modeling the GHG emissions and characterizing the climate change impacts with the LCIA methodology EF 3.0 (Fazio et al., 2018; Sacchi et al., 2022; Wernet et al., 2016). When combining the different LCI datasets to represent the life cycle of a conventional aircraft in the short-term time horizon (reference year 2030), a total carbon footprint of 127 g CO_2-eq./passenger.km (pkm) was found. This result shows a relatively good agreement with the carbon footprint estimate of 117 g CO_2-eq./pkm obtained using the LCI from the ecoinvent process "Transport, passenger aircraft, short-haul - GLO" updated for 2030 and the same LCIA method (Sacchi et al., 2022; Wernet et al., 2016). The ecoinvent process assumes the same load factor but a slightly higher weight per passenger (105 kg). In both sources (current study and ecoinvent process), the main contributions were similar, with first the emissions due to the burned fuel in flight and second the fuel production. The lower granularity and limited coverage in the ecoinvent aircraft LCI dataset (e.g., exclusion of EOL, aircraft interiors, and fuel systems) may explain the difference between the two carbon footprint results despite a higher weight per passenger. It is additionally worth noting that the results obtained when computing the carbon footprint of our LCI datasets are consistent with previous studies in the literature, in particular, the study by Lopes (2010), who reported 126 g CO_2-eq/pkm (using ReCiPe2008, v. 1.04; Huijbregts et al., 2017) for medium-to long-haul flights, with a same identification of main contributors, namely the crude oil production feeding into the fuel production (Lopes, 2010). Rupcic et al. (2023) provided ranges of carbon footprints for different propulsion systems that align with the value found in the current study, i.e., 150 g CO_2-eq/pkm for conventional long-haul flights (Ueckerdt et al., 2021).

Based on these results, the completeness of the LCI was deemed satisfactory, at least for processes and elementary flows relevant to climate change impacts such as energy demand and GHG emissions.

3.3. Uncertainty evaluation and limitations of LCI datasets

Modeling LCI datasets on a highly detailed level (see input/output flow coverage in Table 2) is linked to several limitations and sources of uncertainties, in particular (i) variability in the completeness across the LCI datasets due to different technology maturity levels and data availability, and (ii) nature of the data sources (expert evaluation, literature sources, etc.) and accessibility issues.

The extensive datasets in this study result from a collaboration of experts within the aeronautic field. The LCI building method ensured that the level of detail provided by partners was consistent; however, dataset variability could not be avoided (Saavedra-Rubio et al., 2022). Besides, our prospective approach included emerging technologies, which bear higher uncertainties by definition. As a result, LCI datasets for the hybrid aircraft configurations are more uncertain than the ones for the conventional aircraft in all time horizons. A strong focus was put on the manufacturing and use LCI data. Nonetheless, the energy demand and ancillary materials for the manufacturing and the resulting direct emissions were provided to the extent of what was possible with current knowledge regarding the forecasted technologies. Information regarding the EOL is generally lacking, and information about EOL was provided in Appendix rather qualitatively than proper LCI data (except for the batteries). The substance coverage would increase coupling the LCI datasets with environmental databases such as ecoinvent or premise in LCA studies (Sacchi et al., 2022; Wernet et al., 2016).

Additional uncertainty comes from the source of the LCI data. Some datasets were scaled based on LCI datasets established in the literature (e.g., airport, power electronics), while others had to be built from scratch based on expert assessments due to the general lack of manufacturers' data or due to the prospective aspect of the study (e.g., battery, SOFC, PEMFC). Moreover, the mass of multiple components in the LCI data was based on the aircraft's preliminary design and the expertise of component manufacturers. Therefore, slight differences in component mass are present across datasets in the case of the hybrid configurations (e.g., between the powerplant and the battery, generator, power electronics, motor drives, or H_2 tanks) and affect the uncertainty of the LCI results. In case of discrepancy, the mass prescribed by the component manufacturer was always preferred for establishing the LCI datasets because it was considered more robust than the preliminary design estimate. These variations for the hybrid configurations result in a higher mass than predicted for long-term fuel cell configurations. However, the weight increase is insufficient to entail significant maximum take-off weight exceedance as, in both cases, the operating empty mass increases by less than 0.5%.

The uncertainty evaluation was mainly based on the pedigree matrix (Table 3). The pedigree matrix was used to derive uncertainty for 50%–100% of the processes in the LCI datasets of the powertrain, airframe, battery, and battery EOL, battery charging station, and H_2 production and supply. In the cases of the power electronics and drives, battery EOL, fuel cells, and H_2 onboard storage, it was possible to provide parameter distributions for 40–60% of the processes because primary data were used to build these LCI datasets (Thonemann et al., 2023). The airport had the lowest uncertainty coverage, with 70% of the processes without uncertainty information due to a lack of data. Moreover, the uncertainty factor derived from the pedigree matrix can be interpreted as the variability related to the data quality in the LCI in Table 3 (Weidema et al., 2013; Weidema and Wesnæs, 1996). Hence, the higher the uncertainty factor, the higher the uncertainty on the LCI dataset. Overall, the uncertainty varies across technology blocks, but no clear relationship exists between time horizon, technology readiness level today, and uncertainty factor. For instance, the uncertainty factor of the airframe increases slightly between the medium- and long-term scenarios due to the introduction of novel bio-based materials, which is expected. Similar trends for batteries, H_2 storage, power electronics, and drives can be observed. In contrast, the uncertainty factor of the charging station and H_2 supply remains constant, and the uncertainty factor of the innovative SOFC is lower than that of state-of-the-art PEMFC. Therefore, the uncertainty information derived from the pedigree matrix should be interpreted as reflecting the method and data sources used for building the LCI dataset rather than the uncertainty of the technology itself.

3.4. Potential applications of the LCI datasets

Beyond demonstrating the applicability of the LCI data collection framework – and the operability of its associated LCI data collection template – the generation of the LCI datasets in the current study paves the way for several relevant applications within the field of LCA.

The LCI datasets can be integrated into environmental databases, such as ecoinvent, and used by practitioners to perform more detailed LCAs of aviation systems (Wernet et al., 2016). Few LCI data are currently publicly available, partly due to confidentiality requests from industrial stakeholders, and there is a need for the generation of LCI datasets to enable more LCA applications (Rupcic et al., 2023). For example, in Europe, the recently launched Clean Aviation program, which has embarked major aviation stakeholders in Europe to develop future aircraft technologies, requires LCA to be applied to the developed aircraft systems to facilitate ecodesign. Hybrid-electric aircraft systems, the core of the current study and LCI dataset generation, are one of the main topics addressed in Clean Aviation.

The LCIs could be rescaled to model other types of aircraft than the ATR-42, as Cox et al. (2018) have done by modeling the Swiss aircraft fleet. This rescalability of LCI datasets applies mainly to the LCIs relevant to the conventional configuration as hybrid electric aircraft are technically restricted to short-haul flight with a range limited to approximately 1000 km (Bicer and Dincer, 2017; Gnadt et al., 2019; Schäfer et al., 2018).

The developed LCI datasets can be used in a prospective life cycle assessment (pLCA) of alternative propulsion and fuel technologies. Comparing the potential environmental impacts of each aircraft

Table 3
Overview of the uncertainty data for each LCI dataset.

	Component	Short-term		Medium-term			Long-term		
		ICE	ICE + Bat	ICE	ICE + Bat	PEMFC + Bat	ICE	SOFC + Bat	PEMFC + Bat
Aircraft	Powertrain	0.286 (98%)	0.124 (86%)	0.213 (100%)	0.181 (99%)	0.229 (100%)	0.274 (100%)	0.243 (100%)	0.243 (100%)
	Airframe	0.244 (92%)	0.244 (92%)	0.244 (92%)	0.244 (92%)	0.244 (92%)	0.251 (92%)	0.251 (92%)	0.251 (92%)
	Power Electronics and Motor Drives		0.195 (50%)		0.388 (50%)	0.388 (50%)		0.388 (50%)	0.388 (50%)
	Battery		0.043 (94%)		0.035 (58%)	0.035 (58%)		0.132 (75%)	0.132 (75%)
	Battery EOL		0.221 (19%)		0.220 (40%)	0.220 (40%)		0.220 (60%)	0.220 (60%)
	Fuel Cells					0.751 (19%)		0.026 (18%)	0.751 (19%)
	H_2 storage onboard					NA (0%)		0.458 (11%)	0.458 (11%)
Airport	Airport	1.094 (30%)	1.094 (30%)	1.094 (30%)	1.094 (30%)	1.094 (30%)	1.094 (30%)	1.094 (30%)	1.094 (30%)
	Battery Charging Station		0.359 (90%)		0.359 (90%)	0.359 (90%)		0.359 (90%)	0.359 (90%)
Fuel	H_2 production & supply					0.960 (91%)		0.960 (91%)	0.960 (91%)

The percentage corresponds to the number of processes with pedigree uncertainty compared to the total number of processes in the LCI dataset. EOL processes are not included except for the battery. The aircraft use stage is included under the power plant LCI. The number is the average standard deviation of the log-normal distribution obtained from the pedigree matrix.

configuration would help identify alternatives that can reduce the impacts of short-haul flights. Possible reductions would support technology research and investment decisions for more sustainable regional aviation. To perform such pLCA, a detailed mapping of the LCI datasets with prospective LCI databases such as premise is first needed (Sacchi et al., 2022; Wernet et al., 2016).

Finally, the provided LCI datasets can be adapted to model other heavy-duty transport systems using hybrid-electric propulsion systems with batteries and fuel cells. The H_2 production and supply LCI is not dependent on the aviation application and, therefore, can be reused for road and maritime transportation (Bethoux, 2020; Van Hoecke et al., 2021). Moreover, the batteries, PEMFC, and SOFC LCIs may be relevant for road and maritime transport systems. However, some adaptation is needed to fit the technical requirements of such applications, e.g., the gravimetric power densities and energy storage parameters.

4. Conclusions and recommendations

Prospective LCI datasets were provided for short-range, hybrid-aircraft configurations based on the stepwise guidance from Saavedra-Rubio et al. (2022). Specific inventories for airframe, powertrain, battery systems, fuel cells systems, regional airport, and H_2 production were built for 2030, 2040, and 2050 in collaboration between industrial manufacturers and academic contributors. The inventories cover emerging technologies such as SOFC, cryogenic H_2 tanks, Li-S, and Li-air batteries.

The resulting 8 LCI datasets present a higher degree of disaggregation than available datasets, with a total of flows ranging from 421 to 976 depending on the configuration while maintaining a similar process coverage compared with existing datasets. Moreover, uncertainty data on the LCI data sources and the LCI building method were provided for all technology blocks with satisfactory coverage (50%–100% of the processes), except the airport, which lacks uncertainty assessment. Our LCI datasets enable more detailed and accurate environmental impact assessment of the technologies in scope by providing more details about the contribution of each component to the environmental impacts and by allowing quantitative uncertainty analysis.

One limitation of this work is that the prospective LCI datasets we developed are based on certain assumptions and projections, which may introduce uncertainty into the results. Additionally, the accuracy of the datasets relies on the availability of reliable data sources and the comprehensiveness of our modeling approach. Furthermore, our study focuses on specific aircraft technologies and configurations for 2030, 2040, and 2050 and does not account for all possible variations and scenarios in aircraft design and technology evolution. These limitations should be considered when using our datasets for environmental assessments and policy decisions.

Future research in the field of short-range, hybrid-aircraft configurations should focus on several key areas. Firstly, there is a need to gather better EOL information to comprehensively assess the environmental impacts associated with the disposal, recycling, or reuse of components and materials. Secondly, there is a need to gather LCI data for other airports than regional airports to enhance the technological coverage for this specific part of the life cycle. Thirdly, parametrizable datasets would allow for the seamless reuse the provided datasets for other applications with different technological requirements. Additionally, conducting a comparative study of the environmental impacts of alternative aircraft configurations using conventional and hybrid-electric propulsion while considering the future development of technologies and the industrial background would help identify the most promising technologies from an environmental perspective. Continuous updating and refinement of LCI datasets is crucial to account for evolving technologies and materials. Lastly, integrating social and economic indicators into the assessment would provide a more comprehensive evaluation of the overall sustainability of these aircraft configurations. By addressing these research areas, we can advance the understanding and development of less-impacting air transportation solutions.

CRediT authorship contribution statement

Nils Thonemann: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Supervision, Visualization, Writing – original draft, Writing – review & editing. **Karen Saavedra-Rubio:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Visualization, Writing – original draft. **Eleonore Pierrat:** Conceptualization, Data curation, Formal analysis, Project administration, Supervision, Visualization, Writing – original draft, Writing – review & editing. **Katarzyna Dudka:** Data curation, Formal analysis, Visualization, Writing – original draft, Writing – review & editing. **Mathilde Bangoura:** Investigation, Writing – review & editing. **Nils Baumann:** Investigation, Writing – original draft, Writing – review & editing. **Christian Bentheimer:** Investigation, Writing – review & editing.

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Declaration of competing interest

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

Data availability

The data that support the findings of this study are documented in (i) an Appendix, containing the methodological details behind the LCI datasets; and (ii) via files, containing all LCI datasets, openly available from the Zenodo repository “Prospective Life Cycle Inventory Datasets for conventional and hybrid electric aircraft technologies” at https://doi.org/10.5281/zenodo.8155003, reference number 8155003.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2023.140314.

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