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ORIGINAL PAPER

Life cycle assessment model for eVTOL aircraft in preliminary design: application within the COLOSSUS project

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Abstract

Electric Vertical Take-Off and Landing (eVTOL) aircraft are emerging as candidates for future Urban and Regional Air Mobility (UAM/RAM). As their development accelerates, assessing environmental performance from the earliest design stages becomes essential. This work presents a simplified and parametric Life Cycle Assessment (LCA) framework tailored to conceptual eVTOL design, enabling rapid environmental evaluations based on subsystem masses and representative material compositions. The model adopts a cradle-to-operation scope and quantifies environmental indicators through mass-driven equations calibrated using industrial inventory data. Application to a representative eVTOL configuration shows that composite structural components dominate production phase impacts, owing to the energy-intensive processing required for carbon fibre reinforced polymers. Lithium-ion battery systems also constitute significant hotspots, particularly in toxicity and resource related categories linked to the extraction and refining of critical materials. Across the full life cycle, operational electricity use emerges as the primary contributor to climate related impacts, while maintenance activities provide a smaller but non-negligible contribution. The findings underline the substantial influence of material choices, component architecture, and electricity sourcing on the overall environmental performance of eVTOL systems. The proposed model offers a compact and transparent tool for integrating sustainability considerations into early design stages and supports the comparative assessment of alternative configurations and technological options for future urban and regional air mobility.

Keywords eVTOL · Urban air mobility · Regional air mobility · Life cycle assessment · Environmental impact · Global warming potential

Abbreviations

AAM	Advanced air mobility
AFP	Automated fibre placement
CFRP	Carbon fibre reinforced polymer
CO_2	Carbon dioxide
ECS	Environmental control system
EI	Environmental indicators
EoL	End of life
eVTOL	Electric vertical take-off and landing
FCS	Flight control system
GWP	Global warming potential
LCA	Life cycle assessment
LCI	Life cycle Inventory
LCIA	Life cycle impact assessment
PMSM	Permanent magnet synchronous motor
RAM	Regional air mobility
TLAR	Top-level aircraft requirement
UAM	Urban air mobility
MTOM	Maximum take-off mass
LIB	Lithium-ion battery
LFP	Lithium iron phosphate
LMO	Lithium manganese oxide
NMC	Nickel manganese cobalt oxide
NCA	Nickel cobalt aluminium oxide
Li–S	Lithium–sulfur
Li–O_2	Lithium–oxygen (lithium–air)
Na-ion / SIB	Sodium-ion battery

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SSB	Solid-state battery
PAN	Polyacrylonitrile
VOC	Volatile organic compound
PCB	Printed circuit board
LCD	Liquid crystal display
PTFE	Polytetrafluoroethylene

Environmental impact categories (ReCiPe 2016)

HCT	Human carcinogenic toxicity (kg 1,4-DCB eq)
HnCT	Human non-carcinogenic toxicity (kg 1,4-DCB eq)
IR	Ionizing radiation (kBq Co-60 eq)
TET	Terrestrial ecotoxicity (kg 1,4-DCB eq)
FRS	Fossil resource scarcity (kg oil eq)
FET	Freshwater ecotoxicity (kg 1,4-DCB eq)
MET	Marine ecotoxicity (kg 1,4-DCB eq)

1 Introduction

With the increasing demand for urban mobility, electric Vertical Take-Off and Landing (eVTOL) vehicles emerge as a promising solution to enhance safety, efficiency, and sustainability, helping to reduce congestion and pollution in urban areas [1]. Electric Vertical Take-Off and Landing vehicles are fully electric aircraft capable of vertical take-off and landing and fall within the broader context of Urban Air Mobility (UAM) and Regional Air Mobility (RAM). These vehicles aim to achieve zero emissions during operation, primarily through battery-powered propulsion systems. However, the transition to fully electric flight introduces new challenges, such as increased vehicle weight due to onboard batteries.

The eVTOL sector is experiencing rapid industrial development driven by growing interest. More than 150 companies worldwide, ranging from aerospace giants like Airbus, Boeing, and Embraer to technology leaders such as Amazon and Google, are investing in eVTOL research and prototyping [2]. This industrial expansion is supported by significant venture capital funding that exceeds one billion dollars in recent years, underscoring a strong belief in the potential of eVTOLs to transform future urban and regional transportation [2].

To enable this transformation, key challenges must be addressed, particularly the environmental impact associated with eVTOL vehicles [3]. Considering projections for large scale deployment of eVTOL fleets, the environmental impacts of their production, operation, and end-of-life phases are expected to become increasingly significant. For instance, the study by Perez et al. [4] estimates that potential Advanced Air Mobility (AAM) commuters may exceed 3000 in the Chicago metropolitan area, emphasizing the need to assess economic, energy, and environmental feasibility. In this context, Life Cycle Assessment (LCA) provides a comprehensive and systematic framework to evaluate the environmental burdens across the entire life cycle of eVTOLs, from raw material extraction (*cradle*) to manufacturing, operation, and final disposal or recycling (*grave*).

Recent studies highlight the importance of LCA for evaluating the environmental performance of eVTOL systems, given the projected growth of UAM fleets. André and Hajek [5] assess three eVTOL configurations (quadrotor, side-by-side, and lift+cruise), focusing on greenhouse gas (GHG) emissions during production and operation phases, and conclude that favorable environmental outcomes require high seat utilization, low hover time, clean energy grids, and significant travel distance savings. Pinheiro Melo et al. [6] explore battery chemistries within an LCA framework and identify trade-offs between energy density and environmental impacts among lithium-based technologies, emphasizing the importance of integrating sustainability considerations early in the design process. More recently, Khavarian and Kockelman [7] analyze eVTOL operations in Austin, demonstrating that electricity production dominates lifecycle emissions and that smaller aircraft offer lower emissions per passenger-kilometer, although eVTOLs still lag behind electric cars in environmental and economic performance. Similarly, Arvidsson et al. [8] show through a cradle-to-grave LCA of a two seat electric aircraft that although GHG emissions are lower than those of fossil-fuel aircraft, battery production and resource depletion remain major concerns.

While these studies provide important insights, they primarily focus on comprehensive life cycle analyses of individual vehicles or detailed operational scenarios, often overlooking the need for simplified models suited to early design stages. The present study contributes to the Collaborative System of Systems Exploration of Aviation Products, Services and Business Models (COLOSSUS) Project [9] by developing a simplified yet comprehensive LCA model tailored for preliminary eVTOL design workflows. This approach facilitates rapid environmental impact assessments to support early-stage design trade-offs, embedding sustainability considerations from the outset.

The simplified LCA model covers the life cycle from cradle to operation, which is particularly critical for electric aircraft due to the significant contribution of battery production and use. This approach is essential in light of the expected growth of the eVTOL market and the COLOSSUS Project's emphasis on integrating environmental performance into innovative aviation solutions.

The model is designed as a parametric tool that fully integrates into early-stage design workflows, allowing rapid exploration of design alternatives. It quantifies

environmental impacts across 17 midpoint categories following the ReCiPe 2016 method [10]. For clarity and practicality, only those categories whose aggregated environmental impact indicators exceed a predefined threshold are selected and reported, focusing the analysis on the most relevant contributions.

The remainder of the paper is structured as follows. Section 2 describes the methodological framework, including the modeling assumptions, material flow definitions, and formulation of parametric equations used to estimate environmental impacts. Section 3 details the reference eVTOL configuration used as a case study. Section 4 presents and discusses the main results, with attention to the relative contributions of production and operational phases, as well as the influence of materials and subsystem design on overall environmental burden. Section 5 concludes the work by summarizing the main findings and identifying directions for future research.

2 Methodology

This study develops a simplified, parametric LCA model specifically designed for the preliminary design phase of a conceptual eVTOL aircraft, within the COLOSSUS Project [9].

The assessment follows a cradle-to-operation scope, including materials extraction, manufacturing, assembly, operation and maintenance, while excluding end-of-life treatment and recycling credits, which are allocated to subsequent product life cycles.

The methodology draws from the streamlined LCA framework proposed by Vivalda and Fioriti [11], based on a modular decomposition of the aircraft and using environmental impact coefficients from the *Ecoinvent* database. The method aligns with the ISO standard [12] and quantifies environmental impacts across the entire product life cycle.

The LCA methodology follows the framework established by ISO 14040 and ISO 14044 [12], comprising four main phases. First, the goal and scope definition determines system boundaries and functional units. Second, the Life Cycle Inventory (LCI) compiles data on processes and resource flows; in this study, the inventory uses the Ecoinvent v3.8 database. Third, the Life Cycle Impact Assessment (LCIA) converts inventory data into potential environmental impacts. Here, the ReCiPe 2016 method [10] is applied, covering 17 midpoint impact categories, including climate change, ozone depletion, and human toxicity. Finally, the interpretation phase evaluates the robustness of the results and identifies opportunities for improvement.

The model adopts a modular structure, calibrating equations based on real data for aircraft manufacturing and material use in each main subsystem. Its simplicity makes it suitable for early design iterations, as it requires only the total mass of each subsystem and the percentage weight distribution of its constituent materials as input. Components are modeled based on their material composition and linked to corresponding production processes up to final finishing, enabling a comprehensive environmental assessment of the overall aircraft configuration.

The assessment adopts a cradle-to-operation scope, encompassing the extraction and processing of raw materials; manufacturing of major components including airframe, propulsion, onboard systems, and cabin interiors; final assembly; operational phase including electricity generation and mission energy consumption; as well as scheduled maintenance and component replacement over the aircraft lifetime.

The End-of-Life (EoL) phase is excluded from this analysis because preliminary assessments indicate that emissions associated with disposal are considerably lower than those generated during production. In line with previous LCA studies [5], the environmental impacts and potential benefits of recycling, particularly in the case of battery recovery, are typically assigned to subsequent product life cycles. For this reason, only emissions related to transport are considered in the present study.

The model does not currently include emissions related to infrastructure, airport operations, or environmental credits from recycling. Additionally, weight estimates rely on established statistical models that may not fully capture the influence of advanced composite materials.

2.1 Parametric equations

To develop a simplified and traceable LCIA model suitable for preliminary aircraft design, the environmental impact of each subsystem is represented through a mass-driven linear relationship based on the parametric equations proposed in [11]. Different coefficients apply for the production and operational phases to account for variations in energy intensity and emission profiles.

2.1.1 Production phase

The environmental impact associated with the production of each aircraft component is computed using a mass-based formulation. Each component is decomposed into its constituent materials, and for each material k the corresponding environmental impact coefficient $EI_{j,k}$ is taken from the *Ecoinvent* database for each midpoint category j defined by the ReCiPe 2016 method.

The total environmental impact of a component for category j, denoted $EI_{\text{component},j}$, is obtained by weighting

the impact coefficients by the mass fraction of each material and the total mass of the component:

$$EI_{\text{component},j} = \sum_k \left(EI_{j,k}\, m_k\, M_{\text{component}} \right), \tag{1}$$

where m_k is the mass fraction of material k in the component, $M_{\text{component}}$ is the total component mass, and $EI_{j,k}$ is the environmental impact per unit mass of material k for category j.

The same formulation is applied to each subsystem of the aircraft. Table 1 summarises the resulting parametric expressions, where $EI_{j,k}$ denotes the impact factor of material or process k, and m_k its mass fraction in the subsystem.

2.1.2 Operational and maintenance phase

The operational phase includes both scheduled maintenance of subsystems and the energy demand associated with aircraft missions. Mission-related emissions are estimated based on the electricity consumed during propulsion according to:

$$EI_{\text{energy}} = 0.25 \times E_{\text{mission}}\,[\text{kWh}] \times N_{\text{missions}} \tag{2}$$

where E_{mission} is the electricity required for a single mission, and N_{missions} is the total number of missions over the aircraft lifetime. The term EF_{grid} represents the emission factor of the electricity mix; in this study a value of $EF_{\text{grid}} = 0.25\,\text{kg CO}_2\text{ eq/kWh}$ is adopted, consistent with the average European electricity mix reported in Ecoinvent v3.8.

Maintenance-related emissions are modeled by accounting for the share of each subsystem mass that requires replacement during service life. The environmental impact of maintenance for each subsystem i is calculated as:

$$EI_{\text{maint},i} = \sum_{j=1}^{N} EI_{\text{prod},j} \times r_i \tag{3}$$

where $EI_{\text{prod},j}$ represents the environmental impact associated with the production of component j, and r_i is the replacement ratio of subsystem i, defined as:

$$r_i = \frac{\sum_{j=1}^{N} (n_j \times m_j)}{M_i} \tag{4}$$

In this expression, n_j is the number of replacements of component j, m_j its mass, and M_i the total mass of subsystem i.

This approach assumes that the environmental burden of a replaced component is equivalent to that of manufacturing a new one, providing a conservative estimate of maintenance impacts.

2.2 Materials and processes inventory

The inventory analysis identifies and quantifies all materials and manufacturing processes associated with each subsystem, ensuring a complete and traceable basis for the LCA. The aircraft is divided into four macro-categories: structure, powerplant, systems, and furnishings. For each subsystem, material composition and the corresponding production routes are mapped to the most representative datasets in *Ecoinvent v3.8*, complemented with literature-based modelling whenever specific processes are not available. This approach ensures consistency with industrial practice and with the reference aircraft configuration.

Table 1 Environmental impact equations ($EI_{\text{subsystem},j}$) for each eVTOL subsystem during the production phase

Subsystem	Equation for $EI_{\text{subsystem},j}$
Fuselage	$(EI_{j,\text{CFRP}}\, m_{\text{CFRP}} + EI_{j,\text{Al}}\, m_{\text{Al}})\, M_{\text{Fuselage}}$
Wing	$(EI_{j,\text{CFRP}}\, m_{\text{CFRP}} + EI_{j,\text{Al}}\, m_{\text{Al}})\, M_{\text{Wing}}$
Tail	$EI_{j,\text{CFRP}}\, m_{\text{CFRP}}\, M_{\text{Tail}}$
Landing Gear	$EI_{j,\text{Landing Gear}}\, M_{\text{Landing Gear}}$
Propulsion Motors	$EI_{j,\text{Motors}}\, M_{\text{Motors}}$
Propellers	$EI_{j,\text{Propellers}}\, M_{\text{Propellers}}$
Batteries	$EI_{j,\text{Batteries}}\, M_{\text{Batteries}}$
Environmental Control System (ECS)	$EI_{j,\text{ECS}}\, M_{\text{ECS}}$
Flight Control System (FCS)	$EI_{j,\text{FCS}}\, M_{\text{FCS}}$
Avionics	$EI_{j,\text{Avionics}}\, M_{\text{Avionics}}$
Electrical System	$EI_{j,\text{Electrical}}\, M_{\text{Electrical}}$
Furnishings	$EI_{j,\text{Furnishings}}\, M_{\text{Furnishings}}$
Generic Component	$EI_{\text{component},j} = \sum_k EI_{j,k}\, m_k\, M_{\text{component}}$

Table 2 Main *Ecoinvent* processes used to model fuselage composite production

Material	*Ecoinvent* process name
CFRP material	Carbon fibre reinforced plastic, epoxy resin, at plant
Electricity supply	Electricity, medium voltage, at grid

Table 3 Main *Ecoinvent* processes used to model aluminium alloy production

Material	*Ecoinvent* process name
Aluminium alloy milling (20%)	Bauxite production; aluminium alloy production; aluminium milling; electricity, low voltage (FR); aluminium anodizing
Aluminium alloy sheet rolling (80%)	Bauxite production; aluminium alloy production; aluminium impact extrusion; aluminium sheet rolling; electricity, low voltage (FR); aluminium anodizing

Table 4 Main *Ecoinvent* processes used to model landing gear production

Material	*Ecoinvent* process name
Steel (60%)	Chromium steel production; steel forging; steel milling, average
Aluminium alloy (25%)	Aluminium alloy milling; bauxite production; aluminium alloy production; aluminium milling; electricity, low voltage (FR); aluminium anodizing
Rubber (15%)	Rubber membrane production

2.2.1 Structure

The structural category includes the wing, fuselage, tail, and landing gear. Two alternative material configurations are considered for the primary load-bearing components: carbon-fibre-reinforced polymer (CFRP) and aluminium alloy. The reference configuration is predominantly CFRP for both wing and fuselage, while the aluminium-based layout is used as an alternative design scenario.

CFRP components are represented through an Automated Fibre Placement (AFP) process followed by autoclave curing [13]. As these specific processes are not directly available in *Ecoinvent*, they are modelled through equivalent datasets combining upstream CFRP production with the electricity demand of autoclave curing. The main datasets used to model fuselage composite manufacturing are summarised in Table 2.

For aluminium alloy structures, two production routes are considered. Approximately 20% of the fuselage mass is represented by aluminium milling followed by anodizing, whereas the remaining 80% corresponds to extrusion and sheet rolling, also followed by anodizing. The modelling includes the full upstream chain, from bauxite mining and aluminium refining to alloy production and surface finishing. Thermal treatments and anodizing are captured through the electricity requirements of the corresponding *Ecoinvent* datasets. The selected processes are listed in Table 3.

The landing gear is represented using a mixed material composition informed by relevant literature and industrial practice. The structure is assumed to consist of 60% steel for primary load-bearing elements, 25% aluminium alloy for secondary structures, and 15% rubber for the tyre and damping components. The corresponding *Ecoinvent* datasets are summarised in Table 4.

Table 5 Material composition and corresponding *Ecoinvent* processes for a permanent magnet synchronous motor (PMSM) [14]

Material	*Ecoinvent* process name
Steel (55.56%)	Steel production, electric; steel milling, average; steel turning
Aluminum (22.56%)	Bauxite mining; aluminum alloy production; aluminum casting; aluminum milling
Cast iron (4.80%)	Iron ore mining; steel milling, average
Magnets (3.36%)	Permanent magnet production
Copper (13.60%)	Copper production; wire drawing

2.2.2 Powerplant

The powerplant includes the electric motors, propellers, and batteries. The propulsion system is modeled using permanent magnet synchronous motors (PMSMs), composed of rare-earth magnets, electrical steel, copper or aluminum conductors, and polyimide insulation materials. The material breakdown of the PMSM components is reported in Table 5. Propellers are assumed to be made of CFRP using an autoclave curing process, consistent with current aerospace manufacturing practices.

Energy storage is modeled through lithium-ion battery systems available in *Ecoinvent v3.8*. The NMC111, NMC811, and NCA chemistries are selected, as they offer energy densities typical for aviation-grade applications. These datasets provide both the material composition and the upstream processes associated with cell and pack production.

2.2.3 Systems

The systems category includes the environmental control system (ECS), flight control system (FCS), avionics, and electrical distribution. Each subsystem is mapped to representative processes in *Ecoinvent v3.8*. For example, the ECS is linked to vapor-cycle cooling components, avionics to printed circuit board (PCB) and display manufacturing, and the electrical system to cable and insulation production. Table 6 summarizes the correspondence between each subsystem and the selected inventory datasets.

Table 6 Mapping between ECS, FCS, avionics, and electrical system components and the corresponding *Ecoinvent* processes

Component / System	*Ecoinvent* process(es)
Environmental Control System (ECS)	
Heat exchangers (steel/aluminum)	Steel production, electric; aluminum sheet rolling; metal working, average steel; arc welding, steel
Pipes (steel)	Steel production, electric; steel casting; steel pipe drawing; steel milling
Compressor (steel)	Steel production, converter; electricity supply, medium voltage
Compressor (iron)	Cast iron production; electricity supply, medium voltage
Compressor (copper)	Copper production; copper metal working
Flight Control System (FCS)	
Actuator casing (aluminum)	Bauxite mining; aluminum alloy production; aluminum casting; aluminum milling
ACE actuators (various materials)	PCB production; electronic instrumentation, active production; electronic instrumentation, passive production
Actuator motors (various materials)	Electric motor production
By-wire control (various materials)	Data cable production
Wiring (steel/PTFE)	Steel production, electric; wire drawing, steel; PTFE production
Avionics	
Active electronic instrumentation	Electronic instrumentation, active production
Passive electronic instrumentation	Electronic instrumentation, passive production
Data cable	Data cable production
Mainboard	PCB production
Display (LCD)	LCD production
Casing (aluminum)	Bauxite mining; aluminum alloy production; aluminum sheet rolling; aluminum milling; electricity supply, medium voltage
Electrical system	
Wiring harnesses (copper/plastic)	Copper production; wire drawing; plastic extrusion
Connectors (aluminum/steel)	Aluminum alloy production; steel production, electric; metal working
Power electronics (various materials)	Electronic instrumentation, active production; PCB production
Insulation materials	Plastic film production; PVC extrusion

2.2.4 Furnishings and operator items

The furnishings include thermo-acoustic insulation, interior panels, seating, and windows. The insulation is modeled as polystyrene-based, in line with common general aviation practices. Interior components are represented using a combination of polystyrene and carbon fibre, while windows are modeled with polycarbonate, with polyvinyl chloride (PVC) considered as an alternative.

Table 7 Main subsystems and associated materials considered in the LCA model database

Subsystem	Main materials
Wing	CFRP; aluminum alloy
Fuselage	CFRP; aluminum alloy
Tail	CFRP
Landing Gear	Steel; aluminum alloys; rubber
Electric Motors	Rare earth magnets; electrical steel; copper or aluminum conductors; polyimide insulation
Propellers	CFRP
Batteries	Lithium-ion cells; battery management electronics; NMC cathode materials
Environmental Control System (ECS)	Copper and aluminum components; steel and cast iron parts; plastic fittings
Avionics	Fibreglass, epoxy resin, copper (PCBs); silicon, indium tin oxide (displays); aluminum alloy casings
Flight Control System (FCS)	Aluminum housings; stainless steel; control electronics; sensors
Electrical Systems	Copper wiring; insulation plastics; power electronics
Furnishings	CFRP interior walls; composite seating; polycarbonate windows; polystyrene insulation

Operator items are limited to the pilot seat, consistent with typical short-range eVTOL operations. The seat is modeled using aluminum (40%) and polyurethane foam (60%), with an alternative version using CFRP also evaluated.

Table 7 summarizes the main subsystems and their associated materials, which form the basis for developing the LCA model database and the parametric environmental impact equations used in the analysis.

2.3 Environmental indicators

Once the materials and processes database is established, the environmental impact indicators (EIs) are quantified using the ReCiPe 2016 midpoint method. In this study, only the midpoint categories that exhibit a non-negligible contribution to the total environmental burden are retained, in order to focus the analysis on the most influential drivers.

The selected midpoint indicators include Human carcinogenic toxicity (HCT), Human non-carcinogenic toxicity (HnCT), Ionizing radiation (IR), Terrestrial ecotoxicity (TET), Fossil resource scarcity (FRS), Freshwater ecotoxicity (FET), Global warming potential (GWP), and Marine ecotoxicity (MET). These categories capture the most relevant impact mechanisms associated with electric aircraft manufacturing, including toxicity-related pathways, resource use, ecotoxicological effects, and climate change potential.

Each indicator is computed for all aircraft subsystems and aggregated to form the environmental impact coefficients used in the parametric equations introduced earlier. The results highlight substantial differences among materials

Table 8 Environmental impacts of aircraft subsystems across selected midpoint categories (ReCiPe 2016)

Subsystem	HCT	HnCT	IR	TET	FRS	FET	GWP	MET
EI_{CFRP}	2.96	59.13	5.49	106.71	21.09	2.90	85.39	3.73
$EI_{\mathrm{Aluminium}}$	4.00	80.25	1.73	156.71	5.08	4.80	19.33	6.97
$EI_{\mathrm{GlassFibre}}$	0.24	1.57	0.17	3.39	2.75	0.06	9.15	0.08
EI_{Tail}	2.96	59.13	5.49	106.71	21.09	2.90	85.39	3.73
$EI_{\mathrm{LandingGear}}$	8.71	32.60	0.78	148.90	2.89	2.16	11.97	3.02
$EI_{\mathrm{ElectricMotor}}$	7.83	90.09	0.44	552.94	2.18	5.90	8.09	7.69
$EI_{\mathrm{Propellers}}$	2.96	59.13	5.49	106.71	21.09	2.90	85.39	3.73
$EI_{\mathrm{Batteries}}$	2.47	130.06	1.91	736.46	4.98	7.46	18.50	9.73
EI_{ECS}	6.62	39.96	0.28	254.87	1.33	2.69	4.70	3.43
EI_{FCS}	14.67	117.05	1.96	751.86	7.73	7.34	92.70	9.81
EI_{Avionics}	8.51	502.74	5.72	672.22	14.89	31.99	60.08	42.69
$EI_{\mathrm{Furnishings}}$	2.56	56.12	3.48	98.45	13.57	3.77	57.38	5.02
$EI_{\mathrm{Electrical}}$	1.32	37.49	2.34	142.15	5.76	5.72	20.98	7.04

Table 9 Main dimensional parameters and subsystem mass breakdown of the reference eVTOL

	Unit	Average value
Wing span	m	10.7
Tail span	m	3.0
Fuselage length	m	8.0
Fuselage diameter	m	1.5
Fuselage aspect ratio	–	1.5
Maximum Take-Off Mass (MTOM)	kg	1826
Empty Mass	kg	1226
Fuselage	kg	220
Landing gear	kg	25.5
Wing	kg	189.5
V-tail	kg	29.5
Motors	kg	58
Propellers	kg	316
Battery pack	kg	345
Pilot (fixed)	kg	100
Passengers (fixed)	kg	400

and components, reflecting the strong influence of energy-intensive composite manufacturing, battery chemistry, and electronic systems production on the overall impact profile.

Table 8 reports the subsystem-level midpoint results for all selected categories. The dataset shows, for example, that Human Non-Carcinogenic Toxicity (HnCT), Terrestrial Ecotoxicity (TET), and Global Warming Potential (GWP) are among the dominant contributors, confirming the relevance of both upstream material extraction and energy-intensive processing in determining the environmental performance of eVTOL systems.

3 Case study

The case study examines a conceptual eVTOL configuration developed within the framework of the COLOSSUS Project [9]. The aircraft is designed according to a set of TLARs addressing both UAM and RAM missions. The targeted mission range spans 50 km for urban routes and up to 200 km for regional operations, with corresponding cruise speeds between 100 and 200 km/h. The baseline layout accommodates four passengers and one pilot, matching the emerging air taxi service model for short-haul applications.

The aircraft features a vectored-thrust configuration with a fixed wing and V-tail, inspired by current industry prototypes such as the Joby S4 and VA-X4. Propulsion is achieved through PMSMs, while energy storage relies on lithium-ion battery systems aligned with the technology maturity expected by 2035. Table 9 summarizes the main geometric characteristics and the mass breakdown of the primary subsystems, which serve as inputs to the LCA model.

The operational profile assumes an average of 16 flights per day over 330 operating days per year, corresponding to a total of 52,800 missions over a 10-year service life. This shorter lifetime assumption reflects the expected high-utilization profile of commercial eVTOL operations, characterized by frequent short missions and a substantially higher number of operational cycles compared with conventional regional aircraft. Additionally, the strong dependence of eVTOL platforms on rapidly evolving technologies, particularly batteries, avionics, and control systems, suggests that technological obsolescence may contribute to shorter fleet replacement cycles. For these reasons, a 10-year operational lifetime was adopted for the present analysis.

Maintenance is focused on high-wear components such as the landing gear, wheels, and braking system, while battery modules are periodically replaced based on degradation

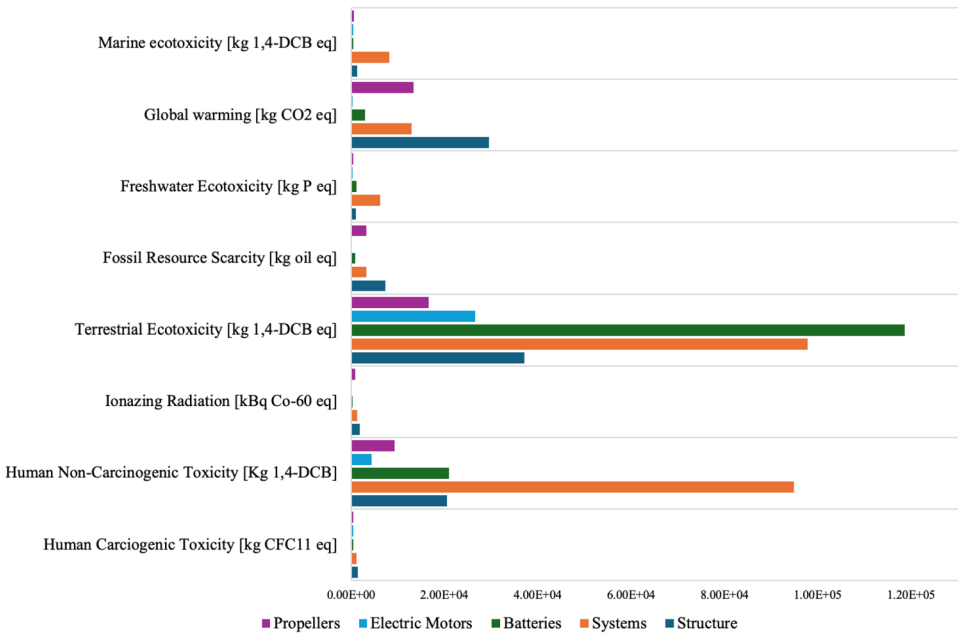


Fig. 1 Environmental impact contributions of eVTOL subsystems across different categories during the production phase

cycles. The EoL phase is excluded from the system boundaries, consistent with the cradle-to-operation scope adopted in this study.

In terms of operations, the representative mission selected corresponds to a cruise speed of 200 km/h and a range of 100 km, which results in an average electricity consumption of approximately 120 kWh. For the LCA, the aircraft is assumed to operate 16 flights per day, 330 days per year, over a service life of 10 years. This results in a total of 52,800 missions.

Maintenance considerations focus on the scheduled replacement of critical wear components subject to frequent operational cycles. In particular, battery systems constitute a distinct maintenance category, as their performance progressively degrades with repeated charge–discharge cycles and therefore requires periodic replacement.

Overall, maintenance contributes significantly to the operational environmental footprint of the aircraft, particularly for components characterized by high material criticality and relatively short replacement intervals, such as batteries. These findings highlight the importance of careful material selection and component design strategies to reduce environmental burdens over the aircraft lifetime.

4 Results and discussion

Figure 1 shows that lithium-ion batteries (LIBs) are the dominant contributors to terrestrial ecotoxicity among all eVTOL subsystems, with an estimated 1.19×10^5 kg 1,4-DCB eq, more than twice the structural contribution. This aligns with previous life cycle findings attributing the major ecotoxicological burden of LIBs to the extraction and processing of critical materials such as lithium, cobalt, nickel, manganese, copper, and graphite, which cause heavy metal release, soil contamination, and acid mine drainage [15].

Table 10 Environmental impact contributions of each eVTOL subsystem by impact category during the production phase

Impact category	Structure	Systems	Batteries	Electric motors	Propellers
HCT [kg 1,4-DCB]	1.40E+03	1.12E+03	3.97E+02	3.76E+02	4.62E+02
HnCT [kg 1,4-DCB]	2.05E+04	9.48E+04	2.09E+04	4.32E+03	9.22E+03
IR [kBq Co-60 eq]	1.90E+03	1.29E+03	3.07E+02	2.12E+01	8.57E+02
TET [kg 1,4-DCB]	3.71E+04	9.78E+04	1.19E+05	2.65E+04	1.66E+04
FRS [kg oil eq]	7.30E+03	3.25E+03	8.02E+02	1.05E+02	3.29E+03
FET [kg 1,4-DCB]	1.01E+03	6.18E+03	1.20E+03	2.83E+02	4.53E+02
GWP [kg CO_2 eq]	2.96E+04	1.29E+04	2.98E+03	2.83E+02	1.33E+04
MET [kg 1,4-DCB]	1.29E+03	8.13E+03	3.69E+02	3.69E+02	5.82E+02

The second-largest hotspot is represented by the systems. Their high contribution is primarily due to the Avionics system, which comprises avionics units, navigation instruments, power electronics, and high-performance semiconductors. These devices rely on rare earth elements, precious metals, and ultrapure silicon derived via energy and chemical intensive processes (Table 10).

Emerging high-energy-density cathode chemistries (LFP, LMO, NMC, NCA) and post-LIB technologies such as lithium–sulfur (Li–S), lithium–air (Li–O_2), sodium-ion (Na-ion/

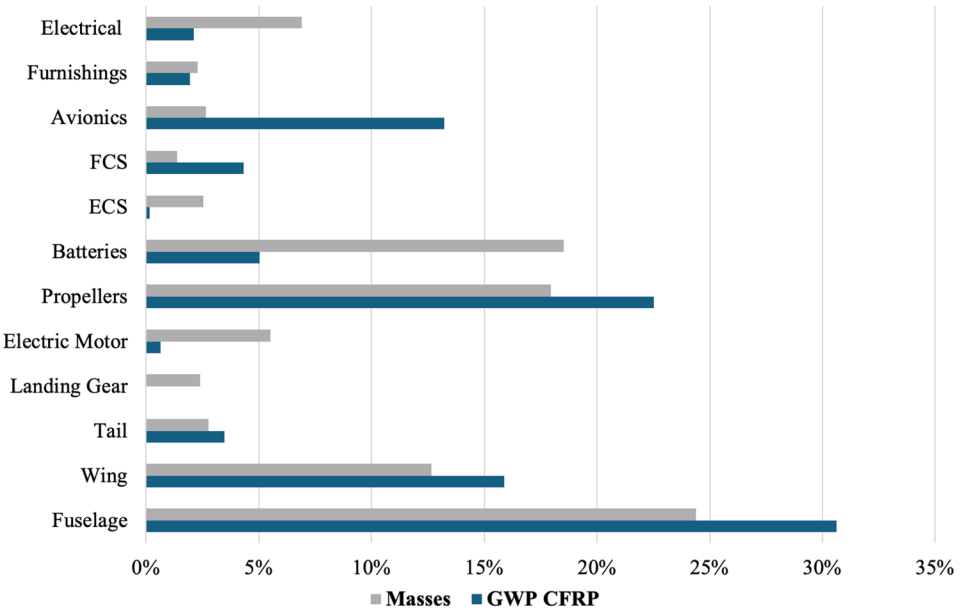


Fig. 2 Mass-normalized Global Warming Potential (GWP) of eVTOL components during the production phase

Table 11 Global Warming Potential (GWP) by component during the production phase

Component	Global Warming [kg CO_2 eq]
Fuselage	1.81×10^4
Wing	9.39×10^3
Tail	2.05×10^3
Landing Gear	1.20×10^1
Electric Motor	3.88×10^2
Propellers	1.33×10^4
Batteries	2.98×10^3
Environmental Control System (ECS)	1.03×10^2
Flight Control System (FCS)	2.56×10^3
Avionics	7.82×10^3
Furnishings	1.15×10^3
Electrical	1.26×10^3

SIB), and solid-state batteries (SSB) have the potential to reduce both toxicity and critical material dependency, representing promising alternatives for future eVTOL propulsion systems [16].

The structure, however, emerges as a major hotspot across several impact categories, particularly terrestrial ecotoxicity (3.71×10^4 kg 1,4-DCB eq), global warming (2.96×10^4 kg CO_2 eq), and human non-carcinogenic toxicity (2.05×10^4 kg 1,4-DCB eq). These results primarily stem from the material composition, which assumes approximately 80% carbon fiber reinforced polymer (CFRP).

CFRP production is characterized by high energy intensity and pollutant emissions. The carbonization and graphitization of polyacrylonitrile (PAN) precursor fibers, processes carried out at elevated temperatures to remove non-carbon elements and improve crystalline alignment, are particularly impactful. These stages not only demand significant electrical energy but also emit volatile organic compounds (VOCs) and nitrogen oxides, explaining the strong contributions to both GWP and human toxicity.

Overall, the results highlight two dominant environmental hotspots: LIB manufacturing, associated with upstream raw material extraction, and CFRP-based structural components, linked to energy-intensive processing. This duality underlines the need for upstream supply chain optimization, low-impact recycling strategies, and alternative material solutions with lower embodied emissions [17].

Figure 2 illustrates the Global Warming Potential (GWP) of each component during production, normalized by mass. The fuselage and wing are the most carbon-intensive components, followed by the flight control system and propellers. Table 11 reports the corresponding absolute GWP values.

The high GWP associated with the structural components derives from the modelling assumption that the fuselage, wings and propellers are entirely manufactured from carbon-fibre-reinforced polymers (CFRP) with epoxy matrices. Under this full CFRP hypothesis, the differences in impact between components no longer originate from their material composition, but from their respective masses and manufacturing energy demand.

As shown in Fig. 1, the fuselage represents the largest contributor to GWP among the CFRP-based elements due to its higher mass fraction ($\approx 30\%$), followed by the propellers ($\approx 25\%$) and the wings ($\approx 17\%$).

The higher CO_2 emissions arise from the inclusion of carbon fibre composites, whose production involves both the energy-intensive synthesis of carbon fibres and the electricity demand required for autoclave curing during

Table 12 Global Warming Potential (GWP) of wing and fuselage made entirely of aluminium (Al) or carbon-fiber-reinforced polymer (CFRP)

Component	GWP (Aluminium)	GWP (CFRP)	Increase (% vs. Al)
Fuselage	4.10×10^3	1.81×10^3	+341%
Wing	2.13×10^3	9.39×10^3	+341%

the polymerisation of epoxy matrices. In contrast, aluminium components represent a more sustainable solution, as aluminium alloys can be recycled with up to 95% energy savings compared to primary extraction. These avoided emissions are accounted for as positive environmental credits, substantially reducing the overall impact [18].

Composite materials, however, require significantly higher energy input during prepreg manufacturing and autoclave processing, and their end-of-life recyclability remains limited (approximately 24%), resulting in low fibre recovery and minimal avoided emissions. Previous studies have shown that CFRP production and disposal phases can lead to up to an 800% higher environmental burden compared to aluminium components [13].

To assess the influence of material selection, Table 12 compares the Global Warming Potential (GWP) of the fuselage and wing for two alternative configurations: one employing an aluminium alloy and the other using CFRP. Replacing aluminium with CFRP increases the fuselage and wing GWP by approximately 341%, confirming the high carbon intensity associated with composite manufacturing, although this substitution results in a significant reduction in the overall aircraft weight.

These findings demonstrate that the selection of structural materials has a decisive effect on the life-cycle climate impact of eVTOL systems. While CFRP offers superior strength-to-weight performance, its production-phase emissions are substantially higher than those of aluminium alloys. Consequently, future design strategies should consider hybrid material architectures, low-energy composite processing methods, and improved end-of-life recovery technologies to reduce the embodied carbon of next-generation eVTOL structures.

The environmental burden is strongly influenced by the mass of each subsystem and the specific material and manufacturing processes involved. The airframe and propulsion systems, composed of energy-intensive materials such as carbon fiber, aluminum alloys, lithium, and rare-earth metals, remain the dominant sources of impact.

The operational phase includes both the energy consumption associated with the mission flight profile and the periodic replacement of components throughout the aircraft lifetime. These effects were modelled according to Eqs. (2)–(4), combining mission-related electricity use and subsystem maintenance contributions.

Table 13 Summary of key results for the operational phase

Parameter	Value / Unit
Average mission energy	120 kWh
Lifetime energy consumption	6.3×10^6 kWh
Electricity emission factor (EU mix)	0.25 kg CO_2 eq/kWh
Energy-related GWP	1.6×10^6 kg CO_2 eq
Battery-related maintenance	4.5×10^4 kg CO_2 eq
Other maintenance contributions	5.0×10^4 kg CO_2 eq
Total operational GWP	1.7×10^6 kg CO_2 eq
Operational share of total GWP	85–90%

For the reference eVTOL configuration, a representative 100 km mission at a cruise speed of 200 km/h requires approximately 120 kWh of electrical energy. Consistent with the assumptions of the case study in Sect. 3, the aircraft is assumed to operate 16 flights per day over 330 days per year, resulting in 5280 missions per year and a total of 52,800 missions during a 10-year service life. This corresponds to about 26,400 flight hours and a cumulative lifetime energy consumption of $E_{\text{total}} = 6.3 \times 10^6$ kWh. Based on the average European electricity mix (0.25 kg CO_2 eq/kWh), the total energy-related Global Warming Potential (GWP) is estimated at 1.6×10^6 kg CO_2 eq, which represents the dominant share of the operational impact.

Battery lifetime was assumed to be approximately 3000 flight hours, consistent with current lithium-ion cycle durability for aerospace applications. Over the aircraft lifetime, this corresponds to multiple replacements, with a cumulative maintenance impact of about 4.5×10^4 kg CO_2 eq. Additional maintenance contributions were estimated for the main rotating and electronic subsystems based on representative overhaul intervals and preventive maintenance practices in light aircraft operations. The resulting cumulative maintenance burden contributes an additional 5.0×10^4 kg CO_2 eq, corresponding to a small fraction of the total operational emissions.

A summary of the main results for the operational phase is provided in Table 13. When combining all effects, the total operational GWP amounts to approximately 1.7×10^6 kg CO_2 eq, which accounts for roughly 85–90% of the overall life-cycle impact.

A sensitivity analysis on the electricity generation mix indicates that transitioning to a fully renewable grid (100% wind and solar) could reduce operational emissions by nearly 90%, whereas carbon-intensive grids may increase them by more than 50%. These findings emphasize the critical influence of the electricity mix and component durability on the environmental performance of future eVTOL systems.

Overall, the operational phase dominates the life-cycle impact, primarily due to electricity generation and the periodic replacement of batteries. Extending battery lifetime

and accelerating the decarbonization of the energy supply therefore remain key levers for improving the sustainability of eVTOL operations.

Maintenance also contributes significantly to the operational environmental footprint, particularly for systems characterized by high material criticality and relatively short replacement cycles, most notably battery systems, which represent a key and rapidly evolving component of the eVTOL propulsion architecture. This finding is consistent with recent LCA studies on conventional aircraft, where maintenance has been identified as a non-negligible contributor to life-cycle impacts [19].

5 Conclusion

This study presented the development of a modular and parametric Life Cycle Assessment (LCA) framework for electric Vertical Take-Off and Landing (eVTOL) aircraft, conceived to support sustainability-driven decision making during the early stages of conceptual design. The model, derived from the ALiCIA tool originally developed for regional aircraft, was adapted to the specific characteristics of eVTOL configurations within the COLOSSUS project, allowing a consistent evaluation of different architectures, materials, and operational profiles.

The proposed framework proved effective in quantifying the environmental performance of eVTOL systems through a simplified but traceable LCA approach. Results confirmed that the operational phase provides the largest contribution to the overall Global Warming Potential (GWP), accounting for about 85–90% of total life cycle emissions. This predominance is mainly due to electricity generation and the periodic replacement of batteries, highlighting the importance of extending energy storage lifetime and reducing the carbon intensity of the power supply.

In the production phase, structural materials such as carbon fibre composites and aluminium alloys represent the main contributors to embodied emissions because of their high energy demand and limited recyclability. Conversely, the adoption of hybrid material solutions and the introduction of advanced recycling techniques, such as pyrolysis for composite recovery, could significantly improve the circularity and sustainability of future eVTOL structures.

Overall, this work confirms the relevance of LCA as a fundamental instrument to guide design decisions towards environmentally responsible aviation. The integration of the proposed model within the COLOSSUS framework demonstrates the feasibility of including LCA in multidisciplinary design environments, linking environmental assessment with engineering design practice. Future research will aim to refine the model using industrial data, expand the scope to additional impact categories, and integrate sustainability metrics within optimisation tools for the next generation of low-impact air mobility systems.

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Data availability No datasets were generated or analysed during the current study.

Declarations

Conflict of interest The authors declare no conflict of interest.

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