Flying with Liquid Hydrogen: An Assessment of CFRP Fuel Tank Manufacturing in the Aviation Industry and Its Challenges

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Abstract The use of liquid hydrogen in aircraft is a promising option for a more sustainable aviation. Concepts for hydrogen-powered aircraft explore the use of lightweight carbon fibre-reinforced polymer tanks without liners. This study aims to support decision makers in the aviation industry by assessing the potential environmental impact of the manufacturing of these tanks. To this end, a life cycle assessment of hydrogen tanks for a defined use case is conducted using primary data from the manufacture of a half-tank, with the parameters defined by aircraft predesign using the common parametric aircraft configuration schema, an aircraft description language. Contribution analysis identifies the main contributors, while a Monte Carlo analysis reveals the model's uncertainties. Finally, a scenario analysis illustrates the differences in datasets from various carbon fibre-reinforced polymer datasets.

1 Introduction

Environmental impacts of aviation in general and especially the effects on global warming are gaining in importance in the research and development of new airplane concepts and their propulsion. Today, the aircraft use phase is responsible for a majority of climate change impacts from a combination of direct CO_2 emissions and non-CO_2 effects like contrails. The impacts depend on a variety of parameters, particularly during the use phase. One of these is flight distance. In 2023, short-haul flights accounted for 54% of CO_2 emissions emitted by the aviation industry (HAV 2024).

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This number demonstrates that short-haul flights are a highly energy- and cost-sensitive segment. This is further demonstrated by comparing it with ground-based transportation options (Ritchie 2023).

To counteract these high impacts, fuel alternatives are taken into focus. Sustainable Aviation Fuels (SAF) and liquid hydrogen (LH2) are promising alternatives to petrol-based kerosene to reduce the environmental impact (Baharozu et al. 2017; Bergero et al. 2023).

From an economic viewpoint, due to the steady growth of the hydrogen sector, the price of sustainably produced hydrogen is expected to drop significantly by 2050, rendering it more cost-effective than synthetic aviation fuel (Gallucci 2022).

Other life phases like raw material extraction, production, Maintenance, Repair and Overhaul (MRO) and End of Life (EoL) just have a minor impact over the life time of an aircraft in comparison to the use phase (Mignanelli et al. 2024). With the upcoming introduction of innovative technologies that aim to emit considerably less greenhouse gases, the relative importance of other phases increases. However, the environmental impacts of SAF and hydrogen production need to be evaluated for better understanding as they depend considerably on the raw materials and production methods. Beside that the indirect climate impact of hydrogen needs to be understood better. Also, high-performance materials like carbon fibres have a considerable environmental impact on their own (Bachmann et al. 2017; Benitez et al. 2021; Kamali et al. 2025), on the other hand, they enable the production of components that fulfil ever rising requirements of future aircraft. Here, Life Cycle Assessment (LCA) can be a precious support for choosing the right materials and processes.

This study is based on the use case of an aircraft configuration taken from the ALICIA (Aviation Life Cycle and Impact Assessment) project. The aircraft concept is a short-range aircraft that uses LH2 as energy carrier and has a mild hybrid electric propulsion (MHEP) system for 250 passengers.

Researchers and industry are currently investigating two different tank arrangements for the aft fuselage tanks (see Fig. 1). The 'side-by-side' approach is advantageous from the perspective of tank manufacturing and certification because only one type of tank with a smaller diameter needs to be produced and certified (FlightGlobal 2024). However, the 'tandem' tank arrangement utilises the given fuselage shape more efficiently.

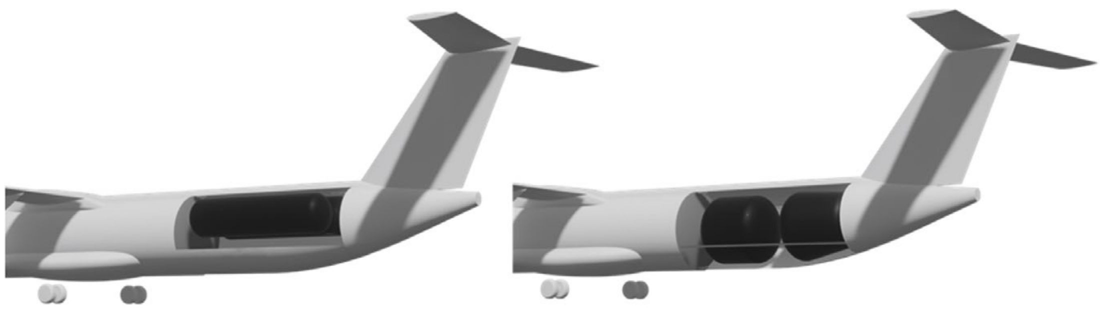

Fig. 1 Aft fuselage mounted 'side by side' (left) and 'tandem' (right) tank

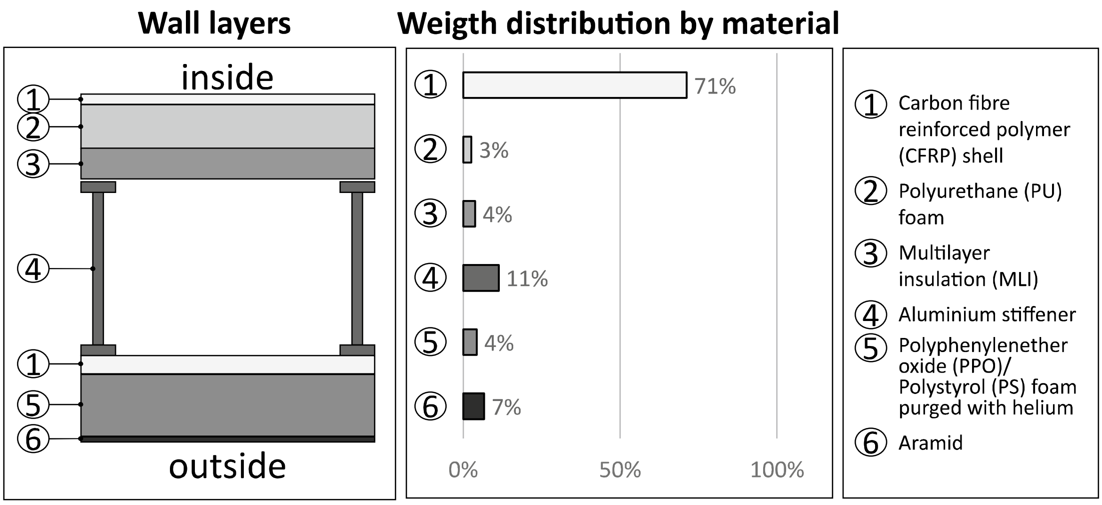

Fig. 2 Exemplary tank wall with layers as defined in the CPACS file and the calculated mass distribution

For this use case, the hydrogen is stored under cryogenic conditions in two tanks in the 'tandem' configuration located behind the rear bulkhead as shown in Fig. 1, right. Figure 2 presents a principle cross section of the tank shells made of an inner and an outer Carbon Fibre-Reinforced Polymer (CFRP) shell including insulation.

The parametrizations of the whole aircraft are defined in the Common Parametric Aircraft Configuration Schema (CPACS) (Alder et al. 2020). More information about the use case can be found in (DLR Institute of System Architectures in Aeronautics 2025).

LCAs of composite hydrogen tanks are scarce in the literature. Most of the assessments in this area relate to the automotive sector and the tanks are mainly included in the assessment of a fuel cell electric car as a component. The main focus is on Type III and IV tanks for 350 and 700 bar gaseous states, manufactured using filament winding technology (Benitez et al. 2021; Evangelisti et al. 2017; Mignanelli et al. 2024). LCAs on Type V pressure vessels for use under cryogenic conditions, especially for aircrafts, are underrepresented.

2 Materials and Methods

This study carries out a cradle-to-gate life cycle assessment of a CFRP LH2 tank in accordance with ISO standards 14040 and 14044, ensuring a systematic approach to quantify potential environmental impacts. This methodology consists of four phases: Goal and Scope Definition; Life Cycle Inventory (LCI); Life Cycle Impact Assessment (LCIA); and Interpretation. All of these phases are covered in the following sections.

2.1 Goal and Scope

The main purpose of this study is to assess the environmental impact of producing hydrogen tanks for the use case (see Chap. 1), based on primary data from an industrial-scale production process involving half of the inner CFRP shell, scaled to the dimensions of the use case. Additionally, a comparison is conducted between the CFRP inner shell and a comparable aluminium shell.

2.1.1 Tank Layers of the Use Case

The manufacturing process of the CFRP shells (carbon fibre + epoxy resin) is based on Automated Fibre Placement (AFP). All manufacturing steps from preparation until dismantling are included as well as the raw material extraction and the assembly with the insulation (see Fig. 3). Uncertainties in the manufacturing process are considered, and a scenario analysis will contribute to provide decision-makers in the field of sustainable aviation with a transparent and detailed overview of the results.

The product system itself consists primarily of the inner and outer composite shells, as well as the various insulation layers (see Fig. 2).

The total mass of the tanks is calculated as 1839 kg, with the cylindrical tank accounting for 55% and the conical tank for 45%. This estimation is based on geometric calculations using data from CPACS and literature. For the purposes of this study, the Functional Unit (FU) is defined as the LH2 tanks of the CPACS aircraft configuration, consisting of a conical tank and a cylindrical tank with insulation layers, as previously described. The two tanks together have a volume of 59.72 m^3.

Figure 3 illustrates the system boundary for the cradle-to-gate study. The study is conducted using the brightway2 package, calculating the 16 impact categories

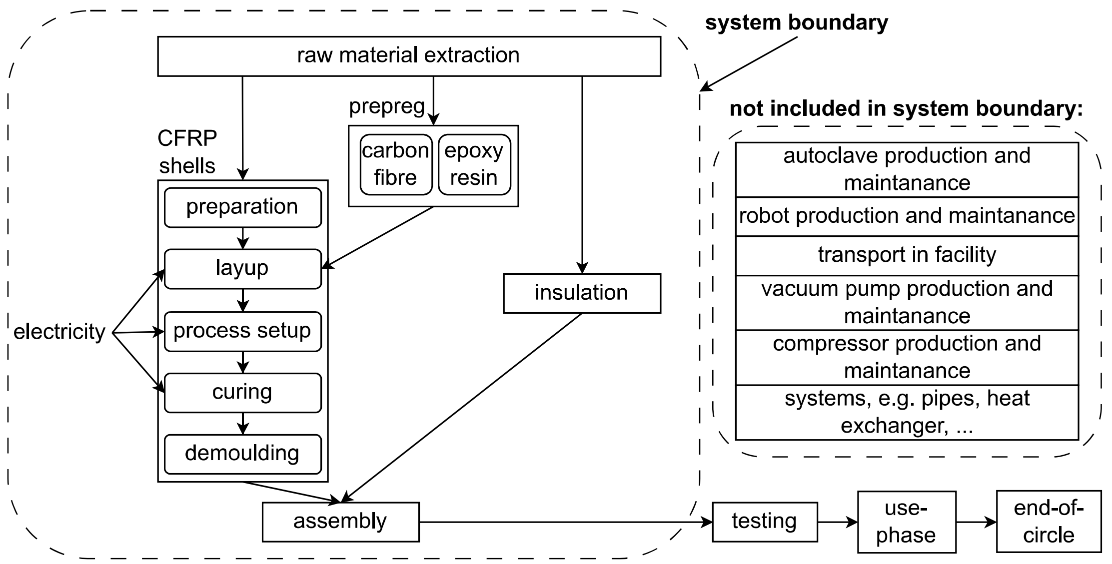

Fig. 3 System boundary

with the related indicators of the Environmental Footprint (EF) v3.1 method. The background database used is the ecoinvent 3.9.1 cut-off version.

The different manufacturing processes are assumed to be located in Europe. It is also important to note that the manufacturing process of the inner shell is assumed to be scalable for the tank diameter of the use case, and that the outer shell is assumed to have the same manufacturing process as the inner shell.

2.1.2 Comparison of CFRP with Metal Inner Vessels

This study includes a preliminary, high-level comparison of metal and composite shells. For this comparison, an inner metal shell based on the same technical characteristics has been designed.

Both vessels use a safety factor of 2.0 as analogy to pressurized fuselages in EASA/CS 25.365 d that requires a factor of 1.33 to the load carrying capability besides the ultimate load factor of 1.5 (CS 25.303). The operational pressure is set to 2 bars and an operational cycling from 1 bar to operational pressure is assumed for each of the 50,000 flight cycles as fatigue load spectrum.

The aluminium mass assessment is based on Barlow's formula as described in the AD2000 (Arbeitsgemeinschaft Druckbehälter e.V. 2016) standard and extended by a fatigue calculation from MMPDS-07 (Rice et al. 2012). Here aluminium 6061 T6 is used. CFRP vessels are calculated using the commercial structural solver µWind from MeFeX (Meyer 2016) in combination with DLRs tank optimization tool tankoh2 (Freund et al. 2025) as described in (Freund & Franzoni 2022) using pucks inter fibre failure criterion. Additionally, internal thermomechanical stresses due to the cryogenic temperatures using classical lamination theory are considered as well as in situ strengths (Camanho et al. 2006).

2.2 Life Cycle Inventory (LCI)

All the collected data is scaled up to the CPACS data for the use case. The primary data is supplemented with uncertainty distributions.

2.2.1 Data Collection for the Tank Layers of the Use Case

The foreground data for manufacturing the CFRP shells is collected from an industrial-scale AFP process used to manufacture a half-tank. This data is either measured or estimated by experts. This includes the various activities shown in Fig. 3, such as preparing the tool, laying up the material (prepreg) and setting up the vacuum build-up, as well as curing in the autoclave. Data for the curing step also includes the use of nitrogen for inert gas filling of the autoclave and the electricity

Table 1 Structural characteristics of the aluminium and CFRP inner shells for comparison

	Unit	Tank 1		Tank 2	
		Aluminium	CFRP	Aluminium	CFRP
Diameter	m	3.592		2.977	
Axial length	m	4.197		3.829	
LH2 volume	m^3	36.518		23.2	
LH2 mass	kg	2225		1414	
Shell mass	kg	395	316	244	220

consumed by the autoclave. Scaling the primary data to the use case dimensions is based on parameters such as surface area and layer volume.

Due to the absence of carbon fibre data in the background database, the detailed virgin carbon fibre (Toray T700 G) production dataset from Benitez et al. (2021) is employed instead.

All layers of insulation are taken from the CPACS file and supported by literature data. Although there is no dataset for polyphenylenether oxide (PPO), it is modelled based on stoichiometric calculations, following the ecoinvent methodology (Hischier et al. 2005). The Multilayer Insulation (MLI) material is assumed to consist of 30 layers of reflector and separator each. It is modelled based on (Finckenor & Dooling 1999).

2.2.2 Data Collection for the Comparison of CFRP with Metal Inner Vessels

The aluminium layer described in Chapter 2.1.2 is modelled based on ecoinvent datasets for aluminium and metal working as well as welding.

The structural masses of the inner vessel shells used are listed in Table 1.

3 Life Cycle Impact Assessment (LCIA)

The LCIA is divided into sections. First, a contribution analysis is conducted to identify the main contributors. Secondly, a scenario analysis illustrates how results can differ when using datasets from different databases for the same product before finally a comparison of the environmental impacts of an inner tank shell made out of CFRP is compared to one out of aluminium.

3.1 Contribution Analysis

The first part of the LCIA is the contribution analysis. As the bottom graph in Fig. 4 shows, the impact of the CFRP shells is consistently greater than 75%. Taking a closer look at the individual activities behind the CFRP shells reveals that the prepreg is the main contributor to impacts in all categories except Ozone Depletion Potential (ODP). Here, the release film from the process set-up has the highest contribution at 95.5%.

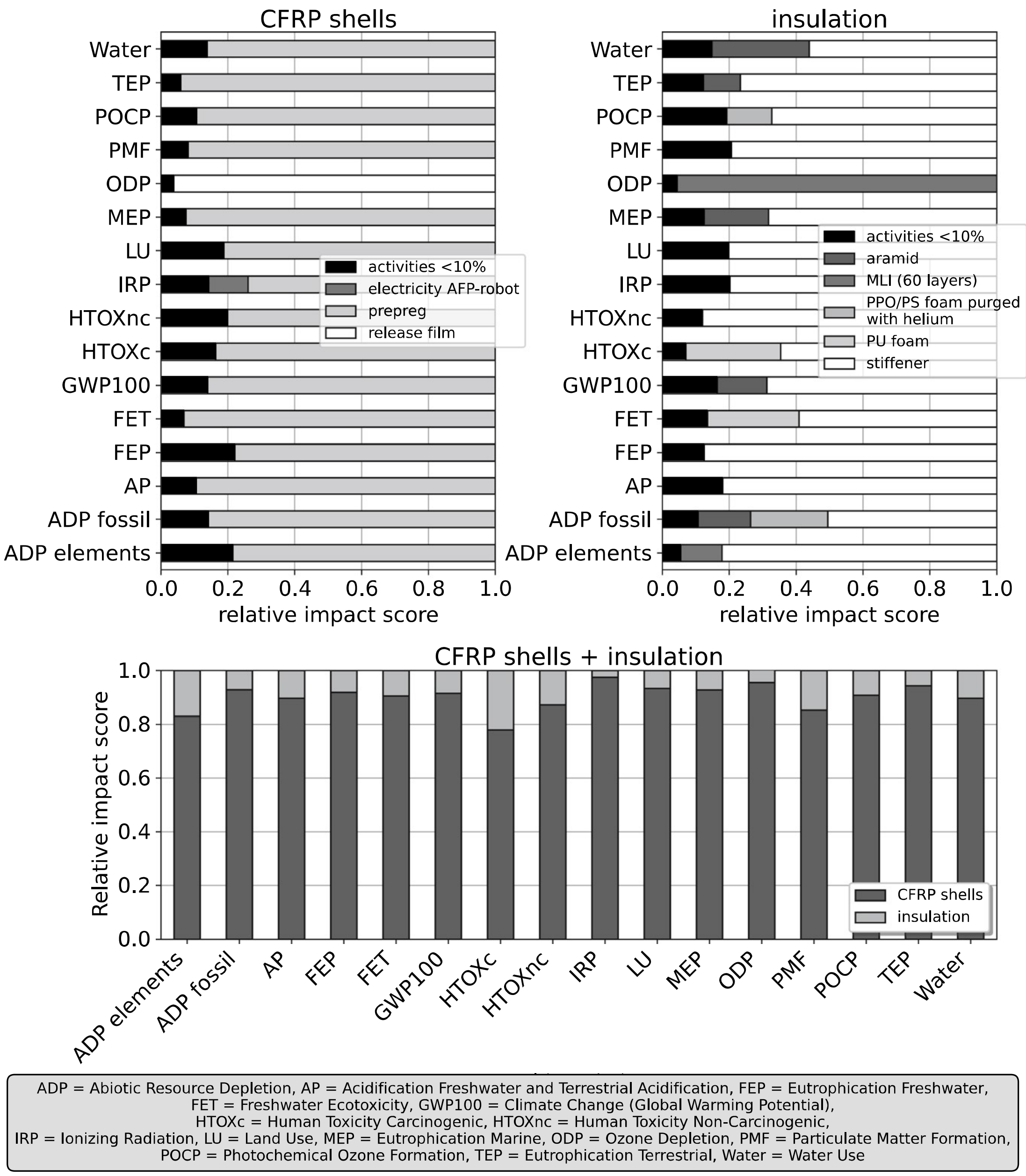

Fig. 4 Relative contributions of the CFRP shells and the insulation to the impacts of all EF v3.1 indicators

In contrast, no obvious element stands out as having the greatest impact on all insulation layer categories. However, the aluminium stiffener layer is identified as the main contributor in most categories, accounting for over 50% of the total in all but three indicators: Ecotoxicity Freshwater (FET), Human Toxicity Non-carcinogenic (HTOXnc) and ODP. For FET and HTOXnc, the Polyurethane (PU) foam is the main contributor. The MLI stands out in the Ozone Depletion category, accounting for 96% of the total impact.

The Global Warming Potential (GWP100) divides into 80,934 kgCO_2eq for the CFRP shells and 7,505 kgCO_2eq for the insulation.

3.2 Scenario Analysis

As shown in Chap. 3.1, the prepreg is identified as the main contributor. The scenarios are chosen based on this. Specifically, alongside the model based on foreground data, two additional datasets are used to represent the production of the CFRP shells as best fits from two LCA databases:

(1) the ecoinvent dataset: carbon fibre-reinforced plastic, injection moulded, GLO
(2) the esa LCA database dataset: CFRP, cured by autoclave process {RER} | production | Cut-off, U.

These two datasets are then linearly scaled by the product weight. For the MHEP use case based on primary data, the scaling is based on certain parameters described in Chap. 2.2.1. The differences between the scenarios are displayed in Fig. 5 for all EF v3.1 categories as deviation from the reference which is defined as the results based on the model with primary data. Existing datasets for CFRP from the ecoinvent 3.9.1 and esa LCA databases show deviations from the model using primary data. While environmental impacts are generally lower using the esa LCA dataset, the ecoinvent dataset shows higher and lower impacts depending on the category.

Based on these data, a high-level LCA was conducted in accordance with the goal and scope outlined in Chap. 2.1, using the data in Table 1. The results show that limiting the assessment to the production phase leads to higher impact of inner shells made from CFRP in all EF v3.1 categories. The absolute difference for GWP100 is 32 t CO_2 eq more for the CFRP shell.

4 Interpretation

Firstly, the main contributors were identified in Chap. 3.1. Coupling the results of the contribution analysis with the scenario analysis shows that, especially for the CFRP shells, the results depend heavily on the data source and the scaling approach.

It should be noted that data on composite production cannot be scaled based solely on weight. This underlines the need for parameterized and representative LCIs for

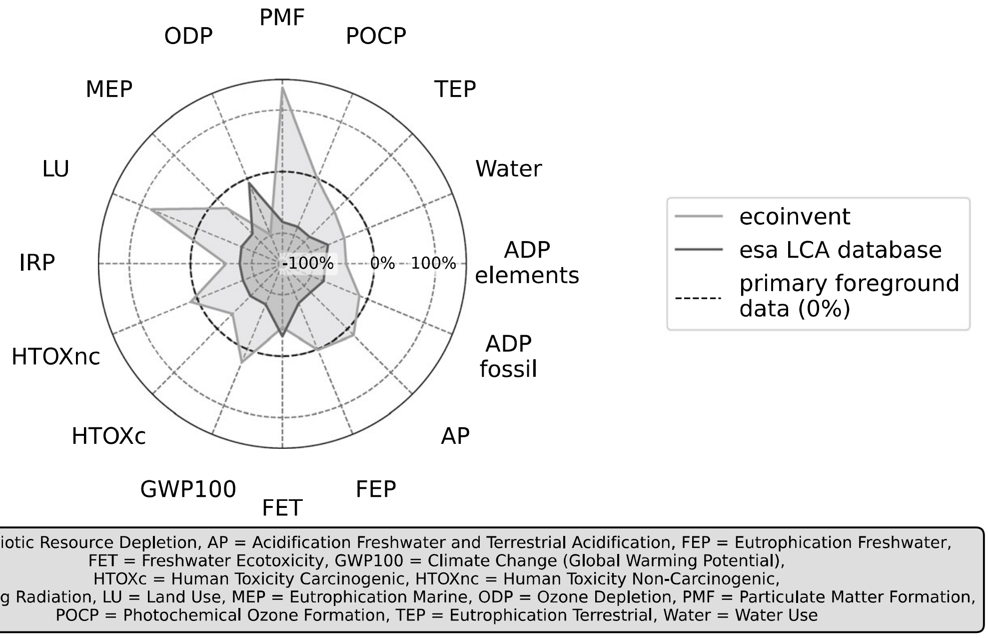

Fig. 5 Relative deviation from using the model with primary data as reference for all impact indicators in EF v3.1

composite production processes that enable a more realistic modelling of real-world processes. The comparison of the environmental impact of manufacturing metal and CFRP inner shells shows the need to consider the entire life cycle of an aircraft, because the CFRP shell's lower weight means that its environmental impact during the use phase will be potentially lower than that of the aluminium one.

The contribution analysis step does not include the characterization of uncertainties. Therefore, a Monte Carlo analysis involving 10,000 runs was conducted. Uncertainties from the background data (lognormal distributions) and for the CFRP shell manufacturing (uniform distributions) are included. Figure 6 shows the distributions of each category using box plots. The boxes represent the central 50% of the values (interquartile), while the median is marked with a horizontal line in the box. The results are normalized to represent the deviation from the mean in % which is set as 0%. The data behind all boxes show that the second quartile is for all smaller than the third which can be characterized by the location of the median in the box. The Human Toxicity (HTOX) and the FET categories show the least concentrated distributions (Fig. 6, right). Also interesting is the indicator Abiotic Resource Depletion (ADP) elements which is the only distribution where the mean is not located in the interquartile. Furthermore, the median is always lower than the mean.

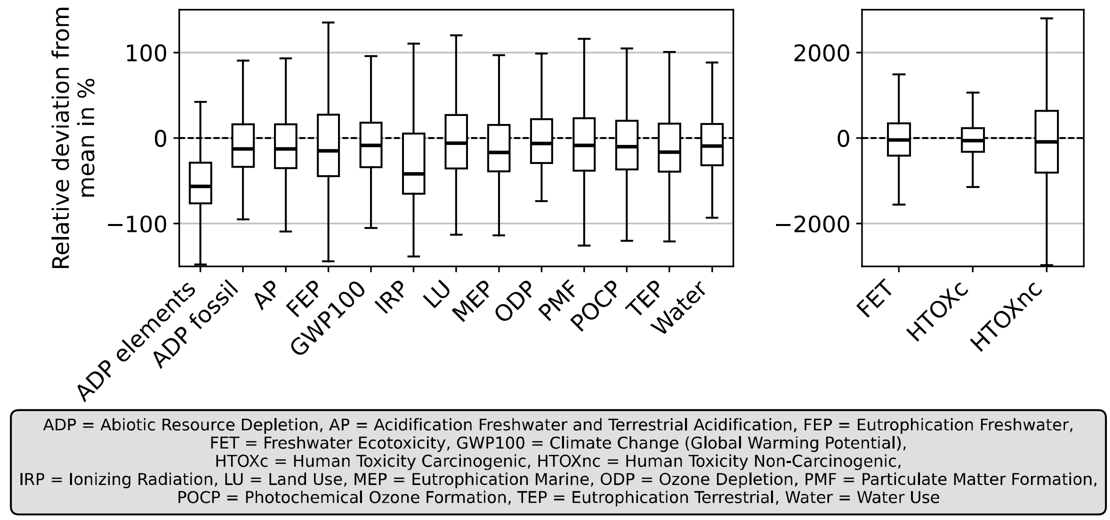

Fig. 6 Box plot of all EF v3.1 indicators showing the distributions of the Monte Carlo results separated into two plots due to the differences in the scale

5 Conclusion and Outlook

Assessing the environmental impacts for the defined functional unit shows that more primary data is needed. However, it is important to bear in mind that even primary data is subject to uncertainty and should always be challenged. The need for parameterized LCIs is also evident, as is the need to consider uncertainties in order to gain a broader understanding of the results. Further work should also include a sensitivity analysis of the identified parameters in order to best interpret the results with their uncertainties.

Also, a full comparison of metal and CFRP tank variants needs to be extended to the full life cycle including weight impacts on use phase fuel consumption, maintenance schedule and end-of-life solutions.

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