



Comparative life cycle assessment of different configurations of type IV hydrogen tank for heavy mobility

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ABSTRACT

Hydrogen is an energy carrier increasingly used in mobility applications through fuel cell systems. Many national hydrogen strategy documents identify compressed hydrogen gas as a promising solution for decarbonising the transport sector, particularly in heavy-duty mobility. However, the processes involved in hydrogen production, storage and conversion, together with the manufacturing and end-of-life management of the associated systems, generate environmental impacts. These impacts arise from resource extraction, manufacturing activities, and the disposal or recycling of system components. In this context, this article presents a life cycle assessment (LCA) focused on gaseous hydrogen storage systems intended for heavy-duty mobility. Four configurations of type IV hydrogen storage tanks are evaluated within a heavy-duty truck scenario with a 44 ton payload and a driving range of 700 km: two configurations based on 9L tanks, one based on a 23L tank, and one based on a 62L tank, as well as their auxiliaries. The results show that carbon fibres and auxiliary components are clearly the main contributors to the environmental impacts of a type IV hydrogen tank, accounting together for more than 90% of the total impact. Among the four configurations, the 62L tank emerges as the most favourable option overall, exhibiting the best environmental performance. Sensitivity analyses performed on the liner material for the 62L system show only limited variations in the results. This limited change is mainly explained by the negligible contribution of the liner compared with the two dominant contributors, namely carbon fibres and balance of plant (BOP) components, which largely drive the impacts across most categories. Regarding the end-of-life stage, solvolysis and pyrolysis of the carbon fibre composite provide the highest environmental credits, with very similar performances across most impact categories.

1. Introduction

In 2023, heavy-duty vehicles emitted 27.9 million tonnes of CO₂ eq, accounting for 22% of greenhouse gas (GHG) emissions from the transport sector in France and approximately 7% of total national emissions. The transport sector remains the largest contributor to GHG emissions in France, with emissions reaching 126.8 Mt CO₂ eq in 2023, corresponding to 34% of national emissions according to French Ministry for Ecological Transition and Territorial Cohesion (Ministry for Ecological Transition, 2024). The transition toward low carbon transport systems is therefore critical to achieving global climate mitigation targets. Among the available technological pathways, hydrogen

represents a particularly promising option, especially for long distance applications and heavy-duty freight transport.

Launched in 2021, the French National Hydrogen Strategy (France 2030, 2021) sets out objectives for the development of low carbon hydrogen in support of France's energy and industrial sovereignty. Five years after the introduction of the initial strategy, the French government has supported more than 150 hydrogen related projects. Hyper-Stock project, as part of the H₂ decarbonized PEPR (Priority Equipment and Research Program), is one of these initiatives. It aims to promote the deployment of decarbonized hydrogen powered heavy-duty mobility by strengthening the necessary scientific knowledge and technological expertise, reducing the carbon footprint of the various hydrogen storage

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tank components, and improving safety, public confidence, and societal acceptance of hyperbaric hydrogen solutions.

This study focuses on Type IV hydrogen storage tanks, which are widely considered a key solution for automotive applications due to their substantial weight reduction compared with Type I, II and III tanks (Barthelemy et al., 2017). These tanks are fully composite overwrapped, typically using high performance carbon fibres such as Toray T720S in the present study. The distinguishing feature of Type IV tanks is the use of a polymer liner, unlike Type III tanks, which use metallic envelop to ensure tightness. In Type IV tanks, the liner primarily serves as a barrier against hydrogen gas, while the thicker outer composite layer supports the mechanical loads induced by internal pressure (Zhang et al., 2015). Owing to the high tensile strength (approximately 5880 MPa) and low density of T720S carbon fibres according to the manufacturer's data-sheet, Type IV tanks can withstand high internal pressures, typically up to 2.25 times operation pressure, while maintaining a significantly reduced wall thickness and overall mass compared with Type I tanks. The type IV tanks also include metal bosses that provide the mechanical interface with the outside and ensure a tight seal with the valve. They also include auxiliary components (also referred to as the balance of plant, BOP), such as seals, valves, pressure relief devices, sensors, and a control unit, which ensure proper operation and safety management.

This study aims to compare the environmental impacts of different hydrogen storage tank configurations with varying capacities and geometries, with a particular focus on identifying the materials and life cycle stages that most strongly contribute to the overall environmental performance. Special attention is given to the carbon fibre composite, which is the most critical material in tank manufacturing due to its energy intensive production cost (Agostini et al., 2018; Benitez et al., 2021; Usai et al., 2021). The technical objects considered in this study are configurations of compressed hydrogen tanks manufactured by the CEA as part of the PEPR H2 HyperStock project, and most of the associated data is also provided by CEA.

Therefore, the research question addressed in this study is: how do the configuration of the compressed hydrogen storage system (i.e. capacity and geometry of Type IV tanks combined) affects the life-cycle environmental impacts of the storage system, and which materials and life-cycle stages are primarily responsible for these impacts.

2. Method

2.1. Goal, scope and functional unit

The goal of this study is to compare the environmental impacts of four type IV hydrogen tank configurations with different characteristics (operating pressure, length to diameter ratio, or volume) in the context of a heavy-duty mobility application. The scope of the study covered the extraction of raw materials for the four configurations, the processes involved in their production but also their end-of-life disposal. The temporal frame of this study is 2020–2026 and 2020 is considered as the reference year for the background LCI data, particularly for the electricity mixes considered. The functional unit selected is designed to provide a range of 700 km for a 44-ton truck. This functional unit focuses on the capacity of the hydrogen tanks to supply enough fuel for the heavy-duty vehicle to travel a distance of 700 km without refuelling. The estimated fuel consumption is approximately 7.2 kg H₂ per 100 km, calculated based on the assumption that the fuel cell system has an efficiency of 65% (IFPEN & ADEME, 2022). The reference flow corresponds to the number of tanks required to fulfil the functional unit, that is, to store 50.4 kg of hydrogen. Each configuration refers to a specific tank design, which is replicated as many times as necessary to achieve the required storage capacity. Table 1 presents the different configurations and the corresponding number of tanks required.

Table 1

Key characteristics of the four Type IV compressed hydrogen gas tank configurations studied, and the number of tanks required to meet the operational unit's requirements: traveling 700 km with a 44-ton heavy-duty truck without refuelling. Data provided by the project partner CEA.

Configuration	9L V1	9L V2	23L	62L
Storage volume (L)	9	9	23	62
Nominal working pressure NWP (bar)	700	350	700	700
Empty mass (kg)	6.85	4.11	18.95	40.5
Length (mm)	1041	1043	609	892
Diameter (mm)	135	126	311	398
L/D ratio	7.7	8.3	2.0	2.2
Stored hydrogen mass per unit (kg)	0.38	0.22	0.96	2.59
Gravimetric efficiency (wt%)	5.2%	5.2%	4.9%	6.0%
Number of tank for F.U.	133	229	53	19

2.2. Approach

The environmental assessment is carried out using a Life Cycle Assessment (LCA) approach, which quantifies and evaluates all materials and energy flows associated with the production, use, and end-of-life phases of the analysed system. This LCA is conducted in accordance with ISO 14040, ISO 14044, and ISO 14049 standards. The study focuses on the French market. The assessment is performed using the OpenLCA software (version 2.1, GreenDelta GmbH, Berlin, Germany) available on openlca.org and background information on materials and energy carriers are taken from the Ecoinvent database (Ecoinvent v3.10 Cutoff, 2023). The impact calculation method applied is the Environmental Footprint EF 3.1 recommended by the European Commission (Fazio et al., 2018), which includes 16 mid-point environmental impact indicators. For ease of reading, the main body of this article focuses on five impact categories: climate change, non-renewable energy resources, material resources (metals and minerals), ozone depletion, and particulate matter formation. However, all impacts of the EF 3.1 method have been calculated and can be consulted in the supplementary data (table S1 to S4). These impact categories were selected based on their relevance to environmental hotspots in high-pressure composite hydrogen storage systems and their alignment with midpoint-oriented LCA frameworks. Climate change was prioritized due to the energy-intensive production of carbon fibres and the significant influence of the electricity mix on hydrogen pathways. Non-renewable energy resources were included to reflect cumulative fossil energy demand, a key contributor to environmental burdens in composite manufacturing and liner processing. Material resources (metals and minerals) were selected to address the depletion of mineral resources used in carbon fibre precursors, metallic components such as aluminium bosses, and other auxiliary materials. Ozone depletion was considered to capture potential upstream emissions from energy supply and chemical production. Particulate matter formation was included for its relevance to human health impacts from industrial processes and high-temperature treatments.

2.3. System boundaries

Fig. 1 presents the life cycle inventory flow chart of a generic type IV hydrogen storage tank and defines the system boundaries. The process begins with the manufacturing phase, during which all components are produced and subsequently assembled. The use phase accounts for the energy required for compressing and cooling the hydrogen to fill the entire volume of the tank, excluding the refuelling infrastructure. The use phase is not considered relevant to the objective of this study, which is to compare different tank configurations, as all configurations store the same amount of hydrogen (50.4 kg). It is therefore included only to allow comparison with the manufacturing and end of life phases. Hydrogen losses during use, which are often controversial, are not considered in this study.

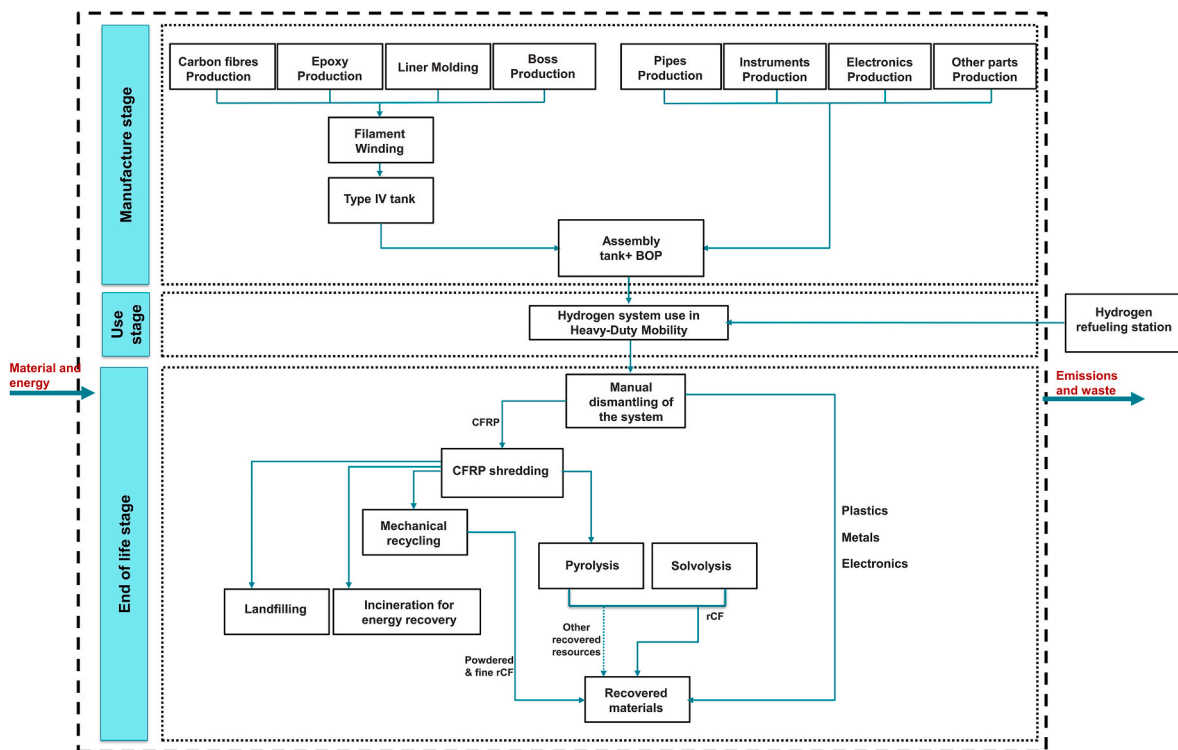


Fig. 1. Life cycle flow chart for a type IV compressed H₂ tank.

After 11,000 cycles, in accordance with the R134 regulation (see Section 4.1.2), the storage system reaches the end-of-life stage. This stage begins with dismantling to separate the tank from its auxiliary components, followed by the separation of the carbon fibre reinforced polymer (CFRP) from the rest of the tank. Five scenarios are considered for the CFRP: recycling via pyrolysis, solvolysis, or mechanical recycling, as well as incineration with energy recovery or landfilling. For the liner, metallic and electronic components, material recovery is assumed.

3. Data

A type IV hydrogen storage tank is designed to store hydrogen at high pressure, typically up to 700 bar. The system is composed of several key materials and components, whose respective masses, depending on the configuration considered, are listed in Table 2 and detailed below. The liner, typically made of a polymer such as high-density polyethylene (HDPE) or polyamide (PA6 or PA11), ensures sufficiently low hydrogen permeability to prevent leakage and also serves as a mandrel during the filament winding process. Surrounding the liner, a carbon fibre composite shell impregnated with epoxy resin provides the mechanical

Table 2

a) Masses of key components of Type IV tank for each considered configuration.
b) Masses of auxiliaries identical for all configurations.

Configuration	9L V1	9L V2	23L	62L
Liner mass (kg)	1.2	1.2	2.2	3.5
Boss mass (kg)	1.2	1.2	1.6	4.4
CFRP overwrap mass (kg)	4.4	1.7	15.2	32.6
Carbon fibres (kg)	3.1	1.2	10.6	22.8
Epoxy resin (kg)	1.3	0.5	4.6	9.8
Auxiliaries				Mass (kg)
Pipes				4
Electronics				1
Instruments				3.3
Valves				3.4
Miscellaneous				2

strength of the tank, with carbon fibres accounting for approximately 70% of the shell mass. At both ends, metallic bosses ensure reliable and leak tight connections with the hydrogen flow control system. In addition, balance of plant (BOP) or auxiliary components enable the transfer of hydrogen between the tank and the fuel cell. These include stainless steel piping for hydrogen transport, valves and pressure regulators to control the operating pressure, as well as sensors and electronic units for monitoring pressure and temperature, and various components made of stainless steel and aluminium. In their study Elgowainy et al. (2012) proposed a functional classification of the BOP components into five groups: electronics, piping, valves, sensors, and miscellaneous equipment. This classification was applied to two compressed hydrogen storage configurations: one operating at 350 bar storing 6 kg of hydrogen, and the other at 700 bar storing 5.8 kg, assuming the same BOP structure for both systems. In this study, the same assumption is adopted: regardless of the volume of the considered vessel (9L, 23L or 62L), the auxiliary components integrated into the storage system remain identical of composition and functionality.

In the next sections, all materials and processes are described and both production and end-of-life stages are presented. The corresponding detailed life cycle inventory (LCI) datasets are provided in the supplementary data (Table S4 to S40).

3.1. Thermoplastic liner

3.1.1. Production

The most commonly used materials for manufacturing type IV hydrogen tank liners include high-density polyethylene (HDPE), polyamide (PA), and various polyether-based materials (Zheng et al., 2012; McWhorter et al., 2014; Simmons et al., 2021). These commercial materials for the tank liner are listed in Table 3 (Wang et al., 2022). Several polymer processing routes have been reported to manufacture cylindrical liners with hemispherical end domes, which serve both as gas barriers and as mandrels for the filament-wound CFRP shell; these include extrusion or injection moulding followed by welding of the end domes, blow moulding, and rotational moulding.

Table 3

Material used for the liner by various companies producing high- and medium-pressure compressed hydrogen tanks.

Company	Liner material	Information sources
Hexagon Purus/ Hexagon Lincoln	HDPE	Hexagon Purus product pages/ datasheets
Lincoln Composites	HDPE	Lincoln Composites reports on HDPE liners
Toyota (Mirai)/UBE	PA6	UBE press releases & Toyota Mirai liner info (UBE, 2021, 2023)
Quantum Fuel Systems/ Quantum	HDPE	Quantum technical reports and literature on liner materials
Kautex Maschinenbau	PA6	Kautex press releases on 320 L PA6 liner (2020)
DSM/Akulon (Envalor)	PA6	DSM/Akulon product pages and papers (2017–2023)
UBE Corporation	PA6	UBE press releases (2014, 2021, 2023)
CEA	PA11	HyperStock project

The liner manufacturing model used in this study is based on the one proposed by (Benítez et al., 2021). The reference material selected is PA11. The liners for the HyperStock project, produced by the CEA, are manufactured using rotational moulding. To represent this process, the injection moulding model proposed by Benítez et al. (2021) was adapted by adjusting the energy consumption based on Naroto (Naroto, 2018), while maintaining the emissions as originally modelled. The process uses pulverised PA11, and the energy requirements are estimated based on (Wanrooe, 2026). PA6 and HDPE are considered in a sensitivity analysis presented in Section 4. However, they are assumed to be produced in the same way as PA11. In addition, due to insufficient data, no sensitivity analysis is performed for the liner manufacturing processes.

3.1.2. End-of-life

For the end-of-life treatment of the liner, the HDPE recycling scenario available in the Ecoinvent database is used, under the process name ‘Polyethylene production, high density, granulate, recycled’. Although this process was originally developed for HDPE, in this study it is applied to the liner material, including PA11. The input flow is adjusted by replacing the generic ‘waste polyethylene, for recycling, sorted’ with ‘polyethylene production, high density, granulate’ to match the material actually used for the liner. This change ensures that the recycled material comes from the liner at the end of its life, rather than from HDPE sourced from unrelated applications. As a result, the model reflects a closed loop recycling scenario specific to the liner after its use in the tank.

3.2. Carbon-fibre reinforced polymer

3.2.1. Production

Carbon fibre reinforced polymer (CFRP) composites have attracted significant interest in various engineering applications for several decades due to their excellent mechanical properties, high durability, and low weight (Vijayan et al., 2023). The mechanical properties of CFRP composites depend on several factors, including the carbon fibre content and the type of matrix used. As a result, their structural load bearing performance can vary significantly from one CFRP manufacturer to another (Pawlak et al., 2022), which may lead to differences in the mass required for filament winding. This aspect is addressed in the sensitivity analysis presented in Section 4.3.2, where a $\pm 5\%$ variation in CFRP content is introduced.

Type IV hydrogen storage tanks can be classified into three categories, namely type IV-a, IV-b, and IV-c, according to the filament winding process (Shin and Ha, 2024). Type IV-a tanks use a wet filament winding process in which carbon fibres are fully applied over the polymer liner, type IV-b tanks rely on a dry filament winding process, whereas type IV-c tanks use an automated fibre placement process with

thermoplastic tape. In this study, all configurations correspond to type IV-b tanks, with 70 wt% carbon fibres and 30 wt% epoxy resin. The fabrication of the overwrapped layer is carried out in two steps: first, a filament winding process using resin impregnated fibres is applied around the liner, which serves as a mandrel; then, the thermosetting matrix is cured by heat treatment. The energy consumption of this process is estimated at 2.32 kWh per kilogram of composite produced (DOE, 2017). The carbon fibre used in this study is Toray T720. However, as no specific inventory data are available for this grade, it is modelled using Toray T700G as the closest approximation, for which complete life cycle inventory data are available. This model is provided by (Benítez et al., 2021).

The carbon fibre manufacturing process is divided into two main stages: precursor preparation and thermal treatment with post processing. Stage I includes the polymerisation of acrylonitrile, spinning and washing of the polyacrylonitrile (PAN) precursor, stretching, and the application of surface finishes and coatings to improve fibre properties and handling. Stage II begins with the stabilisation (oxidation) of the precursor, followed by carbonisation under an inert atmosphere at high temperatures, and exhaust gas treatment to control emissions. Finally, surface treatments such as electrolysis and epoxy coating are applied to enhance fibre bonding. Further details on the carbon fibre manufacturing model are provided in (Benítez et al., 2021).

The LCI of carbon fibre considers a conversion rate from precursor to carbon fibre of 42%, with an output of 1 kg of finished carbon fibre. The data collected from (Benítez et al., 2021) are adjusted using a material supply chain prioritized from France, then Europe, and finally global sources when no regional data are available. The electricity mix is also adapted from the German to the French market. A comparison between the two electricity mixes is presented in Fig. 2. The epoxy resin used as the matrix is modelled using an Ecoinvent dataset.

3.2.2. End-of-life

Several end-of-life scenarios for CFRP are examined with the aim of identifying the recovery option with the lowest environmental impact. The approaches investigated are based on previous work (Li et al., 2016; Mendoza Beltran et al., 2018) and cover a wide range of conventional and emerging recycling technologies.

Mechanical recycling consists of reducing the size of composite waste to produce recycled materials that can be used as fillers in applications with low mechanical requirements. Although this method is relatively simple to implement, it leads to a significant degradation of the mechanical properties of the recovered fibres (Palmer et al., 2009; Pimenta and Pinho, 2011). The process starts with an initial cutting step, where the composite waste is shredded into pieces of 50–100 mm using a shredder, followed by finer milling using a hammer mill. Sorting steps based on sieving and cyclonic separation are then used to separate fibre-rich fractions from powder-rich fractions (Li et al., 2016). Three main fractions are thus generated: fine fibres (24% by mass), fine powders (19%), and coarse recyclates (57%) (Palmer et al., 2009). The fine fibres, referred to here as recycled carbon fibres (rCF), are assumed to replace glass fibres on an equivalent mass basis (1:1), based on studies showing that the mechanical performance of composites made with rCF can be comparable to that of virgin glass fibre composites. This substitution accounts for the avoided impacts associated with the production of virgin glass fibres. In addition, the fine powders generated by the process are assumed to replace calcium carbonate in cement production on a 1:1 mass basis, thereby avoiding the impacts associated with its production. Due to their poor bonding performance with polymer matrices, the coarse recyclates are not reintegrated into composite applications. A final disposal route is considered for this fraction, namely incineration with energy recovery.

Pyrolysis is a thermal treatment carried out in the absence of oxygen to separate the fibres from the matrix at temperatures ranging from 300 °C to 800 °C. The process begins with milling the composite prior to high temperature exposure. Studies indicate that carbon fibres

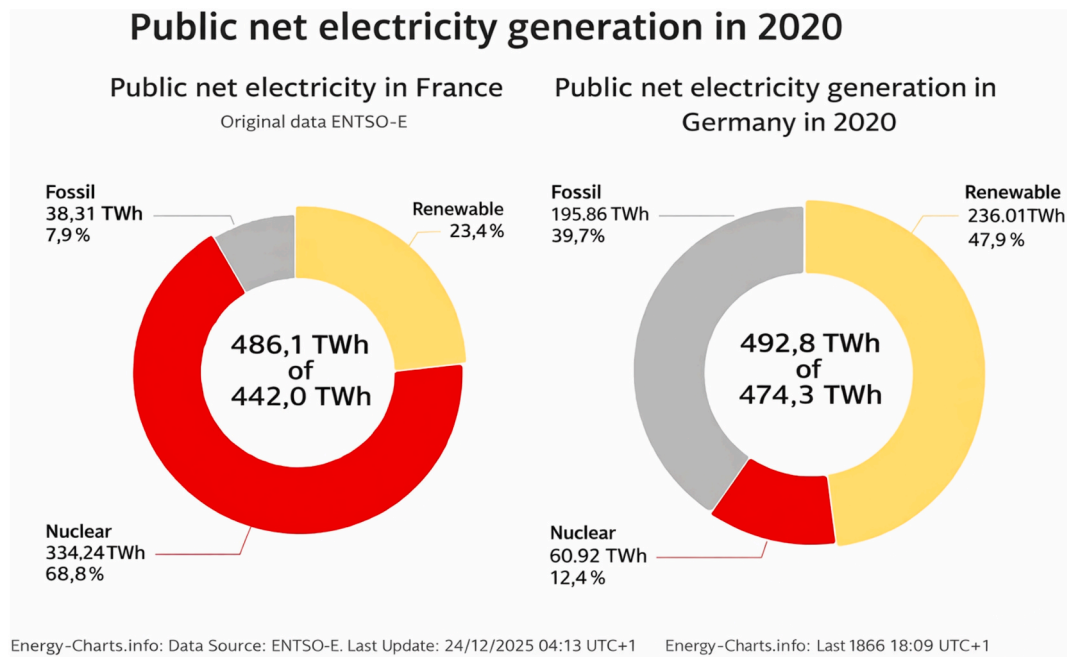


Fig. 2. Electricity Generation Mix in 2020: Comparison of the French mix Versus the German mix based on data from (Energy-Charts.info, 2026).

recovered by pyrolysis can retain at least 90% of their original mechanical properties (Pickering, 2006; Yang et al., 2012; Oliveux et al., 2015; Jiang et al., 2017). Consequently, the environmental impacts associated with the production of virgin fibres can be deducted from the overall environmental balance. In addition, the polymer matrix can be converted into a liquid hydrocarbon phase, providing an additional recovery pathway (Cunliffe et al., 2003). The energy consumption for recycling 1 kg of composite by pyrolysis is estimated at approximately 13.7 MJ of electricity and 23.8 MJ of natural gas, producing rCF, ash, and air emissions. The LCI data are sourced from Meng et al. (2018), with the nitrogen input referenced from (Lefeuve et al., 2017).

Supercritical solvolysis represents the most innovative option among the recycling processes for CFRP. This process uses solvents such as water, ethanol, or methanol at high temperature and pressure to depolymerise the matrix, while recovering intact fibres and matrix fragments that can be converted into monomers or used as feedstock for the petrochemical industry. In this system, CFRP waste is introduced into a reactor without prior milling; the reactor geometry is adjusted to obtain the desired fibre length. Water is pressurised to around 250 bar for supercritical solvolysis (and 170 bar for the subcritical version), with corresponding temperatures of 380 °C and 350 °C. Water consumption is estimated at 10 L per kilogram of composite treated, according to (Pillain et al., 2019). The energy required to heat this amount of water is calculated using the specific heat capacity of water, accounting for its variation with temperature. According to (Vogiantzi and Tserpes, 2025), this corresponds to approximately 23.08 MJ of electricity to treat 1 kg of composite. Regarding the outputs, only the recovered carbon fibres are accounted for as secondary material. The epoxy matrix is considered waste, as no available data confirm the retention of its properties after treatment.

Among the more conventional end-of-life scenarios, incineration with energy recovery is also evaluated. This process involves burning the composites in waste-to-energy plants to produce electricity and heat. Although this method allows partial energy recovery, it results in the complete loss of the fibres and the generation of emissions. The typical calorific value of CFRP is about 30 MJ/kg (Hedlund-Åström, 2005.). For a CFRP composition of 60% fibres and 40% matrix, an energy content of 32 MJ/kg has been reported (Pickering, 2012). This value is retained in this study, where the composition is 70% fibres and 30% matrix. Energy

recovery through incineration is accounted for in this study; conversion efficiencies for electricity and heat are assumed to be 20% and 55%, respectively, giving a total energy conversion efficiency of 75%. This assumption reflects the typical performance of cogeneration incineration plants in France, in accordance with Decree of January 12, 2021 on best available techniques. The electricity produced is assumed to substitute the average French electricity mix, as defined in the Ecoinvent 3.1 database. This mix includes a significant share of nuclear power, as well as contributions from hydropower, renewables, and gas, with a smaller contribution from coal, as shown in Fig. 2. The heat generated is assumed to substitute heat produced from natural gas combustion. CO₂ emissions from the incineration process are calculated stoichiometrically, assuming that all carbon contained in the CFRP is oxidised and emitted as CO₂. Non-CO₂ combustion emissions are considered negligible (Li et al., 2016). Residual materials after combustion are assumed to be landfilled.

Finally, the landfill scenario represents the least favourable option from an environmental perspective, as it provides no material or energy recovery. Disposal is assumed to take place in an engineered landfill for non-hazardous solid waste. The environmental impacts of this end-of-life route are assessed using Ecoinvent data for a landfill compliant with sanitary standards. As CFRP waste is mainly inert, it is assumed not to generate significant emissions such as methane during disposal.

3.3. Boss

3.3.1. Production

The metallic boss is a key component that connects the polymer liner and the overwrapped carbon fibre to the external valves located at the vessel heads. To prevent hydrogen embrittlement, the boss may be manufactured from either austenitic stainless steel S31603 or aluminium alloy 6061-T6 (Zhu et al., 2023), as recommended in ISO 11119 and ISO 11114. In this study, aluminium alloy 6061-T6 is selected for the boss. However, its production process is approximated using a closely related Ecoinvent dataset, namely 'market for aluminium alloy'. Both aluminium alloys contain magnesium as the main alloying element. It should be noted that the T6 heat treatment (solution treatment, quenching, and artificial ageing), which requires additional energy, is not included in this approximation.

3.3.2. End-of-life

Aluminium is known for its high recycling rate, often exceeding 90% (IAI, 2025; Czerwinski, 2021). In this study, a 90% recovery rate is assumed for aluminium from the boss, without accounting for the additional energy required for its processing.

3.4. Auxiliaries

3.4.1. Production

As mentioned earlier in section 2, the auxiliaries are divided into five groups. Instruments are represented by a mass composition of 50% stainless steel 316, 28% aluminium 6082/61-T6, and 16% stainless steel 316Ti. Piping is assumed to be entirely made of stainless steel 316Ti. Valves consist of 75% stainless steel 316 and 25% aluminium 6082/61-T6. The electronics category is modelled using the Ecoinvent dataset for control units. Miscellaneous components include 70% stainless steel 316, 25% S355 steel, and 5% polypropylene (Weiszflog and Abbas, 2022). Stainless steel 316Ti is modelled based on the Ecoinvent dataset 'steel production, electric, chromium steel 18/8', with additional molybdenum and titanium inputs, and adjustments to ferro-nickel and scrap contributions according to Righton Blackburns, 2021.

3.4.2. End-of-life

Metals used in the fabrication of auxiliary components are assumed

to be 90% recycled at the end-of-life, in line with common assumptions for metals with high recovery value. This rate reflects both efficient collection and good metallurgical yields. Following the ISO 14044 end-of-life approach, environmental credits associated with the substitution of primary metals are accounted for, highlighting the benefits of reintroducing recycled material into the production cycle. For electronic components, a shredding process is selected, as it reflects current industrial practices for treating WEEE (waste electrical and electronic equipment), enabling partial recovery of precious metals and other metallic fractions.

4. Results and discussions

4.1. LCA results of a single configuration

4.1.1. Material-to-material environmental impact comparison

Fig. 3 presents, for the reference configuration (9L V1), the relative contribution of the main components to the selected environmental impact categories, while Table 4 provides the corresponding absolute values. The overwrapped composite layer is decomposed into three elements: carbon fibres, epoxy resin, and the filament-winding process. The results reveal strong contrasts between impact categories, indicating that different materials and processes drive environmental burdens differently across the production stage.

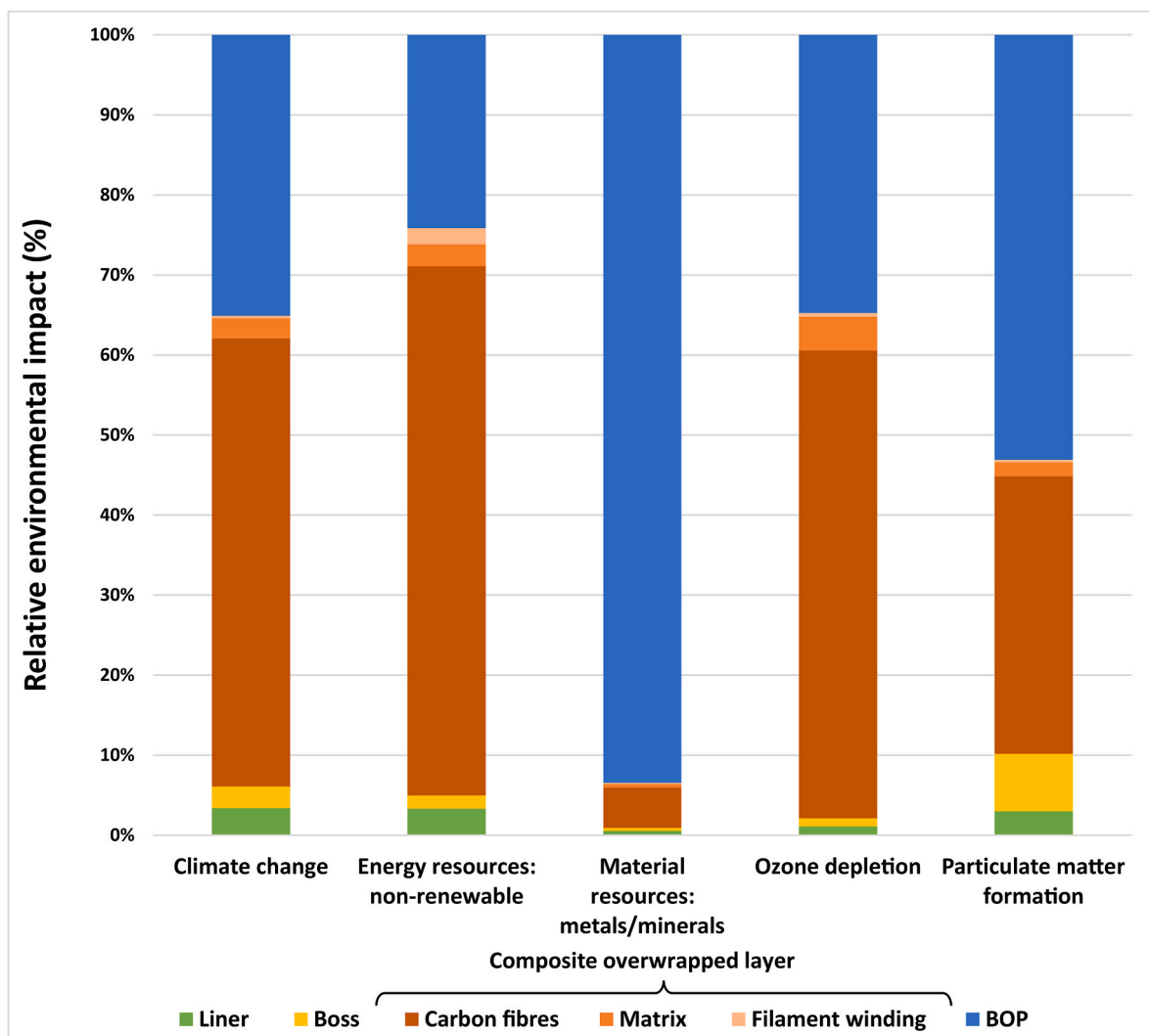


Fig. 3. Proportion of impacts from the main contributing components for a reference tank: one item of the 9LV1 configuration.

Table 4

Absolute environmental impacts of the main contributing components for a reference tank: one item of the 9L V1 configuration.

Tank component	Climate change (kg CO ₂ -eq)	Energy resources: non-renewable (MJ)	Material resources: metals/minerals (kg Sb-eq)	Ozone depletion (kg CFC-11-eq)
BOP	110.6	1311	2.159×10^{-2}	2.099×10^{-6}
Filament winding	0.8469	109.3	4.067×10^{-5}	2.982×10^{-8}
Matrix	7.937	149.7	9.189×10^{-5}	2.555×10^{-7}
Carbon fibres	176.3	3587	1.116×10^{-3}	3.532×10^{-7}
Boss	8.515	91.22	9.729×10^{-5}	6.211×10^{-8}
Liner	10.61	178.2	1.158×10^{-4}	6.482×10^{-8}

For climate change, the impact is largely dominated by carbon fibres, which account for approximately 55–60% of total greenhouse gas emissions. The BOP represents the second largest contribution, at around 35%, while the liner, the boss, and the epoxy matrix remain negligible. This clear dominance is driven by the carbon fibre production process itself. It mainly results from the production of acrylonitrile, combined with the high heat and electricity demands required at each

stage of the process, from precursor conversion through stabilisation, carbonisation, and subsequent treatments. The significant, though secondary, contribution of the BOP reflects the impacts associated with the production and processing of the metals it contains, mainly aluminium and steel.

A similar pattern is observed for non-renewable energy resource use, where carbon fibres again emerge as the main contributor, representing roughly 65–70% of the total impact. The BOP follows with about 25%, while the remaining contributors are marginal. The consistency between the results of climate change and non-renewable energy suggests that these two impact categories are governed by closely related upstream processes. In particular, the dominance of carbon fibres points to energy-intensive production routes that rely heavily on fossil energy carriers.

In contrast, the results for material resources (metals and minerals) show a fundamentally different distribution. This impact category is almost entirely driven by the BOP, which accounts for more than 90% of the total resource depletion. This result highlights a strong dependence of the BOP on metal inputs and clearly identifies it as the main hotspot for resource depletion.

With regard to ozone depletion, the pattern of contributions closely resembles that observed for climate change. Carbon fibres remain the dominant source, contributing approximately 55–60%, followed by the BOP at around 35%. The remaining contributors again play a minor role.

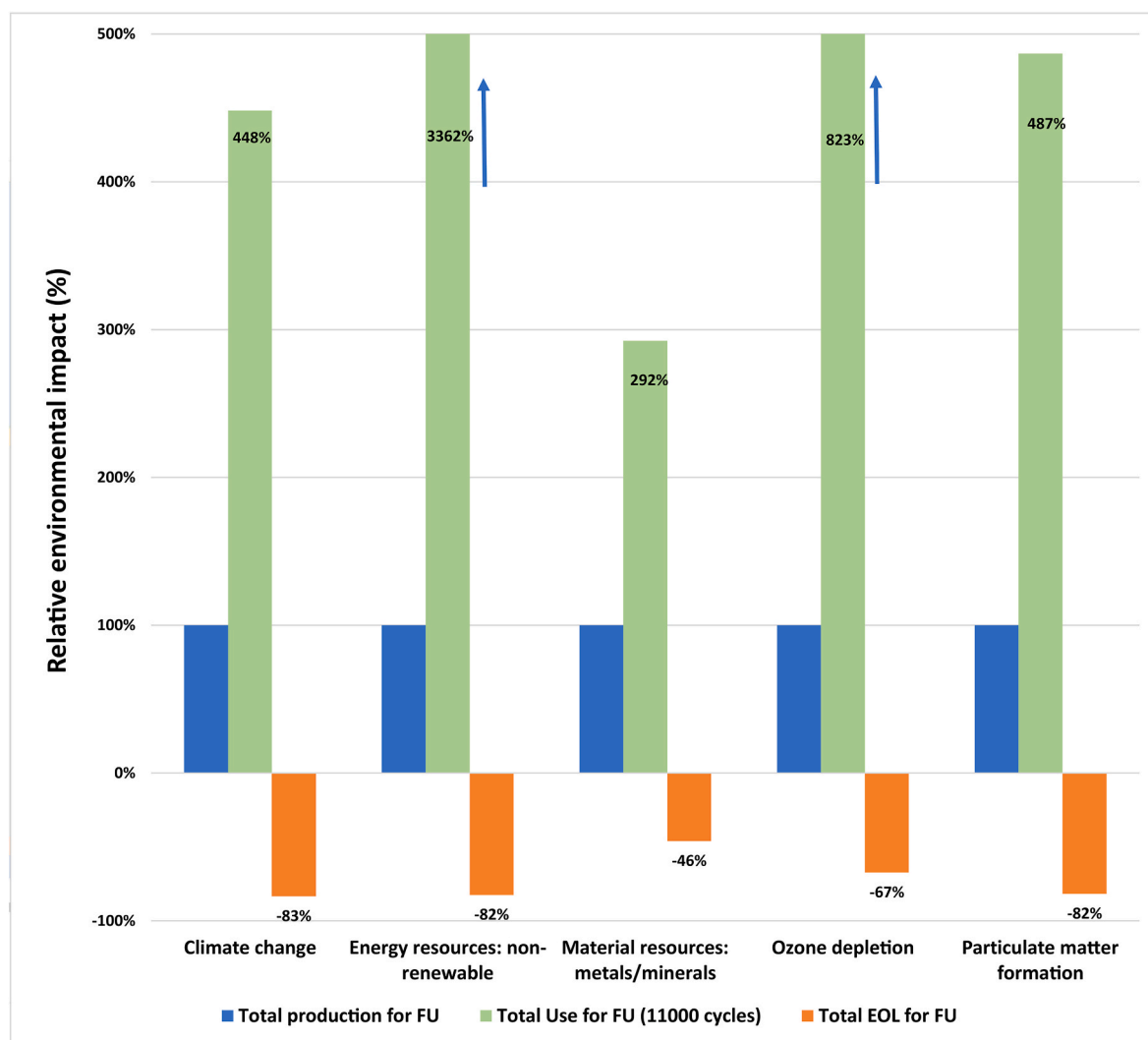


Fig. 4. Comparison of the relative contributions of the different stage of the life cycle (production, use, and end of life) to the five impacts selected for the entire Functional Unit (F.U.). The production stage serves as a reference and is arbitrarily set at 100%. Note that the graph is truncated at 500% for better readability, but impacts exceeding this value, out of the frame, are indicated by a vertical arrow.

This similarity suggests that ozone-depleting emissions originate from the same upstream processes responsible for greenhouse gas emissions, reinforcing the role of carbon fibres as a key driver of atmospheric impacts.

The particulate matter formation category exhibits a more balanced contribution profile. While the BOP becomes the main contributor, accounting for approximately 50–55% of the total impact, carbon fibres still represent a substantial share of around 35%. This reduced contribution of carbon fibres can be explained by the implementation of gas treatment systems (L1 and L2), which significantly limit particulate emissions during production. Notably, the boss shows a more visible contribution in this category, reaching close to 10%, whereas it remains negligible in other impact categories.

4.1.2. Stage-to-stage comparison environmental impact comparison

Fig. 4 illustrates the relative contribution of the production, use, and end-of-life stages to the environmental impacts of the reference configuration 9LV1, with a PA11 liner. For consistency, the energy consumption of a single cycle is multiplied by 11,000 cycles in order to enable a reliable comparison with the other two life cycle stages. For the end-of-life stage, the solvolysis recycling process for CFRP is selected. This choice is justified by its strong environmental benefits and by the good mechanical properties of the recovered carbon fibres.

Overall, the results show a very consistent trend across categories. For all impact categories, the use phase clearly dominates the environmental footprint, with contributions systematically several times higher than those of the manufacturing phase, which is set to 100%. Depending on the impact category, the use phase reaches values between

approximately 300% and 3362%, highlighting its central role in driving the life cycle impacts. This dominance indicates that operating processes during the use phase are the primary source of environmental burdens, mainly due to the energy consumption required for hydrogen compression and cooling, along with the associated upstream emissions. This disproportion between the different stages of the product life cycle strongly depends on the number of cycles taken into account in the operational life of the storage system. We base our calculations on the R134 regulation, consistent with ISO 19881, and UN GTR No. 13 Phase 2, which specifies a maximum of 11,000 fill/drain cycles for the required service life (approximately 15 years) for mobility applications (Li et al., 2024).

In contrast, the end-of-life stage consistently exhibits negative contributions across all impact categories, with reductions ranging from approximately –46% to –83% relative to the manufacturing phase. These negative values reflect environmental credits associated with end-of-life treatments, such as material recycling and energy recovery. These results reflect the choice of a highly virtuous recycling process and optimistic assumptions regarding the reuse of recyclates. This demonstrates the clear benefit of developing recycling infrastructure for CFRP products, which are increasingly common in industrial and consumer applications.

4.2. Comparative environmental assessment of the four configurations

Fig. 5 compares the relative environmental impacts of the four configurations (9L V1 (700 bar), 9L V2 (350 bar), 23L and 62L), normalized to 9L V1 for each impact category, while Table 5 provides

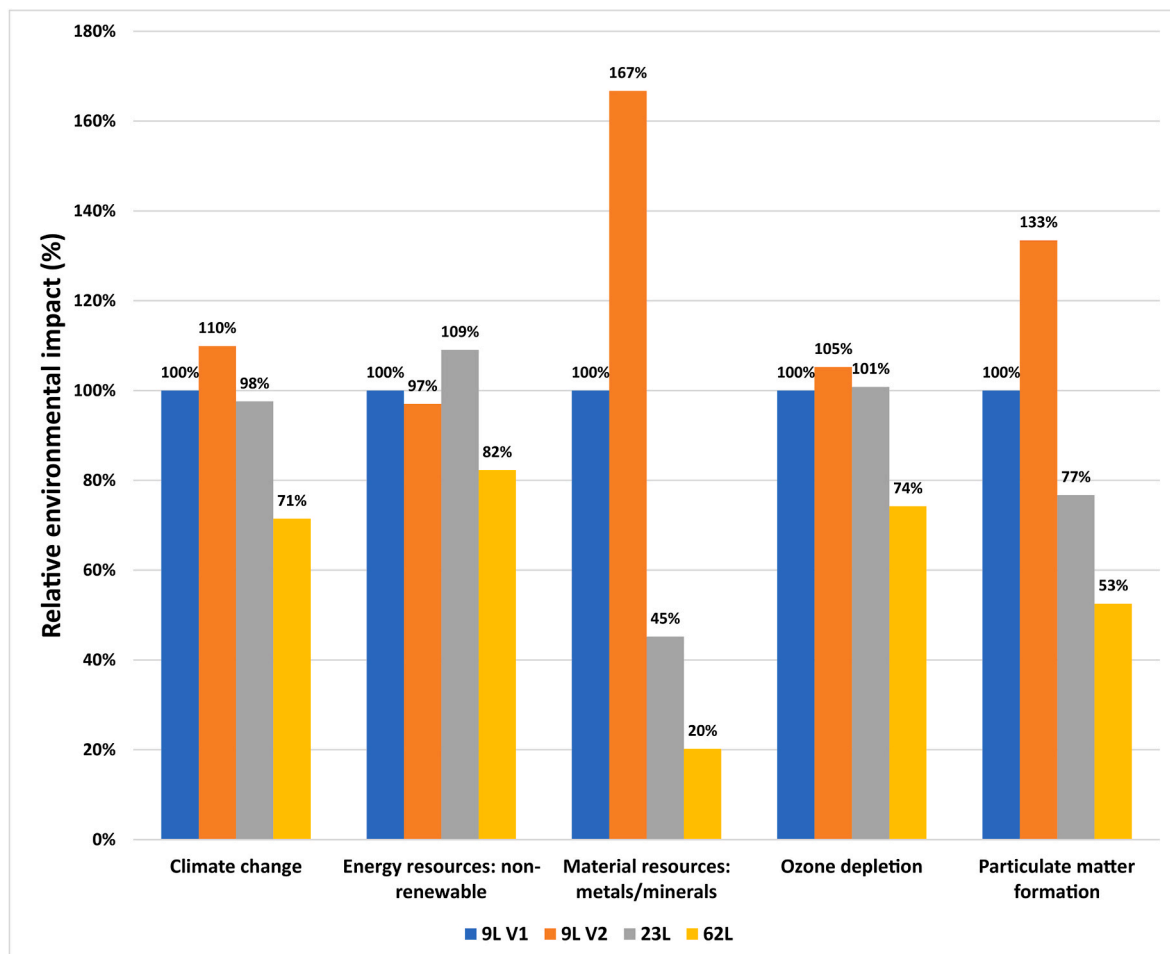


Fig. 5. Relative environmental impacts of the four configurations (9L V1 (700 bar), 9L V2 (350 bar), 23L and 62L), normalized to 9L V1 for each impact category.

Table 5

Absolute environmental impacts of the four Type IV hydrogen tank configurations for the selected impact categories.

Impact category	Unit	9L V1 (700 bar)	9L V2 (350 bar)	23L	62L
Climate change	kg CO ₂ -eq	41,756	45,895	40,737	29,833
Energy resources: non-renewable	MJ	719,620	698,052	784,718	592,092
Material resources: metals/minerals	kg Sb-eq	3.063	5.107	1.385	0.619
Ozone depletion	kg CFC-11-eq	8.02×10^{-4}	8.44×10^{-4}	8.08×10^{-4}	5.95×10^{-4}
Particulate matter formation	disease incidence	2.44×10^{-3}	3.25×10^{-3}	1.87×10^{-3}	1.28×10^{-3}

the corresponding absolute values. All configurations use PA11 liners and assume end-of-life solvolysis for CFRP. The observed differences between configurations can be directly explained by the tank characteristics reported in Table 1, particularly the hydrogen mass per tank, gravimetric efficiency, and the resulting number of tanks required to meet the functional unit.

For the climate change category, 9L V2 shows a moderate increase compared to the reference, reaching approximately 110% of the 9L V1 value, while 23L remains close to the reference level. In contrast, 62L exhibits a clear reduction, with values around 70% of 9L V1. This improved performance of 62L is mainly due to its higher gravimetric efficiency and greater amount of hydrogen carried per tank, which reduce the total amount of composite and metallic materials needed for both the tank structure and the BOP equipment. Conversely, the lower gravimetric efficiency of 9L V2 requires a higher number of tanks, increasing material production and associated greenhouse gas emissions.

A similar, though less pronounced, trend is observed for non-renewable energy resources. While 23L slightly exceeds the reference value, reaching about 110%, and 9L V2 remains close to 9L V1, 62L again shows a significant reduction, with values around 80% of the reference. This reflects the lower cumulative energy demand associated with the production of fewer tanks and reduced material intensity for the 62L configuration.

The most pronounced differences between configurations appear in the material resources, metals and minerals category. 9L V2 shows a very strong increase, reaching approximately 165–170% of 9L V1, which can be directly attributed to its low gravimetric efficiency and the resulting increase in metallic components per functional unit. In contrast, 23L is substantially lower, at around 45%, while 62L presents the lowest impact, with values close to 20% of the reference. These results highlight the strong sensitivity of mineral resource depletion to the number of tanks and the amount of structural materials required.

For ozone depletion, the four configurations exhibit relatively similar impacts, with all values remaining close to the reference. 9L V2 shows a slight increase ($\approx 105\%$), while 23L and 9L V1 are almost identical. 62L again performs better, with a reduction to approximately 75% of 9L V1. This limited variability suggests that ozone-depleting emissions are weakly influenced by tank geometry and are instead linked to background industrial processes.

Finally, for particulate matter formation, more pronounced differences are observed. 9L V2 shows a substantial increase, reaching about 130–135% of the reference, which is consistent with its higher material demand and increased upstream manufacturing processes. In contrast, 23L is moderately lower than 9L V1 ($\approx 75\text{--}80\%$), while 62L again demonstrates the best performance, with values around 50–55%. This confirms that configurations with higher gravimetric efficiency and lower material intensity lead to reduced particulate emissions across the production chain.

For storage tanks 9LV1 and 9LV2, which share nearly identical overall geometries in terms of length and outer diameter, one might initially expect the lower-pressure design (V2 operating at 350 bar) to exhibit reduced environmental impacts, as it requires a smaller mass of CFRP to withstand the internal pressure. This expectation is supported by analysis in Section 4.1.2, which identifies CFRP as the dominant contributor to environmental impacts across all other components in the

production stage. However, lowering the operating pressure results in a reduction of gravimetric efficiency, thereby requiring a larger number of vessels to be integrated into the 44-ton truck in order to achieve a driving range of 700 km without refuelling (functional unit). This multiplicative effect ultimately leads to an unrealistic number of items (229) and to significantly higher life cycle impacts, particularly with respect to the “Material resources: metals/minerals” indicator.

For tanks operating at 700 bar (9LV1, 23L and 62L), the results clearly identify the configuration based on nine 62L tanks as the environmentally preferable option across all impact categories considered. The global vessel geometry, including length, diameter and the L/D ratio, emerges as a key design parameter, as it enables a reduction from 133 small-volume vessels (9L) to only nine 62L vessels for the same functional requirement. Despite only marginal differences in gravimetric efficiency (5.5 wt% for 9LV1 versus 6 wt% for the 62L vessel), climate change impacts are reduced by approximately 70%, while the most pronounced decrease is observed for the “Material resources: metals/minerals” indicator, with a reduction to around 20% of the reference configuration. In a context of increasing scarcity of raw materials, particularly metals, these results suggest that large-volume, compact tanks with low L/D ratios offer a substantial environmental advantage, even if their integration into vehicle architectures may pose greater engineering challenges.

4.3. Sensitivity analysis

4.3.1. End-of-life scenarios of carbon fibre reinforced polymer

Overall, as presented in Fig. 6, the results show that the choice of end-of-life option has a major influence on environmental performance, with clear differences between recycling-based and disposal-based scenarios. Solvolysis and pyrolysis consistently provide the largest environmental credits, with performances very close to each other across most impact categories. These strong negative contributions indicate a high potential for impact offset through avoided primary material production and energy consumption.

Among these options, pyrolysis exhibits particularly strong credits for material resource depletion, exceeding those of solvolysis, highlighting its effectiveness in recovering valuable constituents and reducing the demand for virgin materials used in CFRP production.

In contrast, mechanical recycling shows more limited benefits, with moderate reductions or near-neutral effects depending on the impact category. This indicates that, while mechanical routes can contribute to impact mitigation, their effectiveness remains constrained by lower recovery rates and degraded mechanical properties of the recovered fibres.

Incineration and landfill consistently perform worst, with impacts close to zero or even slightly positive for some categories, indicating little to no environmental benefit. These scenarios mainly act as disposal routes with limited recovery potential, making them less favourable from a life cycle perspective.

The sensitivity analysis was performed by normalizing the solvolysis scenario to 100% for each impact category, in order to assess the relative performance of alternative end-of-life routes, namely pyrolysis, mechanical recycling, incineration, and landfill. Across all selected categories, solvolysis consistently emerges as the most favourable scenario. Pyrolysis shows comparable but slightly lower benefits, while mechanical recycling, incineration, and landfill exhibit significantly poorer

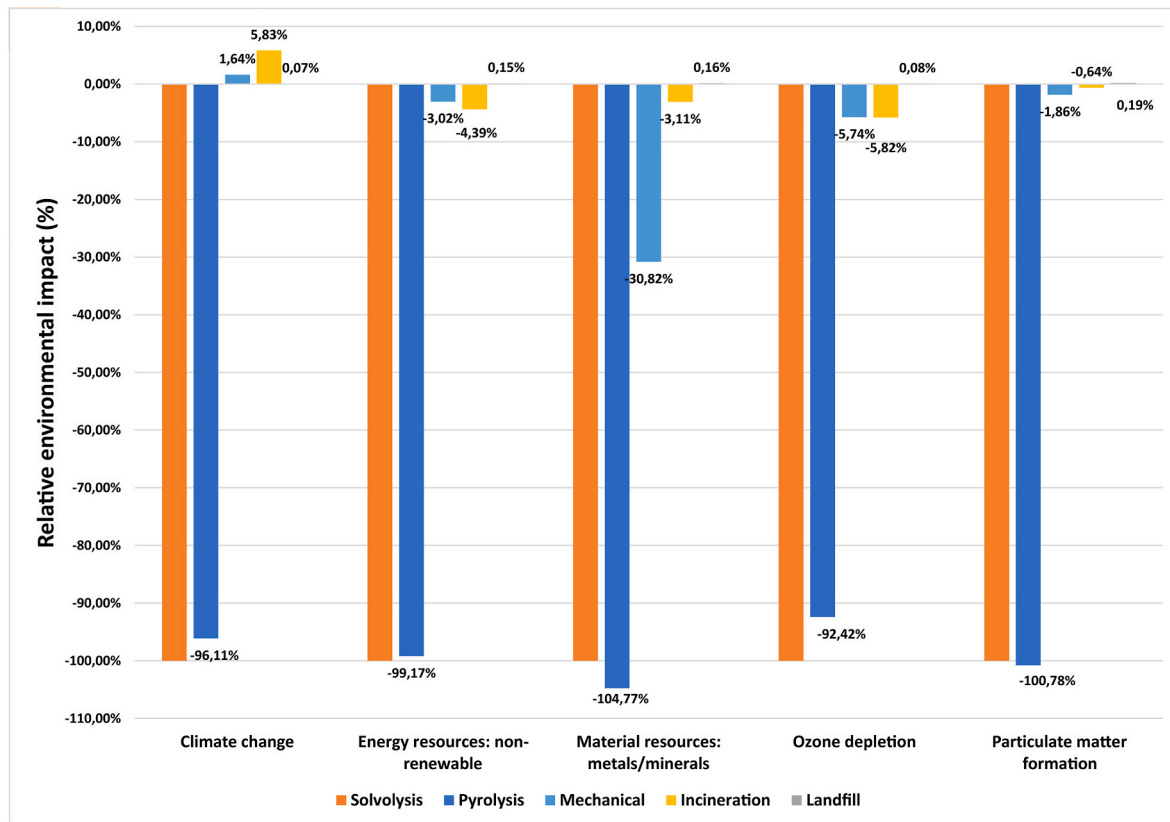


Fig. 6. Sensitivity of environmental impacts to alternative end-of-life scenarios for composite materials (solvolysis, pyrolysis, mechanical recycling, incineration, and landfill) across all impact categories, with solvolysis set as the reference scenario.

environmental performance. These differences can be directly explained by the quality of the recovered materials and their substitution potential, particularly for carbon fibres.

For climate change and non-renewable energy resources, solvolysis and pyrolysis provide the largest benefits due to the recovery of carbon fibres that can substitute virgin carbon fibres, which are the dominant contributor to the life-cycle impacts of type IV hydrogen tanks. In contrast, incineration and landfill show markedly higher impacts, as they do not preserve material value and only recover energy (incineration) or no value at all (landfill). Mechanical recycling occupies an intermediate position, providing limited benefits compared to chemical recycling routes.

A similar trend is observed for material resource depletion (metals/minerals). Solvolysis shows the strongest environmental credit, reflecting its ability to recover high-quality fibres suitable for high-value applications. Pyrolysis remains close to the reference but is slightly penalised by partial fibre degradation. Mechanical recycling yields only modest gains, as the recovered fibres are mainly reused in low-performance applications.

The superior performance of solvolysis can be attributed to its ability to recover carbon fibres with near-virgin properties. By selectively dissolving the polymer matrix under controlled conditions, solvolysis preserves fibre length, surface integrity, and mechanical performance. Several studies report that fibres recovered via solvolysis retain 90–100% of their original tensile strength and modulus, enabling direct reuse in structural composite applications (Oliveux et al., 2015; Pickering, 2012). This high substitution potential explains the strong environmental benefits observed in the sensitivity analysis.

Pyrolysis, while still an efficient recycling route, generally leads to slightly lower performance. High processing temperatures can induce surface oxidation or char deposition on fibres, requiring post-treatment and resulting in a partial reduction of mechanical properties.

Nevertheless, pyrolysed fibres typically retain 70–90% of their initial tensile strength, which remains significantly higher than for mechanically recycled fibres (Witik et al., 2013; Pickering, 2012).

In contrast, mechanical recycling suffers from severe limitations due to fibre fragmentation and damage during shredding and milling processes. The resulting short fibres exhibit a strong degradation of mechanical properties, with tensile strength losses often exceeding 50%, restricting their use to non-structural or filler applications (Witik et al., 2013). This low-quality material recovery explains the reduced environmental credits observed for this scenario.

Finally, incineration and landfill systematically show the poorest performance across all impact categories, as they fail to maintain material circularity. Incineration generates direct CO₂ emissions and only recovers energy, while landfill leads to a complete loss of material and energy potential. These findings are consistent with previous life-cycle assessments of CFRP end-of-life options (Witik et al., 2013).

Overall, the combined results demonstrate that advanced recycling routes, particularly solvolysis, clearly outperform alternative end-of-life scenarios. The sensitivity analysis confirms that this conclusion is robust and fundamentally driven by the ability of solvolysis to recover high-quality carbon fibres, as extensively reported in the literature.

4.3.2. Sensitivity to a $\pm 5\%$ variation in CFRP mass (62L tank, 700 bar)

A $\pm 5\%$ variation around the reference CFRP mass was considered to assess the sensitivity of the environmental performance to variations in the amount of composite material used. This range also provides an indication of the potential variability that may arise when comparing tanks from different manufacturers.

Fig. 7 presents the sensitivity analysis results for the 62L, 700 bar tank configuration, highlighting the effects of a $\pm 5\%$ variation in CFRP mass and the influence of changes in the liner material, which are discussed in the next section.

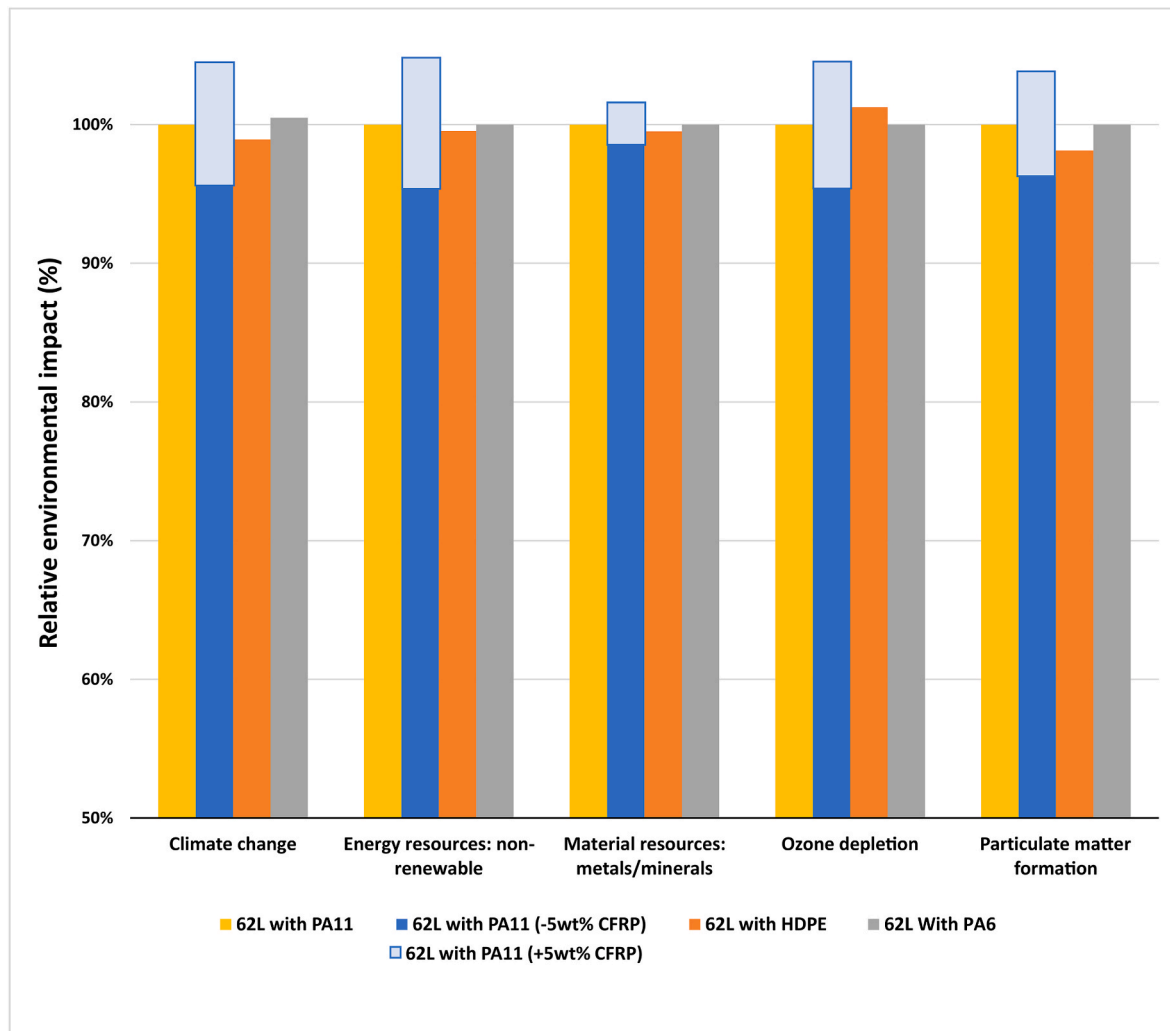


Fig. 7. Sensitivity analysis of 62L tank configuration to liner material and CFRP mass variation.

The results show that climate change varies by approximately $\pm 4\%$, while energy resources: non-renewable, ozone depletion, and particulate matter formation vary by up to approximately $\pm 5\%$. Material resources: metals/minerals is less sensitive, with a variation of approximately $\pm 2\%$. These differences reflect the contribution of the CFRP overwrap to the life-cycle environmental impacts, particularly the contribution associated with carbon fibre production.

Overall, the sensitivity analysis shows that a $\pm 5\%$ variation in CFRP mass results in changes of no more than approximately 5% for the selected impact categories. The comparative conclusions of the LCA therefore remain robust within the range investigated, while the analysis highlights the importance of CFRP mass when comparing Type IV tank solutions from different manufacturers.

4.3.3. Sensitivity to changes in the liner material (62L tank, 700 bar)

In this study, the same liner mass is considered for all configurations in order to isolate the influence of material substitution. It should be noted, however, that in practice the liner thickness, and therefore its mass, may vary in order to ensure the same gas barrier performance. This is due to differences in hydrogen permeability coefficients between materials. For instance, reported hydrogen permeability values are typically on the order of $1.87 \times 10^{-14} \text{ (cm}^3\text{·cm)/(cm}^2\text{·s·Pa)}$ for PA11, $1.72 \times 10^{-14} \text{ (cm}^3\text{·cm)/(cm}^2\text{·s·Pa)}$ for PA6 and $5.88 \times 10^{-14} \text{ (cm}^3\text{·cm)/(cm}^2\text{·s·Pa)}$ for HDPE (Dong et al., 2023). Such differences could lead to adjusted liner thicknesses in an engineering design.

When varying the liner material, a moderate impact variation is

observed for PA11, mainly driven by differences in polymer production routes and associated energy demand. In contrast, no significant change is observed for PA6 in the present model, as it is treated as an approximated fossil-based polyamide in the database. It should be emphasized that PA11 is a biogenic polymer derived from castor oil. If this biogenic origin were fully accounted for, it could lead to a reduction in the climate change impact through a temporary CO_2 storage credit. However, this benefit would likely be offset by a deterioration of the land-use indicator, due to agricultural feedstock production. Unfortunately, robust and consistent life-cycle inventory data are currently not available to accurately quantify these effects, and they are therefore not included in the present assessment.

Overall, the results clearly show that changing the liner material has a negligible influence on the total environmental impact of the hydrogen storage system when compared to a $\pm 5\%$ variation in the CFRP mass. Since the CFRP dominates the life-cycle impacts of type IV tanks, material optimisation efforts should primarily focus on the composite shell. Nevertheless, if a change in liner material is required for engineering reasons, such as improved hydrogen tightness or enhanced resistance to severe rapid gas decompression conditions, as reported in the literature, the associated environmental impact remains marginal at the system level.

5. Conclusion

We present a comparative life cycle assessment of several

configurations of type IV compressed hydrogen storage tanks for heavy-duty mobility applications. The functional unit is defined as ensuring a driving range of 700 km for a 44-ton heavy-duty truck, powered by a hydrogen fuel cell, without refuelling. Four configurations differing in the number of tanks, volume, geometry, and operating pressure were analysed. Sensitivity analyses were performed on key design parameters and end-of-life scenarios of the CFRP overwrap. Five key results can be highlighted.

Firstly, carbon fibre reinforced polymer (CFRP) overwrap and BOP components are the dominant contributors to environmental impacts over the life cycle of type IV tanks. These two elements account for more than 90% of the impacts in most categories. The contributions of the liner and metallic bosses are marginal in comparison. The high contribution of CFRP is mainly driven by the energy and resource-consuming production of carbon fibres, whereas the BOP strongly influences indicators related to metal and mineral resource depletion.

Secondly, the comparison between configurations highlights the critical influence of global geometry on environmental performance. For tanks with similar external dimensions, a lower operating pressure leads to a reduced CFRP mass per unit but results in a significantly higher number of tanks required to meet the functional unit. This multiplicative effect ultimately generates higher impacts, particularly for material resource depletion. As a consequence, lower-pressure solutions do not offer environmental benefits at the system level.

Third, among the configurations operating at 700 bar, the large-volume 62L tank clearly emerges as the environmentally preferable option across all impact categories. Despite only moderate improvements in gravimetric efficiency compared with smaller tanks, the reduction in the number of vessels required leads to substantial impact reductions. Climate change impacts are reduced by approximately 70%, while impacts related to metal and mineral resource use decrease to around 20% of the reference configuration. These results emphasize the importance of compact designs with low length-to-diameter ratios in reducing cumulative material demand.

Fourth, the analysis of life cycle stages shows that the use phase dominates total impacts when the full-service life of 11,000 filling cycles is considered, due to the energy required for hydrogen compression and cooling. Moreover, the end-of-life stage can provide significant environmental credits when efficient recycling routes are implemented. In particular, solvolysis and pyrolysis of CFRP offer the highest benefits, highlighting the strategic importance of developing advanced composite recycling technologies. These scenarios require acceptance of the reuse of recycled carbon fibre for pressure vessels, with all the variability and uncertainty in mechanical behaviour that this may entail. This may lead to heavier structural load-bearing components.

Fifth, sensitivity analyses demonstrate that moderate variations in liner material or in CFRP mass have a limited influence on overall results compared with design choices affecting tank number and geometry. Changes in liner material remain environmentally negligible relative to CFRP-related effects, enabling the investigation of new materials for liners to improve permeability or resistance to rapid gas decompression in case of emergency. This also suggests that design optimisation efforts should primarily focus on reducing the amount of carbon fibre required and improving recycling route efficiency.

6. Limitations and perspectives

The present study provides a comparative environmental assessment of several type IV hydrogen storage tank configurations. Here, a configuration refers to a set of tanks with the same volume and the same operating pressure, as well as the associated peripheral equipment, enabling the chosen functional unit to be achieved. However, some limitations should be acknowledged when interpreting the results.

First, while the comparison of the 9 L, 23 L and 62 L tank configurations provides valuable insights into the influence of tank size and pressure rating on environmental performance, some of these

configurations, particularly the 9 L designs, do not represent realistic storage architectures for heavy-duty vehicles when directly scaled to the functional unit. In practice, satisfying the hydrogen demand associated with the functional unit would require a very large number of small tanks, leading to integration and system complexity constraints that would be impractical for onboard applications. Heavy-duty hydrogen vehicles generally rely on a limited number of large-capacity tanks. For example, tanks with capacities on the order of 200 L could satisfy the functional unit with approximately six tanks, resulting in a storage architecture that is considerably more representative of real vehicle integration requirements.

Nevertheless, the objective of this work was not to propose a deployable onboard storage architecture, but rather to compare different tank configurations on a common functional basis and identify the influence of tank design parameters on environmental performance. The investigated configurations therefore constitute representative design cases that enable the evaluation of scaling effects and material contributions.

The inclusion of large-capacity tanks was not possible in the present study due to the lack of detailed design and life cycle inventory data. Reliable information regarding tank geometry, composite overwrap mass and manufacturing parameters remains scarce for such storage systems. Consequently, future study should extend the assessment to realistic heavy-duty storage architectures based on large-volume tanks in order to provide a more representative evaluation of the environmental performance of onboard hydrogen storage systems.

The present LCA focuses exclusively on the hydrogen storage system, while the vehicle itself lies outside the system boundary. Consequently, neither the vehicle lifetime nor the potential reuse of the storage system across successive vehicles is considered in the present study. Nevertheless, such reuse could be assessed by adopting a broader system boundary. For instance, assuming a theoretical service mileage of approximately 7.7 million km for the H₂ storage system, based on 11,000 fill/drain cycles, and a lifetime mileage of approximately 1 million km per heavy-duty vehicle according to the directive 2009/33/EC (European Parliament and Council of the European Union, 2009) on the promotion of clean and energy-efficient road transport vehicles, the same storage system could theoretically be used successively in approximately seven heavy-duty vehicles. In addition, following its use in heavy-duty mobility, a Type IV tank could potentially be repurposed for stationary hydrogen storage applications operated at pressures lower than its original design pressure, provided that its residual structural integrity and suitability for the new operating conditions are verified. These potential reuse and second-life scenarios are beyond the scope of the present study.

As for future perspectives, the study considered use values from the literature without providing detailed information on the model assumptions, and the lack of access to the carbon fibre model prevents a deeper level of verification. A closer examination of the production model is therefore required to identify sources of variability, such as process efficiency, electricity and heat demand, and solvent demand, which depend on manufacturer know-how.

The transition toward type V composite tanks integrating carbon fibres with thermoplastic matrices offers improved recyclability at the composite level, facilitating end-of-life recovery and material circularity. In parallel, additional reductions in environmental impact may be achieved by progressively substituting carbon fibres with lower-impact bio-based reinforcements, such as flax or hemp fibres, provided that mechanical performance and durability requirements are maintained.

Despite these limitations, the present work provides robust insights into the key drivers of environmental impacts associated with compressed hydrogen storage systems for heavy-duty mobility. The results highlight structuring trends that are sufficiently consistent to inform future design and integration strategies for Type IV tanks, and more broadly for compressed hydrogen storage technologies. In this regard, the findings offer valuable perspectives for assessing the sustainability of

hydrogen-based solutions in heavy-duty transport applications.

CRedit authorship contribution statement

Imad Karim: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **David Chapelle:** Writing – review & editing, Writing – original draft, Validation, Supervision, Project administration, Funding acquisition, Conceptualization. **Anne Maynadier:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Conceptualization. **Frédéric Thiébaud:** Writing – original draft, Supervision. **Hervé Mathis:** Data curation. **Stéphane Villalonga:** Data curation.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Imad KARIM, David CHAPELLE, Anne MAYNADIER reports financial support was provided by French National Research Agency (ANR) under France 2030 program and reference ANR-PEHY-0004 (project PEPH2-HyperStock). Imad KARIM, David CHAPELLE, Anne MAYNADIER reports financial support was provided by EIPHI Graduate School (contract ANR-17-EURE-0002) and the Region Bourgogne Franche-Comté. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.cesys.2026.100523>.

Data availability

Data will be made available on request.

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